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A TECHNOLOGY FOR DYNAMIC SYNTHESIS AND CONFIGURATION OF MULTI-AGENT SYSTEMS OF REGIONAL SECURITY NETWORK-CENTRIC CONTROL

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ТЕХНОЛОГИЯ ДИНАМИЧЕСКОГО СИНТЕЗА И КОНФИГУРИРОВАНИЯ МУЛЬТИАГЕНТНЫХ СИСТЕМ СЕТЕЦЕНТРИЧЕСКОГО УПРАВЛЕНИЯ РЕГИОНАЛЬНОЙ БЕЗОПАСНОСТЬЮ

Abstract. *Background*. The research objective is development of models and technologies for dynamic synthesis and configuration of the distributed multi-level systems of regional security network-centric control. It is essential to property improving of information and analytical support of management activity in situational centers of the region and interaction efficiency enhancement between security operators control under critical situations. *Materials and methods*. The multi-agent system technology serves as the basis for network-centric control implementation tool. The research methodology is based on application of the modified self-organization model of agent coalitions in the peer-to-peer distributed systems on the basis of gradient computational fields. That provides flexible synthesis of the scalable network-centric operating workspaces for virtual control centers of regional security and its system integration within the regional information environment. *Results and conclusions*. Models and technology for dynamic synthesis and configuration of multi-agent decision support systems and associated resource virtual networks for each control field of regional security have been developed. Technology implementation in practice allows formation of network-centric digital platform for security control of the region and potential feature spectrum extension of the existing system of distributed situational centers.

Аннотация. *Актуальность и цели.* Целью исследования является разработка моделей и технологий динамического синтеза и конфигурирования распределенных многоуровневых систем сетецентрического управления региональной безопасностью для повышения качества информационно-аналитического обеспечения управленческой деятельности в ситуационных центрах региона и эффективности взаимодействия органов управления безопасностью в условиях кризисных ситуаций. *Материалы и методы*. Технология мультиагентных систем служит средством реализации сетецентрического управления. Методология базируется на применении модифицированной модели самоорганизации коалиций агентов в одноранговых распределенных системах на основе градиентных вычислительных полей, что обеспечивает гибкий синтез расширяемой сетецентрической среды функционирования виртуальных центров управления безопасностью региона и их системную интеграцию в региональное информационное пространство. *Результаты и выводы*. Разработаны модели и технология динамического синтеза и конфигурирования мультиагентных систем поддержки принятия решений и виртуальных сетей ассоциированных ресурсов для каждой области управления региональной безопасностью. Практическая реализация технологии позволит сформировать сетецентрическую цифровую платформу управления безопасностью региона и рас-

ширить спектр возможностей существующей системы распределенных ситуационных центров.

Keywords: dynamic synthesis, configuration, multi-agent system, model, self-organization, information technology, network-centric control, security, region.

Ключевые слова: динамический синтез, конфигурирование, мультиагентная система, модель, самоорганизация, технология, сетецентрическое управление, безопасность, регион.

Introduction

The analysis of the state-of-the-art research in the field of applied multi-agent system (MAS) engineering [1] shows that, despite the great potential of the modern MAS development and based on its technological solutions for various application domains, the issues of applying agent-based technologies for network-centric management information support problem-solving of regional security [2] are not sufficiently studied in theory and practice.

The use of MAS technology in the field of regional security information support is conditioned by the high dynamics of the security management entities functioning environment, the needs to coordinate decentralized decision-making and take into account the human factor within the management process. The latter is expressed in the active influence of the managed system on the control process.

Application of peer-to-peer multi-agent information systems designed on the basis of SOA-technology (SOA – Service-Oriented Architecture) [3] maintaining cloud and web-services allows an adequate information and analytical environment development for regional security management support and decision-making problem-solving taking into account the distribution, dynamics and structural complexity of the regional socio-economic system components. A foundation of the well-known service-oriented approach is the agent-based orientation principle, which consists in use of intelligent agents and web-services as components of distributed information systems that are autonomously functioning and having purposeful behavior. This approach enables the management processes virtualization of regional security individual components by delegating the functions of information monitoring over the state of various regional security indicators and risk management to intelligent pro-active agents.

