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Determining map partitioning to minimize wind field uncertainty in forest fire propagation prediction

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ABSTRACT

Wind speed and direction are the parameters that most significantly affect forest fire propagation. The accurate estimation of such parameters is critical in providing precise predictions of forest fire propagation. Wind speed and direction can be measured in meteorological stations or estimated from meteorological models, but, in both cases, they are obtained at a very low resolution. Moreover, the meteorological wind is modified by the terrain topography and a complete wind field is generated with different wind speed and direction at any point of the terrain. So, wind field models providing wind speed and direction at a very high resolution (30 m) are crucial in forest fire propagation prediction. WindNinja is one of the most widely used wind field simulators in this area. However, when the terrain map under consideration is very large (30 km × 30 km or more), the execution time becomes unaffordable and the simulator cannot be used in real operation. A map partitioning strategy was developed to parallelize the wind field calculation and reduce the execution time to make it affordable. Map partitioning introduces a certain error in wind field that is propagated to forest fire propagation prediction. So, a complete methodology has been developed to determine the map partitioning that accomplishes real operation execution time constraints and keeps the forest fire propagation error below feasible limits. The experimental results show the execution time reduction accomplished and the accuracy of the wind field generated and forest fire propagation prediction.

1. Introduction

Forest fires are significant natural hazards around the world, especially in places with hot, dry summer seasons such as Mediterranean countries, California or Australia. To fight these hazards and use the available resources in the best possible way, it is necessary to have an accurate prediction of their evolution beforehand. So, propagation models have been developed to determine the expected propagation of a forest fire [12,2,9]. Such propagation models require several input parameters representing the scenario where the fire is taking place to produce the predictions of the propagation. These parameters include the digital elevation map, the vegetation map, the vegetation features, and meteorological conditions, among others. Some parameters are well known, but the values of other input parameters are obtained or estimated from indirect measurements. Such indirect estimations imply a degree of uncertainty concerning the values of the parameters that provoke uncertainty in forest fire propagation prediction.

The parameters that most significantly affect forest fire propagation are wind speed and direction [1]. These parameters can be measured at meteorological stations or estimated from meteorological models, but, in both cases, they are obtained at a very low resolution, typically some a distance of kilometers. This fact is critical because, as is well known, the meteorological wind is modified by the topography of the terrain and, therefore, the values of the wind speed and direction at one point of the terrain are different from the values at other points, depending on the terrain topography, and the values at low resolution are not representative of the actual situation. This may imply that the predictions provided by forest fire simulators are not feasible and not very useful in real operation.

To estimate the wind speed and direction at each point of the terrain, it is necessary to apply a wind field model that determines those values at each point while taking the terrain topography into account. Then, the wind field generated by the wind field simulator is used as input of the forest fire propagation simulator, coupling both simulators, wind field and forest fire, to improve the accuracy of forest fire propagation predictions [4].

Moreover, meteorological wind varies dynamically over time. So, when predicting fire propagation, it is necessary to consider the

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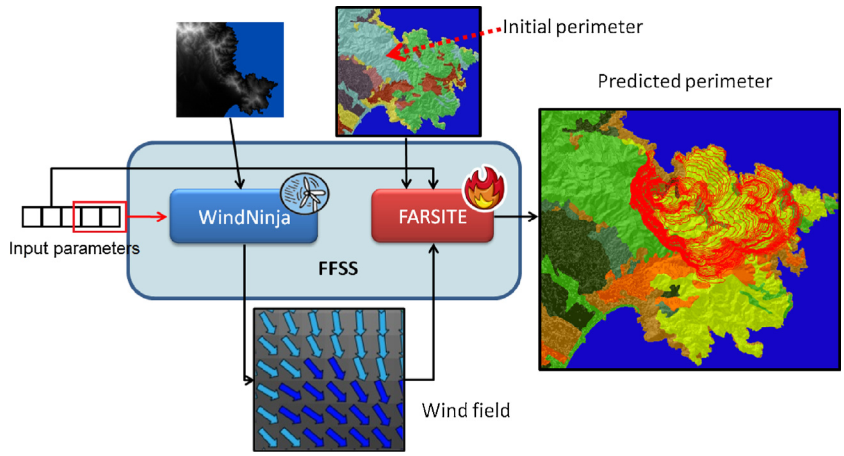

Fig. 1. Coupling wind field and forest fire propagation models.

meteorological forecast provided by meteorological centres at different time steps and calculate the wind field for each time step. During the forest fire simulation, the corresponding wind field must be applied at each time step. So, if the meteorological forecast provides a wind value each hour and the forest fire propagation is predicted for the next 6 h, it is necessary to calculate 6 wind fields (one for each hour) and introduce them into the forest fire simulator.

