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IDENTIFICATION OF SPATIOTEMPORAL CLUSTERS IN MULTI-AGENT SYSTEMS USING AN ENDEMIC MODEL

The paper presents an approach to cluster detection in distributed multi-agent systems using an endemic model. By modelling the "activation" of an agent as an infectious process, the study demonstrates that patterns of joint activation indicate spatial proximity, without requiring explicit information about the distance between agents.

Introduction. Modern systems are characterized by increasing complexity and dimensionality, which makes centralized control strategies resource-intensive in terms of computing and communication costs. This has led to an increase in interest in distributed multi-agent systems that are used in various fields such as unmanned vehicles, distributed sensor networks, group robots and aircraft.

The complexity of such systems creates serious problems for traditional control methods. These methods are often unable to effectively control each individual agent, and they also do not take into account the properties of the system at a macro level [1]. By investigating how individual agents spontaneously form consistent structures at meso-levels, we can obtain important information about how to control multidimensional systems [2], [3]. In addition, many of these systems also have self-organizing properties, which dynamically form clusters. In this regard, control methods need to adapt to these dynamic structures. The paper [4] describes the formation of mesoscopic structures using the example of an aircraft with a large number of "feathers" distributed over the surface, i.e. elements with pressure sensors and rotary devices. It was shown that in conditions of turbulence, when the reaction of the system is nonlinear, the collective movement of the agents of the "feathers" can lead to their self-organization and a change in the flow regime of the aircraft body, thereby forming clusters of agents on the surface of the plane.

Cluster control strategies show better results compared to control approaches for macro and micro levels. Thus, in [5] an adaptive cluster control strategy with feedback was developed. Obtaining the clustering structure of the entire system was based on the compressed sensing method for a compact representation of the aggregated state of the agent, i.e. based on compressed measurements. Compared to micro-scale and macroscale approaches, cluster control outperformed these strategies in terms of convergence time, efficiency, and accuracy.

The problem of efficient cluster identification remains a matter of great urgency. The proposed work considers the formation of clusters based on periodic activation of agents and subsequent analysis of the dynamics of their spread using the endemic SIR (Susceptible, Infected Recovered) model. Just as the spread of infection in the SIR model demonstrates possible contacts in society [6], it is assumed that groups of agents, often activated together, are in spatial proximity to each other. By accurately identifying clusters that represent cohesive groups of interacting agents, we gain a deeper understanding of the internal organization of the system and can develop more effective control strategies. Unlike static approaches, the SIR model reflects the temporal evolution of agent interactions through the process of "activation", which allows us to identify clusters that arise, disintegrate and transform over time.

The proposed work is devoted to the identification of clusters in a distributed multi-agent system through the periodic activation of individual agents.

Problem statement. Consider a system with N agents (in a set of N = {1,...,N}), which are placed into a bounded region and are tasked to reach a certain goal point x^*. Each agent, possesses a state $x_i[t] \in R^d$, which may act as its location on a coordinate plane (therefore d = 2) or in a higher-dimensional coordinate space.

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The aim is to analyse the spatiotemporal patterns of active agents over time and draw a conclusion about the underlying spatial distribution. In this way, identify groups of agents that are often activated together, which will indicate their close proximity.

Conditions for solving the problem. To solve the problem, it is assumed that agents can interact in accordance with the communication graph. The interactions of agents are described through the adjacency matrix $A = [a_{ij}]$,, where $a_{ij} \neq 0$ means the presence of a connection between agents i and j, and $a_{ij} = 0$ means its absence. The dynamics of changes in the states of agents is described as follows: with discrete time intervals $t = 0, 1, 2, \ldots$ a subset of agents is randomly selected for "calling". Let $C_t \subseteq \{1, 2, \ldots, N\}$ be a set of agents called at time t. The selection of C_t is carried out by uniform sampling with a fixed probability. When agent i is called at time t (i.e. $i \in C_t$), its "nearest neighbours" become "active". The function $N(i, r)$, which returns a set of agents within a radius r of agent i, is described:

$$N(i, r) = \{j \in \{1,2, \ldots, n\}: \| p_i - p_j \| \leq r\}, \tag{1}$$

where p is the coordinates of the location.

Activation propagation is described by the SIR dynamic model (simplified view):

$$\dot{G} = F(G) = \begin{cases} \dot{S} = S(A - S) - \beta_\gamma(t) IS \\ \dot{I} = \beta_\gamma IS - \dfrac{rI}{a + I} \end{cases}, \tag{2}$$

where $\beta_\gamma = \beta_0(1 + \Phi(\omega t))$, $G(t) = (S(t), I(t))$, A is the tolerance coefficient for susceptible agents in the absence of activation, γ is the amplitude of periodic oscillations, $\omega > 0$ frequency, β_0 is the rate of activation transmission in the absence of periodicity, a is the delay coefficient during recovery.

Conclusion. As a result of the research, a modelling environment was developed to visualise emerging spatial structures. Analysis of the patterns of pathogen activation over time reveals distinct temporal spikes as shown in Fig. 1. These spikes correspond exactly to moments when the spread of infection in SIR models is simulated during the "activation" process, agents are geographically grouped and isolated. Further research could be aimed at developing predictive models to predict activation patterns and system behaviour which would allow more accurate identification of clusters and consequently better control.

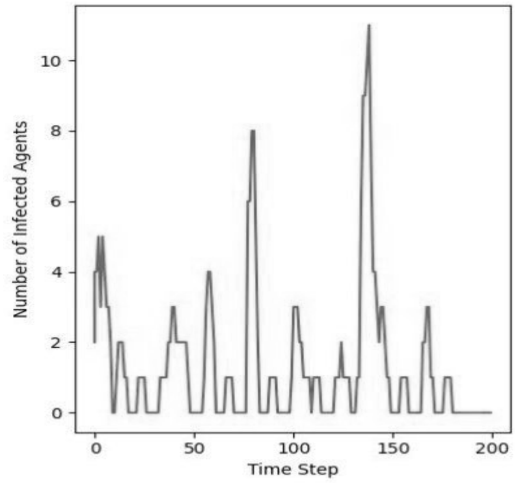

Fig.1. The number of "active" agents over time

The research was carried out within the financial support for the autonomous non-profit organization "Analytical Center for the Government of the Russian Federation" (Agreement No. 70-2024-000120 dated March 29, 2024, id: 000000D730324P540002)

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