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Optimal Fireline Generation for Wildfire Fighting in Uncertain and Heterogeneous Environment

Baisravan HomChaudhuri, Manish Kumar, *Member, ASME* and Kelly Cohen *Member, AIAA*

Abstract— **Fire is a natural component of many ecosystems but wildland fires often do pose serious threats to public safety, properties and natural resources. Forest fire acts as a dominant factor in reshaping of terrain and change of the ecosystem of a particular area. The total damage due to wildland fire shows an increasing trend over the past decade. Forest Fire Decision Support Systems (FFDSS) have been developed for the last thirty years all over the world that supplies valuable information on forest fire detection, fire behavior and other aspects of forest fires but lacks in developing intelligent fire suppression strategies. In this paper, an effort has been made to generate intelligent fire suppression strategies with efficient resource allocation using the Genetic Algorithm based optimization tool in a heterogeneous and uncertain scenario. The goal of this research is to perform intelligent resource allocation along with the generation of optimal firelines that minimizes the total burned area due to wildland fire. The solutions generated at each generations of the Genetic Algorithm (GA) are used to build the firelines in a heterogeneous terrain where advanced forest fire propagation model is used to evaluate the fitness values of each generated solutions. The optimal firelines thus obtained through the Simulation-Optimization technique minimizes the total damage due to wildland fire and eliminates the chance of any fire escape i.e., firefront reaching the fireline positions before they are built. Such techniques integrated with the existing FFDSS hold promise in effectively controlling forest fires.**

I. INTRODUCTION

FOREST fires affect the natural ecosystem and human lives in various ways. The damage due to wildland fire has increased over the past decade and in the last couple of years the damage has increased significantly according to the reports of National Interagency Fire Center [1]. The immediate effects of forest fire are destruction of vegetation, removal of wooden debris and soil organic matter. These and other effects of fire continue to shape forests long after the flames have passed. There are overall three aspects of forest fire management; *fire use*, *fire prevention* and *fire suppression* [2]. Fire use is the process in which the naturally or artificially generated forest fire is utilized to manage fuel distribution in the forest by removal of wooden debris and vegetation. Fire prevention includes taking different steps for the prevention of wildfires such as removal of hazardous fuels and generating wide spread consciousness about forest fires. Although fire prevention steps help in damage reduction and in some cases prevention of forest fires (mostly human generated fires), fire suppression is considered as the most important aspect of forest fire management. Lack of total control over removal of hazardous fuels and most of the forest fires being originated through sources (lightning) which are essentially stochastic in nature, *fire management* aspect of forest fire management requires special attention.

Forest Fire Decision Support Systems (FFDSS) have been developed for the last thirty years which provide valuable information on forest fire behavior, fire detection, and risk assessment. Examples of FFDSS include LANIK [3], Spatial Fire Management System (SFMS) of Canada [4], and FOMFIS [5] and DEDICS [6] of Europe. Each of these systems has its own merits and demerits and some were specially developed for some particular scenario. FFDSS provide the necessary information for the fire fighting incident managers to take appropriate actions for forest fire containment. Recently FAM (Fire and Aviation Management part of the US Forest Service) have developed WFDSS (Wildland Fire Decision Support System) [7] tools to help fire managers and agency administrators make decisions regarding strategies and tactics on wildland fires. WFDSS, unlike other fire behavior prediction software such as FARSITE [8], is probabilistic in nature that can incorporate the uncertainty associated with wildfire behavior. However, all these decision support systems largely lack the optimization and intelligent capabilities that can be used for effective decision making and allocation of resources in a dynamic and uncertain environment that characterizes a complex wildfire. Although usage of such powerful FFDSS software and scientific approach is applied in fire detection, fire behavior prediction, risk assessment, etc, fire suppression is still performed using thumb rules and the experience of the incident managers.

