Parallel Approach to the Simulation Of Forest Fire Propagation[3]

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Abstract

Forest fire is one of the most critical environmental risks in all the Mediterranean Countries. The fight against these emergencies requires useful tools to predict the propagation and behaviour of forest fire in order to take the best decisions. It means it is necessary to know the propagation and behaviour of the forest fire in advance to act in the best possible way. However, this is a complex problem that requires high performance computing capabilities to provide accurate results faster than real time. High performance computing, mainly parallel and distributed systems, provide the computing capabilities to solve this problem in a reasonable time. In this work we present a parallel approach to simulate the forest fire propagation.

1 Introduction

Forest fire is one of the most critical environmental risks in all the Mediterranean countries due to the high temperatures and low precipitation rates, especially during the summer. This is an important problem in the entire world, but in these areas it is extremely dangerous. Every year intensive forest fires burn thousands of hectares destroying lots of trees and natural resources. Moreover, it implies a progressive turning land into a desert with all the associate problems.

For all these reasons, it is very important to fight against these forest fires using all the available resources in order to minimise as much as possible their effects. This fight against the fire must be done at two main different levels. These two levels are:

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1. Forest fire prevention: At this level the administration must promote the education of civil society to avoid risks that can provoke a wild forest fire. However, there are many other things that must be done to minimise the fire effects as much as possible. For example, it is necessary to work on the planning of the terrain to prepare natural fire-breaks, to decide which terrain can be urbanised, to prepare evacuation plans, to design roads and ways to reach all places in the country and so on. If the administrative decisions are made in the proper way, the fire effects can be minimised and the fight against the fire during a real emergency can be made easier.
2. Forest fire fight: During a forest fire emergency it is necessary to use the available resources in the best possible way. However, this fighting against the fires implies the coordination of several groups (planes, helicopters, firemen, volunteers) for the adequate use of the combative resources.

In both cases, fire prevention and real emergency, it is very interesting to have tools that are able to predict the forest fire propagation taking into account the particular conditions. It must be considered that the forest fire propagation is a very complex problem that involves several aspects that must be considered:

1. Meteorological aspects: The meteorological conditions affect the fire propagation in a direct way. Temperature, wind, moisture, and so on modify the fire behaviour and propagation in a significant way. It must be taken into account that these conditions are not static, but they change due to the macro-meteorological conditions or the day-night cycle. Therefore, the forest fire propagation prediction should consider the prediction on the meteorological conditions as well. In a more accurate analysis, it must be pointed out that the fire itself modifies the temperature, wind conditions and so on.
2. Vegetation features: The features of the vegetation influence in a direct way the fire behaviour. However, there are points related to meteorological conditions that modify the features of the vegetation. For example, the moisture contents of the vegetables influences the fire behaviour, but this contents depends on meteorological conditions (past and current).
3. Topographical aspects: The topographical aspects of the terrain are also very significant in order to predict the fire behaviour. But the particular topographical conditions also modify the meteorological conditions. For example, the meteorological wind is modified by the topography of the terrain in such a way that it must be evaluated the particular wind in each point and therefore, it must be analysed as a wind field with a particular value in each point.

For all these reasons it can be concluded that the forest fire propagation prediction is a very complex problem that involves several disciplines that must co-operate to provide accurate models and solutions that predict the fire propagation in a realistic way. The research on these models involves researchers from physics, chemistry, biology or ecology.

The main goal of this field is to provide simulation tools that can be integrated in an information system that provides to the user an accurate information concerning the forest fire propagation. It means that theoretical models developed by scientist must be programmed and must run on a computer. To accomplish this objective it is necessary to apply numerical methods and algorithms that solve the proposed models. This work implies the direct co-operation among scientists and computer scientists.

During the fire prevention phase the system can be used to simulate the evolution of the forest fire using different scenarios, for instance it would be very interesting to simulate considering different weather conditions, or considering the construction of a particular fire-break. The results that are provided by this system would be very useful to decide which actions must be taken to minimise the fire damage.

However, during the real emergency these simulations require high computing capabilities. The main reason for this is that the models involved in the simulation are very complex and they must be solved in a very short time in order to take the best decisions and act in advance. Parallel/distributed computing could provide these capabilities.