The application field expansion of MAS technology to regional security management problem-solving provided the prerequisites for a new class of MAS development, namely situational-coalition multi-agent systems (SCMAS). These SCMAS are focused on decision-making information support in the field of security management of socio-economic systems. The SCMAS represents a set of interacting agent coalitions and associated virtual resource networks dynamically formed to provide situational awareness and risk management in diverse crisis situations. The situation refers to a state of the investigated system, characterized by a set of parameters, at a certain time point. In general case, SCMAS form problem-oriented virtual spaces including a set of agents, which possess necessary competencies to solve situation management problems, and a set of information resources and services.

Problem Statement and Methodology

Agent coalition formation is one of the effective approaches to multi-agent models synthesis and configuration of regional security management organizational structures in heterogeneous crisis situations taking into account dynamically changing conditions. Intelligent agent coalition interaction ensures self-organization and operability of the virtual environment for regional security management, as well as group decision-making coordination. Agent-based monitoring and control are appealed to increase the effectiveness of regional security management information support.

To jointly solve problems in the context of the crisis situation agents can join in coalitions. A coalition of agents is defined as a group of agents united by common goals to solve a problem and having sufficient overall competence to solve this problem. The group goal of agent coalition is defined as an objective function from the individual goals of the agents included in this coalition. The membership of a new agent into the coalition is only possible when it maximizes the objective function describing the group goal of the coalition. There are two ways to form problem-oriented agent coalitions: static and dynamic. In the first case parameters describing the crisis situation and agent competencies are fixed, in the second – they change over the time. In our study we analyze the dynamic formation of agent coalitions.

SCMAS forming problem statement constitutes following main components: set of situations, set of agent coalitions, set of resources and its configuration in the regional virtual environment, which determines possible directions of using the SCMAS in a particular security area.

The SCMAS formal theoretical-multiple model has the following form:

$$SCMAS = \{A, R, VE, ORG, CS, CSC\},$$

where A is a set of agents from which coalitions are formed $COAL|_{CS} \subseteq A$ to solve problems defined within the current situation model; R is a set of resources; VE is a virtual environment in which the SCMAS is located; ORG is a set of basic organizational structures that correspond to the agent specific functions (roles) and relationship between the agents; CS is a set of crisis situations; CSC is a set of crisis situation classes for which the SCMAS are intended.

For SCMAS dynamic formation special models of agent self-organization are required. As such a model, the MAS self-organization model based on gradient (computational) fields [4] is implemented. In peer-to-peer distributed MAS with this self-organization model an analogue of the field and its gradient is certain distributed data structure with a unique identifier. In the agent environment this data structure is represented in a unified form that allows other agents to access it at each point of virtual environment. The field contains contextual (local or global) information about the environment and/or the gradient field initiator needed for decision-making, coordination and self-organization.

The field propagation function is assigned to system agents. In this case agents relay the field to neighbors, modifying its strength. This process of transferring a field from agent to agent is repeated until the force of the field is less than a certain threshold when it is assumed to be zero. Agents can initiate not one, but several different computational fields (including their combination) depending on their role in the system and resource capabilities.

With this approach the agent self-organization consists in automatic formation of problem-oriented multi-agent virtual spaces [5], combining agents with close goals and the required set of competencies in coalitions, within the distributed information environment. At the same time control agent-moderators are generated for each separated virtual space, implementing procedures for task distribution between the agents, inter-coalition migration and reorganization processes coordination, identifying certificates issue, etc.

The formal model of agent computational field is as follows:

$$ACF = \langle ID, LC, PR, t \rangle,$$

where ACF is a agent computational field; ID is a unique identifier of data structure (computational field); LC is a contextual information about the field initiating agent (local context of the agent, including description of its competencies, model of the current situation and tasks to be solved, location in the network, etc.); PR is a rule of field propagation over the network; t is the agent lifetime in the network or the time when its local context is updated.

