Principles of Decentralized Problem Solving Within the Ecosystem of Next-Generation Intelligent Computer Systems

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***Abstract*—The paper considers the principles of decentralized problem solving within the ecosystem of next-generation intelligent computer systems, in particular, the architecture of such an ecosystem is considered from the point of view of organizing the process of problem solving, the roles of systems involved in the process of problem solving are separated. The principles of forming a collective of systems involved in problem solving, the stages of solving a particular problem by the resulting collective are specified.**

***Keywords*—Decentralized AI, multi-agent approach, OSTIS technology, OSTIS Ecosystem, problem solver, sc-agent, ostis-system**

I. Introduction

Currently, one of the key trends in the field of intelligent technologies is the so-called decentralized artificial intelligence [1], [2]. This trend is caused, on the one hand, by the development and widespread use of autonomous mobile devices (both self-sufficient and as part of more complex systems, as in the case of various kinds of sensors), which interact intensively when solving tasks together, which, in particular, led to the emergence and development of such a trend as the Internet of Things. On the other hand, decentralization is necessary when solving problems of complex automation of various processes, for example, production. In this case, the implementation of an automation system with a monolithic centralized architecture becomes impossible, in this regard, the task of integrating a variety of heterogeneous devices and subsystems into a single information space, within which various models and methods of artificial intelligence are subsequently applied. There is a large number of studies aimed at developing the principles of problem solving in distributed teams of interacting computer systems [1]–[3].

In turn, the complex automation of various human activities and the development of corresponding complex intelligent systems of automation leads to the need to integrate within such systems different types of knowledge and different problem solving models and to ensure the possibility of joint use of these models in solving complex problems [4], [5]. In addition, the problem of reducing the labor intensity of not only the development of such systems, but also their evolution and maintenance at all stages of the life cycle is relevant. The solution of the mentioned problem becomes possible when providing syntactic and semantic compatibility of models of representation of different types of knowledge and different problem solving models. In other words, to solve the problem of complex automation of human activity, it is necessary to provide convergence of different models of representation and information processing in intelligent systems.

At the same time, as it has already been noted, an important trend in the development of artificial intelligence technologies is the desire to decentralize the solution of various problems, in connection with which the creation of *next-generation intelligent computer systems* with a high level of ***interoperability*** is increasingly relevant. In this case, by interoperability [6] is meant not just ensuring compatibility of systems at the level of technical implementation (coordination of interaction protocols, program interfaces, etc.), but ensuring their semantic compatibility and ability to collectively solve complex problems. This implies a significant development and increase in the level of formalization of the theory of intelligent computer systems, rethinking of the existing technologies of their development and maintenance in the context of ensuring their convergence, and ultimately – the creation of a comprehensive technology of designing intelligent computer systems of a new generation, taking into account the need to develop not only individual intelligent computer systems, but also decentralized collectives of such systems, capable of jointly solving complex problems.

OSTIS Technology is proposed as a comprehensive design technology for *next-generation intelligent computer systems* [4]. Next-generation intelligent computer systems developed on the basis of this technology are called *ostis-systems*. OSTIS Technology is based on a universal method of semantic representation (coding) of information in the memory of intelligent systems, called *SC-code*. Texts of *SC-code* (sc-texts, sc-constructions) represent unified semantic networks with basic theoretical-multiple interpretation. The elements of such semantic networks are called sc-elements (sc-nodes and sc-connectors, which, in turn, can be sc-arc or sc-edges depending on their orientation).

Universality and unification of *SC-code* allows describing any types of knowledge and any methods of problem solving on its basis, which, in its turn, greatly simplifies their integration both within one system and within a collective of such systems.

The basis of the knowledge base developed according to the OSTIS Technology is a hierarchical system of semantic models of *subject areas* and *ontologies*, among which there is a universal Kernel of semantic models of knowledge bases and methodology of development of semantic models of knowledge bases, providing semantic compatibility of the developed knowledge bases. The basis of the ostis-system problem solver is a set of agents interacting exclusively through the specification of information processes they perform in the semantic memory (*sc-agents*).

All of the above principles together allow to ensure semantic compatibility and simplify integration of various components of computer systems as well as of such systems themselves. Within the framework of *OSTIS Technology* several universal variants of visualization of SC-code constructions have been proposed. This paper will use examples in *SCg-code*, a graphical variant of visualization of SC-code constructs, and *SCn-code*, a structured hypertext variant of visualization of SC-code constructs.

Within the framework of OSTIS Technology the models, methods and means of developing hybrid knowledge bases and problem solvers of next-generation intelligent computer systems are considered in detail, including the issues of providing convergence of different types of knowledge and different models of problem solving [4]. At the same time, the problem of organizing the process of problem solving by a decentralized collective of ostis-systems remains relevant.

Thus, the task of developing a theory of problem solving in <u>distributed</u> <u>collectives</u> of interoperable *next-generation intelligent computer systems* remains relevant.

This task solving is proposed to be carried out on the basis of the concept of ecosystem of interacting ostis-systems (***OSTIS Ecosystem***). In the paper [7] general approaches to problem solving within the framework of the OSTIS Ecosystem are considered, in this paper the architecture of the OSTIS Ecosystem and the principles of organizing problem solving within this ecosystem will be specified.

II. OSTIS Ecosystem Architecture

A. Concept and main tasks of the OSTIS Ecosystem

OSTIS Ecosystem — a sociotechnical ecosystem, which is a collective of interacting semantic computer systems and provides permanent support for the evolution and semantic compatibility of all its constituent systems throughout their life cycle [4], [8].

In order to talk about the principles of problem solving within the OSTIS Ecosystem, it is necessary to clarify the architecture of the OSTIS Ecosystem and the advantages of the concept of such an ecosystem in the context of decentralized problem solving.

The *OSTIS Ecosystem*, is a collective of interacting (via the Internet) [4]:

- *ostis-systems* themselves;
- users of the specified *ostis-systems* (both end users and developers);
- some computer systems that are not *ostis-systems*, but are considered by them as additional information resources or services.

OSTIS Ecosystem is a form of implementation, improvement and application of *OSTIS Technology* and, therefore, is a form of creation, development, self-organization of the market of semantically compatible computer systems and includes all resources necessary for this — informational, technological, personnel, organizational, infrastructural.

One of the important tasks of the OSTIS Ecosystem is to ensure that the compatibility of the computer systems included in the OSTIS Ecosystem is maintained at all times, both during their development and during their operation. The problem here is that during the operation of the systems included in the OSTIS Ecosystem, they may change and thus compatibility may be compromised.

