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Fast and accurate forest fire front reconstruction: A pathway to evaluate fire severity in extreme wildfires

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Abstract

The increased number of extreme wildfires due to climate change generates new challenges in wildfire modelling and prevention actions. One important aspect is to provide current forest fire spread simulation tools with the capability of being faster and more accurate preserving their forecast abilities. In this paper, we propose an alternative forest fire front reconstruction algorithm that could easily be incorporated in the well-known FARSITE fire spread simulator without affecting its functionality. The fire front reconstruction core part in FARSITE represents up to 60% of its total execution time. The proposal alternative algorithm is based on the α-shape algorithm but including some adaptation considering the particular case of forest fire. Meanwhile, the current FARSITE fire front reconstruction algorithm has a complexity of $O(n^4)$, the adapted α-shape algorithm has a complexity of $O(n\,log(n))$. This new approach has the benefit of being parallelizable using a divide and conquer strategy what will allow to significalty reduce the FARSITE's execution time without modifying its forecat results.

1. Introduction

Climate change is affecting the face of the world. One of the critical aspects of this change is the increase of the average temperature generating long periods of drought in areas that areas not used to. Consequently, in the last decades, one can found extreme wildfires in regions such as Finland, eastern Australia, UK that were typically places with a low rate of huge forest fire (United Nations Environment Programme, 2022-02; Perry et al., 2022). Due to this disrupt new events, there appear new ways of evaluating fire risk indexes according to changing weather conditions such as, for example. the Extreme-Fire Behaviour Index (EFBI) (Artes et al., 2021). These indexes allow to determine whether an ongoing wildfire have the potential to become an extreme forest fire or not. However, once a given wildfire is labelled as potential extreme fire, the next useful step would be to determine the severity of the fire in terms of potential burn area, principal propagation direction and the rate of spread. For that purpose, several forest fire spread simulator have been developed such as FARSITE (Finney, 1998), QUIC-Fire (Linn et al., 2020), Wildfire analyst (Artes et al., 2015) WRF-SFIRE (Mandel et al., 2014) with the aim to be used during an ongoing wildland fire. However, to be useful a forest fire forecast system should provide accurate results faster than real fire propagation, especially when dealing with extreme wildfires. This trade-off has been shown to be difficult to achieve because having higher precision results typically is penalized with higher execution times. This feature is quite relevant in FARSITE when forecasting large forest fires that take place in complex terrain. In particular, the part of the code that consumes most of the computing time is the one devoted to reconstructing the fire perimeter at each time step (Finney, 1998). FARSITE's algorithm has a complexity of $O(n^4)$, that prevents it to be used at real time. In this paper, an alternative algorithm for forest fire perimeter reconstruction is presented, which has a complexity of $O(n\,log(n))$, opening the possibility of turning FARSITE into an operational tool.

The original FARISTE's algorithm for fire front reconstruction is described in section 2. Section 3 introduces the proposal strategy. The experimental study is explained in section 4 and, finally, the main conclusions are reported in section 5.

2. FARSITE: Crossover

FARSITE is a forest fire simulator designed by Finney in 1994 (Finney, 1998). It is an iterative model to construct the evolution of a fire front over a time step. To do that, FARSITE defines a forest fire perimeter as a set of points, whose position in the area is evaluated at each time step applying the so called Rothermel's Model (Rothermel, 1972). In particular, FARSITE has two main steps to evaluate forest fire evolution: the propagation step (step 1) and the fire front reconstruction (step 2).

Step 1 consists of applying Huygens' principal approach for elliptical wave-front modelling. The fire is represented by a set of vertices (points) and for each vertice, the propagation equations of the Rothermel's model (Rothermel, 1972) are applied to evaluate their new positions. Once all vertices have been evaluated, then step 2 is carried out. The fire front reconstruction (called *Crossover* in the FARSITE's code) consists of finding an ordering on the boundary vertices (points) such that there are no intersections between the edges given by any two consecutive points. This is currently done by iteratively comparing all possible combinations of vertices composed by any two edges against each other, in a naïve algorithm. The main objective of such a process is to detect burnt areas and prevent the reconstruction process of generating complex loops and knots without any meaningful. Figure 1 shows this kind of situations. The figures referred as *Before* correspond to fire front obtained once FARSITE' step 1 has finished, and no extra corrections has been performed. Meanwhile the images referred as *After* are the final correct burnt areas (preserving or not preserving an enclave) once FARSITE's step 2 has finished,

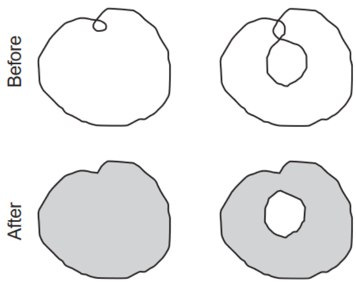


Figure 1- Example of a fire front reconstruction from (Finney, 1998).

