Modelling Wildfire Dynamics via Interacting Automata

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Abstract. The modelling of wildland fire spread across a heterogeneous landscape is significant because fire dynamics are sensitive to local spatial characteristics. The development of accurate fire models and simulations is important due to the economical and social losses wildland fire can cause and the resulting need to better understand, predict, and contain fire spread. We present a methodology for encoding the spread of wildland fire in a set of interacting automata. The Circal formalism is used to explicitly describe the transmission of fire as an interaction between discrete cells of landscape. We demonstrate the potential for the methodology to accurately model spatial dynamics by giving results of our implementation of a fire spread model that includes a heterogenous environment.

Keywords: modelling wildfire spread, cellular automata, Circal.
CR Classification: F.1.1 Models of Computation and I.6.5 Modeling Methodologies.

1 Modelling fire spread

Fire spread is a phenomenon that deserves attention from scientists; not just because it is socially and economically important, but also because the phenomenon is complex, difficult to model, and computationally expensive to simulate. Indeed, there does not exist a verifiable method for better-than-real-time simulation of the phenomenon. The heterogeneity of a landscape is a specific problem of fire spread simulation. The landscape comprises the heterogeneous variables fuel (including fuel load, fuel type, moisture), slope of terrain, and wind direction and strength. In Section 2, we describe our method for capturing the heterogeneities of the landscape in the state of finite automata and for building a structure of connected automata as depicted in Fig. 1. We then describe a method for describing the interaction of these automata that is also heterogenous; the next-state transitions depend on the features of the landscape.

Throughout the world, and specifically in Australia where the climate is dry and hot, wildland fire is a significant problem because it causes loss of life and property. The scientific challenge is to produce accurate, spatially dependent models and tractable, powerful simulations that can be used to investigate 'what if' questions, containment strategies, and to develop training tools for firefighters.

Rothermel's research on understanding the physics of fires [1], forms the basis for many approaches to modelling the behaviour of fires in wildland environments. Some approaches to modelling fire spread are discussed in Section 1.1.

1.1 Related Research

Previous approaches to modelling the fire spread phenomenon can be categorised as either empirically-based, physically-based, or a combination of both of these. The techniques used to implement these models include cellular automata techniques (such as Cell-DEVS and other formalisms that involve discretisation) [2–5], numerical implementations of differential equations [6–9], fractal geometry [5], and artificial neural networks [10]. In this section, we highlight the problems faced by researchers when trying to deal with the heterogeneous nature of real landscapes in fire spread simulations using cellular automata techniques.

Bossert et al. [11] validate their simulation against a real scenario where the turbulence of wind (the turbulence is affected by wind speed and the fire itself) caused a marked increase in the spread of the fire due to convection. Research

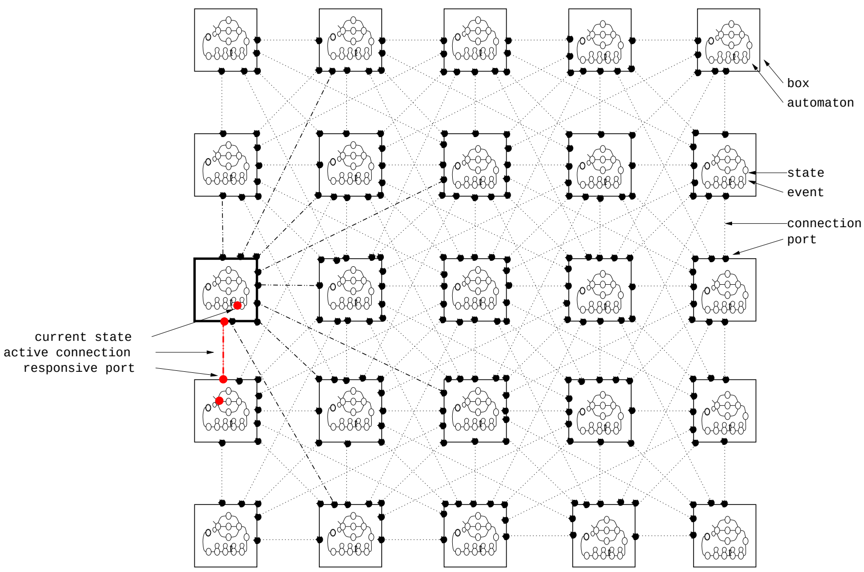

Fig. 1. This figure shows the structure of a simple homogeneous landscape of 25 cells. The state of the centre-left cell (burning) causes a synchronisation of actions/events between the automaton of the centre-left cell and the automaton of the cell below it.

by Linn et al. [8, 9] clearly demonstrates the notion that a heterogeneous environment produces phenomena that cannot easily be predicted by extrapolating fine-scale experimental data.

