Mental Actions and Modelling of Reasoning in Semiotic Approach to AGI

Alexey K. Kovalev[1,2] and Aleksandr I. Panov[2,3]

[1] National Research University Higher School of Economics, Moscow, Russia
[2] Artificial Intelligence Research Institute, Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences, Moscow, Russia
3 Moscow Institute of Physics and Technology, Moscow, Russia
`panov.ai@mipt.ru`

Abstract. The article expounds the functional of a cognitive architecture Sign-Based World Model (SBWM) through the algorithm for the implementation of a particular case of reasoning. The SBWM architecture is a multigraph, called a semiotic network with special rules of activation spreading. In a semiotic network, there are four subgraphs that have specific properties and are composed of constituents of the main SBWM element – the sign. Such subgraphs are called causal networks on images, significances, personal meanings, and names. The semiotic network can be viewed as the memory of an intelligent agent. It is proposed to divide the agent's memory in the SBWM architecture into a long-term memory consisting of signs-prototype, and a working memory consisting of signs-instance. The concept of elementary mental actions is introduced as an integral part of the reasoning process. Examples of such actions are provided. The performance of the proposed reasoning algorithm is considered by a model example.

Keywords: Cognitive Agent, Sign-Based World Model, Semiotic Network, Modeling of Reasoning.

1 Introduction

Cognitive architectures as a way to model the higher mental functions of a person to this day remain the main tool for creating global models of thinking, activity and decision making. On the one hand, this approach uses research materials in neuroscience and psychology. On the other hand, it allows combining a variety of methods and techniques to achieve the goal. For example, in [1–3] the cognitive architecture of the DSO based on the Paul McLean model of the triune brain [4] and extended by using Bernard Baars' global workspace theory [5, 6] is presented. In [7] several formal models are proposed, each of which can be considered as a cognitive architecture. The proposed models are organized in a hierarchy, starting with a basic RL agent capable of observing, exploring the environment, as well as performing actions affecting this environment, and ending with PrimeAGI agent [8, 9], implemented on top of OpenCog platform, which is capable of selecting cognitive actions through the process PGMC [10].

Recently, there has been a process of "equipping" cognitive architectures with the latest advances in machine learning, which often do not simulate any mental process at all. For example, in [11], an approach to generate a description of an image (semantic image retrieval) is proposed, using deep convolutional networks for detecting objects and the cognitive architecture OpenCog for semantic analysis and query processing. Another approach to developing cognitive architectures is to use data derived from neurobiological research. Obvious examples are the HTM [12, 13] and eBICA [14] architectures.

Of particular interest is the above paper [7], which uses the graph approach. The agent's memory is represented by a large hypergraph, called Atomspace. Atoms in such a model are called both vertices and edges of the graph. Moreover, Atoms are accompanied by labels which can mean "variable", "or", "implication", etc. Then an atomic cognition, called "cognit", is an Atom or a set of Atoms. Activation of the cognit, depending on the label, can lead to such results as the creation of a new cognit, activation of one or more cognits, etc. This allows us to consider "graph programs" embedded in a common hypergraph. Additionally, the following hypothesis is applied: most of the operations performed by cognitive processes are a composition of elementary homomorphisms. This approach is close to the SBWM architecture, since the world model, as it will be described in detail below, in SBWM is a complex semiotic network formed by several semantic networks and transition functions between them. However, an important distinction of the model described below presents a process of activity propagation on the network, which allows to model unconscious processes.

2 Cognitive architecture SBWM

In a broad sense, cognitive architecture is said to specify a computational infrastructure that defines various regions/functions working as a whole to produce human-like intelligence [15]. Such a definition in practice is expressed in the fact that cognitive architectures are built on the block principle, where each block performs a specific function, and partial modeling of human intelligence is achieved by the interaction of these blocks.

