AN APPLIED STEP IN FOREST FIRE SPREAD MODELLING

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KEYWORDS

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ABSTRACT

We report in this paper on an experiment in implementing a fire spread modelling system specifically dedicated to fire-fighting activities. First, the corresponding operational framework is introduced. In particular, we stress the importance of time constraints. Then, forest fire modelling techniques as well as some considerations related to our experience and feedback on this issue are briefly tackled. Then, we bring in a model which appears as a mix between the shape approach and raster based models. This one involves both a raster representation of the landscape and an elliptical shape based approach. We conclude on the fact that the corresponding software system calculates fire contours which are correlated with actual ones provided the basic local rates of spread are accurately estimated.

INTRODUCTION

Forest fires periodically devastate forest ecosystems and often threaten local populations. Hence, huge means are usually deployed in order to fight this curse. In this setting, fire growth prediction is a key-concept for forest fire suppression management. Consequently, numerous research works are dedicated to this field. However, for the time being, many of the latter remain in the scope of the academic world. In fact, the leading operational systems are dedicated to North-American climates and vegetation. The adaptation of the latter outside the specific areas they have been designed for seems to be a difficult approach to implement. For the Mediterranean basin, several tools have been developed, e.g. CARDIN (Caballero et al., 1994), FOMFIS (Caballero et al., 1999), E-FIS (Caballero et al., 2001), Fire-station (Lopes et al., 2002), a Greek system presented in (Vakalis, 2004) and Firetactic (Intergraph, 2006).

In all cases, the elaboration of software systems used on the ground by fire-fighter units and with the ability to perform accurate forest fire simulations remains the ultimate goal. Thus, we wish to stress the fact that the applied work presented in this paper has been conducted in close relationship with fire-fighters. Thence, all along the project, the different technical choices have been motivated by a permanent concern of pragmatism.

THE OPERATIONAL FRAMEWORK

Forest fire suppression management

The work described in this paper is part of the Asphodèle project (Dumond, 2006) which brings together, since 2002, the University of Savoie and a fire brigade from the South of France. In this framework, our goal is the implementation of a software system dedicated to forest fire suppression management. Hence, the following are the main functionalities offered by this system:

- The elaboration of numerical battlefields (Figure 1) which synthesizes, along the intervention, the situation on the ground. Hence, fire contour(s), spreading axes, location of the different engaged means, the implemented strategy, etc. are drawn onto different kinds of background map, e.g. geological survey maps, aerial photographs, etc.

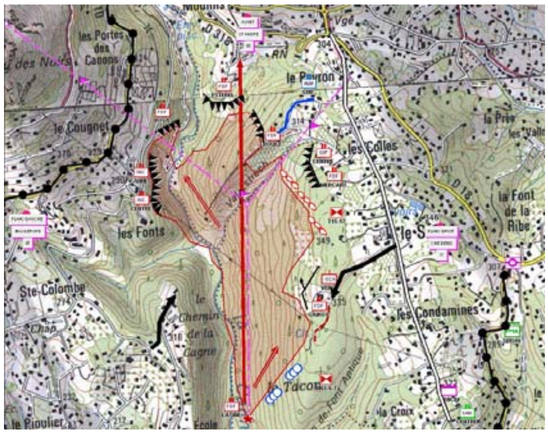

Figure 1: A numerical battlefield elaborated by means of the Asphodèle system © SDIS 06

- The management of all the mobile means involved in the fight, i.e. from the moment they have been requested up to the time they are relieved from their fighting duty. This implies a permanent contact between the officers who are at the head of the intervention and the units deployed on the ground. Moreover, the staff headquarters is periodically kept informed of the situation in the field.

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- Prospective activities, also called *anticipation*, which are directly related to fire growth and its potential consequences. These tasks are carried out by entrusted officers who are freed from the actual management of the intervention. Therefore, they can make accurate analyses in order to suggest evolutions in the implemented strategy. The reasonings carried out in this setting are based on careful study of the intervention zones by means of 3-D display and aerial photographs, as well as on numerical simulation. The contours of ancient fires which occurred in the same areas are also considered.