The advantages of parallel computing have been shown in several simulation fields. The main and obvious advantage of parallel computing is that it offers an increase in the speed of the simulation and, therefore, a reduction in the overall simulation time. Considering these new facilities provided by parallel computing, we have applied parallelisation techniques to the simulation of forest fire propagation.

In section 2 the fire propagation models are described focussing in the particular one selected in our work. In section 3 the parallel programming approaches and their application to propagation models are analysed. Section 4 describes the parallelisation of the selected model and shows the new possibilities offered by the use of parallelism in the simulation process. Section 5 shows the implementations carried out and the results obtained. Finally, section 6 provides some conclusions.

2 Forest Fire Propagation Model

There are several models in the literature to describe the behaviour of forest fire propagation. First of all it must be pointed that the propagation models include two separate models: the global model and the local model. These two models consider two different scales. On one hand, the global model considers the fireline as a whole unit (geometrical unit) that evolves in time and space. On the other hand, the local models consider the small units (points, sections, arcs, cells, ...) that constitutes the fireline. These local models take into account the particular conditions (vegetation, wind, moisture, ...) of each unit and its neighbourhood to calculate the evolution of each unit.

In the literature there are several approaches to solve the global models. These approaches could be classified in the following categories:

1. The fireline is considered as a set of units (points, sections, arcs, ...). It is assumed that each section has its own desegregate movement and then the new position of the fireline by the aggregating the new position of each section.
2. Physical approach based on Huygens principle. The fireline is considered as a set of points. Each point is considered as an ignition point that generates a virtual fireline, that evolves in the same way as a real fire. The new fireline is obtained as the covering of the virtual firelines.
3. Cellular models based on Dikjstra Algorithms. The terrain is divided in a discrete mesh of cells that are characterised by the average values of the parameters. From each cell the fire can propagate to the neighbour cells. There are different models that consider different mesh geometry or different neighbourhoods.

All these models can be generalised in a Global Fireline Propagation Model (André/Viegas 1998) that can be divided in the following steps:

1^{st}) Subdivision of the fireline $\phi(t)$ into a partition of sections $\delta_i\phi(P_i,t)$, with length $\Delta s_i.(\Delta s = max\{\Delta s_i\})$. In these step the model specifies the order (0,1,2) of the sections adopted, and the process of subdivision.

2^{nd}) Resolution of a certain Local Problem for each section $\delta_i\phi(P_i,t)$, giving as result a particular virtual fireline $\Phi_{v,i}(\Delta t)$. Each global model specifies a local problem to be solved.

3^{rd}) Aggregation and coupling of the information inherent to the set $\{\Phi_{v,i}(\Delta t)\}$, providing the definition of $\Phi(t+\Delta t)$. The global model requires to specify the coupling principle postulated for aggregating the movement description of the set of sections.

In this paper we will use the model defined by André and Viegas in (André/Viegas 1994, André 1996). The main goal of this model is to study the movement of the fireline. The operational cycle of this model consists in calculating the next position of the fireline considering the current fireline position (figure 1).

To reach this goal the model is divided into a local fire spread model and a global fire spread model. The local fire spread model calculates the movement of each individual section of the fireline and then the global model calculates the total fireline applying an aggregation process. The local fire spread model takes into account the static and dynamic conditions of the terrain (vegetation, topography, wind, moisture, and so on). The dynamic conditions (mainly moisture and wind) must be evaluated before the local model can calculate the movement of the section.

The global model allows the partitioning of the fireline into a set of sections. In each of these sections certain local balance conditions must be observed (André/Viegas 1994, André 1996). Under these conditions the movement of the fireline can be considered as the separate movement of the different sections, and then it is possible to compose the fireline in the next time step by aggregating the particular movement of the different sections.

