Using cellular automata in modelling of the fire front propagation through rough terrain

A V Pavlova¹, S E Rubtsov¹ and I S Telyatnikov²

¹ Department of Computer Technologies and Apply Mathematics, Kuban State University, 149, Stavropol’skaya str., Krasnodar, 350040, Russia
² Laboratory of Mathematics and Mechanics, Southern Scientific Centre of the Russian Academy of Sciences, 41, Chehova str., Rostov-on-Don, 344006, Russia

E-mail: pavlova@math.kubsu.ru

Abstract. The authors created a cellular automata model simulating the dynamics of a fire source for rough terrain on a triangular grid, including cases of artificial and natural obstacles. The model can be used as a part of a complex of models describing fire propagation and migration of polluting aerosol and gaseous products of combustion in the atmosphere. It is applicable for predicting a possibility of occurrence, intensity, scenario of fire propagation, as well as assessing its impact on environment and also in decision support systems for the prevention of emergency fire situations. For the model description of real settlement areas, we used a digital model of the territory of the Krasnodar Territory built using geographic information systems.

1. Introduction

Among the variety of anthropogenic and natural factors that negatively affect the state of the ecosystem, fires are one of the most destructive, causing enormous environmental and material damage. At present, when studying the processes of natural fires propagation, various models are used that differ significantly in their input data sets, approaches, and algorithms [1–3]. The problem of the fire propagation description is extremely complex and is presented by researchers as a combination of various physical and chemical processes.

The dynamics of natural fires in Russia and abroad confirms the urgent need in development of sound fire control strategies based on an analysis of the fire propagation mechanisms, possible scenarios of its development and prediction of consequences. For effective planning of the fire-fighting measures and successful prevention and elimination actions for such natural disasters and their consequences, one requires not only the development of prognostic models of different levels, but also the usage of ground and satellite data about the modeled processes. The tasks for creating an integrated system, authors are working on, include: developing and implementing algorithms of the fire propagation dynamics taking into account the terrain and the presence of obstacles; modeling of the effects aimed at fire localization; adaptation of the developed algorithms for topographic data obtained from the Geographic information systems (GIS), development of software and carrying out computational experiments aimed at prediction of the fire front location and the spatio-temporal distribution of pollution with their graphical visualization and further export to GIS.

The authors implemented spatial CA models for a number of scenarios of scattering and transformation of impurities [4], created a cellular automata model simulating the dynamics of a fire source for rough terrain on a triangular grid, which can be used as part of a complex of models describing...
fire propagation and migration of polluting aerosol and gaseous products of combustion through the atmosphere, applicable for predicting the possibility of occurrence, intensity and scenario of fire propagation as well as assessing its impact on environment. For the model description of real calculation areas, a digital terrain model of the territory of the Krasnodar region has been built using geographic information systems [5].

2. Some approaches to modelling the spread of fire
Among the first theoretical studies of the natural fires development processes, of which the crown forest fires are the most destructive, works [6–8] can be noted. Based on the analysis of known and original experimental data, general models of forest fires were developed [9 etc.]; the proposed approaches were further developed in the works of domestic and foreign researchers. Reviews of the study results for the problems of the forest fires spread modeling are presented in monographs [10].

Currently, active research on these phenomena is being conducted in Russia and abroad as well as on the development of systems for their monitoring and forecasting. Among foreign fire hazard forecasting systems, one can note the NFDRS (National Fire Danger Rating System) developed in the USA on the basis of an empirical model, the Canadian Forest Fire Danger Rating System and NFDRS, based on the semi-empirical Rothermel model [11]. At the same time the experience of operating such systems, for example, the BehavePlus forest fire modeling system in the USA [12], shows that solving the problem of modeling natural fires requires the use of serious computational resources.