All the aforementioned tasks are achieved from two mobile command posts, i.e. heavy trucks specifically equipped for these purposes: one is the heart of the command line and the second hosts the anticipation tasks. In both cases, the corresponding embedded technology is made of several laptops with dedicated software and additional wide screens. Internet access through connection to the telephone network and radio communication are also provided.

Operational constraints related to anticipation

The anticipation tasks are strongly related to fire suppression management since part of their input data, e.g. fire contours, appear in numerical battlefields. What is more, they are generally performed in times of crisis with potential, if not actual, threats against population. This has at least two important consequences:

- A high level of inter-operability between the software components used to manage fighting activities and those implementing simulation is required.
- Numerical simulations must run efficiently on the available laptops. With respect to that issue, it is admitted that any simulation phase should not exceed a quarter of an hour: this clearly comes from the fact that any implementation of a new strategy on the ground requires a re-dispatching of the mobile means, which may take up to two hours.

The result furnished by an anticipation analysis is made of a digital battlefield including future estimated fire growth at a given term and the corresponding recommended strategy.

FOREST FIRE SPREAD MODELLING

Forest fire spread modelling is a multi-disciplinary field of research. Roughly speaking, it involves two kinds of work:

- Theoretical contributions which aim at elaborating physical models for forest fire spread. From a scientific point of view, this approach is clearly the most satisfying one insofar as it can potentially provide accurate results. However, it is generally hard, if not impossible, to put into practice for at least two reasons: first, it requires an amount of data which cannot generally be provided. For instance, if we consider models based on energy transfer, the precise quantity of burning fuel must be specified, which appears as an insurmountable problem with respect to the extreme heterogeneity of Mediterranean scrub. Second, these models are generally based on partial derivative equations systems which, at least for the moment, cannot be solved in real-time.
- Practical, i.e. statistical or semi-empirical, approaches which can be more easily implemented. Here, the corresponding models are partially the result of analytical works but also consist of the synthesis of numerous experiments, i.e. the corresponding formulae have been elaborated and validated empirically after the observation of actual forest fires (Martins Fernandes, 2001), (Dimitrakopoulos and Drita, 2003). Clearly, such pieces of information are strongly dependant on the setting they have been obtained in and therefore they generally cannot be used elsewhere. Among the tools related to models of this kind, the leading ones are the *Prometheus* system by the Forestry Canada Fire Danger Group (FCFDG, 1992) which has been accumulating data for several decades and the *Behave* (Rabner et al., 2001) and *Farsite* systems (Finney, 1998) from the United States Department of Agriculture which are based on the Rothermel's model (Rothermel, 1972).

Another important issue about fire spread modelling is the way the combined effect of wind and slope are taken into account. For many authors (Weise and Biging, 1997), (Viegas, 2004), these must be managed by means of a vectorial sum between the wind vector and an *equivalent-wind* slope vector. Note that this principle is the one that is applied in the Farsite system. Nevertheless, some studies, e.g. (Van Wagner, 1988), suggest that the influence of slope can be weighted through numerical coefficients that must be applied on the basic rates of spread. Based on experience, we have been led to the conclusion that the first approach is the right one.

At the end, let us mention that very good syntheses on forest fire spread modelling have been published in (Perry, 1998) and more recently in (Sullivan, 2007).

Shape based and raster based approaches

The software tools related to semi-empirical models are implemented either by means of a shape based or a raster based approach, e.g. cellular automata.

In the shape approach, fire contour is considered at time t. The local rate of spread is calculated for a given set of points belonging to the contour. Then, standard geometrical shapes, generally ellipses (Glasa and Halada, 2007) or double-ellipses, are drawn accordingly. At this stage, the corresponding set of shapes defines the fire contour at time $t + \delta t$ (Figure 2).