The solution of the above task involves solving the following subtasks:

- operational implementation of all agreed changes to the standard of *ostis-systems* (including changes to the systems of used concepts and their corresponding terms) [9];
- permanent support for a high level of mutual understanding of all systems included in the OSTIS Ecosystem and all their users;
- corporate solution of various complex problems requiring coordination of activities of several (most often, a priori unknown) *ostis-systems*, as well as, possibly, some users.

Thus, the *OSTIS Ecosystem* is the basis for the transition from independent (autonomous, separate, integral) *ostis-systems* to collectives of independent *ostis-systems*, i.e. to distributed *ostis-systems*.

B. OSTIS Ecosystem Agent Typology

Let us consider the classification of ostis-systems in terms of their independence (interaction with other *ostis-systems* within the *OSTIS Ecosystem*):

ostis-system
⇒ *subdividing**:
{● *independent ostis-system*
:= [complete *ostis-system* that must independently solve a corresponding set of tasks and, in particular, interact with the external environment (both verbally — with users and other computer systems, and non-verbally).]
● *embedded ostis-system*
:= [intelligent computer subsystem developed according to *OSTIS Technology* and realizing part of the functionality of *ostis-system* of a higher hierarchy level]
:= [*ostis-system* integrated into *independent ostis-system*]
⇒ *subdividing**:
{● *atomic embedded ostis-system*
:= [*embedded ostis-system* that does not include any other *embedded ostis-system*]
● *non-atomic embedded ostis-system*
⊃ *ostis-system interface*
}
● *ostis-systems collective*
:= [group of communicating ostis-systems, which may include not only independent ostis-systems, but also collectives of ostis-systems]
:= [distributed ostis-system]
}

We emphasize that the ***independent ostis-systems*** that are part of the *OSTIS Ecosystem* have special requirements:

- They should have all the necessary knowledge and skills to exchange messages and to organize purposeful interactions with other *ostis-systems* within the *OSTIS Ecosystem*.
- In the conditions of constant change and evolution of *ostis-systems* included in *OSTIS Ecosystem*, each of them should self monitor the state of its compatibility (consistency) with all other *ostis-systems*, i.e. it should independently maintain this compatibility, coordinating with other *ostis-systems* all the changes that require coordination, occurring in itself and in other systems.
- Each system included in the *OSTIS Ecosystem* shall:
  – Learning intensely, actively and purposefully (both with the help of developmental teachers and independently).
  – Notify all other systems of proposed or finalized changes to the *ontologies* and, in particular, to the set of *concepts* used.
  – Accept proposals from other *ostis-systems* for changes to the *ontologies* (including the set of concepts used) in order to agree or approve these proposals.
  – Implement approved changes to the *ontologies* stored in its knowledge base.
  – Contribute to maintaining a high level of semantic compatibility not only with other *ostis-systems* within the *OSTIS Ecosystem*, but also with its *users* (i.e. educate them, inform them about changes in ontologies).

Thus, the OSTIS Ecosystem is essentially a distributed *multi-agent system* [10], which includes *agents of OSTIS Ecosystem*, which are the subjects of the activities performed within the *OSTIS Ecosystem*. Let's consider the classification of *agents of OSTIS Ecosystem* taking into account the classification of *ostis-systems* given above. [8].

agent of OSTIS Ecosystem
⇒ *subdividing**:
{● *individual ostis-system of OSTIS Ecosystem*
⇒ *subdividing**:
{● *independent ostis-system of OSTIS Ecosystem*
● *embedded ostis-system of OSTIS Ecosystem*
}
● *user of the OSTIS Ecosystem*
● *ostis-community*
⇒ *subdividing**:
{● *simple ostis-community*
● *hierarchical ostis-community*
}
}

C. The concept of ostis-community

Ostis-community is a stable fragment of *OSTIS Ecosystem*, providing complex automation of a certain part of collective human activity and permanent increase of its efficiency.

A *hierarchical ostis-community* is a *ostis-community*, at least one of whose members is some other *ostis-community*. *Ostis-community* generally includes not only *ostis-systems collective*, but also a certain collective of people (users and developers of the corresponding *ostis-systems*). Each *OSTIS Ecosystem agent* (both individual and collective) can become a member of any ostis-community of the OSTIS Ecosystem on his/her own initiative after proper registration of [4], [8].

OSTIS Ecosystem is the maximal *hierarchical ostis-community* that provides comprehensive automation of all human activities. It cannot be a part of any other *ostis-community*.

Note that the proposed *OSTIS Ecosystem* architecture and the separation of *ostis-communities* is not exclusively part of the approach to organizing decentralized problem solving of applications. The *OSTIS Ecosystem* is a tool for the realization and evolution of the *OSTIS Technology*, in particular a basis for the realization of a component-based approach in the development of *ostis-systems*. In this paper, the architecture of the *OSTIS Ecosystem* is considered and refined in the context of collective problem solving.

Let us clarify the architectural principles underlying the *OSTIS Ecosystem* [4], [8]:

- *OSTIS Ecosystem* is a network of *ostis-communities*;
- To each *ostis-community* mutually unambiguously corresponds the *corporate ostis-system* of this *ostis-community*;
- Each *ostis-community* may join any other *ostis-community* on its own initiative. Formally, this means that the *corporate ostis-system* of the first *ostis-community* is a member of another *ostis-community*;
- Each specialist who is a part of the *OSTIS Ecosystem* is mutually correspondent to his/her *personal ostis-assistant*, which is interpreted as a *corporate ostis-system* of a degenerated *ostis-community* consisting of one person;
- The *corporate ostis-system* of each *ostis-community* stores a specification of the *ostis-systems* belonging to this *ostis-community*, in its turn, each *ostis-system* stores some specification about the *corporate ostis-system* of each *ostis-community* to which this *ostis-system* belongs ("knows" its *corporate ostis-systems*).

Thus, the following levels of hierarchy can be distinguished in the *OSTIS Ecosystem*:

- individual *cybernetic systems* (individual *ostis-systems* and people who are the end users of the *ostis-systems*);
- hierarchical system of *ostis-communities*, the members of each of which can be *individual ostis-systems*, people, as well as other *ostis-communities*;
- *Maximum ostis-community* of the *OSTIS Ecosystem* that is not a member of any other *ostis-community* within the *OSTIS Ecosystem*.

