Description of wildfires spreading and extinguishing with the aid of agent-based models

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Abstract. The article describes a new method of describing wildfires spreading and extinguishing based on agent-based models. The agent approach in conjunction with geoinformation systems (GIS) permits to efficiently describe the interaction of a big number of participants of wildfire fighting: spreading fire, fire brigades, means of mechanization, air means, etc. In the current paper, this approach is illustrated by an example of two types of agents denoted as A and B. The burning fire line is seen as a chain of type A agents, each of which imitates burning of an elementary area of vegetable fuel. The fire line movement is described by Hamilton–Jacobi equation and is calculated based on the moving grid algorithm. Agents of another type—B-agents—describe fire extinguishing, they approach the agents of A type and affect them decreasing fire intensity to zero. This model is presented by a GIS-oriented software system which may be enhanced and be useful both for fire control management and training personnel in wildfire fighting tactics.

1. Introduction

A wildfire is an uncontrollable fire spontaneously arising and spreading in the natural environment. This term implies forest, peat and steppe fires. Wildfire causes great economic and ecological damage to the countries and regions where they occur and result in casualties. By now a great number of information systems were developed to support efficient wildfire fighting. The systems permit to model and forecast fire behavior with various accuracy (systems Behave Plus [1], FARSITE [2], WFDS [3], etc.).

However, besides modeling of the wildfire line itself there is a necessity to model various external impacts on fire to localize and extinguish it. Use of such models may be actively applied in fire control, in particular, to improve efficiency of management of fire fighting forces and means. In practice the choice of the means and methods for wildfire localization depends on a big number of factors which are difficult to formalize. In such conditions, in our opinion, the agent-based modeling (ABM) is a quite efficient method.

The agent-based modeling, ABM, is a new approach to imitation modeling which is aimed at imitating behavior of complex dynamic systems through studying behavior and interaction of autonomous and independent subjects (agents) in a certain environment [4]. Agent-based models are used both in natural sciences (physics, biology) and in social sciences (sociology, economics). This type of models is the most effective in studying behavior of systems consisting of a big number of interacting subjects (from dozens to several thousands) being under the influence accidental impacts.
For modeling wildfire situations geoinformation systems (GIS) also are of special interest, since they have possibilities to store and display spatial information. The joint use of the agent-based modeling and GIS permits to combine the advantages of both directions, use advanced means for modeling processes running on in conditions of a real natural environment and landscape.

The idea of modeling wildfire line by the agent-based approach was considered in papers [4-9]. In these papers the agent-based models were created with the aid of specialized software systems (agent platforms) such as NetLogo, StarLogo, Repast Simphony, etc. This approach permits to simplify software implementation of an imitation model, but considerably complicates integration of agent-based models with GIS. Besides, papers [4-9] carry out modeling of only freely spreading fire without modeling the actions of fire-fighting forces and means.

Thus it is necessary to create imitation systems based on agent approach permitting to model fire situations on a real terrain. The current paper proposes a new method of creating such systems by presenting an example of an agent-based model, which imitates spreading of ground forest fire and a direct method of its extinguishing by non-mechanized firefighting brigades.

2. Description of fire front dynamics

The model of fire dynamics reviewed below is based on the following assumptions.

1. The area of modeling is a fragment of the map of a real territory covered with a layer of vegetable fuel. It permits to combine the data of GIS and agent models. The map contains the layers representing various elements of modeling environment: settlements, rivers, lakes, roads, ravines, forest ranges and other objects. The coordinates of each element are given. The so called model of thin layer of vegetable fuel [10] is used. This model does not consider the vertical structure of vegetable; and fuel materials are considered as a homogeneous layer on the top of the ground with average characteristics. Such characteristics are stored in the database of pyrologic descriptions of forest plots.

2. The process of fire spreading along the fuel layer and the process of fire spreading combating are considered as projection on the horizontal plane (on a map of corresponding scale). The coordinate system \( X = [x^1, x^2]^T \) is mapped-referenced \( X \in D \), where \( D \) – is the scenery area in review.

3. The micrometeorological, topographic parameters and characteristics of fuel materials in each map point are assumed to be known. It allows calculating the fire parameters in each map point with the use of known models of vegetable material burning (for example, by R. Rothermel’s model for fire spread prediction [11]).

Let us regard \( \varphi(X, t) = 0 \) as the fire front equation (figure 1). This function describes the movement of fire line and satisfies the Hamilton–Jacoby equation,

\[
\frac{\partial \varphi}{\partial t} + V \cdot \nabla \varphi = 0, \tag{1}
\]

where \( V = V(X) = [v^1, v^2] \) is the row vector of fire front speed.

The column vector of a gradient \( \nabla \varphi = \left[ \frac{\partial \varphi}{\partial x^1}, \frac{\partial \varphi}{\partial x^2} \right]^T = P = [p^1, p^2]^T \) is a normal to the fire front.