Clarke et al. [5] uses a cellular automaton to implement a model based on fractal geometry. The research is significant because historic data is used to calibrate the model. The argument is presented in support of the fractal nature of wildfire spread; the spread of wildfire is highly sensitive to the heterogeneities of the landscape and initial conditions, and fire is self-replicating. One of the distinct differences between the implementation by Clarke et al. and ours, is that we use heterogeneous wind and fuel and we do not use weighted, random processes to simulate the influence of heterogeneity of the landscape.

Muzy et al. have developed several implementations of a semi-physical model of fire spread [2] based on Rothermel's model [1]. They compare the different approaches to implementing the semi-physical model (namely DEVS and Cell-DEVS approaches [12, 13]) and conclude that a more rigorous method of quantisation is required for more accurate and computationally less expensive simulations [4]. Muzy and Wainer [3] have developed such an approach using Cell-DEVS quantisation techniques and they conclude that they have reduced the time taken to run a simulation and increased the accuracy of the results. The discrete, event-based implementation of a model based on Rothermel's original work has accounted for the time and space sensitivities of the fire spread simulation problem.

Our approach to modelling the fire spread phenomenon is different to the approaches described in this section because we explicitly describe the interactions between each discrete cell in the simulation landscape. We discretise the landscape in a way that is typical to cellular automata but then we encode the spatial information of that cell as input of the state of an automaton and use the interactions between the automata of different cells to determine the behaviour in a process algebra way.

In their Cell-DEVS approach, Wainer and Muzy [3] discretise Rothermel's equation for fire spread by the state of the fire (heating, burning, and burnt), but they use continuous arithmetic to describe the heat exchange between cells. We avoid the use of continuous arithmetic for heat exchange by defining a discrete propagation delay (detailed in Sect. 2) that is discrete in both space and time, and relies on a discrete addition operator instead of a continuous multiplicative one. In Sect. 3 we show that we can achieve good results in the simplified homogeneous case using this technique.

2 Modelling Spatial Dynamics via Interacting Automata

Our approach for modelling the fire spread phenomenon is to use interacting automata. This approach requires the discretisation of the landscape into (usually) equally sized cells. The discretisation of the spatial information that determines the spread on a cell-by-cell basis is encoded within each cell's automaton in terms of state and a next-state transition function.

The automaton that corresponds to a specific cell is a finite automaton (deterministic or probabilistic) with a set of states S, alphabet Σ, a next-state transition function δ, and an initial state i. In this section we present an argument for this approach and show how to encode the fire spread model in a set of interacting automata.

How is the information encoded in the automaton? The state of the automaton captures the spatial features of the particular cell to which it belongs. The state ($s \in S$) of the automaton is defined by the set comprising slope gradient, slope orientation, wind, and fuel as follows:

$$\begin{aligned}
\text{state} \quad s \,:\, & S = F \times T \times W, \text{ where} \\
T &= S\ell \times O, \\
S\ell &= \{flat, slight, mid, steep\}, \\
O &= \{n, s, e, w\}, \\
W &= \{f, n, nw, w, sw, s, se, e, ne\}, \text{ and} \\
F &= \{unburnt, burning, burnt\}.
\end{aligned}$$

The above sets refer to the gradient (slope $S\ell$), the aspect (orientation O) of the terrain T, the wind direction W, and the state of the fuel F at the location of each cell. Figure 2 shows the deterministic finite automaton in which this information is encoded for the example where the slope is mid-ranged (mid), the orientation of the slope is northerly (n), the wind is easterly (e), and the fuel is not yet burnt ($unburnt$).