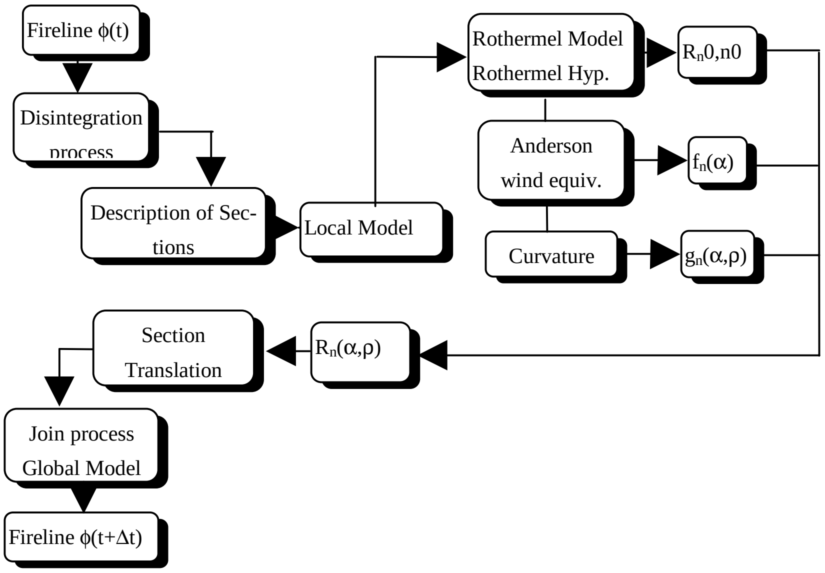


Figure 1
Diagram of the operation cycle

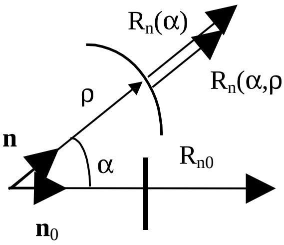
In order to calculate the movement of each section (by the local model) it is necessary to determine the propagation speed, which is calculated considering the direction normal to the particular section of the fireline. The computation of this speed (Rn) involves three separate factors:

a) Calculation of the speed in the maximum propagation direction (Rn0).

b) Calculation of the term that takes into account the difference between the normal and the maximum speed directions (fn).

c) Calculation of the effect of the curvature of the particular section (gn). The speed in the normal direction is obtained by the multiplication of these three factors. Figure 2 shows these three factors for a section of the fireline.

Some of these factors can be subdivided into several subcalculations:



$$R_{n_0} = R_{max} = R_n(0^{\rho}, \rho \to \infty)$$
$$R_n(\alpha) = R_n(\alpha, \rho \to \infty)$$
$$R_n(\alpha,\rho) = R_{n_0} \cdot f_n(\alpha) \cdot g_n(\alpha,\rho)$$

Figure 2
Rate of spread in normal direction

a) Rn0, Factor in the direction of maximum speed: The calculation requires the local parameters: vegetation, topography and meteorology (wind). The determination of this factor can be divided into three main components:

   1) Calculation considering no slope, and wind speed zero;
   2) Calculation considering slope, but no wind;
   3) Calculation without slope but considering the wind speed.

   In order to do these calculations the Rothermel model (Rothermel 1972, Rothermel 1983) is used. This method provides the maximum propagation Rn0, and the maximum propagation direction n0.

b) fn, angular speed dependency: This factor considers the effect of the angle between the maximum propagation speed direction and the direction normal to the section. It calculates the variation that the maximum propagation speed suffers when the normal direction to the section is considered. However, this calculation is very complex due to the fact that the fireline usually has very strange and irregular forms, which are very difficult to express using numeric calculus. Therefore, the calculation is done based on regular forms already studied in the literature, such as the double ellipses described by Anderson (Anderson 1983). Then, using an inverse analysis, the parameters to calculate fn can be estimated. In this estimation, the equivalent wind hypothesis (André/Viegas 1994, André 1996, Andrews 1983) is used. This wind speed is used as an input parameter to define the double ellipses. Then, by using iterative methods and starting from the angle between the maximum speed direction and the normal to the section, the equivalent angle in the double ellipse allows the calculation of the factor fn (André/Viegas 1994, André 1996).

As it has been shown this forest fire propagation simulation involves several processes that requires complex calculus. Therefore, the computing power required to solve this problem in an acceptable time is very high. In such situation, parallel/distributed computing should provide power computing to the improve the simulation time and make such simulation feasible.