The equation (1) is considered in initial conditions,

\[
X(0) = X_0(\alpha), \quad P(0) = P(\alpha), \tag{2}
\]

where \( X_0 \) and \( P(\alpha) \) are a parametric representation of an initial fire line and multiple normals to it, \( U \) is an admissible set of values of the parameter \( \alpha \).

For the purpose of the numerical modeling of fire dynamics it is more convenient to use normal speed of a fire front \( V_n = V \cdot P / |P| \), where \( |P| \) is a length of a normal and \( P / |P| \) is a unit vector of a normal to the front line.

And the equation (1) is transformed to the form
\[
\frac{\partial \varphi}{\partial t} + V_n |P| = 0. \tag{3}
\]

The equation (3) is also considered in initial conditions (2).

As it follows from the theory of burning processes and observations, the fire spreading speed depends on a set of external environment parameters, in the first run, on wind speed and a surface slope, where burning takes place. Therefore, normal speed of fire front movement may be presented as a function of several arguments,

\[
V_n = V_n (X, t, W, S, \beta, \gamma) \tag{4}
\]

where \( W \) is wind speed, \( S \) is a surface slope, \( \beta \) is an angle between a wind direction \( \vec{W} \) and a direction of a normal to the front line \( P \), \( \gamma \) an angle between a slope vector and a direction of normal to the front line. Normal speed of fire front movement at any point of a fuel materials layer may be presented as a product of two functions:

\[
V_n (X, t, W, S, \beta, \gamma) = V_0 (X, t, W, S) \chi_n (P, W, S), \tag{5}
\]

where \( V_0 \) is a maximum fire spreading speed, when the direction of the normal to the line coincides with the wind direction and the surface slope direction.

The multiplier \( 0 \leq \chi_n (P, W, S) \leq 1 \) determines a degree of fire spreading speed reduction \( V_n \) in other directions when the direction of a normal to the line does not coincide with the direction of wind and a slope. This function determines local directions of fire front movement and is called an indicatrix of the front's normal speed or according to H. Minkowski and H. Rund [12], a figurotrisa of the spreading process. The properties of this function are reviewed in paper [13]. For simplicity of representation we further on will designate the figurotrisa as \( \chi_n (P) \).

The use the figurotrisa permits to create an effective algorithm of numerical modeling of the fire front spreading. The idea of algorithm implies use of the methods of moving grids proposed by S. Godunov. The backbone of the method consist in that the computational grid of a task is not built a priory, but is determined by the current solution of the task. The grid moves and develops while the computations are being made.

Let us consider the construction of a computational grid. The fire line at the moment \( t \) is a closed line going through the points \( C_i \), \( i = 1,..., N \) (figure 1). Each point \( C_i = C_i (t) \) is determined by the vector \( C_i (t) = \{ X_i, L(i), R(i), t \} \), where \( X_i = (x_i, x^2_i) \) are coordinates of a point on the map, \( L(i) \) and \( R(i) \) correspondingly are the numbers of adjacent points located left and right from \( C_i \).

The algorithm includes the following stages:

1. Creation of the grid nodes at the following moment \( t + 1 \) (first iteration). For each point \( C_i (t) \) a new vector of coordinates is computed

\[
X_i (t + 1) = X_i (t) + V_0 (X, t) \chi_n (P_i) \Delta t \tag{6}
\]

Here \( P_i \) is a vector of the normal to the front at the point \( C_i (t) \). This vector is determined as the normal at the point \( C_i (t) \) to the line passing through points \( C_{i-1} (t) \), \( C_i (t) \), \( C_{i+1} (t) \); \( \Delta t \) is the time step of the calculation.

2. Grid ordering

In modeling fire spreading across terrain the distances between adjacent angles change and the grid may become irregular. To support a grid's regular structure two actions are foreseen: introduction of a new node, if a distance between adjacent nodes exceeds a maximum value \( l_{max} \) and exclusion of one of the nodes, if such distance turns out to be less than a given value \( l_{min} \). For example, if a distance between nodes \( C(i) \) and \( CR(i) \) is bigger than \( l_{max} \), then a new node is introduced \( C(j) \) between them.
and references to the adjacent nodes are changed: $R(i) = j$, $L(R(i)) = j$, $R(j) = R(i)$, $L(j) = i$. Similarly, if a distance between $C(i)$ and $C(R(i))$ is less $l_{\text{min}}$, the node $C(i)$ is excluded from the list and references change: $C(R(i)) = C(L(i))$, $C(L(i)) = C(R(i))$.

Due to the list structure of a fire front description modeling of the movement of several separate fires, their separation or merging is possible.

Input data for calculating fires are typical for many models [10]. Vegetable fuel parameters are taken into consideration:

- type of fuel materials,
- stock of fuel, kg/m$^2$,
- fuel calorific efficiency $Q$, J/m$^2$.

Parameters of external environment:

- fire hazard class as per weather (from 1 to 5),
- speed and direction of wind $W$ according to data of the nearest weather station, m/sec
- value and direction of a surface slope, grades

These parameters are the most important for calculating burning intensity on the fire line $I$, W/m, maximum spreading speed $V_0$ m/min, figuretrisa parameters $\chi_n(P)$, which permits to calculate the speed of front movement at its any point.