However, this approach has its drawbacks. For instance, modern works on neurophysiology speak of a uniform structure of the brain and the absence of an exact localization of the processes occurring in it. Also, most architectures are limited to modeling the memory of the agent and the set of some actions on this memory and do not use developments in the field of activity theory of behavior. As another drawback, one can point out a situation where a group of agents operates acting as carriers of cognitive architecture. In this case, the agents will be identical, copies of one system, up to the data loaded in them, which does not allow to model the individual characteristics of the agents obtained in the process of functioning. There are approaches to the development of so-called lifelong learning systems, in which it supports an iterative process of additional training due to which individual characteristics can arise, however, this has not yet become widespread in the construction of cognitive architectures.

The sign-based world model (SBWM) architecture is based on principles of the cultural-historical approach of L.S. Vygotsky and activity theory of A.N. Leontiev, which allow to eliminate these shortcomings. The main element of architecture is a sign, a distinctive feature of which is the presence of a personal meaning component. This component allows to store and use the individual characteristics of the agent, obtained in the course of activities in the environment and, as a result of processing the experience is gained. The main idea of the approach is that the agent acting in the environment keeps its own view on this environment. Moreover, on the one hand, this view represents the assimilation of well-known rules and patterns of behavior (the cultural and historical heritage of the collective), and on the other hand, is the result of accumulated experience gained in the process of performing any actions in this environment. Thus, the agent's view on the environment is subjective, depends on experience, and may be different for different agents. In contrast to the classical approach to cognitive architectures, in which the resulting system is a collection of individual blocks, the SBWM uses a uniform representation of knowledge and processes: on the semantic level, in the form of signs, and on the structural, in the form of distinct networks on a set of causal matrices. Such an approach shows its expediency in the tasks of cognitive hierarchical planning [16, 17] and anomaly detection [18], etc. In this paper, SBWM architecture is used to model a particular case of reasoning with a cognitive agent. The ability to reason is one of the most important tools necessary for functioning in a partially observable and/or non-deterministic environment. With the help of reasoning, the agent is able to generate new knowledge that is not in their world model, using available knowledge, known patterns, and connections between them. Although the processes of reasoning and planning are often considered separately, in essence, they complement each other. In [17], an alternating approach is considered for planning and reasoning. The updated agent’s world model, obtained at the stage of reasoning, is used at the subsequent planning stage.

Further, we will describe the principles of SBWM in more detail, following [18, 19], originally described in [20, 21]. The main element of the system is the sign, which corresponds with the agent's view on an object, action or situation. Further, for simplicity, an object, action or situation will be called an entity. The sign consists of four components: *image* p, *significance* m, *personal meaning* a, and *name* n. The *image component* corresponds to the characteristic feature of the described entity. In the simplest case, the image refers to signals from the agent's sensors that is consistent with an entity. In general, one can say that the image of the sign is relative to the set of characteristic features of the entity which the sign corresponds with. The *significance of the sign* describes the standard application of the entity, taken from cultural and historical experience. In practice, this is expressed in a priori knowledge obtained by an agent from outside, for example, when processing a corpus of texts, and not depending on experience. The *meaning of a sign* is understood as a relation of the agent to the entity or experience of the agent's interaction with this entity. Thus meanings are formed in the interaction process of the agent with the environment.

To describe the components of the sign, we introduce a special structure – the causal matrix. A *causal matrix* is a tuple $z = \langle e_1, e_2, ..., e_t \rangle$ of length t where events e_i are represented by a binary vector (column) of length h. For each index j of the event vector e_i (row of the matrix z), we will associate a tuple, possibly empty, of causal matrices Z_j, such that $z \notin Z_j$. We divide the set of columns indices of the causal matrix z into two disjoint subsets I^c and I^e. The set I^c for the matrix z will be called the indexes of the condition columns, and the set I^e – the indexes of the effect columns of the matrix z. If there are no effect columns in the matrix, then we will say that such a matrix corresponds with the object. The presence of effect columns in the matrix means that such a matrix corresponds with an action or process. It is also worth noting that the matrix cannot consist only of effect columns. Thus, the structure of the causal matrix makes it possible to encode uniformly both static information and features of an object, as well as dynamic processes. The ability to specify causes and effects allows to represent a causal relationship.