Each person who is a member of *OSTIS Ecosystem* unambiguously corresponds to his/her personal assistant in the form of *personal ostis-assistant*. The collective consisting of a person and her corresponding *personal ostis-assistant* will be called a *minimal ostis-community* [4], [8]. Since formally non *minimal ostis-communities* do not include persons, but their corresponding *personal ostis-assistants*, all *ostis-communities* except *minimal ostis-communities* are *collectives of ostis-systems*.

ostis-community
⇒ *subdividing**:
{• *minimal ostis-community*
• *collective of ostis-systems*
}

A *corporate ostis-system* is a central *ostis-system* that coordinates, organizes, and supports the evolution of the activities of the members of the correspondent *ostis-community*. The *corporate ostis-system* is the representative of the correspondent *ostis-community* in other *ostis-communities* of which it is a member. Consequently, the main purpose of the *Corporate system of OSTIS Ecosystem* is to organize common interaction in the performance of various types and areas of human activities, which may be either fully automated, partially automated or not automated at all.

The *OSTIS Metasystem* is considered as the *Corporate system of OSTIS Ecosystem*, which is also implemented based on *OSTIS Technology* and whose knowledge base contains [4]:

- Formal theory of ostis-systems;
- Ostis-systems and OSTIS Technology Standard (*OSTIS Standard*);
- Core Library of reusable ostis-system components (*OSTIS Library*);
- Methods and tools for supporting the life cycle of ostis-systems and their components;
- Description of the structure of the *OSTIS Ecosystem*, including a description of the hierarchy of *ostis-communities* and their composition.

Figure 1 shows an example of a fragment of the *OSTIS Ecosystem* in education. As can be seen from the example, the same ostis-community can be part of several other ostis-communities. Each ostis-community corresponds to its *corporate ostis-system* (only a part of it is shown in the figure).

Within the framework of this work *corporate ostis-systems* is proposed to be considered as one of the important means of organizing the problem solving process in *OSTIS Ecosystem* [4], [8].

III. Features of problem solving within the ecosystem of next-generation intelligent computer systems

A. General principles of information processing within the framework of OSTIS Technology

The basic principles of information processing in memory ostis-systems are formulated in the previous works of the author [4], [11]:

- All problem solving processes are proposed to be divided into *logically atomic actions*, into those depending on what actions are performed before and after them and what more general actions they are part of;

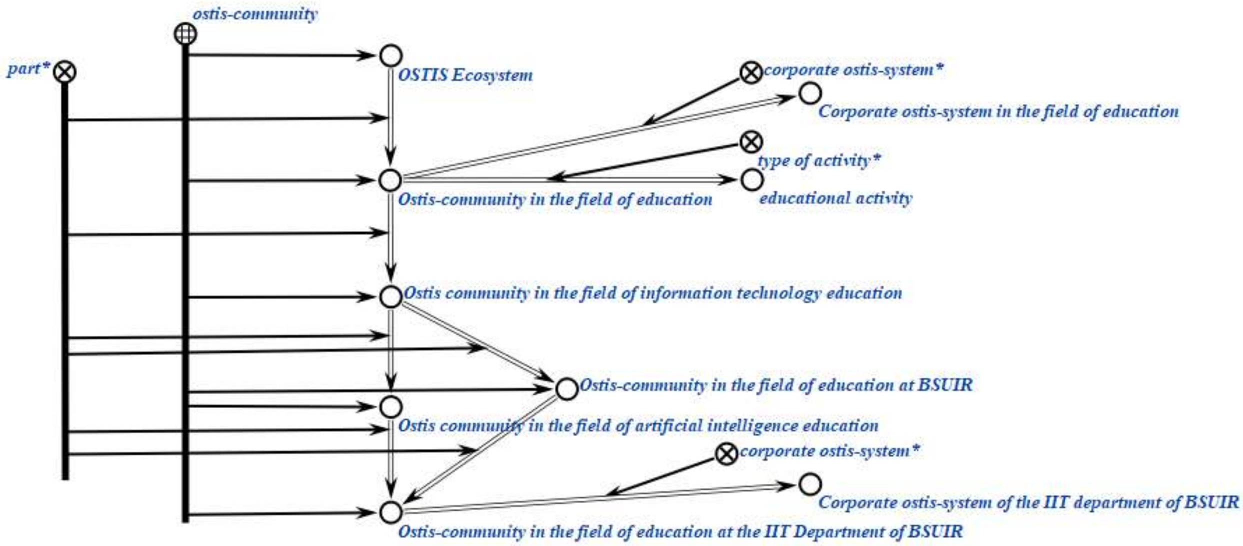

Figure 1. Example of ostis-community hierarchy

- Each *class of logically atomic actions* corresponds to a solver component (sc-agent) capable of performing actions of the specified class;
- Sc-agents react to various events in the ostis-system memory (sc-memory) and communicate with each other only by specifying the actions they perform in this memory. Direct message exchange between sc-agents is excluded;
- Each sc-agent has a corresponding specification, which is also stored in the same sc-memory as the constructs being processed;
- The ostis-system problem solver is treated as a hierarchical system of sc-agents. Two aspects of organization of such hierarchy are distinguished:
  - hierarchy of sc-agents in terms of the *l*evelmethod representation language (programming language). Lower-level sc-agents interpret methods corresponding to higher-level sc-agents;
  - hierarchy of sc-agents within one *method representation language*. A sc-agent may correspond not to a specific *method* describing the sc-agent's program of actions, but to a family of simpler sc-agents, and the level of such "nesting" is not limited in principle. Sc-agents decomposable into a collective of simpler sc-agents are called *non-atomic sc-agents*.
- Classes of functionally equivalent sc-agents, which have a common specification but are realized in general in different ways, are called *abstract sc-agents*.

The above principles allow to ensure hybridity, modifiability of ostis-systems problem solvers, as well as convenience of their design and evolution [4], [11].

The key difference between the distributed ostis-system and the internal system of sc-agents within an individual ostis-system is the absence of a common memory storing a common knowledge base for all sc-agents and acting as a medium for communication between sc-agents. In general, as a means of communication between the participants of a distributed collective of ostis-systems can be used [7]:

- Shared unallocated (monolithic) memory, as in the case of sc-agents over sc-memory;
- Shared distributed memory. In this case, from a logical point of view, agents may think that they are still working on a shared memory, where the entire available knowledge base is stored, but in reality the knowledge base will be distributed among several ostis-systems and the performed transformations will have to be synchronized among these ostis-systems;
- Specialized communication channels. Obviously, when solving a problem in a distributed collective of ostis-systems, there should be language and technical means allowing to transfer messages from one ostis-system to another.