By context is meant according to [6] a model describing the knowledge relevant to user task and shared by the information environment components in the course of solving the task. In other words the context is any information that can be used to characterize the situation in which a certain object is currently located and information that can be obtained from that object. The object may be an agent, a user, an external environment, a physical object or an application program. The situation occurs when objects interact. As a result, the context forms a part of the information environment used by the objects in their interaction [7].

Agents have access to the field by perceiving the values of its parameters and changing it to reflect the local context representing the location and/or state of the agent. An agent located at a specific point in the virtual space perceives parts of the gradient field from its neighbors and selects a behavior strategy (deterministic or probabilistic) controlled by the resulting field. It interacts with neighbors in some form, for example, it moves to them, sends messages through them, inquires them for information, etc. The source of coordinating information during this selection remains the gradient field and its local characteristics, which are perceived by each agent.

The necessary and sufficient condition for SCMAS formation in the virtual environment is the gradient collinearity and co-directionality of computational fields of the given set of agents and certain source initiator. Formally, this rule is described as follows:

$$\nabla ACF|_{a_k} \uparrow\uparrow \nabla ACF|_{a_i},$$

where $\nabla ACF|_{a_k}$ is a gradient of agent computational field $a_k \in A$ that initiated the field; $\nabla ACF|_{a_i}$ is a gradient of other agent computational field $a_i \in A, i = \overline{1...N}$ in the virtual environment. At the same time initiating agent $a_k \in A$ "attracts" agents $a_i \in A, i = \overline{1...N}$ to itself and is the managing agent-moderator within the framework of problem-oriented virtual space formed around it.

The agent "movement" coordination in the virtual space (MAS dynamics) is carried out by the shape of the field and its change from node to node, from agent to agent. Information about the agent "movement" direction is obtained by evaluating the changes of computational field and agent local context represented in it in various directions.

Technology Implementation Procedures

To dynamic configuration problem-solving of the multi-agent system for regional security control (MAS RSC) by forming agent coalitions and associated virtual networks of resources and web-services at different levels of management in each area of regional security, an agent-based technology for dynamic synthesis and configuration of problem-oriented SCMAS has been developed. The technology structure and functional components are represented at figure 1.

The technology implements the following procedures:

1) synthesis of virtual organizational management structures (VOMS) models using automated method [8] for different types of situations, determination of its structure and composition;

2) potential VOMS participants selection at the strategic and tactical planning levels based on analysis of the security management entities competencies and profiles registered in MAS RSC;

3) agent coalitions formation such that its total competencies meet the requirements of solved tasks of the regional security management in crisis situations of a certain security class;

4) virtual networks of resources formation associated with security management problems for various situations and with synthesized agent coalitions that form the VOMS;

5) search and composition of web-services for processing and analysis of data sets generated during execution of the fourth procedure for each area of regional security and multiple tasks to be solved;

6) quality analysis of the generated VOMS configuration and efficiency assessment of its implementation;

7) parameters additional determination of the agent local context or MAS RSC information objects based on the results of the sixth procedure, if necessary, and further reconfiguration of the generated VOMS;

8) formation of problem-oriented multi-agent virtual spaces, which are SCMAS, based on synthesized VOMS for each regional security area;

9) reorganization and reconfiguration of MAS RSC in case of obtaining new information from the external environment, connection (deactivation) of MAS RSC components (agents, web-services, data sources), registration of new security management actors in the system, integration of third-party information systems elements, etc.

The SCMAS formation is one of the effective methods for implementing the synthesis of network-centric management systems of regional security.