A sign means a quadruple $s = \langle n, p, m, a \rangle$, where the name of a sign n expressed by a word in some finite alphabet, $p = Z^p$, $m = Z^m$, $a = Z^a$ are tuples of causal matrices, which are respectively called the *image, significance,* and *meaning* of the sign s. Based on this, the whole set of causal matrices Z can be divided into three disjoint subsets: images Z^p, significances Z^m, and meanings Z^a which are organized into semantic networks, which we will call causal.

A *causal network on images* will be a labeled directed graph $W_p = \langle V, E \rangle$, in which each node $v \in V$ is assigned a causal matrices tuple $Z^p(s)$ of the image of a certain sign s, an edge $e = (v_1, v_2) \in E$, if the sign s_1 is an element of the image s_2.

Causal networks on significances and meanings are defined in a similar way. The network on names is a semantic network whose vertices are the names of signs, and the edges correspond to special relationships. Thus, each component of the sign forms a causal network with a specific set of relationships. These four causal networks are connected by using transition functions $\Psi_i^j,\ i, j \in \{p, m, a, n\}$ to the semiotic network. The transition function Ψ allows to switch from one component of the sign to another, for instance. A semiotic network can be considered an agent's knowledge base of the environment, taking into account the experience. In other words, the semiotic network is a sign-based world model of an agent.

Formally, we will call the semiotic network $\Omega = \left\langle W_m, W_a, W_p, W_n, R, \Theta \right\rangle$ a sign-based world model, where W_m, W_a, W_p, W_n are causal networks of significances, meanings, images, and names, respectively, $R = \left\langle R^m, R^a, R^p, R^n \right\rangle$ is a family of relations on sign components, Θ is a family of operations on a set of signs. Operations Θ include such actions on signs as unification, image comparison, updating while learning, etc.

An important element of the SBWM is the concept of the *spread of activity* on the semantic network. By the *activation level of the sign component* $\lambda_i,\ i \in \{p, m, a\}$ will be called a real number $0 \le \lambda \le 1$ where 0 corresponds to the absence of activation, and 1 is the maximum possible activation. The *activation threshold* $\theta_i^S,\ i \in \{p, m, a\}$ sets the activation level so that when $\lambda \ge \theta^S$, i.e. activation of a component is equal to or exceeds the threshold, the sign component becomes *active* and is assigned an *activity label* α. The component of the sign, the activation level of which is not zero, but less than the threshold, i.e. $0 < \lambda < \theta^S$, considered *pre-activated*. A sign becomes active and an activity label is assigned to it if its components are active. Thus, the activation of the sign components corresponds to replenishment of the sets of active causal matrices Z_i^*, $i \in \{p, m, a\}$, and the activation of the sign corresponds to replenishment of the set of active signs S^*. Activation of components and signs occurs in the process of spreading activity on a semiotic network. It is worth noting that in the simplest case, the activity of the components can only increase with time, however, situations are possible when signs and their components are no longer active, excluded from the sets Z^* and S^*, then the *attenuation coefficient of the activity* γ_i, $i \in \{p, m, a\}$ can be entered at which the activity will decrease at each step: $\lambda^t = \lambda^{t-1} - \gamma$. The need for the attenuation coefficient of the activity may arise, for example, when the power of the sets Z^* and S^* greatly increases in the course of the agent activity in the environment.

Spreading activity on a semiotic network is subject to *globa*l and *local* rules (*ascending, predicting, descending, causal*) for spreading activity listed in Table 1.

