Modeling of dynamic processes on the Earth's surface

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Abstract. Due to global climate change, the probability of damage from natural and man-made disasters has increased. These processes are becoming less predictable in scale and impact. If we consider the heterogeneous natural and anthropogenic processes on the surface of the Earth, we can see that despite their different physical nature they have the following common features. All these processes, due to their characteristic dimensions, are amenable to mapping. In this regard, the use of GIS technologies in their modeling becomes necessary. Remote monitoring methods can be applied to all classes of such dynamic processes. From the point of view of control theory, the listed objects are objects with distributed parameters and distributed control. The possible methods of controlling these processes are similar and often do not depend on the nature of the process. The purpose of this work is to create and implement models of dynamics and control of the above processes as GIS-oriented multi-agent systems based on the use of the formalism of embedded Petri nets. At the same time, as a specific process, on the example of which modeling and control methods are considered in more detail, wildfire is selected.

1. Introduction

Due to global climate change, the probability of damage from natural and man-made disasters has increased. They often look like spontaneous dynamic processes on the Earth's surface. Floods, mudslides, landslides, wildfires, the spread of plant pests are examples of such processes. These processes are becoming less predictable in scale and impact. In addition, it harms nature and human activity [1-5]. If we consider the heterogeneous natural and anthropogenic processes on the surface of the Earth, we can see that, despite their different physical nature, they have the following common features.

- All these processes can be described as moving areas on the surface of the Earth, having the ability to expand, contract, move, split and merge. In the following, we will also use the term “propagation process”.
- As a first approximation, the boundaries of the propagation processes can be represented as single plane waves on the surface of the Earth, the movement of which obey the Huygens principle.
- All these processes, due to their characteristic dimensions, are amenable to mapping. In this regard, the use of GIS technologies in their modeling becomes necessary.
Remote monitoring methods can be applied to all classes of such dynamic processes: space and aviation, including using unmanned aerial vehicles. From the point of view of control theory, the listed objects are objects with distributed parameters and distributed control. The possible methods of controlling these processes are similar and often do not depend on the nature of the process. Thus, one of the methods of dealing with a process is direct influence on its front to reduce the speed of propagation or stop it; another common control method is localization, i.e. creating insurmountable barriers to the movement of the wave.

The purpose of this work is to create and implement models of dynamics and control of the above processes as GIS-oriented multi-agent systems based on the use of the formalism of embedded Petri nets. At the same time, as a specific process, on the example of which modeling and control methods are considered in more detail, wildfires are selected.

Let’s consider a few examples of dynamic processes on the surface of the Earth. Undoubtedly, there are many more examples of such processes.

Figure 1 shows a processed satellite image of a forest fire in the Irkutsk Region in 2016, obtained using two different satellite systems: equipment installed on the MODIS satellite (ISDM-Rosleskhoz system) and GIS-processed LANDSAT [4] satellite image. Comparison of images allows you to judge the dynamics of the process.

**Figure 1. Contour of a forest fire (processed two satellite images).**

Figure 2 shows the composition of four ASAR Envisat radar images showing the spread of the oil slick from 04.26.10 to 05.02.10 in the Gulf of Mexico [3].
Figure 2. The composition of four ASAR Envisat radar images showing the spread of the oil spill from 04.26.10 to 05.02.10 in the Gulf of Mexico.

Figure 3 shows the process of focal distribution of the Siberian silkworm in the Yenisey dark coniferous taiga in the period from 2013 to 2017 years. In 2017, this outbreak of silkworm propagation covered more than 800 thousand hectares of forest stands, including 300 thousand hectares of the dead. The starting conditions for the development of the silkworm were the increased aridity of climate, warming and lengthening of the growing season. Stem pests, including the Ussuri polygraph, aggressive bark beetle, have become more active in tree stands damaged by silkworm [5].

Figure 3. The outbreak of the Siberian silkworm spread in the Yenisey dark coniferous taiga in the period from 2013-2017. Growth of damage territory from 2013 to 2017.

It is easy to see that all the processes considered above have properties 1-5 indicated in the abstract and can be described in a uniform way as propagation processes.