The state of an automaton captures the spatial information of the cell to which it belongs, and this encoding is therefore a heterogeneous description of the landscape. Figure 2 depicts the state and labelled transitions of the finite automaton where the cell slopes upwards towards the north and has an easterly wind direction. We have used a similar discretisation of fuel as Wainer and Muzy [3], but we also use discrete values for the description of wind and terrain. The result of this approach is a set finite automata that are encoded with information describing the landscape as a combination of terrain, wind, fuel, and fire.

2.1 The Significance of the Circal Formalism

To allow the automata to interact, we need to capture explicit, non-homogeneous interaction between automata. For this, we use Circal [14–16], a process algebra that has been used for describing and verifying complex systems such as digital hardware including asynchronous logic and communication protocols. In this section, we detail the use of the Circal formalism as a *specification language* for encoding the spatial dynamics of fire spread as a set of connected and interacting automata, after the landscape has been discretised using the cellular automata paradigm.

Circal is an appropriate formalism for this approach because it has the necessary constituents to permit these modelling concepts to be well-captured [17,18].

Circal is a rigorous formalism and allows concurrent communication between an arbitrary number of processes. We use Circal to explicitly describe the interactions between automata and encode the spatial information of each cell in the states of each automaton.

How do the automata interact? We impose a structure on the landscape as we discretise it; defining areas where fire communication may occur. The adjacent neighbours of a cell can see an abstracted view of the automata because of the way the structure is built. Below, we describe the terminology of the structure, and the procedure for determining the next state transition function.

The communication of fire spread between cells is captured by the actions of each automaton in conjunction with automata that it connects itself with. The *actions* (or transitions) of each automaton are the alphabet set Σ. We say that two automata are *connected* if their associated cells are neighbours as depicted in Fig. 1. In the case of the simulations described in this paper, neighbours will always include the area of cells within a radius (in the cellular automata sense of the word) of two from the cell in question, but two automata could be connected arbitrarily within the landscape using the methodology. This is equivalent to the neighbourhood term used in cellular automata based simulations. Figure 1

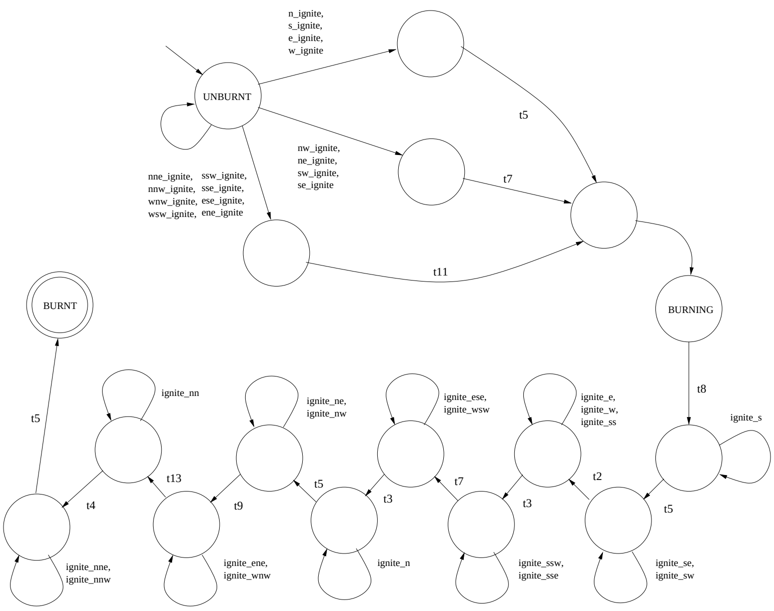

Fig. 2. This figure depicts the state and transition actions of a deterministic finite state automaton that encodes the slope, terrain, and fuel information of a cell in a landscape. This cell slopes upwards towards the north, has a midranged gradient, and has an easterly wind direction.

shows a landscape of size five by five and depicts all the cells that make up the neighbourhood of the centre cell. The centre-left cell and its connections are highlighted in the figure. The specific terms used in the figure are defined in the following paragraphs.

In the Circal formalism, the *composition operator* [18] uses similarly labelled actions to 'wire together' structures such as the cells in Figure 1. The dashed lines in Figure 1 are *connections* between connected automata are built using the composition operator. This is called the *synchronisation-of-actions* technique.