All of the above means of communication can be combined depending on the class of the problem solved, the knowledge and skills required for its solution, and the currently available set of ostis-systems.

When solving a particular problem by a distributed collective of ostis-systems, in general the following "organizational" subproblems related to the organization of the communication process of the ostis-systems themselves must be solved before proceeding directly to problem solving within the subject domain:

- which ostis-system will provide the environment for interaction of other ostis-systems;
- what set of ostis-systems will be involved in solving this problem solving (knowledge and skills of which ostis-systems will be required);
- how the overall problem solving plan will be formed and refined, on the basis of which problem solving strategy it will be formed, how this strategy will be selected;
- where the overall problem solving plan will be stored and how it will be interpreted;
- where the result of problem solving will be formed and intermediate results of the solution will be stored;
- how the sub-tasks will be distributed among the participants in the solution process;
- how the intermediate results of individual subtasks will be synchronized with each other.

B. Special features of information processing within the OSTIS Ecosystem

The very idea of *OSTIS Ecosystem* and complex automation of human activity implies the need for self-organization of agents performing problem solving within the ecosystem. Currently, there is a large number of works devoted to the issues of self-organization of participants in the process of decentralized information processing [1]–[3]. In modern works it is common to use the classification of self-organization mechanisms proposed in the works [12], [13]. The work [1] even suggests the idea of expediency of creating libraries of standard algorithms for decentralized computing and group management of networks of autonomous objects, including consensus protocols, protocols for leader selection, protocols for contractual networks, auction protocols, protocols for common intentions, protocols for information exchange in the interests of maintaining situational awareness of participants in group behavior, and many others.

At the same time, the proposed architecture of the *OSTIS Ecosystem* has a number of important features in comparison with traditional multi-agent systems, within the framework of which the existing self-organization mechanisms are implemented.

- Agents in traditional self-organizing systems usually have rather limited functional capabilities, a small amount of knowledge about the environment and relatively low reliability. This is especially pronounced in the works devoted to the so-called "swarm intelligence", where each agent in the system is maximally simplified, and the number of agents in the system grows accordingly.

  In turn, each ostis-system within the *OSTIS Ecosystem* is a complex computer system with an extensive knowledge base and functionality that allows such a system to solve a variety of problems from the relevant subject domain. The implications of this distinction are as follows:
  - In traditional self-organizing systems, it is assumed that the vast majority of tasks can be solved only by a collective of agents. In *OSTIS Ecosystem* many problems can be solved by one particular ostis-system, therefore, it is often relevant not to form a collective of ostis-systems for solving a problem, but simply to search for an ostis-system capable of solving the problem;
  - In traditional self-organizing systems, it is usually assumed that agents have similar functional capabilities or at least there are groups of agents with similar functional capabilities. Special attention is paid to the problem of rational distribution of subtasks (load optimization) among such agents. Within *OSTIS Ecosystem* a number of functions can be duplicated in different ostis-systems, but it is assumed that each ostis-system has a sufficiently large set of unique functionalities available only to it. In this regard, the problem of efficient resource allocation is replaced by the problem of finding the most appropriate performer or forming a collective of performers suitable for problem solving;
  - In traditional self-organizing systems, much attention is paid to the issues of system reliability and preservation of its performance in case of failure of one or more agents. The issue of reliability of ostis-systems is undoubtedly important and relevant, however, taking into account the presence of unique functional capabilities of each ostis-system, the issue of automatic replacement of some ostis-systems by others during collective problem solving is not considered at the current stage of development of the idea of OSTIS Ecosystem.
- Traditional self-organizing systems are usually not considered as hierarchical structures, all agents are considered as autonomous units within the system, interacting with similar agents at the same level. The exception is the approaches to self-organization, which imply the allocation of special coordinating agents or agents-arbitrators, whose task is to control other agents. Within the *OSTIS Ecosystem* framework, it is assumed to explicitly distinguish a hierarchy of agents corresponding to the hierarchy of *ostis-communities*, besides, *OSTIS Ecosystem* agents are classified according to the role they play in the process of collective problem solving, in particular, *corporate ostis-systems* are distinguished.

The hierarchical nature of the agent system makes it easy to develop and modify such systems by analogy with the hierarchical structure of problem solvers in *individual ostis-systems* [4], [11].

- In traditional systems, often all agents of the system, or at least a significant part of them, may be involved in problem solving. Taking into account the complexity of ostis-systems included in the OSTIS Ecosystem, such a situation is unlikely in the OSTIS Ecosystem and most often in the near future several ostis-systems, most often belonging to one ostis-community, will be involved in problem solving.
- Traditional self-organizing systems are usually considered in isolation from the means of representation of information processed in such systems, i.e. neither the form of representation of processed information, nor the semantics of processed information are explicitly fixed. An important advantage of *OSTIS Ecosystem* and *OSTIS Technology* as a whole is the orientation on unified and universal models of information representation, realized in the form of *OSTIS Technology* and a family of top-level ontologies built on its basis. This approach allows us to say
  - about universality of the developed mechanisms of collective problem solving within *OSTIS Ecosystem*, i.e. the possibility to unlimitedly increase the possibilities of *OSTIS Ecosystem* to automate different kinds of human activities in various fields;
  - about the possibility to describe the agents of the OSTIS Ecosystem by the same means that are used to describe the information processed by the agents, with the required degree of detail. Thus, it becomes possible to analyze the specification of some agents (e.g., their functional capabilities, classes of solved tasks, etc.) by other agents, which opens new opportunities for self-organization in collective problem solving.
  - about the possibility of exchanging information constructions of arbitrary complexity between agents, there is no need to limit the possible semantics of such messages and, moreover, to fix their structure, as it is often done in traditional approaches. It should be emphasized that agents in the framework of the proposed approach do not exchange messages directly, but specify in a common knowledge base the actions they perform, so there are no fundamental restrictions on the content of such specification.

The analysis of the presented features allows us to draw the following conclusions:

- Direct application of existing approaches to self-organization in multi-agent systems for solving *OSTIS Ecosystem* problems is not possible due to its essential features, but many known approaches can be adapted for solving a number of specific problems, for example, when organizing the exchange of messages between ostis-systems at the physical level, searching for the most suitable executor for solving this or that task and so on;
- At the same time, *OSTIS Ecosystem* features allow not to consider at the level of collective problem solving a number of non-trivial problems related to reliability assurance and optimization of load distribution between ostis-systems, and open new opportunities to expand the range of possible spheres of human activity automation, to ensure interoperability of corresponding intelligent systems and their collectives and to reduce the labor intensity of their maintenance and evolution.

