Digital multi-agent system for simulating natural fire fighting processes

G A Dorrer¹, S V Kobijzhakova²,³ and S V Yarovoy¹

¹ Reshetnev Siberian State University of Science and Technologies, Krasnoyarskiy Rabochiy street, 31, Krasnoyarsk, 660037, Russia
² FSBOU VO Siberian Fire and Rescue Academy of the Ministry of Emergency Situations of Russia, North Str., 1, Zheleznogorsk, 662972, Russia
³ E-mail: svetkob84@mail.ru

Abstract. A system for modeling and supporting decision-making on the use of forces and means to eliminate wildfires, based on a digital model, implemented in the software "Taiga-Analyst", is proposed. The system works on the basis of agent-based simulation and allows you to select forces and means to fight a fire, simulate its propagation and elimination with reference to a digital terrain map using a geographic information system. The possibilities and scope of the "Taiga-Analyst" system are described. A decision-making scheme for fighting natural fires is shown, and the use of the system in the process of training fire safety specialists is described.

1. Introduction
The Fourth Industrial Revolution, which is currently taking place, and Industry 4.0, which is being created at the same time, presuppose the mass introduction of cyber-physical CFS systems into the production and service of human needs, including life, work, security and leisure. It is expected that the changes caused by this revolution will cover a variety of aspects of life: the labor market, the living environment, political systems, the technological way of life, human identity, and others. Human interaction with the environment will not be left aside, which should move to a new level, ensuring the harmonization of human needs and the preservation of the natural environment.

The cyberphysical system assumes the presence of a digital model of a physical object and the possibility of influencing it (feedback). Within the framework of the development of Industry 4.0, depending on the degree of automation of the data exchange process, the following systems are distinguished [1, 2]: digital model, digital shadow, digital double. A review of publications from 2015 to 2020 [2] shows that the most common areas of application of FSCs are the following: smart homes, smart cities, manufacturing, and healthcare.

Cyber-physical systems can play an important role in the environmental sphere. However, in the literature, this direction is not given due attention.

In this paper, we consider a digital model of the processes of spreading wildfires and fighting them, implemented in the form of a multi-agent system using a digital terrain model.

2. The concept of agents and multi-agent systems
Let's look at the basic terms related to agent systems.
A digital agent is a software system that has specific properties: the ability to show their own activity, to act independently and proactively to achieve the set goal, to interact with other agents, as well as with the external digital environment, to react and influence its state. Dynamic agents have the property of simulating movement in the external environment. Many interacting agents form a multi-agent system. The property of such systems is considered in [3–6].

The multi-agent system "Taiga-analyst" developed by the authors is designed for digital modeling of the processes of propagation and localization of wildfires [7, 8].

Let's list the main functions of this system.

- The system contains a digital model of the environment in which a natural fire occurs. The environment model contains all the necessary data for calculating the processes of fire propagation and elimination, and also displays the dynamics of these processes on the map of the real area of the required scale.
- The system simulates the processes of gorenje and the spread of natural fire in a given environment, and this process is displayed on the map of the area.
- The system simulates the process of interaction of a fire with fire-fighting forces and means with various methods and tactics of fire fighting.
- The system is implemented as an independent software product "Taiga-Analyst" with the possibility of integration or joint use with both existing remote monitoring systems and e-learning systems.

Currently, the system contains the following software components: a digital model of the environment; agents that simulate the dynamics of the fire front (A-agents), agents that simulate the action of fire-fighting forces and means (B-agents), agents that affect the digital model of the environment (D agents); agents-managers that coordinate the actions of other agents (M-agents). If you need to refine or change the model, new types of agents can be introduced. The operating components of the system are described below.

The operation of the digital system is controlled by the user-operator, who determines the goals and objectives of modeling processes in the system and evaluates their results.

3. Digital environment model
A digital model of the environment that determines the conditions for the spread of fire is created using a geographic information system. The map of the area and its associated database contain information about the topography and infrastructure of the area, about the properties of plant fuels and weather conditions, as well as about the available means of fire control and their characteristics.