Cerone and Milne [19] describe a process for the hierarchical description of interacting automata in their research into asynchronous micropipeline digital electronics. The connections between cells are the medium for the spread of fire from one cell to another and are built between similarly labelled ports. The *ports* are associated with the actions in the automaton that are not abstracted as a part of the procedure described below:

1. All actions are *relabelled* to have the same name as the port they are connected to or to an anonymous name if they are not connected to a port.
2. The separate cells are *composed*; similarly named ports are 'wired up' with connections.
3. The actions inside each cell that are not connected to a port cannot be seen from outside the box and are *abstracted*.

Figure 1 shows an example of the structure that has been connected using the process described above. In this case, each of the actions in an automaton's alphabet Σ have been relabelled to reflect the coordinates of the associated cell in the landscape. The automata are composed to build connections using the Circal formalism's composition operator and the alphabet is reduced (abstracted) to remove the actions that are not visible from outside the cell.

The synchronisation-of-actions corresponds to the next state transitions function δ in the automata with the actions taken from the alphabet Σ. In this case, the transition function δ becomes a function that determines the next state of each automata based on a current set of enabled actions and hence indirectly on the state of the automata in the connected cells. An action is *enabled* if it can synchronise with the other similarly labelled actions through a *responsive* port. A port becomes responsive when all the associated actions emanate from the current states of the automata that they are associated with.

Why is it good to do it this way? We have developed a method for describing heterogeneous landscapes using finite automata and using a rigorous formalism to describe the interactions between the automata. The methodology couches the structure and operation of simulations in the paradigm of cellular automata.

Unlike the cellular automata approach, we define heterogeneous landscapes by encoding the spatial information as the state of each automaton. Like the classical cellular automata approach, the state information of the neighbours of a cell determines the next state of the cell. Although we use cellular automata principles to discretise the time and space of the model, the interactions between the cells are defined explicitly as a set of actions using the synchronisation-of-actions technique rather than as a homogeneous update.

3 Experiments and Results

We have identified heterogeneity of landscape as an important feature of modelling the fire spread phenomenon. In this section, we describe the experiments we have carried out using an implementation of the fire spread model. The main aim of these experiments is do demonstrate the effect of the abstractions we have made on the shape of the fire spread and to show the effect of simulating the heterogeneous landscape explicitly using interacting automata. All of the experiments conducted use a landscape with homogeneous fuel.

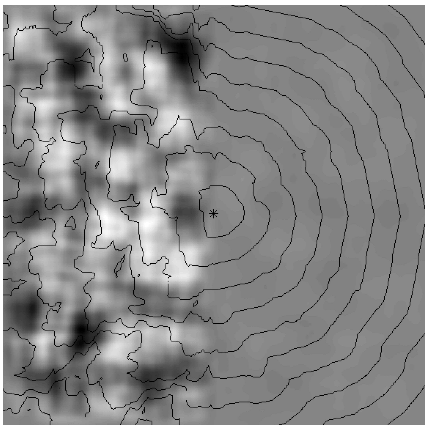

Fig. 3. This figure shows the effect of terrain on fire spread. The elevation of the terrain is indicated by the intensity (greyscale) and the contours indicate the position of the fire front at regular intervals. The effect of the direction and magnitude of the terrain's gradient on the rate of spread is visible; the greater the slope, the greater the difference in the rate of spread of the fire.

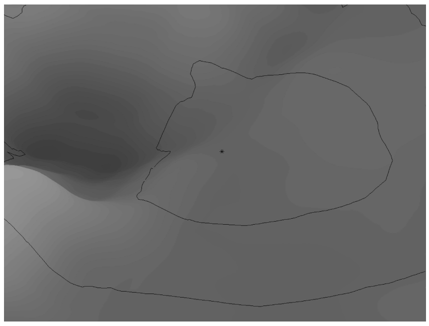

Fig. 4. This figure views a section of the simulation results presented in Figure 3 from a different position, highlighting the effect of terrain on the rate of spread of the fire. The fire front spreads more quickly on an uphill slope than on a downhill slope. The effect of the difference between uphill, flat, and downhill slopes on the shape of fire spread can be seen in this figure. The elevation is again given by the intensity.