IV. Proposed approach to problem solving within the next-generation intelligent computer systems ecosystem

The key difference of the proposed approach to the organization of decentralized problem solving in *OSTIS Ecosystem* in contrast to traditional approaches to self-organization is that within *OSTIS Ecosystem* we initially in the process of ecosystem development form a hierarchy of ostis-systems and their specification so as to further simplify the process of organizing collective problem solving, in particular, the formation of a collective of performers, the transfer of messages between performers, etc., leaving the opportunity for continuous refinement and improvement. Thus, the agent system is initially built in such a way as to make self-organization more convenient by analogy with the way top-level ontologies are developed to ensure compatibility of ontologies instead of developing ontologies independently of each other and then solving the problem of ontology alignment, which most often turns out to be not trivial at all.

In the paper [14] a methodology for the design of multi-agent systems including five stages is proposed. Let us consider in more detail the application of this methodology in the context of problem solving within the *OSTIS Ecosystem*:

- **Step 1: Analyze the objectives for which the system is being developed**. The purpose of the work in this case is to ensure the potential possibility of solving any problems arising within the *OSTIS Ecosystem*, which requires the availability of universal and unified means of describing the goals and objectives. Within the *OSTIS Technology* framework, common unified means of specification of actions and tasks are proposed [4]. As far as semantic completeness of such tools is concerned (taking into account all possible classes of tasks that may arise), it is proposed to take as a basis the task ontology proposed in [15].
- **Step 2: Designing the overall structure of the multi-agent system**. Within the framework of the

considered approach, the structure of the multi-agent system is based on the architecture of the *OSTIS Ecosystem* discussed above and is constantly refined taking into account the addition of new agents to the *OSTIS Ecosystem*. In terms of classification of *agents of OSTIS Ecosystem* at the current stage it is proposed to single out only *corporate ostis-systems* into a separate class due to the fact that they play a special role in the process of organizing collective problem solving. The principles of agents' communication via *corporate ostis-systems* are discussed in more detail at Step 4.

- **Step 3: Designing the internal structure of the agent and the principles of its operation**. Since all *OSTIS Ecosystem* agents are ostis-systems (even users of the OSTIS Ecosystem interact with it through personal ostis-assistants, which are ostis-systems [4], [8]), additional specification of the principles of their structure is not required, as it is discussed in detail in the works devoted to the OSTIS Technology [4], [16]. To ensure the possibility of interaction between ostis-systems over the network, it is proposed to add an interface subsystem to each system, which is discussed in more detail in Step 5.
- **Step 4: Develop the principles of agent interaction**. As mentioned earlier, it is proposed to base the principles of agents' communication within *OSTIS Ecosystem* during collective problem solving on the principles of agents' communication in the memory of ostis-systems (sc-agents). In the work [7] an approach is proposed assuming that one of the ostis-systems included in the collective of ostis-systems will be used as a tool of communication for the participants of the collective of ostis-systems. If such collective is formed on a permanent basis (is a *ostis-community* or a part of it), it is proposed to use the *corporate ostis-system* of the specified *ostis-community* as such communicator system. If a collective of ostis-systems is formed temporarily for solving one or several complex problems, i.e. it is necessary to temporarily involve *ostis-systems* belonging to several *ostis-communities*, two variants of organizing communication of ostis-systems are possible:
  - One of the systems belonging to such a temporary collective of ostis-systems is selected as a communicator system. In this case, such an ostis-system becomes temporarily the *corporate ostis-system* of the temporary *ostis-community*. Accordingly, in this case it is required to install in the ostis-system an interface subsystem for ostis-systems and to load into its knowledge base the specifications of other ostis-systems participating in the problem solving process. Thus, the cost of preliminary preparation of a collective of ostis-systems for problem solving can be quite serious, and this approach may be ineffective for relatively simple problems solving.
  - The *corporate ostis-system* of the closest hierarchical *ostis-community* is chosen as the communicator system, such that all ostis-systems required for the solution belong either to this ostis-community or to more private ostis-communities (possibly on several hierarchical levels). In the example of the *ostis-communities* hierarchy fragment shown in Figure 2, assuming that the problem solving requires the participation of *ostis-systems* ***OS1***, ***OS2***, and ***OS3***, then the *corporate ostis-system* of *ostis-community* ***OC1*** will be selected as the communicator system.

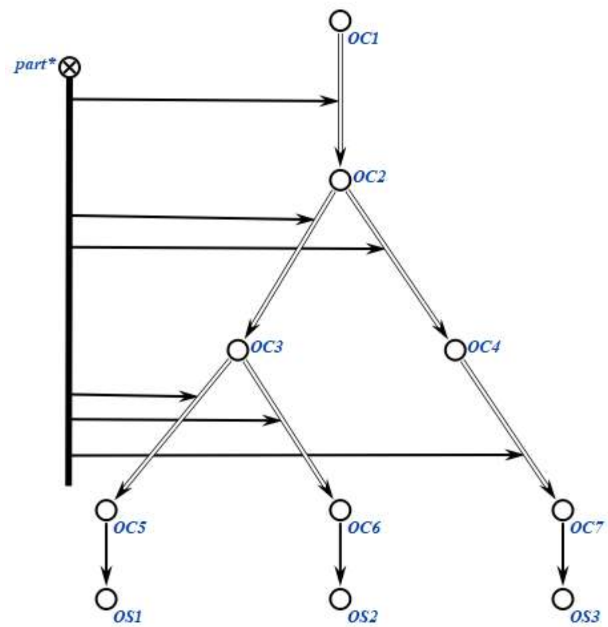

Figure 2. Example of communicator system selection

According to the above architecture of the *OSTIS Ecosystem* such an ostis-community will always exist, in the extreme case the role of such a corporate system will be played by the *OSTIS Metasystem*. The disadvantage of this communication option is that sending messages between the participants of the problem solving process may generally take more time due to the increased path between the corporate ostis-system and the ostis-systems which are performers.