3 Parallelisation of Propagation Models

The parallelisation of simulation models can be done in two main ways: data parallelism and functional parallelism (Foster 1995).

In the data parallelism approach, the same algorithm can be applied to several sets of data independently. This entails that the problem has a very regular structure and the same operation must be done on different parts of the problem. This means, in our case, that the movement of each point of the fireline can be calculated independently. In this case, we apply the same calculations to different sets of data to get the new fireline. This is a typical case of data parallelism.

On the other hand, functional parallelism is obtained when different parts of an algorithm can be executed simultaneously. It implies that the algorithm can be divided into a set of tasks, which cooperate to solve the particular problem. Each task can be responsible of the calculation of a particular part of the algorithm. Some of these tasks can be executed simultaneously and they can exchange data with other tasks (send and receive data from other tasks) of the algorithm.

However, these two types of parallelism are not mutually exclusive and in many cases they can be combined. In our particular case of forest fire propagation, an initial approach has been to consider the propagation of different sections of the fire front (data parallelism).

4 Parallelisation of Forest Fire Propagation simulation

As it has been shown in the previous section, the data parallelism allows the distribution of the input data into several independent sets, in such way that the calculation can be done simultaneously on the different data sets. Taking into account the model that has been considered for the forest fire propagation, this data parallelism can be applied. The calculation of the movement of each section (local model) can be done in parallel, since the model considers that they are independent (André 1996).

Determining the movement of one section of the fireline requires the calculation of the direction with the maximum local speed of propagation. This maximum speed is obtained by the multiplication of three factors: the speed in the direction normal to the section of the fireline, a second factor considering the orientation of the section and a third factor considering the radius of curvature of the section. The calculation of these three factors can be parallelised since they are no dependent. Another source of parallelism is the evaluation of the input parameters of the local model (wind, moisture) which can be done concurrently with the evaluation of the movement of the fireline.

This distribution of the calculations among the processors of the system allows carrying on all these calculations in parallel. In the global model the fireline is composed of a set of independent sections. These sections can be represented in a numerical form as an arc with a normal that points in the direction that the fireline moves. These arcs are interpolated from the points of the fireline. Therefore, the calculation of these sections (interpolation process) can be distributed among the resources of the parallel machine. It is assumed that the fireline is composed of N sections and the parallel system consists of M processing elements. Under these conditions, each processing element can calculate K=N/M sections. This means that theoretically the speed-up that can be obtained is M with respect to the sequential model (Jorba et al. 1998).

From the theoretical point of view, the time spent on the simulation could be reduced in a factor equal to the number of processors. However, the increasing of speed is limited by the fact that the data must be distributed among the processors and the results must be collected, and this implies several communications. These communications takes some time and the increasing of speed depends on the relationship between the computation and communication volumes.

It is necessary to distribute the input data among the processors and after the calculation, the results must be collected. Moreover, it must be noted that although the sections of the fireline are independent, the extreme points of each section are shared with their neighbouring sections. Therefore, if the calculation of each section is distributed to different processors, it is necessary to communicate some data to several processors, and the final results must be collected to generate the aggregated fireline.

The way to minimise these communications is to group in a particular processor those calculations that have some common or dependent data. In our particular case, when one processor must calculate K sections, these sections should be consecutive because in this way the communications among different processors are reduced.

Due to the initial independence of the sections, the use of the local model to determine the movement of each section can also be done simultaneously on different sections. The calculation of the fn factor can also be done in parallel, due to the independence among the sections. Moreover, in this case there is a total independence among the calculations for each section and, therefore, it is not necessary to communicate the different processes and the speed-up can reach the M factor mentioned above.

In the previous discussion it has been explained that the use of parallel computing reduces the simulation time and this fact offers new attractive possibilities for the application of simulations:

a) Sensibility studies: Several simulations can be executed considering some variation in the input parameters in order to analyse the effect on the simulation results. These studies would provide which parameters are more critical for the forest fire propagation models.

b) Multiple scenario simulations: It would be possible to run several simulations considering different scenarios (wind conditions, moisture, temperature) to decide which actions must be taken in the real fire fight.

c) More complex models: Forest fire simulation requires a set of complementary models to consider the dynamic behaviour of the environment that affects the fire propagation. Parameters such as moisture or wind vary dynamically (Jorba et al. 1998). Wind is a very important factor that requires heavy models to solve the non linear equations involved. Such models are good candidates to be included in a simulation system based on parallel/distributed computing.