The processes of fire propagation and control, calculated using the above-mentioned agents at discrete time points (simulation steps), are displayed on the map.

Agents that simulate the dynamics of the fire front (A-agents). Each A-agent models the behavior of a fire edge fragment. The set of A-agents forms a digital fire contour (figure 1). The spatial coordinates of this type of agents are calculated at each step of the simulation based on the solution of the Hamilton-Jacobi equations and using the mobile grid algorithm, which are described in detail in [6–9]. In addition, in accordance with the mentioned algorithm, in the process of modeling, under certain conditions, agents can "go out" or, on the contrary, new ones can arise. The Gorenje properties of A-agents are determined by the parameters of the combustion of vegetable fuel, the speed of the fire front movement and the possible directions of its propagation.

Type A agents generate a heat flow and a smoke jet, which are calculated using a separate model. Gorenje heat flow depends on the combustion conditions and can be reduced to zero under the influence of agents of type B, while the A-agent "goes out" and no longer enters the digital fire circuit.

Agents that simulate the action of fire-fighting forces (B – agents). Type B agents act on type A agents, thereby simulating the action of fire-fighting teams. Their goal is to "extinguish" all the gorenje nodes. To do this, each B-agent moves through the digital simulation environment to the nearest A-
agent and, approaching it, at each step of the simulation, reduces the intensity of its heat release by a certain amount – until agent A "goes out". Agent B then moves to the nearest active agent A and starts interacting with it in a similar way.

Agent B is characterized by the following parameters:

- current spatial coordinates;
- the number of the nearest agent of type A by distance;
- the direction and speed of movement in the area;
- the direction of the fire contour bypass-clockwise or counterclockwise;
- the intensity of fire extinguishing, which is determined by the means used to combat wildfires [10,11].

The initial location, number and characteristics of A-and B-agents are set by the user at the beginning of the modeling process.

Agents acting on a digital terrain model (D-agents). D-type agents simulate the forces and means used in an indirect method of fighting a fire by changing the digital terrain model, which leads to restrictions for a spreading fire. These agents can simulate the operation of various types of fire-fighting equipment, such as tractors, air tankers, and others, while they do not directly interact with the A-agents, but obey the commands of the agent-manager M and the system user.

For example, the D-agent in modeling the process of laying a fire strip is characterized by the following parameters:

- current status: traffic, lane laying, parking.
- current spatial coordinates;
- speed and direction of movement on the terrain;
- speed of laying fire strips.

When executing these agents, they use direct user commands that determine the type and necessary parameters of the work. For example, after receiving a command to lay a barrier, the D-agent adds special polygons of a given width to the map when moving. As a result, there is a certain strip on the map, which is perceived by A-agents as an impassable section.

The speed of movement, duration of operation and other characteristics of D-agents are set according to the specifications of the specific equipment and reference books.

The number and types of available equipment (D-agents), as well as their characteristics, are set in advance, based on the modeling goals, and are stored in a database. The user in the process of modeling has the opportunity to use the available technology, issuing tasks using a special interface.

Agent-manager who coordinates the actions of other agents (M-agent). An agent of type M in the system under consideration is present in the singular. It is designed to interact with the user and independently control the actions of other agents in the simulation process. In particular, it synchronizes the movement of type A and B agents on a digital terrain model, analyzes the fire contour, and adds and removes type A agents in accordance with the mobile grid algorithm [9].

4. Implementation of a multi-agent system

Based on the multi-agent model described above, the Taiga-Analyst software package was developed, which has a client-server architecture and a web interface [8]. The server stores a database that contains data about the digital terrain model. The program code of the server part is implemented in PHP. The client side of the system is implemented in JavaScript (JS) using the open source library OpenLayers. The library is designed for developing maps based on a software interface (API) and allows you to create a web interface for displaying map materials, working with data from map services such as OpenStreetMap, Google, Yandex, etc.
During the simulation process, a protocol of all user and system actions is compiled. The success and time of fire localization, the area covered by the fire, the cost of fire prevention measures, and other indicators can be evaluated. The following describes how to use the system and provides an example of a single simulation session.