It is important to note that in the presence of such a communicator system, agents at the logical level do not exchange messages directly, but communicate by specifying their actions in the shared memory of the communicator system; nevertheless, at the physical level, messages are forwarded between ostis-systems, generally physically located in different nodes of the network, arbitrarily distant from each other. This idea of separating the logical and physical layers of communication is realized within the concept of *overlay networks* [17]. An overlay network is a virtual network whose structure differs from the real communication network on the basis of which this overlay network functions. The idea of using *corporate ostis-systems* as a basis for agents' communication in such a network and a repository of agents' specifications and methods provided by them can be considered as a new stage of development of the idea of P2P agent platform developed by the FIPA consortium [17]. The main idea of such a platform is to provide all agents in the network with the possibility of semantic search for the services they need, as well as to search for agents that possess the required services. Another function of the platform is to support transparent communication between agents-customers and agents-owners of services [17]. In general, an agent network may have several such platforms, each responsible for a different segment of the network, similar to the way a *corporate ostis-system* is responsible for a corresponding *ostis-community*.

To implement the language of interaction between ostis-systems, it is proposed to use the ideas of wave programming [18], [19], as well as insertion programming [20], [21] as a basis. Later variants of the wave language theory development were called Spatial Grasp Technology [18], [19], within which Spatial Grasp Language is developed accordingly.

Implementing such interaction requires the development of at least two levels of languages:

- transport layer defining the principles of recording SC-code constructions in some format convenient for network transmission. As a variant of such language it is proposed to use SCs-code [4];
- semantic level defining the content of messages transmitted over the network. The SCP language, which is the basic programming language for ostis-systems, is proposed to be used as a basis for such a language [4].

It is important to note that within the framework of the proposed approach, the *corporate ostis-system* acts as a common information resource and notifies the participants of the problem solving process about the events, but does not control the problem solving process directly. Thus, it is not a question of rigid imperative management, but of more flexible declarative. This allows us to realize the advantages of the sc-agent interaction mechanism in a shared semantic memory [4], [11], such as modifiability of the agent system, convenience of its design and others.

- **Step 5: Develop the detailed architecture of the multi-agent system**. At this stage, it is supposed to clarify the principles of interaction between agents and the environment, taking into account the previously clarified agent structure and the principles of their interaction.

  Implementation of the proposed approach assumes that each ostis-system will include a communication interface subsystem that will receive messages from the external environment (from the *corporate ostis-system*), transform them into tasks for internal sc-agents of the *ostis-system*, and then transform the result of their work into a response message and send it to the corresponding recipient. An important feature of such a subsystem is that it behaves as a sc-agent when interacting with internal sc-agents and communicates with other sc-agents according to the same principles. This allows to ensure the independence of the development and evolution of such a subsystem from other components of the ostis-system and to exclude the necessity to take into account the fact of future interaction of the ostis-system with other ostis-systems at the stage of its design. In other words, an ostis-system solves a subtask within a distributed collective of ostis-systems just as if it were solving a problem explicitly formulated, for example, by a user. This approach greatly simplifies the design of ostis-systems collectives, eliminating explicit dependencies between them and the need to provide for the necessity of collective problem solving in advance.

  In turn, each *corporate ostis-system*, when interpreting a particular *method*, interacts with other ostis-systems as if they were internal sc-agents of this ostis-system. Thus, each *corporate ostis-system* includes an interface subsystem that converts events in the memory of the *corporate ostis-system* into messages to other *ostis-systems* and response messages from these *ostis-systems* into corresponding information constructs in the knowledge base of the *corporate ostis-system*. This approach allows to ensure the independence of *corporate ostis-systems* from other ostis-systems participating in the problem solving process and to exclude the necessity to provide in advance the necessity of collective problem solving not only when designing conventional ostis-systems, but also when designing *corporate ostis-systems*. An illustration of this approach will be given below.

From the point of view of the modern classification of self-organization methods in multi-agent systems [17], the proposed approach of agent interaction at the logical level can be considered as a kind of mechanism based on indirect interactions of organizational agents. Mechanisms of this kind assume the absence of direct interaction between autonomous entities composing the system, but their interaction through a common environment, which in the framework of the proposed approach is a common semantic memory (both within the *individual ostis-system* and within the collective *ostis-system*).

V. Means of specification of next-generation intelligent computer systems in the context of collective problem solving

An important role in the proposed approach to problem solving within the *OSTIS Ecosystem* is played by a rather detailed and unified specification of ostis-systems included in the *OSTIS Ecosystem*. Each ostis-system included in the *OSTIS Ecosystem* is subject to a number of requirements [4], [8], the fulfillment of which is necessary to ensure the principle possibility of collective problem solving, to increase the efficiency of the evolution of *OSTIS Ecosystem* and *OSTIS Technology*, to reduce the requirements to the developers of ostis-systems and the labor intensity of their development. The most important of these requirements is the requirement to ensure compatibility (both syntactic and semantic) of each *ostis-system* with others, and in particular with the *OSTIS Metasystem* containing the current version of the *OSTIS Standard*, and to continuously analyze and maintain such compatibility.

At the same time, in order to organize problem solving within *OSTIS Ecosystem* it is additionally necessary to have a detailed specification of functional capabilities of each ostis-system and to ensure the relevance of such specification in the process of evolution of this ostis-system. This specification is part of the knowledge base of *corporate ostis-systems ostis-communities*, to which the specified ostis-system belongs. If the *ostis-system* is not currently a part of any *ostis-community*, the *corporate ostis-system* is the *OSTIS Metasystem*.

The basis of the knowledge base of any ostis-system is a hierarchical system of *sc-models of subject domains* and their corresponding formal *ontologies* describing the properties of entities studied within the specified subject domains [4], [22]. Thus, the knowledge base of the *corporate ostis-system* contains sc-models of those subject domains, on the automation of various activities in which the corresponding *ostis-community* is oriented. In order to provide the possibility of automatic determination of the collective of ostis-systems necessary for solving a particular problem and clarifying the plan of solving this problem, it is necessary to develop for each subject domain the corresponding *ontology of subject domain problem classes and problem solving methods*. [4], [9].

The specified ontology includes a description:

- *classes of problems* solved in the corresponding subject domain;
- *methods* of problem solving corresponding to the specified *classes of problems*;
- *skills* of problem solving corresponding to the specified *classes of problems*, i.e. *methods*, supplemented by the description of *sc-agents* implementing the specified *methods* with the corresponding specification [4];
- *method representation languages* specific to the subject domain;
- *strategies of problem solving* specific to the subject domain, i.e. meta-methods of forming other *methods* of problem solving;
- and other entities, the description of which is necessary to organize problem solving processes within the subject domain. For example, if there are several methods of solving problems of the same class, it is reasonable to describe their comparison in order to be able to choose the method most suitable for the current situation.