5 Implementation and Results

The main goal of all the implementations based on propagation models is to provide an integrated simulation system of forest fire propagation. The global and local models and the required environmental information must be integrated to obtain a simulation system that provides the space-time forest fire evolution. The general “ideal” structure of such systems is shown in figure 3 (André 1996).

The main components are the following ones:

a) Input information databases, concerning the physical environment, including: 1) Ignition point or current status of the fireline, 2) vegetation maps that include the characteristics of the vegetation of each region, 3) topographic information of the terrain where the fire is burning, and 4) meteorological information, usually the wind field.

b) Propagation models: The global and local models described in section 2.

c) Complementary models: These models include those parameters with a dynamic behaviour, as it has been shown in section 2.

The diagram of figure 3 includes all these components. However, the current state of forest fire research does not allow to include all the components in a real system. There is active research in all these fields but there are not final results that can be included in the simulation systems. Therefore, the real current simulation systems has a simplified structure (figure 4). However, it must be pointed that in the near future the research results will be introduced in these simulation systems.

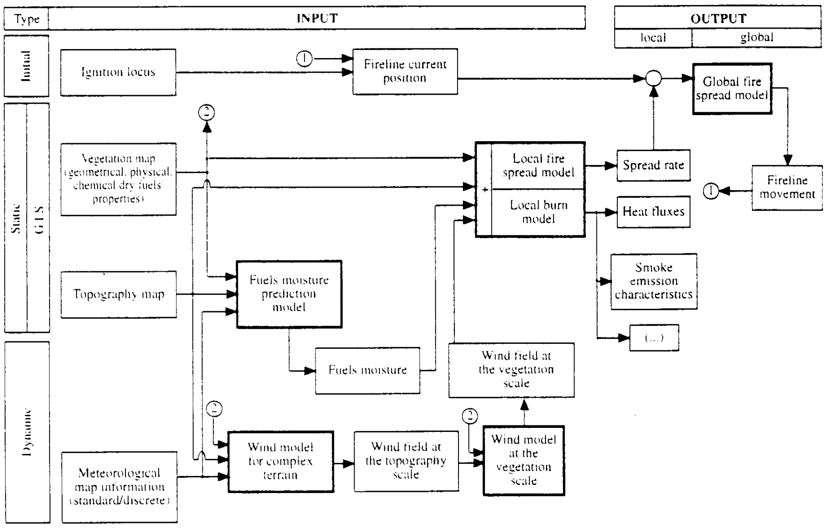


Figure 3
“Ideal” components of a simulation system

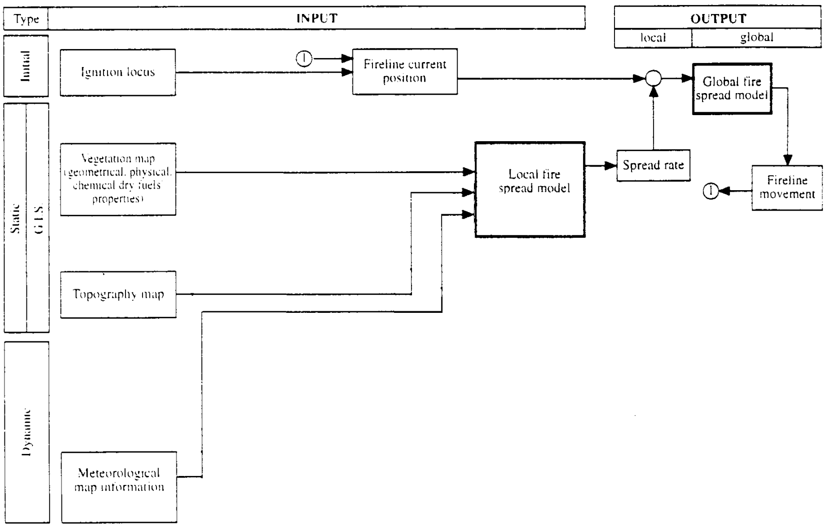


Figure 4
Components of a simulation system

In our work, considering the theoretical models discussed in section 2, several implementations have been developed on different machines. The first implementation was a sequential implementation that runs on a PC or SUN workstation. This sequential version was used to validate the results of the future parallel/distributed versions and also to compare the performance obtained.