In real life wildfire fighting scenarios, a limited number of resources are available and the goal is to use the resources in the best possible manner so that the total damage due to the forest fire is minimized. One of the strategies to fight a wildfire is to construct a "fireline" around the wildfire. A fireline is a strip of land cleared of flammable materials like plants and shrubs. When the firefront reaches the fireline it stops propagating further due to the lack of additional flammable materials. At times, there may be a possibility of fire jump when the firefront intensity is high enough to cross the width of the fireline resulting in fire escape. The possibility of fire jump has not been considered in this paper.

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Baisravan HomChaudhuri, is a graduate student of Mechanical Engineering Dept, University of Cincinnati, Cincinnati, Ohio 45221

Dr. Manish Kumar is an Assistant Professor of Mechanical Engineering Dept, University of Cincinnati, Cincinnati, Ohio 45221.

Dr. Kelly Cohen is an Associate Professor of Aerospace Engineering Dept, University of Cincinnati, Cincinnati, Ohio 45221

Optimum resource utilization and allocation is an important part of forest fire fighting. Over time, researchers have come up with fire fighting strategies to minimize the damage due to wildland fire such as in [10], [11] and [19]. The paper [11] has put forward a general framework for the formalization of problems relevant to forest fire emergency management through real time resource assignment. Researchers in [10] have used the Genetic Algorithm to construct the best combination of available resources for forest fire fighting but optimal fireline building and realistic fire growth models have not been used. In this paper, the Genetic Algorithm (GA) is used to generate the *optimum fireline* that minimizes the damage due to forest fire and provide the location of the firefighting crews on the landscape from which fire suppression should start so that the fire doesn't escape and the total damage that can be quantified as the total burnt area is minimized at the same time. In our last paper [19], we used the GA to generate the *optimal fireline* when fire propagation was only considered for a homogenous terrain and homogenous weather condition (constant wind). This paper makes further contribution to the strategy by incorporating heterogeneity in terrain (e.g., hilly terrain) and uncertainty in wind direction and velocity. The incorporation of these aspects lead to more realistic implementation of the proposed GA based strategy and the solutions are expected to be more robust to uncertainties in weather conditions.

The Simulation-Optimization technique is used in this paper. In the proposed simulation-optimization technique, the forest fire is allowed to progress in simulation with the help of fire propagation models with added uncertainty when the fireline is built concurrently. A population of solutions that have different parameters representing different strategies of the firefighting agents are generated by the Genetic Algorithm and their performance is evaluated when the wildfire is propagated concurrently. The fitness value of each solution is sent back to the GA where new populations are generated with the performance index information of the previous generation. The performance index of the GA is a measure of goodness of the solutions and has been represented as the total damage due to wildfire. After a number of generations, the optimal solution is provided by the GA which minimizes the performance index.

II. FIRE PROPAGATION MODEL

A. *Fire propagation in homogenous terrain*

Over the years researchers have developed a number of forest fire simulating models under homogenous conditions. In [9], researchers proposed a general framework of forest fire propagation model. Assuming a uniform fuel distribution, uniform landscape, uniform weather and a constant wind direction, forest fire propagation can be modeled using Richard's mathematical model [12]. It considers the firefront to take elliptical shape under uniform conditions and the parameters of the elliptical fireline are dependent on the wind speed and direction. This model uses the Huygens principle of wave propagation, where each point on the firefront is considered to be a new source of fire generation. It is popularly known as the Envelop Model since the generated new elliptical firefront envelops the small elliptical firefront generated by each point on the previous firefront. The fire propagation is shown in Fig. 1. The plot on the left shows the firefronts at different time steps when the wind direction is along the Y-axis. On the other hand, the plot on the right represents a case when wind direction is at angle 20^0 with the Y-axis.