2. Model of the propagation process dynamics
We are starting from the hypothesis that the propagation process is a single wave on a horizontal plane (displayed on the corresponding scale map of the area). The coordinate system $X=[x_1, x_2]^T$ is attached to the map, $X\in D$, where $D$ is the scenario area under consideration.
The theory of spatial waves of various physical nature is well developed [6-7]. We will use the simplest model of this process.

Let \( \varphi (X, t) = 0 \) be the equation of the wave front, and the function \( \varphi (X, t) \) is assumed to be continuous, smooth and satisfying the Hamilton-Jacobi equation:

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

where \( V = V(X) = [v^1, v^2] \) is the string vector of the wave front velocity, \( t \) is time.

The gradient column vector:

\[
\nabla \varphi = \left[ \frac{\partial \varphi}{\partial x_1}, \frac{\partial \varphi}{\partial x_2} \right]^T = P = [p^1, p^2]
\]

is a normal to the front line.

Equation (1) is considered under initial conditions:

\[
X(0) = X_0(\alpha), \quad P(0) = P_0(\alpha),
\]

where \( X_0(\alpha) \) and \( P_0(\alpha) \) are a parametric representation of the wave front and the set of normals to it at the initial time \( t = 0 \), \( \alpha \in U \) is an admissible set of \( \alpha \) parameter values.

For the purpose of the process dynamics numerical simulation, an approach is based on the use of the normal front spreading \( V_n = V*P/|P| \), where \( |P| \) is the length of the normal and \( P/|P| \) is the unit vector normal to the front line.

In this case, equation (1) is converted to

\[
\frac{\partial \varphi}{\partial t} + V_n|P| = 0.
\]

Equation (3) is also considered under initial conditions (2).

The rate of spread of the wave front depends on a variety of parameters of the external environment. In the framework of this approach, the normal spreading of the front \( V_n \) at any point in the region considered can be represented as the product of two functions:

\[
V_n(X,t,W,S,\beta,\gamma) = V_0(X,t,W,S)*K_\beta(P,W,S).
\]

where \( V_0 \) is the maximum propagation speed of the process.

The multiplier \( 0 \leq K_\beta(P,W,S) \leq 1 \) determines the local directions of motion of the wave front and is called the indicatrix of the normal spreading of the front or figuratrix [8]. Using figuratrix allows you to create an effective algorithm for the numerical simulation of the spatial wave propagation process based on the method of movable grids [8].

This algorithm allows us to go to the agent-based representation of processes dynamics.

3. Agent modeling of the distribution process management system

An agent-oriented system containing two types of agents, denoted as \( A \) and \( B \) [9,10], was developed. Agents of \( A \) type simulate the movement of a wave front. They can be in active and passive states. The \( A \)-agent, which is in the active state, determines the movement of the process front. Agents of type \( B \) (\( B \)-agents) model the impact on the \( A \)-agents. They have a single goal - to transfer all \( A \)-agents to a passive state. For this, the \( B \)-agent moves along the modeling locality to the nearest \( A \)-agent and, coming up to it, trying to destroy it. So, the \( B \)-agents simulate the action of forces opposing the propagation process. Modeling the interaction of the agents \( A \) and \( B \) is an independent problem.

4. Program realization

The system described implemented in the form of the Taiga-3 program [9], which served, among other things, as the basis for the creation of the FIREMAN training complex for training personnel in the tactics of combating natural fires using MOODLE training system [11].

The system performs the following functions in particular:
• mapping scenarios for the development of the process and its management on a map;
• determination of the reachability of certain states;
• assessment of process control and make decision;
• assessment of possible damage during the development process;
• assessment of the correctness of the decisions taken in the training of personnel.

Conclusion
A methodology of modeling the dynamics and control processes such as waves on the surface of the Earth was proposed. This methodology was implemented as GIS-oriented multi-agent system. The results are applied to modeling the dynamics of wildfires and processes of fighting them. The system is used as a part of the computer simulator for training personnel in the basics of tactics for dealing with wildfires.

Further development of the described system will consist in expanding the information base, including the cartographic one, as well as the functions performed by the agents.

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