Using nested Petri nets for modeling multiagent systems

Georgy Dorrer1,2, Alexandra Dorrer1,2 and Sergey Yarovoy1

1Reshetnev Siberian State University of Science and Technology, Krasnoyarsk, prospect “Krasnoyarsky rabochy” 31, Russia
2Siberian Federal University, Krasnoyarsk, prospect Svobodny 79, Russia

E-mail: g_a_dorrer@mail.ru

Abstract. The multi-agent simulation system is presented in the form of a two-level nested Petri net. The semantics of the interaction of agents is described. A GIS-oriented information system has been developed that implements the behavior algorithms of various classes of active agents. The system can be useful both for making decisions on dealing with emergencies and for training operational personnel. An example of a nested Petri network describing the processes of spreading and extinguishing of the wildfire is given.

1. Introduction

The methodology of modeling complex hierarchical systems, represented as a set of interacting agents (objects with an internal structure and having their own goals), is currently an independent branch of the science of artificial intelligence. That area has attracted many researchers from various fields of science. The reason for such interest may be the vastness and specificity of the tasks that solved with the help of the theory of agents, as well as significant advances in information technology, computer networks and computer equipment.

The behavior of multi-agent systems, as a rule, is quite complex and requires special tools, including graphic ones, for its description and analysis.

As it known, one of the most common and effective formalisms for modeling and analyzing complex distributed systems is Petri nets [3, 4]. Petri nets contain two types of nodes, called positions \( p_i \) and transitions \( t_j \). These nodes connected by two sets of arcs: \( A_P \) from \( p_i \) to \( t_j \) and \( A_T \) from \( t_j \) to \( p_i \). The positions contain some resources, and transitions govern the redistribution of these resources.

The functioning of Petri nets allows describe a system in terms of “condition-event”, which makes it possible to build various scenarios of system behavior, to identify the reachability of certain states, possibility of cycles, conflicts, interlocks and other behavioral features.

In recent years, work is underway to expand the functionality of Petri nets to write off object-oriented and agent-oriented systems in order to create models that reflect the hierarchical and multi-agent structure of systems. One of the tools to solve this problem is so-called Nested Petri nets [4]. These networks are an extension of ordinary Petri nets, in which independent Petri nets can act as imbedded resources, acting as satellite agents in relation to the System network. At the same time, actions of satellite agents synchronized both with the System network and with other satellite agents. Synchronization carried out by simultaneous triggering of labeled transitions in different networks; for this purpose, special functions for marking transitions are provides.
2. Agent model of wildfire propagation and localization

The use of nested Petri nets in this paper is illustrated by the example of the agent-based simulation model of wildfire propagation and localization [2]. The model’s work is based on GIS data and reflected on a map of real terrain. The map contains layers reflecting various terrain features: settlements, rivers, lakes, roads, ravines, forest plantations, and other objects.

An agent model of wildfire propagation and localization was developed. The model uses two types of agents, denoted by the symbols A and B. A-agents are designed to simulate the spread of fire, their behavior is based on two models: model of the combustion process that causes the spread of fire, and model of the propagation process based on the movable grid method [5]. Description of this algorithm given in [2]. Type B agents simulate the action of forces opposing to fire and affect to the A agents. Their goal is to transfer all A-agents to a passive state. To do this, a B-agent moves along the modeling environment to the nearest A-agent and, coming up to it, reduces the intensity of combustion that causes spread of the process. The action of the agent B is determined by the expression:

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

where \( I_A(t) \) is the intensity of the agent A combustion, \( \Delta I_B(t) \) is a decrease of \( I_A(t) \), caused by a B-agent in one simulation step.

After “extinguishing” the next A agent, the B agent moves to the next nearest A agent and repeat these actions.

3. A formal description of the nested Petri Net

A two-level GIS-oriented nested Petri Network \( NPN \), which simulates the interaction of the agents A and B, is a tuple:

\[ NPN = \{ SN, (NA_1, ..., NA_k), (NB_1, ..., NB_m), A, G \}. \]

In expression (2):

\( SN \) is a system network, which is a colored Petri network, it controls the functioning of the satellite networks. This network contains satellite networks as resources.