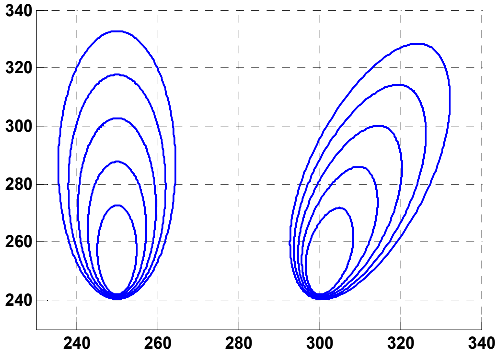

Fig. 1. Envelop Model for forest fire propagation

The following equation describes the envelop model of forest fire propagation.

$$X_t = \frac{a^2 \cos\theta (x_s \sin\theta + y_s \cos\theta) - b^2 \sin\theta (x \cos\theta - y_s \sin\theta)}{\sqrt{b^2 (x_s \cos\theta + y_s \sin\theta)^2 - a^2 (x_s \sin\theta - y_s \cos\theta)^2}} + c \sin\theta$$

$$Y_t = \frac{-a^2 \sin\theta (x_s \sin\theta + y_s \cos\theta) - b^2 \cos\theta (x \cos\theta - y_s \sin\theta)}{\sqrt{b^2 (x_s \cos\theta + y_s \sin\theta)^2 - a^2 (x_s \sin\theta - y_s \cos\theta)^2}} + c \cos\theta \qquad (1)$$

Here "X_t" and "Y_t" are the rate differentials and the angle θ is the wind direction. "x_s" and "y_s" are the orientation of the vertex on the on the fire front in the terms of component differentials. The location of the new fire-front is available by multiplying the rate differentials with the step time.

B. *Wind-Slope Correction*

Fire propagation rate and direction is primarily affected by weather and topology of the terrain. In a homogenous terrain (no slopes) the rate and direction of fire propagation is primarily determined by the wind speed and direction. In heterogeneous terrain (with slopes), the fire propagation rate is higher when going upslope and the rate decreases when moving down-slope. The direction of fire propagation is further affected by the slope and aspect on each point of the terrain. In order to obtain a more realistic forest fire propagation model, the slope and wind correction model is required to be incorporated. Researchers in [13] have listed the different wind-slope models available, such as models of McArthur, Rothermel, Albini and Finney, and have proposed a more general framework for such a correction.

The wind-slope correction can be approached in both scalar and vector methods. In the scalar method, the rate of fire propagation at a particular point in the terrain is the product of "R_w", the wind induced rate of spread, and a scalar quantity that is a function of the slope at the given point. In McArthurs model [14], the rate of fire propagation at a particular point in the terrain is given by:

$$R(w,\gamma_s) = R_w \exp(0.069\gamma_s) \tag{2}$$

Here γ_s is the slope faced by the firefront at a particular point. The aspect γ_a at a particular point of the terrain is the direction of the horizontal component of the vector normal to the terrain at that point. The angle γ_a (Aspect Angle) is shown in Fig. 2. If $H(x,y)$ denotes any surface, $\tan\gamma_s = ||\nabla(H(x,y))||$. The aspect angle is given by a vector, $-\nabla(H(x,y))$. The general framework of wind-slope correction in forest fire propagation proposed in [13] is expressed by:

$$R(w,\gamma_s) = B_{-\gamma_a} S_{\gamma_s} B_{\gamma_a} R_{\mathbf{w}} \tag{3}$$

Where "$B_{\gamma a}$" is the change of basis matrix which facilitates a transformation from cardinal coordinates to the terrain-following coordinates. The *terrain-following* $\{\mathbf{t,u}\}$ coordinates aligns with the upslope and across slope directions while the cardinal coordinates $\{\mathbf{x,y}\}$ are the global coordinates of the terrain where y-direction is towards the north and x-direction is towards east. The matrices "$B\gamma_a$" and "$S_{\gamma s}$" are given by Equations (4) and (5).

$$B_{\gamma_a} = \begin{bmatrix} -\cos\gamma_a & \sin\gamma_a \\ -\sin\gamma_a & -\cos\gamma_a \end{bmatrix} \tag{4}$$

