Integrating Fire Suppression into a DEVS Cellular Forest Fire Spread Model

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Keywords: Atomic model, coupled model, forest cell, fire spread, Parallel DEVS

Abstract

This paper deals with modeling and simulation of surface forest fire spread and suppression using the discrete event system specification (DEVS) cellspace approach. The event-based modeling approach allows for timely simulation-based predictions of forest fire spread and suppression in uniform and non-uniform environmental conditions. This paper proposes a conceptual model for a coupled forest cell model comprising of a *forest cell agent atomic model* and a *forest cell atomic model*. The forest cell agent atomic model will allow for modeling and simulation of more complex fire suppression strategies to control fire spread. The proposed basic model provides an advance toward developing a real-time or fast-as-can decision support simulation system for predicting forest fire spread and the effects of fire suppression attempts.

1 INTRODUCTION

Forest fires or wildfires are an ecological problem that has come to the attention of many societies today due to their frequent occurrence and destruction. [Andrews and Queen 2000] points out that at the strategic level greater attention must be focused on the underlying causes, the effect of land management on fire ecology, wildfire risk, the dynamics of vegetation fuel, and how to reduce the likelihood of catastrophic fires . However, once a forest fire has being ignited, a real-time or fast-as-can simulation decision support system for accurately predicting where and how fast the fire will spread is needed at the tactical level.

Modeling and simulation of an ecological problem concerned with propagation processes, such as a forest fire, often requires to develop models that take into account the system evolution in both time and space. Thus such problems are generally of a large-scale nature and are hard to model and simulate efficiently. In addition, the models for simulating the processes underlying the ecological problems are spatially distributed and require large amounts of data. Recently there has been an interest in developing discrete-event-based models and simulations towards addressing this problem. [Ntaimo et al., 2004] develops a cellular DEVS model [Zeigler et al., 2000; Zei-

ISBN: 1-56555-290-8

gler and Sarjoughian 2002] of forest fire spread that includes fire suppression control measures. The cellular DEVS modeling approach is chosen due to its ability to effectively represent large-scale spatial dynamic phenomena for timely simulations [e.g. Ameghino et al., 2001; Muzy et al., 2002; Zeigler 2003].

In the cellular DEVS approach, the actual forest is divided into forest cells. Fire spread is abstracted and modeled within a forest cell as follows. First, a one-dimensional rate of fire spread and direction using a given fire spread mathematical model such as Rothermel's model [Rothermel 1972] is computed. This model uses the forest cell fuel properties, topography, wind speed and direction as input. Once the major rate of spread and direction are determined, a decomposition algorithm is applied to calculate fire spread in two dimensions. Fire spread is modeled as spreading from the center of an ignited cell towards the neighbor cells.

This separates all fire suppression aspects from the forest cell atomic model, which is concerned with fire spread computations, and designates them to the forest cell agent atomic model. This separation would allow for flexibility in simulating more complex forest fire suppression scenarios.

The rest of this paper is organized as follows. In the next section we give a brief review of fire suppression activities. In Section 3 we present the proposed forest cell coupled model. In section 4 we express the forest cell agent atomic model in Parallel DEVS and provide concluding remarks and future research directions along this line of work in Section 5.

2 FOREST FIRE SUPPRESSION

Societies today are faced with the challenge of being able to effectively suppress wildfires in order to limit the damage and loss that results from these wildfires. We refer the reader to [Martell 2001] for a comprehensive review on forest fire management. [Parks 1964] developed a simple single fire suppression model that is used in describing how components of a fire management system interact to determine the final area burned as well as the economic impact of the fires.

Forest fire suppression activities can briefly be described after [Martell 2001] as follows. Fires are started by people or some natural agent such as lightning. Once ignited, the forest fires burn with an active open flame and emit smoke until they are either extinguished due to lack of combustible fuel or detected and reported to the duty officer (initial attack dispatcher). It is the initial attack dispatcher who decides what type of suppression resources will be dispatched to the fire. The initial crew travels to the fire and sets up its suppression equipment and begins fire suppression action as soon as possible. In some cases the ground crew is assisted by air-tankers that drop water or fire retardant on, or just ahead of the active fire front.