3. Agent-based model

The model contains two types of agents, which are $A$ and $B$. Below structure and functioning of the agents are described.

The agents of the type $A$ ($A$-agents) are utilized for modeling fire spreading as a combustion wave based on the Hamilton–Jacoby equation and the moving grid algorithm reviewed above. Each node $C(i)$ of the moving grid corresponds to one agent, $A_i$. An array of $A$-agents are a fire line (figure 1). The spatial coordinates of the agents of this type $X_i(t)$ are calculated at each step of modeling. Besides, as was described above within modeling under certain conditions agents may perish or au contraire the new ones may arise. The figure also shows the movement of an agent $A_i(t)$ at the following time step $A_i(t+1)$. Vector $P_i(t)$ is a normal to fire front line at the point $A_i(t)$; $W$ is a wind vector; $V_0\chi_n(P_i)\Delta t$ is a distance for which an agent moves $A$, for one step.

![Figure 1. Presentation of fire line as a chain of $A$-agents, which move according to the moving grid algorithm.](image)

The agents of the type $A$ may be in an active and passive state. $A$-agent in an active state generates a heat current $I(t)$ and a smoke plume. Intensity of a heat current depends on burning conditions and may subside under the influence of the agents of type $B$. As value $I(t)$ reduces to zero $A$-agent becomes passive and no more takes part in the process of modeling.

The agents of type $B$ model actions of fire fighting forces and influence the agents of type $A$. They pursue only one goal, which is to extinguish all nodes of burning, i.e. to make all $A$-agents passive. For
this, B-agent moves across the modeling environment to the nearest A-agent and upon approaching reduces fire intensity $I_A(t)$:

$$I_A(t + 1) = I_A(t) - \Delta I_B(t),$$

(7)

where $\Delta I_B(t)$ is reduction of fire intensity caused by $B$-agent within one step of modeling. Having extinguished a successive $A$-agent, $B$-agent moves to the nearest active $A$-agent and continues its actions.

Before the start of modeling number, location and characteristics of $A$- and $B$-agents are set. The characteristics of $A$-agents are set with burning parameters, speed of fire front movement and $V_0$ figurotrisa $\chi_A(p)$. Performance of $B$-agents is determined by wildfire fighting instructions [14, 15].

4. Implementation of an agent-based model

On the basis of the proposed multiagent model a software with client and server architecture and web interface was developed. There is a database on a server, which contains information on a modeling environment (real terrain). The program code for the server part is implemented in the PHP language. The system's user interface is implemented in JavaScript (JS) with the use of OpenLayers, an open source code library. This library is designed for creating maps based on the program interface (API) and permits to create a web interface for displaying cartographic documents. This library works with data of various cartographic servers, such as OpenStreetMap, Google, Yandex, etc.

Below an example of modeling with the aid of the developed system is given.

5. Example

Parameters of a modeling environment:
- type of vegetable fuel – lichen;
- fire hazard class – 2;
- wind speed under cover – 1 m/sec, wind direction – south-west.

The forest plot is located on a slope which is indicated by level lines. According to [14, 15] intensity of the modeled fire is determined as weak, therefore the scheme of fire extinguishing is along the whole perimeter. 3 fire brigades, each of 6 persons in number were engaged. The brigades were deployed around the fire line and got a task to go round fire counterclockwise. The area of the fire spot when detected is about 4 ha. Figure 2a represents the initial position of the fire brigades and the initial fire line.

Figure 2b represents the position of the brigades and the fire line 4 hours after the start of extinguishing (in 48 iterations of the modeling process). As it is seen from the figure after 4 hours the
fire continues to be in progress, less than 50% of the active fire line is extinguished. Besides, the total length of the burning fire line at the 4th hour of extinction is approximately equal to the length of the initial fire line, which evidences that 3 fire brigades of 6 persons in number each fail to cope with this fire.

The given example of a negative result in planning a fire fighting event confirms, in our opinion, that the agent-based modeling is effective. The point is that the standards of using fire fighting forces [14, 15] give rather rough estimates, which with regard to terrain features may result in taking wrong decisions.

6. Conclusion
A new method of imitation modeling of wildfire spreading and extinguishing based on agent-based approach permitting simultaneous modeling wildfire spreading and combating therewith is proposed. The developed multiagent model for imitating a direct method of extinguishing a ground forest fire by non-mechanized firefighting brigades and the software developed on the basis of this model can be used for solving a wide range of problems. Firstly, the system may be useful for prompt determination of spreading parameters of ground forest fire in forest ranges, and for developing a complex of measures to prevent and combat fires. Secondly, this system may serve as a basis for instructional training systems designed for teaching students of forestry industry institutes and colleges, as well as forestry staff and Ministry of Emergency Situations in the basics of wildfire combating tactics in a form of a training-game. The possibilities of the proposed method may be enlarged by introducing new agents imitating behavior of other participants of wildfire combating, which will enhance modeling efficiency and reliability.

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