An analysis of studies and publications on modeling of various environmental processes, including those related to the problem of the fire forecasting and elimination, shows an increased interest in the use of discrete cellular automata approach [13, etc.], as well as hybrid discrete-continuous agent models. In this work, methods of cellular automata modeling are proposed. The presented approach allowed us to develop and implement cellular automata algorithms for the dynamics of fire propagation, taking into account the terrain and the presence of obstacles. The methods are implemented in the form of a software application.

3. Model of The Fire Front Propagation on rough terrain
Currently, many researchers are engaged in the development of cellular automata models (CA models) studying the possibility of simulating various physical and chemical processes based on the use of CA. Among such models, one can distinguish the so-called diffusion, aggregation, and reactionary ones [14, 15 and others]. The scope of such models is constantly expanding. In particular, cellular automata are used to create models for the propagation of a fire front (the surface reached by the process of burning particles propagation).

When creating cellular-automata models, rectangular grids are most widely used. But often, when modeling a particular process, it is necessary to take into account the shape of the surface, for example, the topography. In such cases, the use of triangulation grids, which make it possible to construct systems of disjoint triangles with vertices at the reference points of the surface, is more preferable. An alternative in the form of triangulation grids allows us to simulate complex processes of various nature, modeled by the joint work of many finite-state machine, on curved surfaces in three-dimensional space. Moreover, triangles in the triangulation do not have to be regular and equal in area. This feature should be taken into account when implementing cellular automata that require rectification of the simulation for the process on certain surface areas. Thus, we can use triangular grids, when modeling the spread of fire over rough terrain, including cases of artificial and natural obstacles.

The investigated spatial region of finite dimensions is represented by a cell array \( \Omega \) whose element names are defined on a set \( M = \{m_i : i = 1, \ldots, N\} \), called a set of names. To each cell of the array a pair \((a, m)\) is assigned, where \( a \in A \), \( m \in M \), hereinafter referred to as the state of the cell and also denoted \( a(m)\). The Boolean state alphabet \( A = \{0,1\} \) is given. In the cell space \( \Omega = \{a(m), m : m \in M\} \), for
each cell \((a,m)\), the so-called neighborhood patterns are defined, i.e. subsets including nearby cells.

Triangular grids can also be used for construction of complex CA, in which a number of transition rules model diffusion. By configuring a cellular automata that imitates naive diffusion on a triangulation grid, the transition rule can be set by randomly choosing one of the neighboring cells and exchanging states. But, to use the geometric features of the simulated surface, the transition rule can be expanded. For example, if necessary, it is possible to balance the probabilities when a neighboring cell with the shortest common edge (or smaller area) is selected with a higher probability than the one with the longest common edge (larger area).

To simulate the propagation of the fire front a composite cellular automata was used, which is based on naive diffusion implemented on a triangulation grid.

During the construction of such CA, several rules are applied to the elements of the triangular grid on each cycle, in this case the following: after diffusion iteration, the whole introduced cell space \(\Omega = \{a(m), m : m \in M\}\) is averaged, i.e. values of average particle concentration \(\phi\) are determined.

The computer implementation of the model provides the user with the opportunity to switch from Boolean values to a more demonstrative continuous distribution of particle concentration. This transition is carried out by averaging the state values of the automata cells over the selected neighborhood. Various algorithms are used for averaging; frequently used ones include, for example, circular averaging. From the center of each triangle a circle is drawn whose radius is determined by the user. The cells of the grid \(N\) in the circle are counted, while the cell where the center is located automatically falls into the circle. Let there be \(N_1\) cells that have the state "1" out of the total number of cells. Then the average concentration is found by the formula \(\phi = \frac{N_1}{N}\). Such an algorithm has computational complexity \(O(n^2)\) [15], where \(n\) is the number of triangles of the grid. Greater computational complexity is the main drawback of this approach.