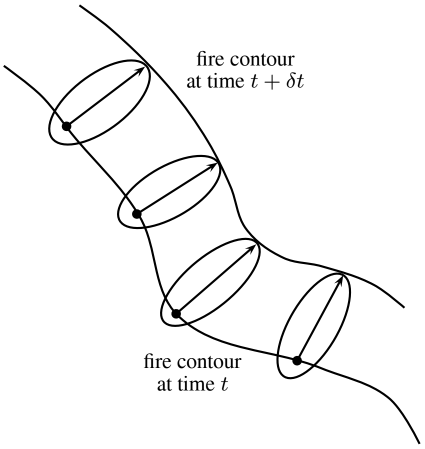

Figure 2: Shape approach based on ellipses

In cellular-automata based approaches (Bodrozic et al., 2006), (Hernándes Encinas et al., 2007), and more generally in raster based ones (Green et al., 1990), (Vasconcelos and Guertin, 1992), the landscape is divided into a large number of cells. The corresponding grid is generally defined under the form of a 2-D array of square cells. Nevertheless, hexagonal cells (Trunfio, 2004) are sometimes employed. In such a framework, the relevance of the system essentially depends on the set rules that specify the conditions of fire propagation between cells. Furthermore, raster based software systems run faster than those based on shape approaches.

OUR EXPERIENCE FEEDBACK

In an earlier work (Dumond, 2007), we have implemented a software system for fire spread modelling. The latter was mainly dedicated to peri-urban areas characterized by a little accentuated relief. Thus, the salient features of this system were the following:

- We worked with the proviso that, in any case, fire would spread in the direction of local winds. Hence, the effect of slope was taken into account by means of numerical coefficients after (Van Wagner, 1988). In other words, we worked under the assumption of a pre-eminence of wind effect on slope effect.
- Fire spread modelling was implemented by means of a cellular automaton.

After experimentation in the field, we were led to two main conclusions. First, although main flame front locations were generally correlated with the reality, fire shapes were almost always too wide. Furthermore, the use of the system in hilly landscapes showed that our management of wind and slope effects was not suitable outside the scope the model was designed for. In fact, the influence of the slope was clearly under-estimated. For instance, the following phenomena were usually observed:

- Fire spreading uphill against an opposite wind due to steep slope.
- Fire spreading stopped on hill ridges whenever it faces an intense opposite wind (Figure 3).

Figure 3: Example of combined effect of wind and slope: here, fire spread is stopped on hill ridges © SDIS 83 - Groupement Est

Thus, it was clear that effects of wind and of slope can very well act against each other. In addition, the excessive breadth of fire contours was clearly due to orthogonal projections of the calculated rates of spread on the axes of the cellular automaton. These observations initiate the elaboration of a new model. Furthermore, we wished to take advantage of the relevance of the shape approach. This led us to the mixed model presented in this paper where the rates of spread along the different edges of a grid representing landscape are calculated by means of ellipses.

THE PROPOSED APPROACH

The available data

The following is the list of the data available for the calculation of fire growth:

- An altimetric database: a grid of square cells 50m x 50m is mapped onto the landscape. An altitude measure is assigned to each cell.
- A set of wind maps which provide the effect of the relief on the wind, thus providing local winds. The latter are specified by means of vectors, i.e. numerical data representing both intensity and direction *in 3-D* space. It is worth noting that these data can very notably vary between ridges and thalwegs (the latter are the lines defining the lowest points along the length of river beds or valleys). Again, the landscape is divided in cells, the dimensions of which are 50m x 50m. Also note that the two kinds of grid, i.e. altimetric database and wind maps, precisely overlap. Moreover, we have different maps which correspond to the set of all the different dominant winds, with various intensities, in the areas concerned.

- Vegetation maps which allow the definition of combustibility classes the landscape can be divided in.
- Furthermore, all the meteorological data, i.e. the direction and the intensity of the current wind, the temperature in the shade, the air moisture content, etc. are provided in real-time by the forecast service.

We specify hereafter the process of calculation of fire growth. Note that, in a first time, the problem is handled in a generic way, i.e. the different formulae actually used are specified later on in the paper.

Rate of spread calculation

Let us consider two cells $\mathcal{C}_1$ and $\mathcal{C}_2$ of the altimetric database. The calculation of the fire rate of spread from the centre of a burning cell A to that of a non-burning cell B involves the following steps:

- First, note that the milieu (fuel characteristics, wind) is supposed to be homogeneous in the areas crossed respectively by the half-edges $[A, H]$ and $[H, B]$ (Figure 4). Hence, the calculation must be performed successively on the two half-edges. Hereafter, we treat the case of the first one, i.e. $[A, H]$. Let $\vec{S}$ be the "equivalent-wind" slope vector between the points A and H: $\vec{S}$ is at the vertical of $[A, H]$ and its orientation is defined with the proviso that on the ground, the altitude of the point H is superior to that of A: the value of the angle α is given as a function of this difference.