As it is stated in the FARSITE's documentation (Finney, 1998), this process could be extremely expensive in terms of execution time. In particular, the *Crossover* routine has a complexity of $\boldsymbol{O(n^4)}$, what clearly penalize the total FARSITE's execution time. In the next section, an alternative algorithm for fire front reconstruction is described, which exhibits a high potential degree of parallelization and, therefore, it arises as a good alternative to accelerate FARSITE's simulations.

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 (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-shapes and conformal α-shapes share most of their properties, but the conformal α-shapes are 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 alternative algorithm that we propose, 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.

This approach, in addition to saving computation time, allows us to work with a data distribution with which the α-shape might not give us the expected results.

3.2. 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 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.

3.3. 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.

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 **α-**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* α-shape algorithm. Therefore, in order to be fair, the comparison has been done by feeding both programs with the same format of data and generating both the same output data format. Those formats are conformal with the ones used in FARSITE.

4.1. Execution time

The main contribution of the alternative proposal to reconstruct the fire front is the algorithm's complexity reduction. One the one hand, the original naïve FARSITE *Crossover* procedure exhibits a complexity of $\boldsymbol{O(n^4)}$, meanwhile the *boundary* α-shape approach has a complexity of $\boldsymbol{O(n\,log(n))}$ what implies a significant reduction of the execution time of this component of the simulator, which currently represents 60% of the total execution time of FARSITE. In figure 2, one can observe the time spent in executing both reconstruction algorithms when using different numbers of points for the fire perimeter. As we can observe, as the number of points increases, the execution time spent by the new algorithm decreases compared to the time spent by FARSITE approach. This performance improvement is more significative when dealing with a huge number of points being able to achieve a performance improvement of twenty time when using 100000 points. This result could lead to a FARSITE total time execution time of 50%. Describing the fire front with a huge number of points implies to describe the forest fire behavior with better precision but, typically this improvement in the fire front resolution has a direct impact in the execution time. Our proposal has the ability of provide accurate results without penalizing the total execution time.

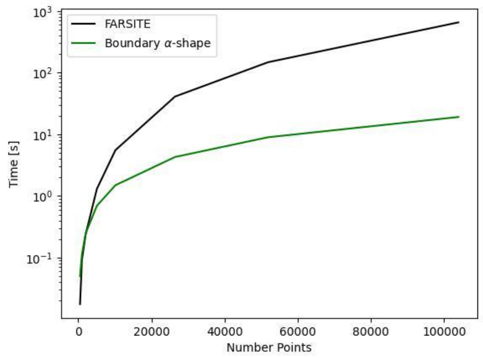
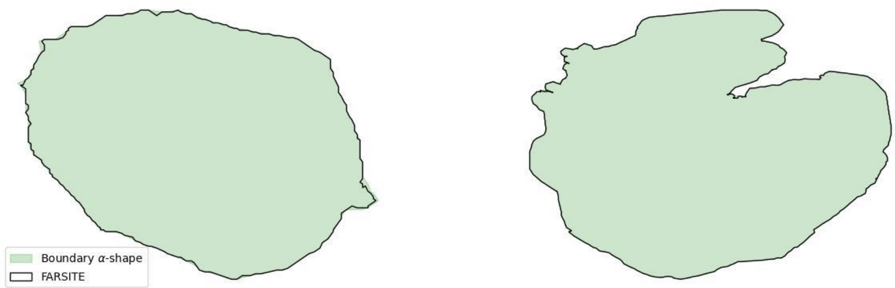


Figure 2 - Execution times of FARSITE Crossover and boundary α-shape with different numbers of points

4.2. Propagation results

The modification of the fire front reconstruction process could lead to different fire behaviour, 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. The experimental results shown in this section has been obtained using as α value the resolution of the perimeter, which, in this case, has been set to 30 meters. Figure 3 shows the output provided by the original fire front reconstruction made by FARSITE (black line) and the output provided by the new strategy (green shape). In particular, the two cases depicted in this figure corresponds to two real fires, figure 3(a) is a fire that took place in Pendilhe (Portugal) in 2013 and figure 3(b) was an event that happened in Arkadia (Greece) in 2011. As we can observe, the results are almost the same, however, if we analyze the shape and the line in detail, one can found certain regions where the green shape overpass the black line. Nevertheless, those difference are not significant enough to affect the global behavior of the wildfire,



a b

Figure 3- The fire front reconstruction obtained when applying the FARSITE Crossover algorithm and the boundary α-shape proposal to two real wildfires.

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 loosing 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 of 20 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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