The effectiveness of the fire suppression efforts depends on the composition of the fire fighting crew, how soon the crew arrives at the fire, the fuel and terrain in which the fire is burning, the weather conditions, and of course the fire's behavior. [Andrews 1986] and [Rothermel and Rinehard 1983] have proposed four general reliable rules for fire suppression. The rules are based on fireline intensity (fli) or flame length (fln) and can be summarized as follows:

1. if ($fln < 1.2$ meters) fires can generally be attacked at the head or flanks of the fire by persons using hand tools.
2. if ($1.2 \leq fln < 2.4$ meters) fires are too intense for direct attack at the head of the fire by personnel with hand tools but equipment such as bulldozers and retardant aircraft may be effective.
3. if ($2.4 \leq fln < 3.4$ meters) control efforts of the fire will probably be ineffective. Indirect attack is probably the only means of suppression.
4. if ($fln \geq 3.4$ meters) control efforts at the head of the fire are ineffective by any known means of suppression. Indirect attack may be the only means to slow the spread of the fire in certain directions.

We incorporate the above four rules in the proposed forest cell coupled model which is described next.

3 THE DEVS FOREST CELL COUPLED MODEL

The proposed forest cell coupled model comprises of a *forest cell agent* atomic model and a *forest cell* atomic

ISBN: 1-56555-290-8

model in a hierarchical manner as shown in Figure 1. Unlike the forest cell atomic model introduced in [Ntaimo et al., 2004], the proposed forest cell coupled model has all the fire suppression activities removed from the forest cell and are modeled by the forest cell agent atomic model. In addition, we introduce a forest fire suppression *dispatcher* model (not shown in the figure) that is higher in the hierarchy and is in charge of initiating fire suppression efforts. The dispatcher will model the activities of the initial attack dispatcher or duty officer in charge of dispatching suppression efforts (forest cell agents) to forest cells.

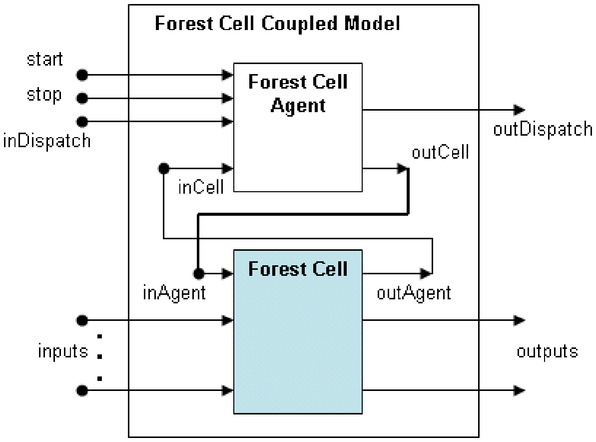

Figure 1: The forest cell coupled model

The proposed approach of having a forest cell coupled model has the advantages of separating the concerns of dealing with fire suppression from those of fire spread. For example, fire suppression rules can be modeled separately in the forest cell agent atomic model without concern about the fire spread model calculations, which will be done in the forest cell atomic model. However, the proposed approach has the disadvantages of increased communication and couplings within and among the forest cell coupled models in a cell space. Nevertheless, the distributed simulation techniques as well as the computational power available today may overcome these disadvantages.

In Figure 1 the external input port “inDispatch” and the external output port “outDispatch” to the forest cell coupled model allows for modeling information exchange between the initial attack dispatcher and the forest cell agent. The information passed from the initial attack dispatcher to the forest cell agent via the “inDispatch” port will constitute fire suppression commands (*cmds*) to the agent, while the feedback ($fdbk$) on the progress of the fire suppression efforts on the forest cell will be passed back to the dispatcher via the “outDispatch” port. The external input and output ports “inputs” and “outputs”, respectively, allow for forest cell neighbor-to-neighbor couplings and fire spread information exchange as defined in [Ntaimo et al., 2004]. The coupled model also has two additional inputs, “start” and “stop”, for initializing and stopping the simulation, respectively.