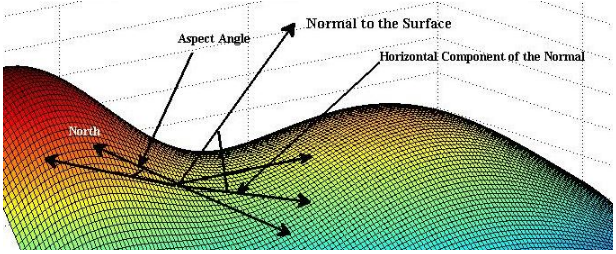

Fig. 2. Schematic Diagram Showing the Topographic Aspect of the Terrain

$$S_{\gamma_s} = \begin{bmatrix} 1 & 0 \\ 0 & \sigma \end{bmatrix} \tag{5}$$

The term "σ" is the scalar factor similar to the one used in Equation (2). Performing the matrix operation as in Equation (3), the rate vector of fire propagation at a particular point is available whose magnitude and angle is the rate and direction of forest fire propagation in that point of the heterogeneous terrain.

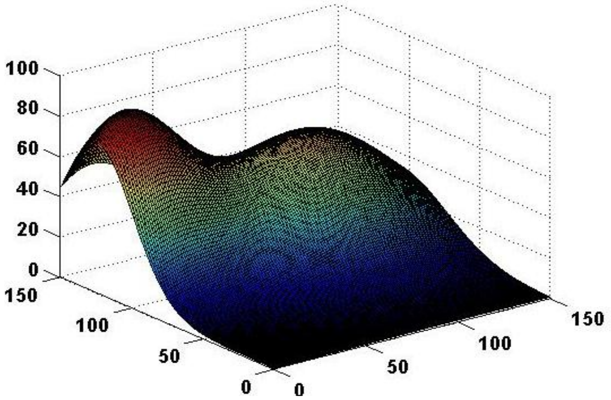

Fig. 3. A Randomly Generated Terrain used for Developing Fire Fighting Startegies

In Fig. 3, an arbitrarily generated terrain is shown which we have used in this paper as an example terrain to apply the fire propagation model and verify fireline building strategy generated by the proposed GA based technique. Fig. 4 shows a simulation of forest fire propagation in the above terrain. A grid based method is used in the simulation with a grid size of 3x3 units. Since most of the forest fire propagating software like FARSITE and others use raster files to represent the terrain, wind-weather conditions, and other information such as vegetation/fuel distribution, a grid based representation of terrain is more suitable for generation of resource allocation and fire fighting strategies. Furthermore, the grid based method facilitates easy integration with Geographic Information Systems (GIS) that are widely used in disaster management. The simulated result shows the tendency of the fire rate increase towards the upslope of the terrain.

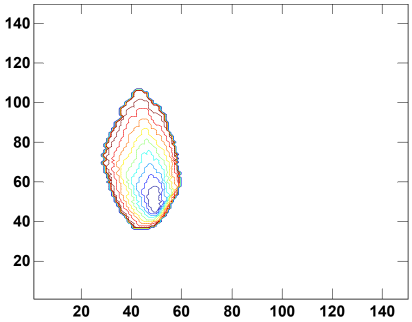

Fig. 4. Fire propagation after wind and slope correction

III. PROBLEM DESCRIPTION

The objective of this paper is to develop an optimization scheme for decision making in the containment of forest fires. This paper considers fireline construction as the firefighting strategy, and determines allocation of fireline construction resources and shapes of firelines for optimal containment of wildfire. After the initial attack to mitigate the wildfire, firelines are built around the firefront that contains the wildland fire. The optimization problem is to find the optimal fireline that minimizes the total burned area to the maximum extent and also takes into account that fire does not escape. Fire is said to escape when firefront reaches the semi constructed firelines and thus escapes.

In this paper, a finite number of firefighting crews are considered that builds firelines according to specified polynomial curves. The optimization problem is to find the locations of the firefighting crews in the given terrain from where fireline building would start and the parameters of the polynomial curves that define the shapes of the firelines. The uncertainty or noise associated with the wind speed and direction results into inaccurate fire behavior prediction. Fire behavior prediction is also affected by the uncertainty present in terrain and fuel distribution modeling. Thus the optimal fireline to be built should be robust enough to contain the fire under such uncertainties in measurements or random changing behavior of forest fire. This kind of intelligent resource allocation promises better and more robust results in minimization of forest fire damage in a real world scenario.