As mentioned earlier, the ontology presented in [15] is proposed to be used as a basis for the content of the general ontology of all possible problem classes solved within the *OSTIS Ecosystem*. Thus, the set of problem classes described within a particular *ontology of subject domain problem classes and problem solving methods* will specify some subset of problem classes from such a top-level *problem ontology*. Examples of describing specific classes of problems and corresponding methods of their solution using the example of neural network methods of problem solving can be found in [23].

Thus, each ostis-system being a part of some ostis-community should be specified using the concepts of *ontology of subject domain problem classes and problem solving methods* presented within the corresponding *corporate ostis-system*. In its turn, within each individual ostis-system, this ontology can be further refined. Note that the same methods (and, accordingly, skills) can be duplicated between different ostis-systems, but the information about it is explicitly recorded, which allows us to take it into account when forming a problem solving plan and determining the composition of participants of the collective of ostis-systems taking part in the solution.

Accordingly, when adding ("registering") an ostis-system to an ostis-community, the following steps must be performed:

- Integrate the *ontology of subject domain problem classes and problem solving methods* into the corresponding ontology of the *corporate ostis-system*. Thus, the *corporate ostis-system* will receive information about new problem classes and methods of their solving, if there are any in the added ostis-system;
- Using the obtained integrated ontology, generate a specification of the added ostis-system in the knowledge base of *corporate ostis-system*;
- When the functionality of a *ostis-system* changes, it must notify the *corporate ostis-systems* of all *ostis-*

communities of which this *ostis-system* is a part, which in turn will lead to corresponding changes in the knowledge bases of these corporate *ostis-systems* and possibly to refinements of their corresponding *ontologies of subject domain problem classes and problem solving methods*. Note that this approach has an advantage over many traditional approaches to agent communication in multi-agent systems, where for successful subsequent operation of the system it is required to inform about the addition of a new agent all agents already in the system, since in the process of problem solving agents exchange messages directly and must "know" each other.

The considered specification of *ostis-systems* within the framework of *OSTIS Ecosystem* can be used not only for organizing problem solving, but also for other purposes, in particular, for implementing the idea of component design of ostis-systems [24]. Besides, the considered specification of *ostis-systems* is also necessary for the developers of *ostis-systems* in order to understand what capabilities are already presented within *OSTIS Ecosystem*, within which *ostis-communities*, with the developers of which ostis-systems it is necessary to coordinate these or those components of the developed system, and for solving a number of other design problem solving.

VI. A general plan for solving a specific problem within the next-generation intelligent computer systems ecosystem

According to the proposed approach to problem solving within the *OSTIS Ecosystem*, solving a particular problem generally involves the following steps:

- **Problem formulation**. In general, two options are possible at this step:
  - the initiator of problem solving is an ostis-system, which is a part of *OSTIS Ecosystem*. In this case, the problem formulation is placed in the knowledge base of the corresponding *corporate ostis-system*. To describe the problem formulation at the first stage, both the top-level *ontology of subject domain problem classes and problem solving methods* (included in the *OSTIS Standard* and, respectively, in the knowledge base of the *OSTIS Metasystem*) and more particular *ontology of subject domain problem classes and problem solving methods* corresponding to the *ostis-systems* belonging to the given *ostis-community* can be used.
  - the initiator of problem solving is an external cybernetic system, in particular a human user. In this case, it is assumed that communication with the *OSTIS Ecosystem* is carried out by a *personal ostis-assistant* corresponding to this cybernetic system. Thus, in this case, the task formulation is placed in the knowledge base of the *personal ostis-assistant* and then moved to the knowledge base of the *corporate ostis-system* of the ostis-community of which this *personal ostis-assistant* is a member. If a user is a member of several *ostis-communities* through his/her *personal ostis-assistant*, then the problem of optimal selection of the *ostis-community* within which it is most expedient to start solving a problem becomes relevant. At the same time, the proposed approach to decentralized problem solving in general does not depend on which *corporate ostis-system* the problem formulation initially enters, it affects only the total time of problem solving.

  Thus, as a result of this step, in any case, the problem formulation enters the knowledge base of some *corporate ostis-system* (in general, not necessarily that *corporate ostis-system*, which will act as a communication environment in the process of solving this problem).
- **Determining the set of ostis-systems to be involved in problem solving**. In general, it may be sufficient to involve only *ostis-systems* representing one *ostis-community*, or a set of *ostis-systems* belonging to different *ostis-communities*. The specific mechanism of this stage requires clarification, but the following principles are suggested as its basis:
  - the initiator of this stage is the *corporate ostis-system* whose knowledge base contains the corresponding problem formulation. For this purpose, the specified *corporate ostis-system* interacts with other *corporate ostis-systems*, if necessary involving *corporate ostis-systems* of a higher level. Development of a protocol for such interaction is an actual task;
  - the key role at this stage is played by the previously discussed *ostis-systems* specifications describing *classes of problems*, *methods* of their solving, etc;
  - in the process of performing this stage, the initial problem formulation may be refined taking into account particular *ontologies of subject domain problem classes and problem solving methods*.
- **Definition (selection) of *corporate ostis-system*, which will be the communication environment for solving the currently formulated problem solving task**. The principles of such a selection have been discussed above.
- **Formation of a problem solving plan**. At this stage of development of the theory of decentralized problem solving within the *OSTIS Ecosystem*, we will assume that the solution plan of a particular problem is formed, stored and refined entirely within the corresponding *corporate ostis-system*. In general, we can talk about the possibility of distributed