The internal input ports “inCell” and “inAgent” to the forest cell agent and forest cell atomic models, respectively, and the corresponding internal output ports “outCell” and “outAgent”, allow for modeling information exchange between the two atomic models. The information through the port “inCell” is the sensed feedback on the agent’s fire suppression efforts on the forest cell. The nature of this information depends on the sensing capabilities assigned to the forest cell agent. In this basic model we will assume that this information is a triple $\{cellphase, fli, fln\}$, where *cellphase* is the current state of the forest cell, fli is the *fireline intensity* and fln is the *flame length*) of the fire in the forest cell. The forest cell agent’s fire suppression efforts on the forest cell are transmitted through the port “outCell”. In this basic model this information will consist of a pair $\{delay, stype\}$, where *delay* is the random duration of the agent’s fire suppression efforts, and *stype* is the type of fire suppression (*direct* or *indirect*) on the forest cell. Next we describe the *forest cell agent* and the *forest cell* atomic models in more detail.

3.1 The DEVS Forest Cell Agent Atomic Model

We now describe a basic forest cell agent atomic model that can be extended to allow for modeling more complex fire suppression strategies. The model will follow after [Ntaimo, et al., 2004] who adapt the four general reliable rules for fire suppression [Andrews 1986; Rothermel and Rinehard 1983] summarized in Section 2. Based on the four rules we propose a forest cell agent model with four basic states, *passive, to-attack, direct-attack and indirect-attack*, as shown in Figure 2. Additional states can be incorporated into the model based on the complexity of fire suppression strategies to be modeled. The forest cell agent atomic model is initialized in the *passive* state with the agent's type of fire suppression capabilities defined by the initial dispatcher. The type of fire suppression capabilities could be personnel on the ground with hand tools, air-tankers with water-based fire retardant, and so on. In this basic model we allow for two fire fighting strategies; *direct* and *indirect* attack. Direct attack means that fire suppression efforts are directed at the head or flanks of the fire (rules 1 and 2 hold), while indirect attack refers to fire suppression efforts in forest cells that have not caught fire yet (when rules 3 and 4 hold).

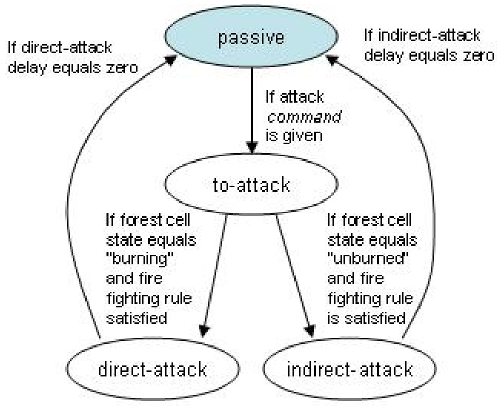

Figure 2: Forest Cell Agent State Transitions

We note that in any type of fire suppression effort there is a chance that the fire can escape since the effectiveness of the initial fire attack force depends upon its composition, how soon it arrives at the fire, the fuel and terrain in which the fire is burning, and the fire's behavior [Martell 2001]. Thus we simply model the fire suppression effort of a given forest cell agent atomic model in terms of a random *delay*, which represents the time it takes to perform the suppression effort, and *stype*, the type of fire suppression (direct or indirect) on the forest cell. Calculation of the random delay would be based on the composition of the attack crew as well as the fire's behavior. The probability of fire escape in a given forest cell can also be incorporated into the model. This information will be assigned to the forest cell agent by the initial attack dispatcher.

