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A new paradigm for forest fire spread prediction: Faster decisions at high resolution

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Abstract

Climate change has led to a significant increase in the number of wildfire events and their severity. To mitigate their impact, it is necessary to be able to make quick decisions according to the fire behavior. In order to assist on these decisions, we rely on forest fire spread simulators. However, one of the main problems associated to these tools lies in finding the appropriate balance between execution time and simulation resolution, which has a direct impact on the accuracy of the simulated results. Simulations at high resolution are computational intensive in terms of execution time and, therefore, they are not used for real-time evolution forecast. FARSITE forest fire spread simulator has arisen as the most recognized simulation tool based on the Elliptical Wave Propagation (EWP) scheme. However, its main drawback consists of high execution times due the perimeter reconstruction algorithm used. In this paper, we propose an alternative algorithm to perform the reconstruction process based on the α -shape algorithm. The proposed algorithm, *Boundary α -shape* algorithm, has been design bearing in mind that it could be easily parallelized. The obtained results when executing FARSITE by exchanging its reconstruction algorithm by the new one highlights that the *Boundary α -shape* allows a notable execution time reduction.

Keywords: Forest Fire Spread Simulator, Perimeter Reconstruction Algorithm, *Boundary α -shape*, Decision Making

1. Introduction

The scientific community focused on the study of forest fires is playing an increasingly relevant role due to climate change. This community covers a large number of areas ranging from forestry and atmospheric modeling to computer sciences. When facing the problem from the computational point of view, the main aspect to analyze is the computational performance in opposition to the quality of the results. On the one hand, to analyze the computational performance of forest fire spread prediction tools, the main concern is related to the time incurred in obtaining the forecast results. On the other hand, when the quality of the results is considered, one refers to the similarity of the simulated propagation with the real evolution of the fire. These two characteristics are crucial when dealing with this kind of hazards, however, having a good performance in both aspects is impractical in most cases. That is, most of the current wildfire simulators can solve one of them quite well, however, when it comes to delivering high-resolution results, the time invested in obtaining them is usually too large to be used at real-time. Examples of wildfire prediction tools that have this dichotomous situation are FARSITE Finney (1998), QUIC-Fire Linn et al. (2020) and WRF-SFIRE Mandel et al. (2014). Each one of these three wildfire spread simulators falls into one of the three categories into which wildfire simulators are classified based on their spread strategy Richards (1990), Sullivan (2007): *Elliptical Wave Propagation (EWP)*, *Cellular Automata (CA)*, and

Level Set Method (LSM). CA approach considers the problem as a set of contiguous cells (uniform grid) that can be either burnt or not. EWP spread methods are based on vector implementations where the fire perimeter is treated as a closed curve discretized through a number of points and, finally, LSM uses the Hamilton-Jacobi equation to describe the propagation of the fire front, which is defined implicitly by means of a level-set function. This work is focused on the EWP approach because its design characteristics has a great parallelization potential although it has not been widely exploited. Since FARSITE is the reference forest fire spread simulator within the EWP category, in this paper we focus on modified the most time consuming block of this simulator by an alternative algorithm that reduces the original FARSITE's complexity and incorporates the design key points for being later massively parallelized using computing accelerators such as GPUs.

This paper is organized as follows. Section 2 describes the main components of FARSITE forest fire spread simulator. Section 3 is devoted to describe the proposed *boundary α -shape* algorithm. Subsequently, in section 4 the experimental study and the obtained results are reported and, finally, in section 5 the main conclusions and the open lines of this work are summarized.

2. FARSITE description

FARSITE is a fire area simulator released in 1998, used to model fire growth and expansion Finney (1998) and it is highly recognized by the scientific community. In order to correctly reproduce the evolution of a forest fire, FARSITE requires cer-

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tain input data related to the environment where the fire is taking place. This input data is georeferenced data describing terrain features, fuel types (vegetation), weather variables such as environmental humidity and wind direction, and the ignition point. Generally, these inputs will not be homogeneous over the terrain, so FARSITE assumes that perimeter points lie on an evenly spaced landscape grid, where the input parameters remain constant throughout the simulation time Liu et al. (2017). Reading and initializing all these data is made once at the beginning of the forest fire spread simulation execution and, afterwards, the wildfire growth process starts. The FARSITE's spreading procedure is divided into two stages, which are repeated for each time step until the total simulation time has been achieved. These two stages are the point propagation and fire front reconstruction stages. Figure 1 graphically describes the basic workflow of FARSITE. In FARSITE, there is a parameter that controls the accuracy of the simulation, the *Perimeter Resolution*. The Perimeter Resolution determines the maximum distance between points used to define the fire perimeter. When lower Perimeter Resolution, more perimeter points, therefore, the curvature of the front and the heterogeneities of the terrain can be represented in more detail. However, when the number of perimeter points increases, the time incurred in performing the forest fire spread simulation also increases. To understand the influence of the *boundary α -shape* in the fire evolution, it is necessary to measure its impact in the fire front propagation. The choice of metrics has been done to be able to carry out validation, verifying that the results with the new method are not significantly different from FARSITE. In order to quantify the difference between simulations, two metrics have been used: Discrepancy and the Hausdorff Distance, see Figure 6.