storage of the problem solving plan, but the interpretation of such a plan will require additional costs for interaction between ostis-systems and the development of additional mechanisms for the transfer of intermediate information and synchronization of actions between ostis-systems, the feasibility of which is difficult to assess at the moment in the absence of a sufficiently large number of applied examples of solving such complex problems.
The development of a general strategy for forming a plan for solving an arbitrary problem is currently an actual direction of development of the approaches considered in this paper. It is important to note that the problem solving plan in the general case will be constantly refined in the course of its implementation, which may require the refinement of the collective of ostis-systems involved in implementing this plan. This strategy is based on the idea of situational management [25] in conjunction with general methodological ideas related to the theory of behaviorism and the ideas of its application in computer science that are gaining popularity [26]–[28], TRIZ [29], as well as SMD-methodology proposed by the school of G. P. Shchedrovitsky [30].
- **Step-by-step interpretation of the problem solving plan**. The basic principles of interaction between *corporate ostis-system* and other *ostis-systems* participating in the problem solving process were considered earlier in the context of specifying the architecture of the multi-agent *ostis-systems* within the *OSTIS Ecosystem*. Implementing these principles requires specifying the architecture of the *ostis-systems* subsystems responsible for interaction between them in the process of problem solving and developing an appropriate interaction language.
Figure 3 shows an example of the interpretation of a problem solving plan stored in the memory of a *corporate ostis-system* by a collective of *ostis-systems*. As can be seen from the example, *ostis-systems* interact with each other by means of corresponding communication subsystems, while the problem solving process itself does not take into account the fact of decentralized solution in any way.
- **Specification of the result of problem solving and its transfer to the initiator**. At this stage, the specification of the problem solving result (including the result itself, if it is an information construct) is formed, the composition of which generally depends on the problem class, and the obtained specification is transferred to the *ostis-system*, which was the initiator of the problem solving (in case of the end user *OSTIS Ecosystem*, the specification is transferred to his *personal ostis-assistant*).

It should be noted that the presented general plan of problem solving within the *OSTIS Ecosystem*, as can be seen from the explanations to its stages, is preliminary and in the future requires detailed specification of each of the stages.

VII. Conclusion

This paper considers the basic principles of decentralized problem solving within the next-generation intelligent computer systems ecosystem (*OSTIS Ecosystem*). In particular, the architecture of *OSTIS Ecosystem*, the typology of *agents of OSTIS Ecosystem*, and the features of problem solving within *OSTIS Ecosystem* are specified. The approach to problem solving within *OSTIS Ecosystem*, means of specification of *ostis-systems* in the context of collective problem solving is proposed. A general plan for solving a particular problem within the *OSTIS Ecosystem* is proposed.

At the same time, the solution of a number of promising tasks remains relevant:
- Development of a general strategy for solving problems of an arbitrary class, the principles of forming a general plan for solving a particular problem;
- Clarifying the language of the problem statements and objectives;
- Development of a general *Ontology of problem classes and problem solving methods*, clarification of the principles of development of private *ontologies of subject domain problem classes and problem solving methods* on its basis and principles of specification of internal *sc-agents* and whole *ostis-systems* using these ontologies;
- Development of a language of interaction between *ostis-systems* at the stage of collective formation of *ostis-systems* of a particular problem solving;
- Development of a language of interaction between *ostis-systems* at the stage of problem solving (interpretation and refinement of the problem solving plan);
- Refinement of the architecture of the *ostis-systems* subsystems responsible for the interaction between them in the process of problem solving.

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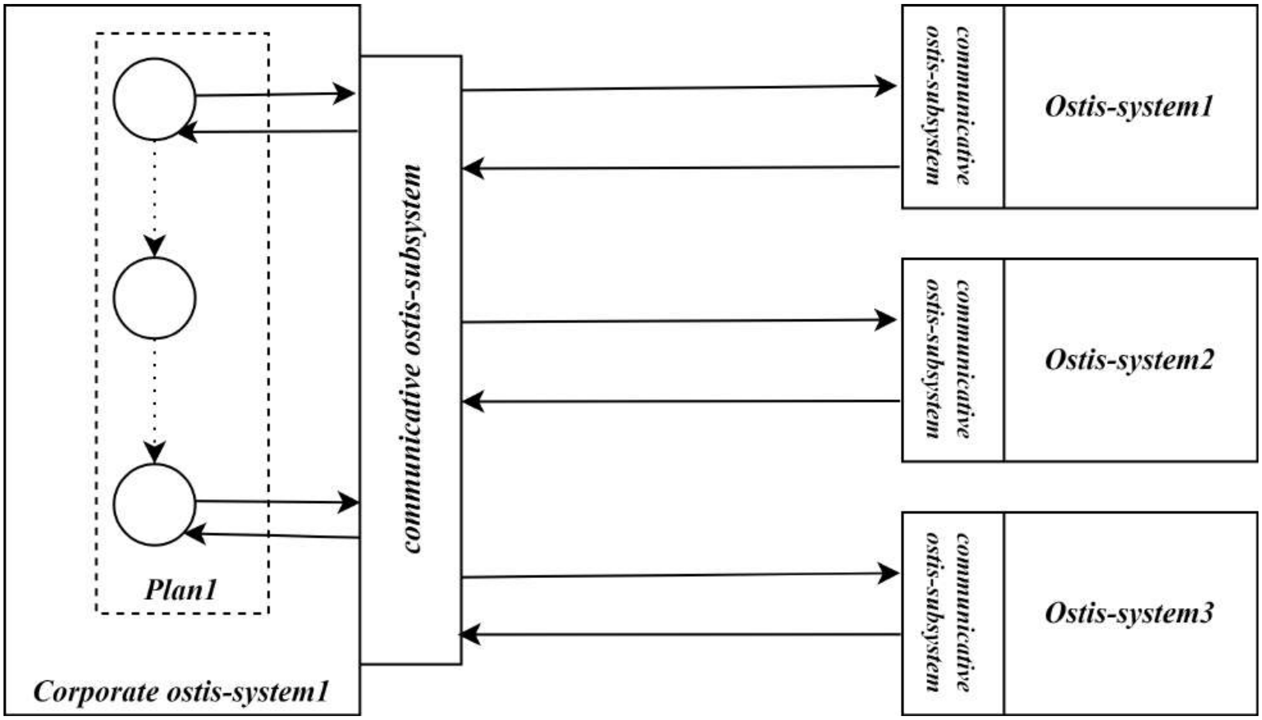

Figure 3. Example of method interpretation by the ostis-systems collective

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ПРИНЦИПЫ ДЕЦЕНТРАЛИЗОВАННОГО РЕШЕНИЯ ЗАДАЧ В РАМКАХ ЭКОСИСТЕМЫ ИНТЕЛЛЕКТУАЛЬНЫХ КОМПЬЮТЕРНЫХ СИСТЕМ НОВОГО ПОКОЛЕНИЯ

Шункевич Д.В.

В работе рассмотрены принципы децентрализованного решения задач в рамках экосистемы интеллектуальных компьютерных систем нового поколения, в частности рассмотрена архитектура такой экосистемы с точки зрения организации процесса решения задач, выделены роли систем, участвующих в процессе решения задач. Уточнены принципы формирования коллектива систем, участвующих в решении задач, этапы решения конкретной задачи полученным коллективом.

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