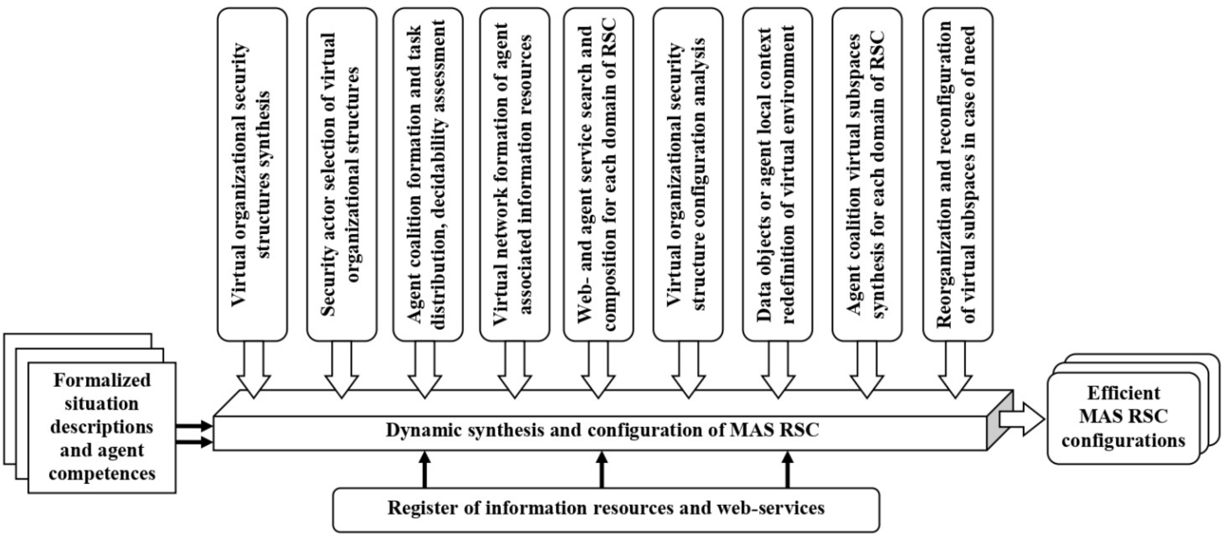

Fig. 1. Structural model of technology for dynamic synthesis and configuration of multi-agent system of regional security control (MAS RSC)

Various SCMAS configurations are designed and tested on the basis of the JADE-platform (Java Agent Development Environment) [9] and using the Netlogo software agent simulator [10].

The configuration of the MAS RSC directly depends on the configuration parameters of the generated problem-oriented multi-agent virtual spaces for each regional security area. That is, the MAS RSC configuration model as a part of unified information environment of the region is described by a set of configuration models:

$$VE_{MAS\ RSC} = \left\{ VE_i |_{CSC_i} \right\},\ i = \overline{1..M}\ ,\ VE_{MAS\ RSC} \subset VE_{region}\ ,$$

where VE_{region} is a configuration model of regional information environment; $VE_i |_{CSC_i}$ is a configuration model of problem-oriented multi-agent virtual space, formed for management information support problem-solving under crisis situations of the i security class; M is s number of problem-oriented multi-agent virtual spaces forming the MAS RSC, and at the same time M can be fixed both in the case of using the generally accepted tree-like crisis classifier for various types of security, and dynamically change taking into account the self-organization of MAS RSC elements, new nodes connection, agent generation, crisis situations registration or new information receipt in the system.

Formally, the configuration model of a problem-oriented multi-agent virtual space is described by a tuple of sets:

$$VE_i |_{CSC_i} = \left\{ SS^i, R^i, AS^i, WS^i, Z^i |_{CSC_i} \right\},$$

where SS_l^i is a set of VOSM forming the i virtual space, $SS^i = \left\{ coal_{f_{z_q}^j, i_{z_q}^k} \subseteq A \right\}$, $coal_{F_{z_q}^j, I_{z_q}^k} \subseteq A$ is a set of agent coalitions participating in problem-solving $z_q \in Z^i |_{CSC_i}$ with functional (F) and informational (I) competencies $\left(F_{z_q}^j, I_{z_q}^k \right)$; R^i is a set of information and analytical resources integrated within the i virtual space; AS^i is a set of services; WS^i is a set of web-services registered in MAS RSC used in i virtual space; $Z^i |_{CSC_i}$ is a set of tasks to be solved within the framework of crisis situations of the i security class; CSC_i is a i security class according to the tree-like classifier of crisis situations.

The structural model of MAS RSC configuration process is shown schematically in figure 2.