IV. APPROACH

The Genetic Algorithm search and optimization technique is used to solve the proposed problem. The Genetic Algorithm (GA) is a search and optimization technique used in computing to find the exact or approximate global solutions to an optimization and search problem. The Genetic Algorithms are based on mechanics of natural selection and natural genetics [15]-[17]. They combine survival of the fittest among the candidate solutions with randomized, yet organized, information exchange to form search algorithms with capabilities of natural evolution.

The GA starts with a random creation of a population and further generations of improved solutions are obtained by the operations like Reproduction, Crossover and Mutation. The steps involved in GA for simulation-optimization is as follows:

Step 1: Initialize a population-string of individuals (candidate solutions)

Step 2: Use simulation models to evaluate the fitness of each individual

Step 3: Carry out the genetic operations (See Fig. 5) viz. reproduction, crossover and mutation

Step 4: Test for termination criterion.

The GA operates by finding a solution that minimizes a performance index. A performance index is the measure of goodness or effectiveness of a solution. In this case, performance index is the total burned area due to wildland fire. The mentioned Simulation optimization technique (Fig. 6) is used for the evaluation of the fitness value of each generated solution of the GA.

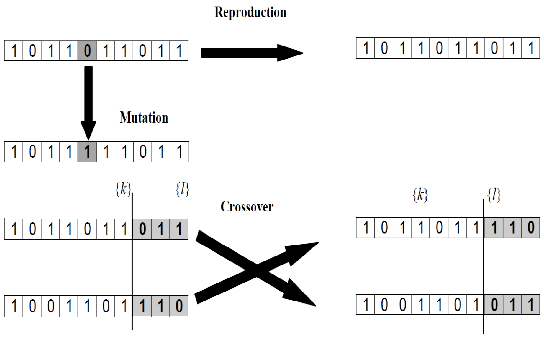

Fig. 5. Genetic Algorithm Operations

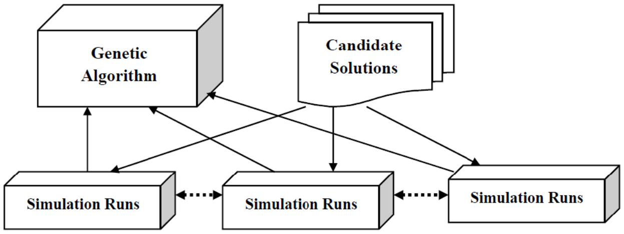

Fig. 6. Schematic Representation of the GA based Simulation Optimization technique.

To obtain the optimal fireline for the containment of the forest fire, the location of the firefighting crews are required from which fireline building will start and the parameters of a certain polynomial shaped firelines to be built. In this paper four firefighting crews are considered to build quadratic function shaped firelines (see Equation (6)).

$$y = a_k x^2 + b_k x + c_k \tag{6}$$

Where $k=1,\ldots 4$ represent the four firelines.

To obtain an overall closed curve through four different quadratic function shaped firelines, each crew should move from its assigned starting point in the terrain to the starting point of the next crew. The Equation governing such fireline building is shown below which represents the firefighting agent building the fireline '*k*' move from point (x_i, y_i) to (x_j, y_j):

For x going from x_i to x_j

$$y = y_i + a_k(x^2 - x_i^2) + b_k(x - x_i) \tag{7}$$

When the locations x_i, y_i and x_j, y_j and the parameter b_k is available, the fireline building parameter a_k can be computed simply (Equation (8)).

$$a_k = \frac{(y_j - y_i) - b_k(x_j - x_i)}{x_j^2 - x_i^2} \tag{8}$$

The location of the four firefighting crews in the terrain, $\{\boldsymbol{x}, \boldsymbol{y}\}$ coordinates, along with the parameter "$\boldsymbol{b_k}$" of each of the firelines (Equation (6)) are the required parameters to be optimized by the GA where $k = 1$ *to* 4. When the locations and the parameters "b_k" are available, the parameter "a_k" can be computed as shown in Equation (8). As mentioned previously, the GA will initialize a population of solutions containing the twelve discussed parameters.