Table 1. Local and global rules

Rule name	Description
Ascending	If at some point in time the component of the sign becomes active, then all occurrences of this component in the causal matrix of other signs become active
Predicting	If at the time moment t an event e_t is active in any component of the sign s, then the events e_{t+1} of the same component are pre-activated
Descending	If at some point in time each event in the tuple of causal matrices of some component of the sign is active, then these components of all signs included in the event are pre-activated
Causal	If an event is active at some point in time, then predictive and descending rules are consistently applied to all event-effects, with the amendment that the maximum activity applies
Global	If one of the components of the sign becomes active at some point in time, the other components become pre-activated, i.e. their activity level is changed by a certain value determined for each component

The process of spreading activity is iterative, i.e. at each i step, new active matrices and signs are added to the sets of active matrices and signs for the step $i-1$.

3 Reasoning in SBWM

We introduce some concepts that we need in the future.

A semiotic network expressing the agent's knowledge of the environment can be divided into *long-term* and *working memory*. The conditionality of such a division arises because of impossibility to localize a region in a semiotic network that would be responsible only for one of them. They differ only in the types of signs they may contain. Abstract knowledge of an agent of a certain entity, its characteristics and possible interactions with this entity, obtained as a result of the assimilation in which cultural and historical experience are integrated or the experience of the agent, will be called a *sign-prototype* $\dot{S}$.

By a *sign-instance* $\hat{S}$, we mean the specific implementation of the sign- prototype. The sign-instance does not reflect all the properties available to the sign- prototype, but only those that are important at the moment. At the same time, the connection with the prototype through the name component is retained, which allows updating the description of the sign-instance as necessary. Updating occurs due to the removal (forgetting) of the current sign-instance and the creation (recall) of the sign-instance with an extended set of properties. The fact that the sign $\hat{S}$ is an instance of the sign-prototype $\dot{S}$ will be denoted as $\hat{S} \simeq \dot{S}$.

Long-term memory M_L, or simply *memory*, will be called a part of the agent's sign-based world model, expressed with the help of signs-prototype. Although structurally long-term memory is a network, it can be described as the set of all signs-prototype.

Working memory M_W is part of the agent's sign-based world model in which information that is actively processed is stored. Such information is expressed by means of signs-instance. As well as long-term memory, working memory can be represented as a set of all signs-instances.

By *active edges*, we will mean edges, which are currently spreading activity. The *activation of the edge* corresponds to the beginning of the spread of activity along this edge.

We proceed directly to the formalization of reasoning. To begin with, we define that a binary predicate $P(x, y)$ can be regarded as a binary relation, then the predicate $P(x, y)$ is true if and only if the pair (x, y) belongs to the relation P. We will use the terms binary predicate or, simply, the predicate and relations interchangeably.

We define a *situation* as any fixed state of the environment. Then, the configuration of the environment in which the agent operates is generally specified by listing the objects in the situation and the relations between them. We denote D_f the set of all possible relationships between all objects presented in the situation. Such a set will call a *complete description of the situation*. Obviously, such a complete description of the situation is redundant, for example, if it is known that “object A to the left of object B”, using the interrelation between relationships, can be inferred that “object B to the right of object A”. We will say that D is *a description of a situation* if $D \subseteq D_f$.

We formulate the problem solved by the agent as follows: the agent is given a description of the situation D and asked a question Q in the form of predicate conjunction $P_1(x_1, y_1) \cdot P_2(x_2, y_2) \cdot \ldots \cdot P_n(x_n, y_n)$. The agent must determine whether the question is fulfilled (the predicate conjunction takes the value true) in the given description. The task of the agent is to replenish the description D to some description D', in which the question is solved or to establish the impossibility of its implementation.

At the initial moment of time, the agent has access to a set of active signs S_0^*, from which they can choose one of the signs to start the reasoning. We will assume that the signs are chosen randomly and equally likely. Having chosen a sign, the agent gets access to the incoming and outgoing edges of this sign. With the selected sign, the agent can perform one of the available elementary mental actions. An *elementary mental action* corresponds to a transition along one of the edges of a chosen sign, as a result of which a sign is activated at the other end of the edge. Depending on the types of signs connecting the edge, different elementary actions arise listed in Table 2.