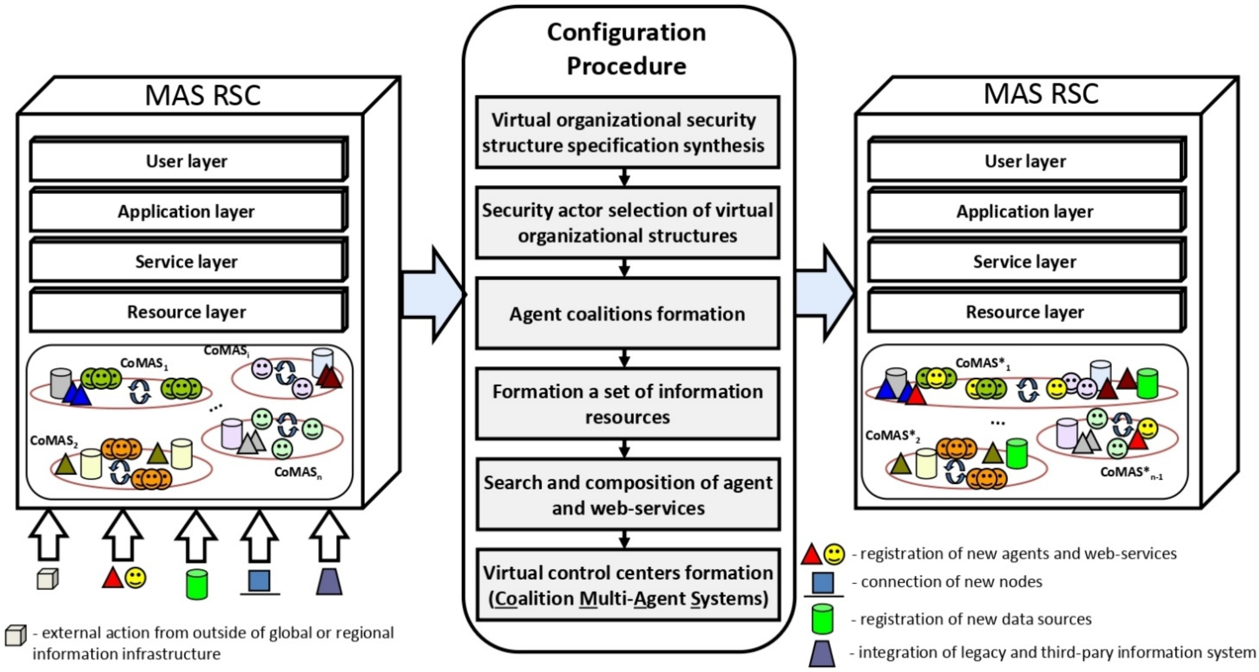

Fig. 2. Conceptual scheme of configuration procedure of virtual environment for regional security control based on coalition multi-agent systems (CoMAS)

Discussion

Dynamic configuration and self-organization of MAS RSC components are a necessary and sufficient condition to maintain its operability and self-development in the regional information environment. The application effect of MAS RSC is higher than larger and more meaningful its internal volume is, i.e. number of registered heterogeneous security management entities and their virtual representatives (agents), web-services, connected nodes, information resources, integrated software components of departmental information systems, etc. However, the growth of system volume naturally leads to an increase of the problem complexity of information elements and services retrieval and VOMS variants composition because of polynomial growth of the number of alternatives. In order to the system is not losing its availability under conditions of its own unrestricted growth, special self-organization mechanisms allowing its internal structure dynamic formation are needed. Such mechanisms implementation provides volume reduction of processed and transmitted data during the new information resources and web-services registration in the system as well as during the search for joint activity agents on the distributed system nodes and its competencies assessment followed by agent coalition formation and effective VOMS models synthesis.