Now, as the fireline is built from one point to another, some combinations of the four points will result in intersection of two firelines which is a practically wrong solution. Hence, concepts from the Travelling Salesman Problem (TSP) [18] are introduced here to obtain the proper sequence of the points so that all the points are touched with no intersection of two or more firelines.

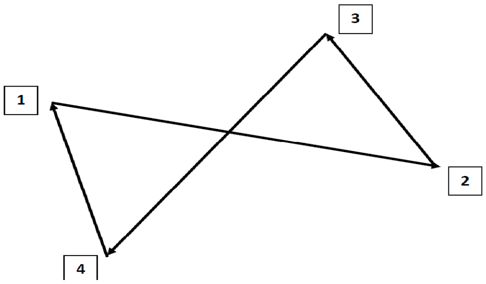

Fig. 7. Incorrect Travelling Order

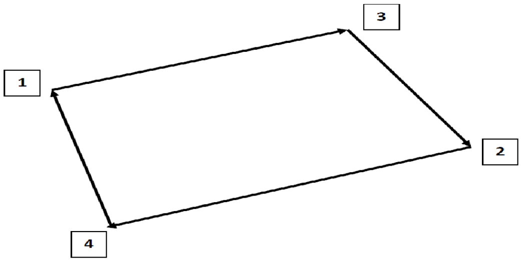

Fig. 8. Correct Travelling Order

Both the figures (Fig. 7 and Fig. 8) show the location of the firefighting crews (1, 2, 3 and 4) generated by Genetic Algorithm. Fig. 7 shows the incorrect travelling order with a sequence 1-2-3-4-1. The intersection between the generated firelines signifies an impractical solution. Fig. 8 shows the correct order, 1-3-2-4-1, after applying the travelling salesman problem that negates the possibility of intersection of generated firelines.

V. SIMULATION RESULTS AND DISCUSSION

In this paper, a grid based approach is considered where the whole terrain is divided into grids of size 3x3 units. Whenever the firefront touches a particular grid, that grid is considered to be on fire and will act as the source of fire propagation in the next time step according to the Huygens's principle of wave propagation. Using four quadratic function shaped firelines with different parameters, a lot of flexibility on the overall fireline shape is added for the forest fire suppression. In this problem, four firefighting agents are assumed to be working at a constant rate and when any crew finishes its assigned task of fireline building, it helps the next crew to complete its assigned task and hence their combined rate of fireline production increases. In this case, Genetic Algorithm has 12 parameters to optimize which consists of the (x,y) locations of the four fire fighting agents and the parameters “b_k” in Equation (7) for the four firelines.

A moderate grid size of “3x3” square units is chosen in this paper for the simulation purpose which provides a fairly good resolution of the solution as well as manageable search space. In every iteration, in the GA generated solution vector, a travelling salesman problem algorithm is utilized to obtain the proper order of the solution points. Simulation of fire propagation model is used to measure the effectiveness of the various solutions using a performance index which is the total area burnt.

The GA generated solutions are considered un-acceptable if the initial firefighting agent locations and the firelines that are yet to be built are on grids which are already on fire and for those cases, a penalty is given by associating a very high performance index with those solutions.

Since the search space for the GA is large in this problem, 300 generations and a population size of 301 are used in the GA. The mutation probability is generally considered low and is taken as 0.0077 and the crossover probability of 0.77 is considered. Steady State GA is used with a steady state population size of 31. It is assumed that the fire suppression effort starts after $t = 4$ units of time. The fireline building rate of each firefighting agents are considered same and is considered to be 12 grids per time step.