3.2 The DEVS Forest Cell Atomic Model

We now provide further details on the conceptualization of a DEVS forest cell atomic model with fire suppression activities removed and designated to the forest cell agent model. We refer the reader to [Ntaimo et al., 2004] for a detailed discussion on fire spread aspects of the cell. Since all fire suppression computations and effects on the forest cell are now performed by the forest cell agent model, the forest cell atomic model will have the basic states shown in Figure 3

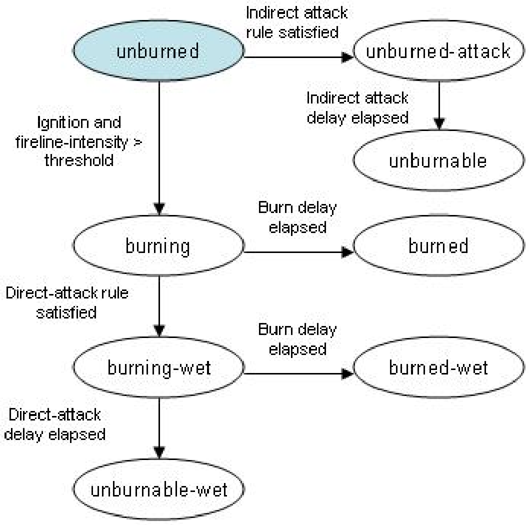

Figure 3: Forest Cell State Transitions

The forest cell atomic model is initialized in the *unburned* state. In this state only indirect fire suppression efforts will lead the cell into the *unburned-attack* state. The cell will stay in this state for the duration of the indirect fire suppression efforts. This duration is a random time *delay* computed by the forest cell agent model and passed on to the forest cell atomic model. Once this delay elapses, the cell transitions into the *unburnable* state. In the forest cell atomic model presented in [Ntaimo et al., 2004] the two states *unburned-attack* and *unburnable* are represented by one state, the *unburned-wet* state.

If on the other hand the cell is in the *burning* state, only direct fire suppression efforts are possible. This allows for the cell to transition into the *burning-wet* state. The cell stays in this state for the duration of the direct fire fighting efforts or until the cell burns out. If the fire fighting efforts are successful, the cell transitions into the *burned-wet* state. Otherwise, the cell burns out and transitions into the *burned-wet* state. The duration of the direct fire fighting efforts is a random delay determined by the forest cell agent atomic model, while the duration of the burning process is computed within the forest cell atomic model using a fire spread algorithm (e.g. [Rothermel, 1972]).

Finally, if there are no fire suppression efforts on a forest cell in the *burning* state, the cell burns out and transitions into the *burned* state. Again, the duration of the burning process is computed within the forest cell atomic model using a fire spread algorithm.

4 EXPRESSING THE FOREST CELL AGENT MODEL IN PARALLEL DEVS

We now demonstrate how the proposed forest cell agent model can be expressed in Parallel DEVS [Zeigler and Sarjoughian 2002]. We first state the formal definition of Parallel DEVS. A basic Parallel DEVS is a structure:

$$DEVS = (X_M, Y_M, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$$

where

$X_M = \{(p,v) \mid p \in InPorts, v \in X_p\}$ is the set of input ports and values;

$Y_M = \{(p,v) \mid p \in OutPorts, v \in Y_p\}$ is the set of output ports and values;

S is the set of sequential states;

$\delta_{ext} : Q \times X_M^b \rightarrow S$ is the external state transition function;

$\delta_{int} : S \rightarrow S$ is the internal state transition function;

$\delta_{con} : Q \times X_M^b \rightarrow S$ is the confluent transition function;

$\lambda : S \rightarrow Y^b$ is the output function;

$ta : S \rightarrow R_0^+ \bigcup \infty$ is the time advance function;

with $Q := \{(s,e) \mid s \in S, 0 \leq e \leq ta(s)\}$ the total set of states.