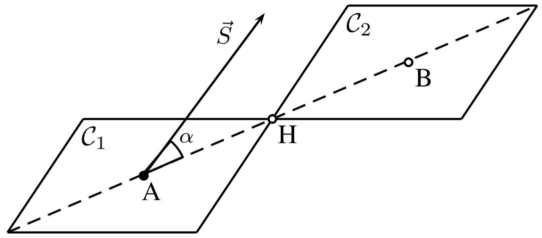

Figure 4: Slope vector $\vec{S}$ w.r.t. the edge $[A, H]$

- Let $\vec{W}$ be the wind vector in the cell $\mathcal{C}_1$. Thus, the calculation described hereafter can very well be performed *in the plane defined by the two vectors* $\vec{S}$ *and* $\vec{W}$ (Figure 5). Thus, the vectorial sum $\vec{C} = \vec{W} + \vec{S}$ specifies the combined effect of wind and slope on the fire spread on the ground *at the vertical of the edge* $[A, H]$. In the present setting, we do not regard opposed-wind fire spread as a credible hypothesis. Hence, if the value of the angle made by the vectors $\vec{S}$ and $\vec{C}$ exceeds $\frac{\pi}{2}$, then fire spread is considered as impossible on the edge $[A, H]$. Otherwise, by application of a given formula, e.g. the one given at the next section, we calculate the norm of the basic rate of spread vector $\vec{B}$ on the axis specified by the vector $\vec{C}$. The norm in question is generally defined as a function of the norm of $\vec{C}$ as well as the kind of vegetation and some physical parameters, e.g. air, soil and vegetation water content, temperature, sun exposure, etc.

  At this stage, we can apply to the present setting the elliptic shape hypothesis (Richards, 2005), (Glasa and Halada, 2007). Hence, the shape of local fire is assumed to be represented under the form of an ellipse, the rear focus of which being the ignition point. Hence, we consider that, once it has been calculated, the norm $|\vec{B}|$ of the basic rate of spread vector defines the distance between the rear focus of the ellipse, located at the point A, and the opposite extremity of the latter. Note that the ellipse's eccentricity is provided by a formula as a function of the norm of the wind-slope resultant vector.

  Then, the norm of the vector $\vec{R}$, i.e. the fire rate of spread on the ground at the vertical of the edge $[A, H]$, is provided by a radial projection according to the defined ellipse (Figure 5):

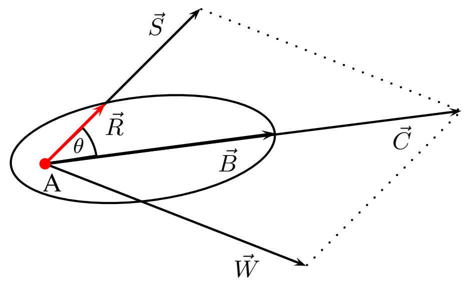

Figure 5: Calculation of the norm of the vector $\vec{R}$ by means of a radial projection according to an ellipse.

- At the end, the rate of spread vector $\vec{R}_s$ along the edge $[A,\ H]$, i.e. *on the underlying 2-D grid*, is obtained by an orthogonal projection of $\vec{R}$ on the line defined by the points A and H (Figure 6):

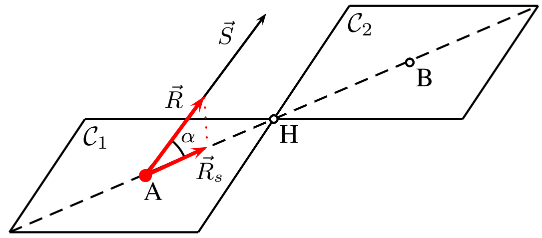

Figure 6: Calculation of the rate of spread $\vec{R}_s$ along the edge $[A,\ H]$

The above calculation process deserves the following comments:

- First, it must be repeated for all the edges on which the fire rate of spread have to be calculated. On flat land, i.e. if $\vec{S} = \vec{0}$, and in an homogenous milieu, it leads to an elliptic shape under the assumption of a constant wind, and to a circle in case of absence of wind.
- The sense (always bottom-up) of the slope vector $\vec{S}$ is given by the relative altitudes associated to the two points considered, here A and H.