A different approach – averaging over the nearest neighboring cells – is less demanding on computing resources. In this case, the calculation of cells with a state "1" is performed among a predetermined number of neighbors according to the formula \(\phi = \frac{N_1}{N_2 + 1}\), where \(N_2 \in \{0,1,2,3\}\). Such algorithm has computational complexity \(O(n)\), but the result is much less informative, because the concentration function can take only one of seven values \(\phi \in \{0, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}, 1\}\). However, this same approach can be generalized to a higher-level neighborhood. The averaged concentration will be displayed more clearly if we extend the algorithm from the first to the \(j\)-th level of the neighborhood, \(j \geq 2\).

The next step for the automata is discretization. After averaging, the found values are replaced in each cell by a value \(\psi = 0.5\phi(1-\phi)\) thereby simulating the flow. Next, the inverse of averaging operation is performed, actually called discretization, i.e. to each cell containing a value \(\psi \in [0,1]\), a Boolean value is assigned according to the formula

\[
\tau' = \begin{cases} 
1, & \tau < \psi; \\
0, & \tau \geq \psi, 
\end{cases}
\]

where \(\tau\) is a random number from the interval \([0,1]\). The described cellular automata in particular can simulate the spread of the fire front by taking into account the real features of the process.

### 4. Evolution of a cellular automata on a triangular grid

To study natural processes and environmental monitoring of the region’s territory, we built a digital elevation model (DEM) of the terrain for the mountainous and coastal regions of the Krasnodar Territory...
and developed a technology for creating an interactive 3D terrain model of these territories (figure 1).

**Figure 1.** Interactive 3D model of a stretch of terrain (a fragment of the visualization window of the terrain modeling program)

For a small area of the simulated surface, we built a cellular automata on a triangulation grid. Let us consider an example of using CA to simulate the process of surface fire propagation, taking into account the direction of the wind and the combustibility coefficient of the underlying surface. Wind speed and direction are set by a vector in three-dimensional space.

Figure 2 shows the spatial view of the surface along which a fire spreads at the start of computation. Here, the cells of the green massif, in which ignition is possible, are shown in dark gray, the cells of the burning forest correspond to light gray areas, the non-combustible areas (obstacles) correspond to the white cells. The arrow corresponds to a given wind direction.

**Figure 2.** The computational results for a composite CA on a triangulation grid

Figure 3 illustrates the computation stages of the automata, which contains four types of cells: cells of the green massif, in which ignition is possible (shown in the figure in dark gray); cells of a burning
forest (light gray areas); a burned out surface where repeated ignition is not possible (displayed in black); obstacles, such as a rocky areas which are not subject to burning (white areas). The figure shows the results for the 1st, 50th, 100th and 200th iterations of the automata. The combustible characteristics of the array are assumed to be the same.

As can be seen from the figure, the fire spreads most rapidly in the direction of the wind.

The presented example of the CA operation allows us to estimate the ignition area and the front length. The implemented cellular-automata model on a triangular grid provides the possibility of its expansion, in particular, the introduction of obstacles and variable wind characteristics. The proposed algorithm for the software implementation of the CA makes it easy to illustrate the process on any surface, making it possible to dynamically obtain areas and contours of the natural fires spread.

![Figure 3. Results of the computation for CA-model](image)

5. Conclusion
Combining the capabilities of discrete and continuous models of fire dynamics can serve to further develop the approaches already in use and expand the possibilities of developing effective solutions to combat natural fires and their consequences. The development of approaches to modeling the dynamics of fires and the spread of pollutants generated by combustion, with the subsequent development of effective computer models that can be included in decision support systems for the prevention of emergency fire situations, is very relevant for the region. For a model description of real calculation areas, in the future we plan to use the constructed digital terrain model of the Krasnodar region territory using data from geographic information systems.

We can use the created digital model [5] to analyze the data of environmental as well as seismological monitoring of the region. At the same time, the GIS turns into a common interface for working with both existing and new software tools for calculating the characteristics of various processes, an interface for interacting with seismic monitoring systems, allowing you to effectively solve the problems of analyzing and visualizing data with spatial reference, as well as creating cartographic materials.

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