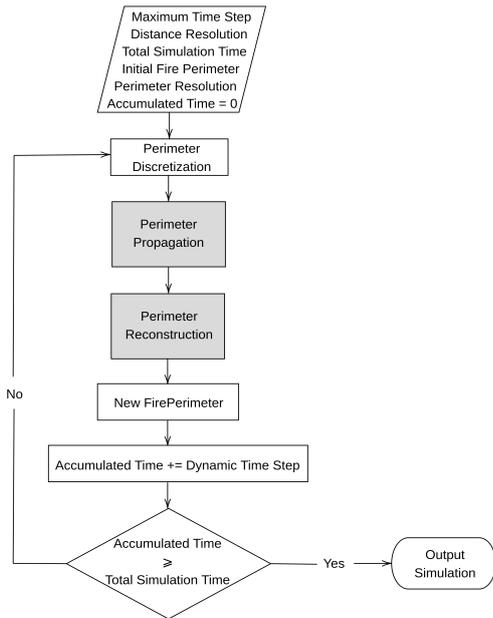


Figure 1: FARSITE's workflow.

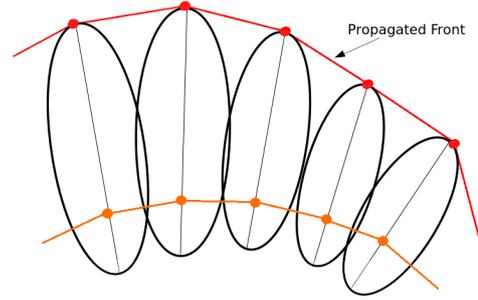


Figure 2: Elliptical wave propagation from t_1 to t_2 .

2.1. Propagation model stage

In the forest fire spread simulators based on the EWP, the fire front is divided into a set of points Huygens (1912). To obtain the evolution of each point, an ellipse is generated for each point based on the Rothermel's semi-empirical forest fire model Andrews (2018); Rothermel (1972), which is the foundation of most forest fire simulators (see Figure 2). Rothermel's model can be formulated in the following way:

$$R = R_0 \cdot (\vec{n} + \vec{\phi}_w + \vec{\phi}_s) \quad (1)$$

where R represents the Rate of Spread (ROS) in a particular point, R_0 is the rate of spread in a particular point with no wind and no slope, \vec{n} is the normal direction to the fire perimeter on that particular point, $\vec{\phi}_w$ is the wind component, and $\vec{\phi}_s$ the slope component. Applying this formula to each boundary point, one can predict the propagation of the fire and build up the next set of points. Finally, the new perimeter is obtained by joining the obtained new points. In terms of propagation, each point is independent of each other, and this characteristic allows to treat the propagation of each point independently.

2.2. Fire front reconstruction stage

Forest fire simulators based on EWP have the drawback of not intrinsically distinguishing between burned and unburned areas as it is exemplify in Figure 3. This limitation can lead to the formation of artificial complex loops and knots in the fire front simulation. If these intersections and complex loops are allowed to persist without detection, it can result in inaccurate representations of the fire front and hinder the ability to make informed decisions. To address this issue, post-processing steps are applied after each propagation stage to remove these artificial intersections and refine the fire front.