To solve this problem we propose a mechanism for agent self-organization, improving the implementation effect of self-organization model based on gradient (computational) fields. Our self-organization mechanism is based on generalization procedures of the formalized descriptions of crisis situations and solving managerial tasks using tree-like conceptual models of the knowledge domains. Formal generalization procedures in detail are proposed in [11]. The search criteria for web- and agent services and information resources retrieval in the semantic space (knowledge domain ontology) used during VOMS synthesis are weakened under generalization process. A semantic space is represented by the conceptual model of regional security [12]. This also uses a tree-based crisis situation classifier for different security areas. The generalization procedure provides semantics automated synthesis of the group of solving control problems within the framework of a generalized crisis situation and, through this, a potential increase of the number of alternative VOMS variants generated within the virtual environment. Technically, the semantic description generalization of several security management tasks or crisis situations consists in creating a new task or situation that "covers" the initial ones, and generating of software agent possessing a necessary set of competencies to solve this problem or situation and representing generalized competencies of the agent coalition.

With this approach the preliminary formation of problem-oriented multi-agent virtual spaces is carried out by mapping the agent goals and competencies to tree-based conceptual models of the knowledge domain followed by subsequent localization of the main part of agent retrieval and other requests within the group and further activity analysis of its communications with each other. The similarity of interests (including solving tasks, required set of competencies or services, etc.) leads to the fact that the most active and information-rich agent communications are concentrated inside a single virtual space, while outside it information exchange is less active. The approach is based on multi-agent technology for virtual integration platforms formation proposed in the study [5]. This technology provides the possibility to reduce network traffic and load on system nodes by reducing the number of communications between system agents and reducing the volume of data processed and transmitted by agents in a distributed information environment.

To solve the dynamic configuration problem of problem-oriented virtual spaces and MAS RSC in general special agent learning methods are required. For this purpose an approach to agent learning based on the combined use of agent simulation apparatus and polymodel complexes that are part of the MAS RSC distributed agent platform [13], as well as a model generally accepted in the collective intelligence theory based on collective (group) learning with reinforcement [14, 15], which is a special case of the learning by instruction method is proposed. At the same time the instructor role appears both the environment itself and its model embedded in the agent simulation apparatus and developed by it. As one of varieties of collective learning models with reinforcement we propose to use the modified Q-learning method [15] based on the Q-routing and optimization algorithms implementation according to the ant colony principle (Swarm Intelligence). This approach provides agent behavior strategy focused selection based on the previous interactions experience with the environment and with other agents. The Q-learning method limitation [16] is its applicability only to situations that can be represented in the form of Markov decision process.

The contribution of the proposed method of agent learning consists in integration of collective learning model with reinforcement (Q-learning) based on ant colony principle (Swarm Intelligence) and external environment system-dynamic model implemented in agent simulation apparatus [17]. This improves the autonomy and efficiency of software agents in solving user problems in conditions of incomplete semi-structured data.

Conclusion

A multi-agent virtual environment for network-centric control information support of regional security is a distributed system of autonomous software agents, information resources and web-services, as well as special software that supports the joint use of elements of this system in a single information environment. To functioning support of such an environment under conditions of decentralized management and external environment high dynamics, a technology for dynamic synthesis and configuration of virtual resource networks with dedicated organizational management centers of regional security has been developed. The technology is based on agent self-organization models in open multi-agent systems and provides operability enhancement of relevant information collecting and processing to decision-making support at all levels of regional security management.

Distinctive features of the developed technology are:

– behavior modeling of the each subject of management as an autonomous pro-active entity with its own interests and goals;

– implementation and use of cognitive agents with a simulation apparatus having a hybrid architecture;

– implementation of network-centric control principles;

– implementation of modified agent self-organization model based on gradient computational fields;

– agents high adaptation to external environment dynamics due to combined use of collective learning methods with reinforcement (Q-Learning) and system-dynamic models embedded in the agents' simulation apparatus.

Proposed technology implementation in practice ensures the achievement of the following system effects: adaptability, self-organization and self-contextualization abilities, decentralized control coordination, self-identification, infomobility.

Technology application limitations may be the reasons associated with the occurrence of abnormal situations within the MAS itself. Examples of such situations are: incomprehensible information receiving from the external environment that is difficult for system agents to perceive and which does not induce the agents to take any actions; the computational field initiated by the agents is not perceived by other agents and its action is useless, which decelerates agent self-organization process into problem-oriented virtual spaces and interrupts the coordination of its behavior.

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