- The above approach can easily be generalized to any edge crossing a given cell: this makes possible to consider fire spread between non-adjacent cells. Hence, the altitude of the points defining the different edges concerned must be calculated by interpolation. Thus, in the algorithm given below, fire spread from a burning cell is potentially considered in the direction of 16 different cells, 8 of them being in the immediate neighbourhood of the initial cell and 8 being beyond (Figure 7):

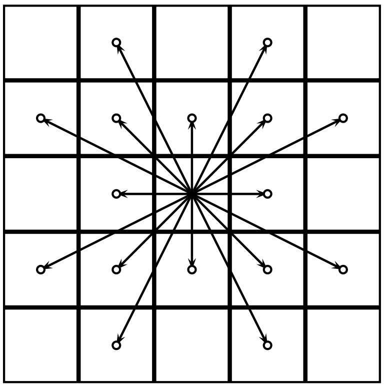

Figure 7: Fire spread in 16 potential directions

Fire spread calculation

The conditions of fire spread from a cell to another being specified, the overall algorithm is fairly simple. Thus, we start from a set of burning cells which belong to one or several fire contours. Then, for each of these ones, we discriminate over the 16 potential targets, the cells which are not already burning. Then, we calculate the corresponding rates of spread and consequently the spread durations respectively associated to each edge concerned.

Thus, when this task has been completed, the set of cells that are in a position to be fired by the burning cells has been elaborated. This one is hereafter referred to as the *fire vicinity*. At this stage, we select in the fire vicinity, the cell associated to the shortest edge, in terms of duration: the latter will be the next one to be reached by the fire. Thence, once the durations respectively associated to the corresponding edges have been calculated, the cell in question is replaced in the fire vicinity by those which are its potential targets. This iterative process is stopped when the deadline, i.e. the lapse of time considered in the simulation, expires.

Implementation

We provide hereafter some pieces of information related to the implementation of the above specified approach:

- The norm of the slope vector is given by a formula which provides an "equivalent-wind" value as a function of the angle α of the considered edge with the horizontal. For instance, the formula given in (Lopes et al., 2002) is:

$$|\vec{S}| = 15.275 * \beta^{-0.0225} * (tan(\alpha))^2 \qquad (1)$$

where:

- α is the slope.
- β is a parameter which depends on the fuel bed.
- tan is the tangent function,

Based on our experience, the formula $12 * (tan(\alpha))^2$ is suitable for the heterogeneous Mediterranean scrub. In particular, it provides an equivalent-wind speed of $12\, m.s^{-1}$ for a slope of 45 degrees.

- The norm of the basic rate of spread vector $|\vec{B}|$ is obtained by means of the Drouet's formula (unpublished work):

$$|\vec{B}| = 180 * e^{0.06*T_s} * tanh(\frac{100-S_w}{150}) * (1 + 2 * (0.8483 + tanh(\frac{|\vec{C}|}{30} - 1.25))) \qquad (2)$$

where:

- T_s is the temperature in the shade, given in Celsius degrees.
- S_w is the soil water content, expressed in millimeters.
- $|\vec{C}|$ is the norm of the wind-slope vector, given in kilometers per hour.
- $tanh$ is the hyperbolic tangent function.

Note that although this formula has been designed for the Mediterranean zone, it does not deal with vegetation and air moisture content which is an actual shortcoming. Hence, we have to take into account the nature of the vegetation by means of numerical coefficients. Moreover, a study of the influence of air moisture content on fire rate of spread is in progress at the present time.