The perimeter reconstruction algorithm used in FARSITE looks for artificial loops and knots, see Figure 4. This algorithm requires three preliminary steps, FireLab (2007):

1. The vertices of the fire perimeter must be ordered beginning from a vertex on the outside edge of the fire polygon; this is guaranteed by employing one of the polygon vertices that define the farthest extent of the polygon along a given horizontal axis.
2. A list of pairwise points comparisons is made to identify intersections between each perimeter segment and another

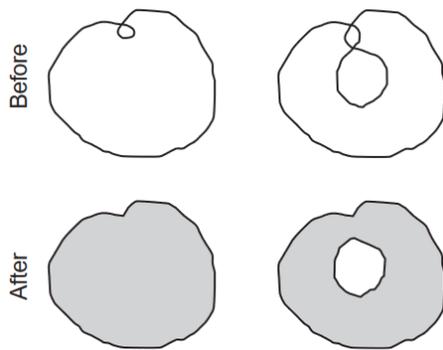


Figure 3: Correcting fire perimeter expansions is necessary because there is no inherent detection of previously burned areas. Examples of clipping of simple crossovers or loops and clipping illogical overlap but preserving an enclave. Finney (1998)

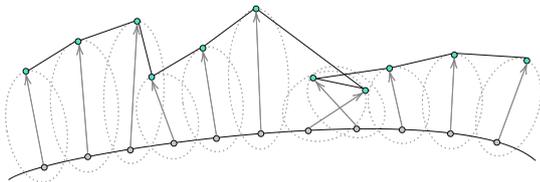


Figure 4: Example in which a fire front reconstruction is necessary

perimeter segment of a given burned area. If an intersection is found, its pairs of points are stored in the order found and designated by the order number of the first vertex on the crossing spans.

3. The intersection list is reviewed to identify multiple intersections within a given segment. Multiple intersections on a segment are reordered to appear in the sequence in which they would be encountered starting from the first vertex.

If intersections are detected during the preliminary steps, the algorithm corrects the fire polygon by following the outer edge from the first vertex of the polygon. For an outward burning fire, it proceeds with each perimeter segment (pair of vertices) until an intersection with another segment is encountered. The intersection point is stored as the next vertex of the new fire polygon. The process continues until the algorithm arrives at the start and determines the vertices that now define the outermost fire perimeter. This process is repeated until no remaining unprocessed crosses are on the original fire perimeter polygon. The obtained new perimeter will be used as the initial fire perimeter for the following propagation. While the process is expensive in time and computing power, it is essential for maintaining the integrity of the fire perimeter. This algorithm is very inefficient, boasting a complexity of order $O(n^2)$. In big fires, this part of the simulation takes around 60% of the total execution time.

3. The *boundary α -shape* algorithm

The proposal described in this section is based on the *α -shape* algorithm, which is a generalization of the convex-hull and a subgraph of the Delaunay triangulation Delaunay (1934). In a roughly way, given a set of points, the *α -shape* algorithm could generate different shapes from the Delaunay triangulation of those points, according to the α value selected. This value will control the precision degree of the generated shapes. A conformal *α -shape* Edelsbrunner et al. (1983); Cazals et al. (2005) is very similar to an *α -shape* but instead of a global parameter α , it uses a local scale parameter. Even so, *α -shape* and conformal *α -shape* share most of their properties, but the conformal *α -shape* is very useful when the data is non-uniformly sampled. In this section, we outline the proposed conformal *α -shape* algorithm that is designed to substitute the current fire front reconstruction algorithm included in FARSITE.

3.1. Algorithm description

The proposed algorithm is based on an *α -shape* but is adapted to the needs of the problem, making it more akin to a conformal *α -shape*. In the new algorithm, the inner edges of the Delaunay triangulation will use $\alpha = \infty$, making them irrelevant, while the boundary of the triangulation will use a meaningful α value. The boundary and the inner edges are defined dynamically as we iterate over the edges and remove and add edges to the boundary edges. This approach, in addition to saving computation time, allows to work with a data distribution with which the *α -shape* might not give us the expected results.

3.1.1. Inputs & Outputs

The FARSITE fire front reconstruction process starts from a vector of points and returns another vector of ordered points, not necessarily of the same size. Since we want that the new algorithm could be used in an easy *plug&play* scheme being transparent to the FARSITE's user, we must adapt the inputs and outputs of the alternative algorithm to match those of FARSITE to be able to use it in an interchangeable way. The desired input for the *boundary α -shape* is a vector of unordered points, but the alternative algorithm previously requires a Delaunay triangulation. As such, the first step to be carried out should be to obtain the Delaunay triangulation by means of an unordered vector of points. Obtaining the Delaunay triangulation is the most time-consuming part of the proposal; however, it exhibits a complexity of $O(n \log(n))$, what supposes a great improvement considering the original complexity of the current FARSITE algorithm. The adaptation of the output data of the new proposal algorithm is simple since we already have identified the border of the concave hull.

3.2. Parameter selection

In the *boundary α -shape* algorithm, as in the basic *α -shape*, it is necessary to choose an α value that will determine the shape obtained. From the context of the problem, the most logical thing to do is to use FARSITE's perimeter resolution parameter, since it is a parameter that the user decides. However, a deeper study of this point should be performed.