\( NA_k, i=1, ..., k \) are satellite colored Petri nets, modeling the behavior of A-agents,

\( NB_j, j=1, ..., m \) are satellite colored Petri nets simulating the behavior of an agent of B type,

\( A = A_v \cup A_h \) is the function of the transitions marking, with the help of which the vertical \( A_v \) and horizontal \( A_h \) synchronization of the elements of a nested network are performed.

\( G \) is function of displaying the network status on the locality map.

A nested Petri net network structure is shown in figure 1.

The structure of networks included in \( NPN \) is similar for both system and satellite networks. The colored network of Petri PN in accordance with the formalism of K. Jensen [11], is a tuple:

\[ SN = \{ 0, \Sigma, P, T, A, C, E, I, A \}, \]

where:

\( \theta \) – discrete time,

\( \Sigma \) – color set (types of resources),

\( P \) – set of positions, \( P = \{ p_1, ..., p_N \} \),

\( T \) – set of transitions, \( T = \{ t_1, ..., t_M \} \),

\( A \) – set of arcs, \( A = \{ a_1, ..., a_K \} \),

\( C \) – color function \( \Sigma \rightarrow P \),

\( E \) – expressions on the arcs, which determines the net functioning,

\( I \) – initialization function \( M_0 \rightarrow P \), where \( M_0 \) - initial marking of the network.

\( A = A_v \cup A_h \) - is the transitions marking function that perform vertical \( A_v \) and horizontal \( A_h \) synchronization.

Vertical synchronized transitions marked with a tilde: \( \tilde{t}_{AS} \), and the horizontal one with a horizontal bar: \( \bar{t}_{i+1} \).
4. Brief description of the agent imitation system realized with Petri net

Figure 1 shows the common structure of the agent simulation system, represented as a two-level nested Petri net. Figure shows the simulation of the propagation of a wildfire front as a set of agents $A$ and its localization with the help of two agents $B$.

Let’s explain the components of the system $SN$ nodes.

Position $P_1$ stores $A$-agents that are in a passive state, position $P_2$ stores active $A$-agents. Similarly, the position $P_4$ stores $B$-agents, ready for action, and the position $P_3$ - deleted $B$-agents. Transitions $\tilde{t}_1-\tilde{t}_4$ provide interaction and control of satellite agents. Transitions $t_5$, $t_6$ and $t_8$, $t_9$ interact with the system operator, transition $t_7$ returns $B$-agents to active state.

Displaying on the locality map

Figure 1. Common structure of a two-level GIS-oriented nested Petri net.
Structure of Petri net simulating activity of an A agent is shown in figure 2(a).

Resources in the positions $P_1$ - $P_4$ store the coordinates of the agents adjacent to $A_i$, which are necessary for the formation of the front by the algorithm of moving grids. At position $P_5$, the components of agent $A_i$ are stored: the number of the agent, its status (active or not), coordinates, spatial step, time step. The resource in position $P_6$ includes the next components: agent number $A_i$, its status (active or not) fuel supply, current time, time step. Position $P_7$ contains agent status $A_i$ and its coordinates. The position $P_8$ stores the amount of fuel reserve reduction for each step when exposed to $B_j$.

Structure of Petri net simulating activity of a B agent is shown in figure 2(b).

![Petri net simulation](image)

**Figure 2.** Structure of the Petri network simulating agents A and B activity.
Similarly, a resource characterizing the state of an agent of type $B$ contains components: the number of the agent, its status, coordinates on the map, the spatial step, the current time, the time step, the speed of movement, the intensity of reduction of fuel when interacting with agent of type $A$.

The positions $P_1 - P_k$ store the coordinates of the agents $A_i$, which are necessary for determining the one nearest to $B_j$. The position $P_r$ stores a resource characterizing the state of an agent of type $B$, it contains the components: agent number, its status, coordinates, spatial step, current time, time step, intensity of fuel supply reduction when interacting with agent of type $A$.

The transition $t_1$ collects data on the coordinates of all agents of type $A$ and transmits data on the nearest agent $NA_{\text{min}}$. The transition $t_2$ affects the selected agent of type $A$. The transitions $\tilde{t}_{AB}$ synchronize with the satellite networks $NA_{\text{min}}$. The transitions $\tilde{t}_{BS}$ synchronize with the system network $SN$.

**Conclusion**
The presented model of the multi-agent system in the form of an embedded Petri net allows to analyze the behavior of system’s agents and to improve its work. 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. The developed imitation system is the basis of personnel training system in decision making in fighting wildfires [6].

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