5. Using the developed system
The digital multi-agent system "Taiga-analyst" is currently used in the Siberian Fire and Rescue Academy of the Ministry of Emergency Situations of Russia as a training simulator for cadets when preparing them in the specialty 20.05.01 "Fire Safety" and the direction 20.03.01 "Technosphere safety" in the course "Physical and chemical foundations of fire development and extinguishing", when studying the topic "Natural fires" in the 6th semester of training (3rd year). Working with the system allows you to increase the competence of students in the use of distance learning technologies and management. In addition, when modeling the process of spreading a fire, its elimination, students develop decision-making skills on the use of forces and means to extinguish a fire, with an assessment and understanding of the consequences of the decisions made. For one course of training in the "Taiga – analyst" system, an average of up to 500 protocols are compiled to solve these problems. It is also possible to use the system for conducting competitions for the best solution to the task of fighting a fire.

At the same time, the experience of practical application of the "Taiga-analyst" system as a disadvantage indicates a small choice of fire fighting equipment (type B agents), in particular, the lack of aviation extinguishing equipment in the system and restrictions on the number of foot firefighters, which does not comply with regulatory documents.

Example of modeling the processes of spreading and fighting a forest fire
The digital terrain model is based on the use of GIS, which contains a map of the forest area where the fire occurs. Natural and weather conditions, as follows:
- the forest area with a predominant spruce stand is located on a slope, as indicated by the level lines on the map of the area;
- the type of predominant plant fuel is lichen;
- fire hazard class-2;
- wind speed under the forest canopy – 1 m/s, wind direction-southwest;
- the area of the fire center when detected is 4 hectares.

These data indicate that the expected intensity of the simulated fire is low, so it is acceptable to use manual means to influence the fire around the entire perimeter. It was decided to involve three firefighting teams of 6 people each, which are placed around the edge of the fire and were assigned to bypass the fire counterclockwise. The performance of the selected teams to extinguish the edge of the fire was determined by reference books [10,11]. Figure 1A shows the initial configuration of the fire and the initial position of the fire brigades.

**Figure 1.** An example of modeling the process of fire localization. The light points on the fire contour are the agents of type A, the pictograms of the firemen are the agents of type B. A is the initial configuration of the fire, B is the configuration of the fire through 4 operations of the fire brigades.
The simulation was carried out with a time step of 5 minutes. Figure 1B shows the position of the commands and the outline of the fire after 48 steps of the simulation process, i.e. 4 hours after the start of extinguishing. The figure shows that the fire continues to develop, the length of the burning edge has not decreased, and the area covered by the fire has more than doubled. All this indicates an erroneous choice of tactics and means of fighting the fire, that three groups of firefighters of 6 people are not able to cope with this fire.

The given simple example of a negative result when planning a fire-fighting event speaks, in our opinion, about the realism and usefulness of the process of digital agent modeling in comparison with volitional decision-making, since the reference books give rather rough estimates that do not allow us to take into account the specifics of the current situation and can lead to erroneous decisions.

6. Conclusion
The digital multi-agent system for modeling the processes of fighting wildfires presented in this paper allows us to solve a number of tasks: modeling the dynamics of wildfires, making decisions on tactics and methods of fighting fires, and attracting the necessary forces and resources for this purpose. Further development of the system is associated with the expansion of its functionality by increasing the number of active agents, in particular fire planes and helicopters and other means, with the creation of knowledge bases for decision-making and with the gradual transformation of the system into a digital twin of the process of fighting natural fires. It is planned to gradually introduce the system into the work of the operational headquarters of the Ministry of Emergency Situations to support decision-making in the fight against wildfires. In addition, as the existing experience has shown, the system can serve for training personnel in the areas of fire safety.

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