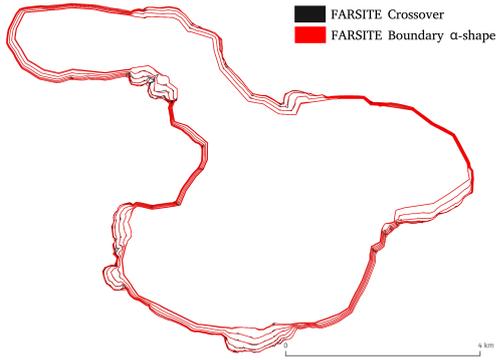


Figure 5: Fire-front simulation with the FARSITE Crossover (black) and *boundary alpha-shape* (red) of a fire in Ruzic.

4. Experimental results

In this section, we provide the preliminary results obtained in terms of execution time and accuracy of the prediction results when using the original FARSITE fire front reconstruction method and when using the proposal *boundary alpha-shape* algorithm to generate the new fire perimeter.

The performance results reported in this section, are based on running the fire front reconstruction component of FARSITE in an isolated way and compared to the proposed *boundary alpha-shape* algorithm. Therefore, to be fair, we have created a workflow in which FARSITE propagation occurs and you can choose whether the fire front reconstruction is to be done using the original FARSITE version or the *boundary alpha-shape*.

4.1. Quality Assessment

The modification of the fire front reconstruction process could lead to different fire behavior, that is, the output shapes of the simulation tool could be slightly different. However, this substitution should provide similar enough not to modify the overall behavior of the fire. As it is well known, the α -shape algorithm generates quite different results depending on the value of the α parameter. It is essential to remark that in this paper, the main objective is to compare the obtained fire front evolution of both fire perimeter reconstruction algorithms and not to compare against the real fire propagation.

As a study case, we selected a past fire that took place in Ruzic (Croatia) in 2012. The data of this fire belongs to EFFIS database (*European Forest Fire Information System*), (Centre, 2011). Figure 5 shows the output provided by the original fire front reconstruction made by FARSITE (black line) and the output provided by the new strategy (red shape). As we can observe, the results are almost the same, however, if we analyze the lines in detail, one can find certain regions where the black line overpass the red line.

To understand the influence of the *boundary alpha-shape* in the fire evolution, measuring its impact in the fire front propagation is necessary. The choice of metrics has also been made to be able to carry out validation, verifying that the results with the new method are not significantly different from FARSITE. To quantify the difference between simulations, two metrics have

Minutes	Hausdorff Distance (m)	Discrepancy
60	23.7236	0.01%
120	21.0584	0.01%
180	75.6118	0.10%
240	55.8464	0.16%
300	149.9385	0.25%
360	179.0893	0.27%
420	86.3550	0.27%

Table 1: Hausdorff distance and discrepancy between the simulations areas with FARSITE Crossover and *boundary alpha-shape* in a fire in Ruzic.

been used: Discrepancy and the Hausdorff Distance, see Figure 6.

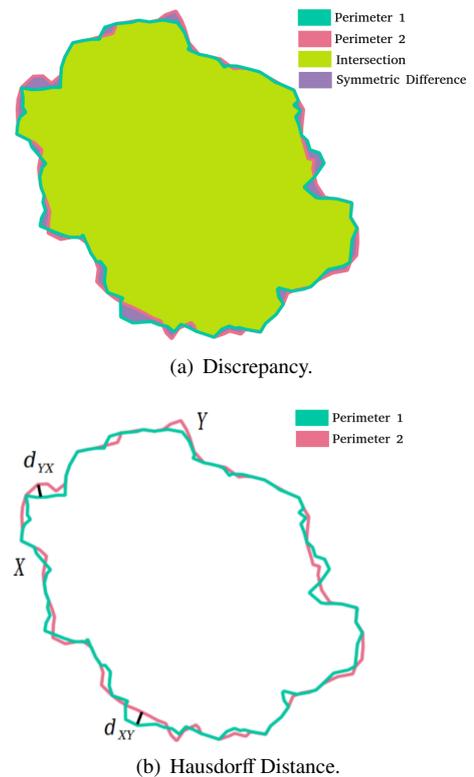


Figure 6: Quality assessment metrics.