FARSITE [5] is a widely used forest fire propagation simulator that has been extensively tested on real fires and produces successful results. It is a fire behavior and fire growth simulator that incorporates both spatial and temporal information on topography, fuels and weather. It includes temporal variation in fire conditions. FARSITE is an elliptical wave propagation simulator and avoids a typical problem in cell-based simulators of reproducing the fire shape in heterogeneous conditions, due to their reduced number of propagation paths.

For the wind field simulator, WindNinja [7] is a mass conservation wind field simulator that, given a meteorological wind and a digital elevation map, generates the wind field at the needed resolution (30 m). One of the main advantages of WindNinja is that the output generated can be directly used as input by FARSITE. This simplifies the coupling of both models. Fig. 1 shows the coupling of WindNinja and FARSITE.

WindNinja has also been used in other simulation environments and coupled to simulators such as WildFireAnalyst [11], Phoenix RapidFire [15] and WIFIRE [3].

However, when the studied terrain map is large (for example, 45 km × 45 km) and uses a high resolution (for example, 30 m), coupling a wind field model with the forest fire propagation implies a significant increase in the execution time that is not affordable since the propagation prediction has strict real time constraints in order to be operational. Therefore, it is necessary to apply computational methods to reduce the execution time of both, the forest fire propagation model and the wind field model. In this work, the main goal is to reduce the WindNinja execution time for large terrain maps such as 45 km × 45 km and 1500 × 1500 cells, in order to make it operational in real scenarios while accomplishing operational real time constraints.

A map partitioning approach to parallelize WindNinja was proposed in previous works [14]. In this approach, the terrain map was divided into smaller parts, and the wind field can be calculated in parallel on each part of the map and the wind fields of the different parts are then aggregated to form the global wind field. As stated, the map partitioning strategy can reduce WindNinja execution time, but it can also introduce a large error in wind field that can make the approach unfeasible. On the one hand, WindNinja presents certain effects in the cells close to the map border that make that the values of the wind parameters in those cells are unreliable. Therefore, it is necessary to introduce a certain degree of overlapping among the different parts to avoid such limitations. On the other hand, when the map is partitioned, the system of equations is solved for each part, but, in this way, there is a loss of global information that modifies the solution and the consequent wind field. These facts have been brought to light by preliminary studies, and it has been proved that it is necessary to develop a complete methodology to reach a tradeoff between execution time and wind field accuracy. The result must be a map partitioning methodology that reduces execution time below operational requirements and provides accurate partitioned wind field that, when gathered, reaches insignificant fire propagation differences.

In this methodology several factors such as map part shape, map part size, map resolution, part overlapping, and others must be considered. Some preliminary studies have been carried out [13], and it has been proved that some of these parameters are interrelated. The goal of this work is to establish a complete methodology that, given a map size, an operational wind field computation time and a maximum forest fire propagation error, is able to provide the map partitioning required to accomplish such requirements or to indicate the values that cannot be reached.

In this paper, such a complete map partitioning methodology to accelerate wind field calculation is presented. So, the paper is organized as follows. Section 2 describes the main features of WindNinja and presents its main limiting factors. Section 3 introduces the map partitioning approach to overcome the execution time and memory limitations of WindNinja. Section 4 presents the methodology to determine the most adequate map partitioning to minimize wind field uncertainty and reduce execution time. Section 5 summarizes the results of the experimental study carried out. Finally, Section 6 shows the main conclusion of this work.

2. WindNinja wind field simulator

Wind speed and direction are two of the parameters that most significantly affect fire propagation. Such parameters suffer from temporal and spatial variation. Such variations introduce a high degree of uncertainty in the results of forest fire propagation prediction. As is well known, wind is not constant. Therefore, a weather forecast model must be introduced to predict the future evolution of the wind. On the other hand, the meteorological wind is modified by the topography and vegetation type of the terrain under consideration. At each point of the terrain, there is a different value of wind speed and direction. So, it is necessary to introduce a wind