The parallel/distributed version (discussed in section 4) was developed using PVM (Geist et al. 1993) libraries and there are two versions that run on different systems although they are absolutely equivalent from the design point of view:

a) A distributed version that runs on a cluster of workstations (or even PCs) connected by ethernet. This solution offers the possibility of increasing the computing capabilities of the system at low cost.

b) A parallel version that runs on a parallel Parsytec CC with 8 processing nodes. In this case, the system includes an internal high-speed connection network that improves the interprocessor communications. However, the cost of such machines is extremely higher compared with the cluster of workstations.

The distributed version exploits the capabilities of easily available systems although the communication speed is not very high and limits the speed up obtained. Meanwhile, the parallel version tries to exploit the high capabilities of a real parallel system with a high speed communication network.

Figure 5a shows the results obtained by using a different number of processor when the fireline was initially defined by 256 points, and figure 5b considers a fireline defined by 2048 points.

The experimental results show (figures 5a and 5b) that the simulation time is reduced in both, parallel and distributed implementations. It can be observed (figure 5a) that the execution time is reduced when the number of processors is increased, but when we reach the number of 8 processors the execution time is not significantly reduced. This fact is due to the small problem size. In this case the computation/communication ratio is too low. When the problem size is increased to 2048 points (figure 5b) it can be observed that when we increase the number of processor to 8 the execution time is also reduced. Concerning the effect of the parallel system or the distributed cluster of workstations it must be pointed the difference in the execution time is due to the different processor speed (133MHz vs. 75 MHz), but not to the faster communication system in the parallel machine.

However, the current models have a low computation/communication ratio that implies that the processes requires many communications and performs few computations. This fact penalises the parallel and distributed version in a significant way.

More precise models will be developed in the near future to simulate the evolution of the fireline in a more realistic way. These new models will be adapted to the parallelism capabilities and they will include much more heavy equations. There-

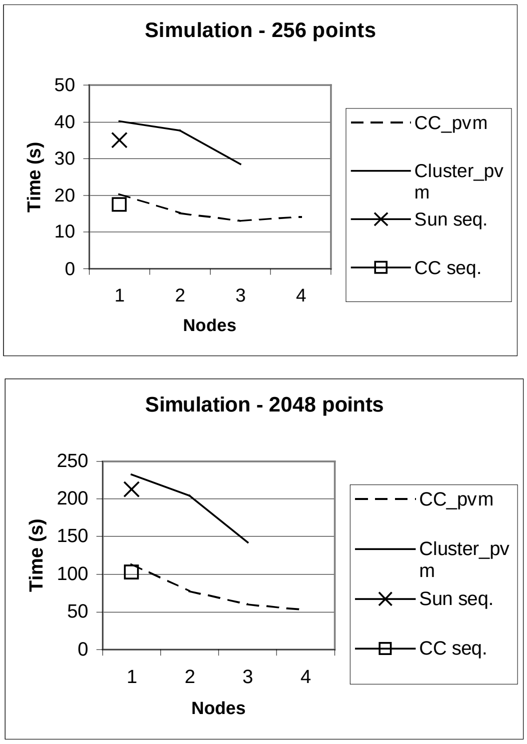


Figure 5
Some results for the implementation versions

fore, the computation/communication ratio of such models will be higher. This fact will allow to obtain better improvements by the application of parallelism.

6 Conclusions

The simulation of forest fire propagation involves several research fields and the co-operation among researchers of these different fields is important to develop more accurate models, which reproduce the fire's behaviour in a more realistic way. Moreover, the simulation of these complex models should be fast in order to predict the fire behaviour in advance and use this information to decide which actions should be taken to control fire propagation. These accurate models require high performance capabilities in order to provide the results in a satisfactory time. Distributed computing provides the required computing capabilities at a relatively low cost.

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