The forest cell agent atomic model can be defined in Parallel DEVS as follows:

$$DEVS = (X_M, Y_M, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$$

where

$X_M = \{(p,v) \mid p \in InPorts, v \in X_p\}$ is the set of input ports and value pairs with InPorts = {"start", "stop", "inDispatch", "inCell"}, $X_{inDispatch} = \{cmds\}$, and $X_{inCell} = \{cellphase, fli\}$;

$Y_M = \{(p,v) \mid p \in OutPorts, v \in Y_p\}$ is the set of output ports and values pairs with OutPorts = {"outDispatch", "outCell"}, $X_{outDispatch} = \{fdbk\}$, and $X_{outCell} = \{delay, stype\}$;

To define the other parameters in the expression for DEVS we introduce the following additional variables: *phase* denotes a control state that is almost always used in DEVS models to keep track of where the full state is; σ holds the time remaining to the next internal event. This is precisely the time-advance value to be produced by the time-advance function; and e is the elapsed time in a given state.

External Transition Function:

$\delta_{ext}((phase, \sigma, cmds, cellphase, fli, fln), e, (p,v))$
$=$
("passive", $\infty, cmds, cellphase, fli, fln$),
if $p =$ "start"
($phase$, $\infty, cmds, cellphase, fli, fln$),
if $p =$ "stop"
("to-attack", 0, $cmds, cellphase, fli, fln$),
if $phase =$ "passive" & $p =$ "inDispatch"
$\{delay, stype\}$ = `computeFireAttackDelay(`$cmds$`,` $cellphase$`,` fli`,` fln`)`
$(phase, \sigma - e, cmds, cellphase, fli, fln)$
otherwise;

Internal Transition Function:

$\delta_{int}((phase, \sigma, cmds, cellphase, fli, fln), e, (p,v))$
$=$
("direct-attack", $delay, cmds, cellphase, fli, fln$),
if $phase =$ "to_attack" & $cellphase =$ "burning" & $stype = direct - attack$

("indirect-attack", $delay$, $cmds$, $cellphase$, fli, fln),
if $phase =$ "to_attack" & $cellphase =$ "burning" & $stype = indirect - attack$
("passive", ∞, $cmds$, $cellphase$, fli, fln),
Otherwise;

Confluence Function:
$\delta_{con}(s, ta(s), x) = \delta_{int}(\delta_{ext}(s, 0, x))$;

Output Function:
λ(phase, σ, $cmds$, $cellphase$, fli, fln) =
(outDispatch, this.$cellid$, $fdbk$)
if $phase =$ ("direct-attack" || "indirect-attack") & $delay = 0$
(outCell, $\{delay,\ stype\}$)
if $phase =$ "to-attack"
$\emptyset$ (null output)
otherwise;

Time advance Function:
$ta(\text{phase}, \sigma, cmds, cellphase, fli, fln) = \sigma$;

We have demonstrated how to directly express the forest cell agent model in Parallel DEVS. However, we omit the expression of the forest cell atomic model in Parallel DEVS due to space considerations. The expression is similar to that given in [Ntaimo and Zeigler, 2004] for a forest cell model used in the fire spread model presented in [Ntaimo et al., 2004].

5 CONCLUSION

Modeling and simulation of surface forest fire spread has to include fire suppression attempts in order to develop a real-time or fast-as-can decision support simulation system for predicting forest fire spread and the effects of fire suppression attempts. This paper has proposed integrating a forest cell agent atomic model into the forest cell model. The advantage of the proposed forest cell coupled model is to separate fire suppression concerns from the forest cell atomic model, which is concerned with fire propagation calculations. This would enable more flexibility in simulating diverse fire suppression scenarios more realistically since the fire suppression control rules are separate from the forest cell atomic model.

Future research along this line of work includes implementation of the proposed forest cell coupled model and simulation of realistic fire spread and suppression scenarios using the proposed model. This work will require integration of fire behavior modeling and suppression into the ArcInfo GIS environment. The model would provide the needed comprehensive fire behavior prediction and suppression information to the forest resource managers where it can be most effectively applied.

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ISBN: 1-56555-290-8

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