Along with wind-slope correction to the fire propagating model, uncertainty is added to the wind-slope and the final rate of propagation and direction of the forest fire. The source of uncertainty can be noisy wind speed and direction measurement, or uncertainty in terrain modeling and fuel distribution. Though no heterogeneous fuel distribution is considered, the uncertainty added to the final rate of spread and direction of fire propagation takes care of heterogeneous and uncertain fuel distribution. The wind direction is sampled from a normal distribution with a mean of 20° and a standard deviation of 10° i.e. wind direction changes in each time step and the range is 0°-50°. The wind speed is also considered to be normally distributed with a mean of 15 miles/hr and a standard deviation of 3 miles/hr.

In Fig. 9, the blue dots on the landscape denote the fire crew locations when the red grids denote the firefront. Fig. 10 shows the evolution of best performance index value in different generations and its convergence to the optimal value.

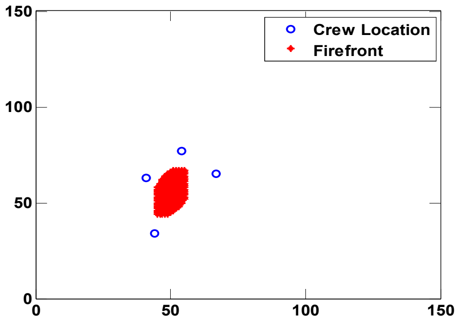

Fig. 9. Fire Fighting Crew Initial Locations and Initial Fire Propagation

Fig. 11 shows the fire is properly contained without escape. The red grids here represent final firefront while the blue grids are the fireline.

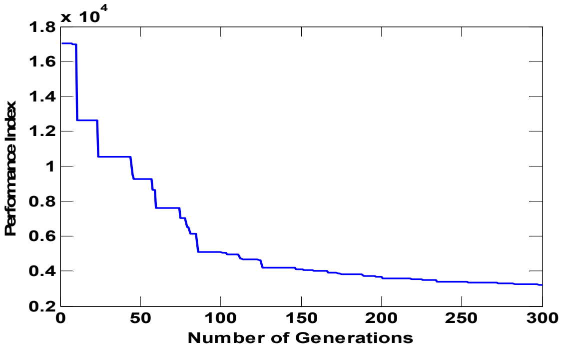

Fig. 10. Performance Index vs Number of Generation

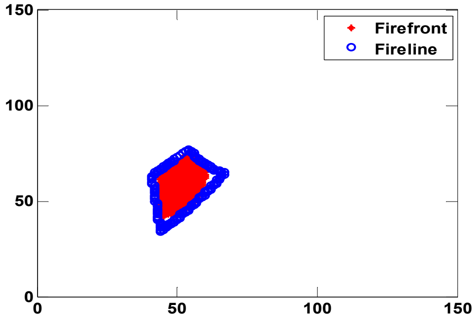

Fig. 11. Final Fireline

The GA generates a population of several solutions that gets evaluated in each generation via simulation of the fire propagation model. All these calculations make the proposed GA based simulation-optimization technique computationally extensive. In-spite of this, real time applicability of this technique is not of much concern because of time scale in which wildfires are fought and also due to the fact that the proposed technique can be easily adapted to facilitate parallel computations.

VI. CONCLUSION

In this paper, a Genetic Algorithm based simulation-optimization framework for generating intelligent wildfire fighting strategies has been developed for better containment of wildland fires in heterogeneous and uncertain environment. To incorporate heterogeneity in the terrain, the fire propagation model used has been modified to incorporate wind-slope correction. Furthermore, uncertainties in wind direction and speed have been incorporated to obtain robust firefighting strategies. The optimization framework uses the fire propagation model to determine the best strategy for fireline construction that minimizes the total burnt area. The GA generated optimal solution is shown to handle the uncertainty in the fire behavior. One of the major contributions of this paper is to apply the GA based simulation-optimization technique to a wildfire fighting scenario where wind-terrain conditions and hence the fire behavior is uncertain, and demonstrate that such techniques can be used to arrive at better resource utilization decisions. The availability of accurate fire propagation models, new technologies to gather and process information, and accurate weather prediction models can be used with simulation-optimization techniques as proposed for more efficient and robust decision making in complex wildfires.

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