Hargrove et al. describes how the shape of a fire front approximates an ellipse after it has burned for a period of time [20]. In the case of a homogeneous environment (homogeneous wind, flat terrain, and no wind), the ellipse degrades to a circle. Figure 3 demonstrates the difference between a near-flat terrain and a hilly terrain in a scenario that uses a homogeneous fuel landscape and no wind. More detail is shown in Figure 4, which is a different view of a section of the results presented in Figure 3. The results show the circular contours on flat terrain (the right hand side of Figure 3) and the effect of terrain on the rate of spread of the fire.

Balbi et al. and Santoni et al. describe the effect of slope on wildfire spread [21, 22] and the shape can be approximated by a double ellipse. From visual inspection of the results, we can conclude that the results of our experiment give a reasonable approximation to both the circular shape we expect in the case where the terrain is relatively flat and the elliptical shape we expect on a hilly terrain. Figure 4 gives a clearer view of the effect of slope on wildfire spread in our experiment that corresponds to the shape described by Balbi et al. and Santoni et al.

When wind was introduced into the scenario described above, the results showed that the effects of both wind and terrain on the shape of a spreading fire front are captured by the implementation that uses the interacting automata approach. The shape produced in Figure 5 is a good approximation of the ellipse expected for a northerly wind direction on a relatively flat terrain. The effect of both wind and terrain can be seen in Figure 6 where the effects of wind and terrain are captured together.

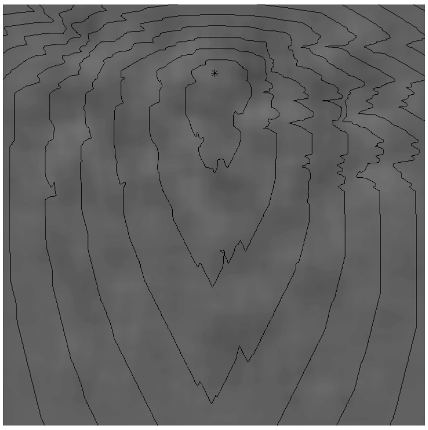

Fig. 5. This figure shows the effect of wind on a relatively flat terrain. An asterisk marks the ignition point, and the wind is homogeneous and its direction is from the top to the bottom of the figure. The contours represent the front edge of the spreading fire at regular intervals.

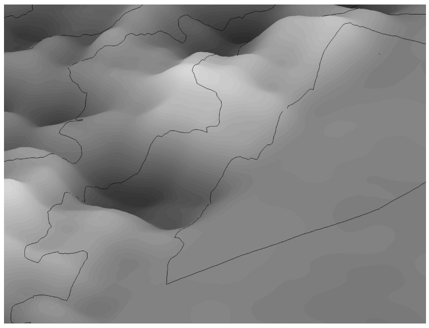

Fig. 6. A view of two types of terrains is presented in this figure. The top-left half of this figure represents a hilly terrain and the bottom-right of this figure represents a flat terrain. These results show the effect of wind (approaching from the top-right) on both flat terrain and hilly terrain. The effects on the shape of the fire front from both wind and terrain are demonstrated in this figure.

4 Discussion

In this paper, we have discussed the significant problem of wildfire spread modelling and introduced a methodology that can be used to capture spatial heterogeneity via state encoding and explicit actions given by current state. A method for capturing spatial heterogeneity as automaton state has been presented and demonstrated in a simulation environment. The suitability of the interacting automata approach to wildfire spread modelling has been demonstrated using the implemented simulator.

The results demonstrate the ability of the methodology to capture spatial heterogeneity of a landscape and simulate the spread of wildfire on a landscape that is regular and non-uniform. We have not addressed the calibration of the model or the effect of heterogeneous fuels in this model. The experiments detailed in the previous section are centred on the demonstration of the interacting automata approach and have shown that it can be used for heterogeneous environments. The interacting automata approach can reproduce the elliptical shape expected of a simulation of wildfire spread in a heterogeneous environment. The approach effectively captures the information about the landscape as the state of an automaton, and uses explicit communication between cells to describe the change in the landscape as the fire spreads.

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