- The equation of an ellipse in polar coordinates, with one focus at the origin, has the following form:

$$\rho = \frac{p}{1 + e * cos(\alpha)} \qquad (3)$$

where p and e are respectively the parameter and the eccentricity of the ellipse. The latter can be expressed as a function of the length to width ratio $\frac{L}{W}$ of the ellipse:

$$e = \sqrt{1 - \frac{1}{(\frac{L}{W})^2}} \qquad (4)$$

Thence, by considering the case $\alpha = 0$, we can deduce that the parameter of the ellipse is given by

$$p = (1 + e) * |\vec{B}| = (1 + \sqrt{1 - \frac{1}{(\frac{L}{W})^2}}) * |\vec{B}| \qquad (5)$$

What is more, some authors provide an estimation of the $\frac{L}{W}$ ratio as a function of the norm of the wind-slope vector $|\vec{C}|$. For instance, the following is the formula given in (Alexander, 1985):

$$\frac{L}{W} = 1 + 0.0012 * (2.237 * |\vec{C}|)^{2.154} \qquad (6)$$

Note that in our setting, this ratio has to be doubled in order to provide realistic fire shapes.

Thus, the data e and p being determined, if θ is the angle between the vectors $\vec{C}$ and $\vec{R}$, the norm of the latter can be immediately deduced from equation (3):

$$|\vec{R}| = \frac{p}{1 + e * cos(\theta)} \quad (7)$$

- The system has been developed in a C++ programming environment and runs under Windows XP. Furthermore, data are provided by the *GeoConcept* geographical information system.

We provide hereafter (Figure 8) an example of simulation performed with the system presented in this paper. This fire directly threatened the suburbs of the city of Cannes (South France) during the night from the 5th to the 6th of July 2007.

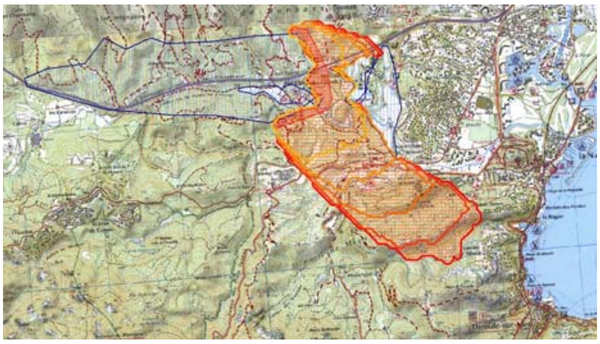

Figure 8: Result of a simulation © SDIS 06

Comments on Figure 8:

- The ignition time was 5 p.m.
- The burned area at 10 p.m. is represented in blue.
- The flame front at 10 p.m. is represented in red.
- The successive fire contours, separated by a time interval of one hour, i.e. from 10 p.m. up to 3 a.m., are represented by means of the different orange lines.
- The burned surface is around 450 hectares. The fire travelled around 7 km in 10 hours, which is an average rate of spread in the framework concerned.
- The simulation given below was obtained in less than three minutes on an Intel Core Duo based laptop with four Giga-bytes RAM.

CONCLUSION

The forest fire spread model presented in this paper takes into account the three following concepts:

- Geographical information that aims to faithfully represent the characteristics of the areas concerned.
- Physical models that make possible the calculation, by means of given set of formulae, of the different local rates of spread as a function of the various available physical and geographical parameters.
- An algorithm that manages fire spread.

At this stage of our work, we can draw the following conclusions:

- Whenever the Drouet's formula provides reliable data, i.e. if calculated basic rates of spread match the measurements taken on the ground, the actual fire shapes are correlated with those resulting from simulation.
- Important differences between the results of the application of the Drouet's formula and actual rates of spread are noted when air moisture content is extremely low.
- Due to the simplicity of the fire spread model, the system fits the operational timing constraints of the setting we are dealing with. Moreover, it offers a high level of inter-operability with the other software components.

Furthermore, the fire spread model will be subject to the following additional works:

- The elaboration of new formulae for basic rate of spread calculation. These ones will have to take into account supplementary data such as vegetation cover and air moisture content.
- Integration of additional geographic data, e.g. cliffs, non-flammable areas, etc. which have a huge influence on fire spread.
- Management of potential fire-fighters actions, e.g. front lines, side attacks, retardant droppings, etc. in order to evaluate the results obtained in the framework of various prospective scenarios.

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AUTHOR BIOGRAPHY

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