The *Discrepancy* is a percentage tells us how discrepant are the resulting areas of the two simulations, Figure 6(a). The discrepancy tells us whether the areas of the simulated fires cover areas similar in shape and size, see Equation 2.

$$Discrepancy = \frac{Area(Symmetric\ difference)}{Area(Symmetric\ difference + Intersection)} \% (2)$$

The second used metric is the *Hausdorff Distance*. It indicates if there has been a significant difference locally in distance between fire fronts, see Figure 6(b).

Table 1 displays the obtained results for different fire evolution times. As can be seen, the degree of disparity between the areas is very low, remaining practically limited to 0.27% throughout the simulation. On the other hand, the Hausdorff

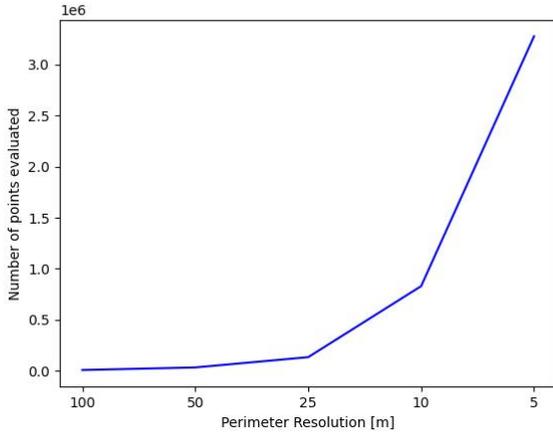


Figure 7: Number of points of the fire front with different values of the parameter perimeter resolution.

distance, despite increasing in the first iterations of the simulation, reaches a point where it remains stable, around $179.1m$, and even decreases. In addition, the maximum Hausdorff distance over time represents less than 2% of the width of the fire. The obtained results highlight that the proposed reconstruction method does not distort the simulation compared to the original algorithm. Although we are in the process of analyzing the impact of executing the proposal algorithm in more real cases, these preliminary results are very promising.

4.2. Execution Time

The main contribution of the alternative proposal to reconstruct the fire front is the algorithm's complexity reduction. On the one hand, the original naïve FARSITE Crossover procedure exhibits a complexity of $O(n^2)$, meanwhile the *boundary α -shape* approach has a complexity of $O(n \log(n))$ what implies a significant reduction of the execution time of this component of the simulator. As we said, the accuracy of the simulation depends on the Perimeter Resolution. The smaller the perimeter distance, the more points we will place and the better we will be able to reproduce the behavior of the real fire. We can observe in Figure 7 how as we increase the resolution of the simulation by decreasing the perimeter resolution parameter, the number of points, n , and therefore the execution time, increase.

Figure 8 represents the speed up of the *boundary α -shape* against the original perimeter reconstruction algorithm. We can observe that the *boundary α -shape* is more efficient in all cases. In addition, we see that the speed up increase as the number of perimeter points rise, or the Perimeter Resolution decrease. In the worst scenario, perimeter resolution equal to 100 meters, the *boundary α -shape* is 1.44 time faster than the original crossover algorithm. When we measure the speed up of the simulations with a high accuracy, Perimeter Resolution of 5 meters, we obtain a value of 11.1. So by increasing the resolution of the simulation each time the new algorithm is more efficient and obtains a better speed up compared to the original FARSITE.

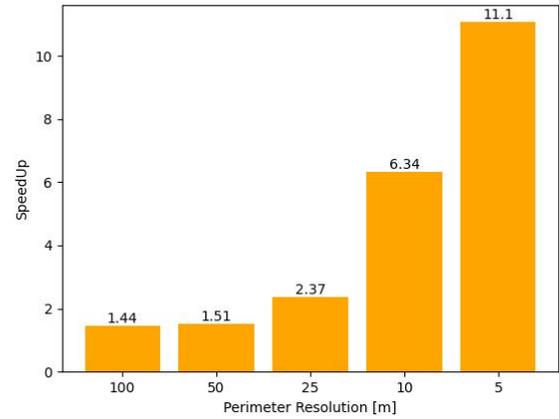


Figure 8: Speed up of the FARSITE with the *boundary α -shape* in comparison with the original FARSITE.

5. Conclusions

Climate change generates an increasing number of wildfires, which are growing in intensity and area affected. To tackle such events, current available tools must be enhanced to be faster without losing their forecast abilities. In this work, an alternative algorithm for FARSITE fire front reconstruction algorithm is presented. The proposal strategy does not affect the simulations results provided by FARSITE but, the preliminary studies show promising results with a reduction of the execution time up to 11 times. The initial validation has been done only with the part of the code associated to the fire front reconstruction and the next step is to integrate the new algorithm within FARSITE.

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