Table 2. Types of elementary mental actions

Name	Label	Description
Abstraction	$inst2prot(\hat{S})$	A transition along an edge from the sign-instance to the corresponding sign-prototype
Concretization to the instance	$prot2inst(\dot{S})$	A transition along the edge from the sign-prototype to the corresponding sign-instance
Generalization	$cl2supcl(\dot{S})$	A transition along the edge from the sign-prototype of the class to the sign-prototype of the superclass
Concretization to a subclass	$cl2subcl(\dot{S})$	A transition along the edge from a sign-prototype of a class to a sign-prototype of a subclass
Transition to the action subject	$act2subj(S)$	Records that the sign S_j is a subject for the action corresponding to the sign S_i
Transition to the action object	$act2obj(S)$	Records that the sign S_j is an object for the action corresponding to the sign S_i

For signs corresponding to some objects or other agents, an elementary action "*transition to action/relation*" occurs, in which the entity described by the sign plays the role of an object $obj2act(S)$ or a subject $subj2act(S)$. Formally, actions $obj2act(S)$ and $subj2act(S)$ are written in the same way as actions $act2subj(S)$ and $act2obj(S)$.

Despite the fact that edges can connect different components of signs, information about available mental actions is recorded on a network of names. This allows to shorten the chain of actions with a sign.

Elementary mental actions can be organized in chains, such a chain will be called a *compound mental action*, or simply, a *mental action*. For example, the transition from one sign-instance to another sign-instance of the same sign-prototype is carried out as follows: abstraction followed by concretization to an instance. Thus, mental action can be understood as any stable sequence of elementary mental actions. A stable sequence means a sequence of elementary actions, which is often repeated when the agent solves problems.

If we denote s_i the active sign chosen by the agent in the i-th step, a_i is the mental action is chosen at the same step, and the application of this action a_i to the sign s_i is denoted as $\nu\left(s_i, a_i\right)$, then $\nu\left(s_i, a_i\right) = s^i$ where s^i is the sign activated in the i-th step. Then the set of active signs on the $i+1$-th step will be equal to $S_{i+1}^* = S_i^* \cup s^i$. To simplify writing, we will denote $\nu\left(s_i, a_i\right)$ as $s_i a_i$, and the set S_{i+1}^* as r_i, i.e. as a result of applying a mental action at the i-th step. Then the sequence $s_1a_1r_1s_2a_2r_2\dots s_na_nr_n$ will be called *reasoning*.

The process described above corresponds to the perceived or verbalized part of the reasoning. However, this is not the only way to replenish the set r_i. The set r_i can also be replenished by spreading the activity using the rules for spreading activities.

Let us replenish rules for spreading activity by the following list:

- on the significance network, the activity spreads both in the direction of the edge and against the direction;
- on networks of images, personal meanings and names, the activity spreads only in direction of the edge.

Let us add the rules for activating the sign components and the sign itself with the following rules:

- on the significance network, the sign component becomes active if at least one outgoing or incoming edge is active;
- on the network of images and personal meanings the sign component becomes active if all incoming arcs are active;
- if the name of the sign s is activated at the step t, then, regardless of the activation level of the components of the sign s at the step $t-1$, the sign s is activated, and all its components are activated accordingly.

We denote the set of signs that were activated at the i-th step by spreading the activity as r_i^{sa}, then the set of all active signs after the i-th step r_i' can be written as $r_i' = r_i \cup r_i^{sa}$.

It is worth noting that in order to proceed and lead to any results in the reasoning process, it is necessary that the agent's long-term memory stores information about the interrelation of the relationships presented in the situation (such as "left", "right", etc.). Such information can be obtained in several ways: 1) from a priori knowledge of an agent, for example, as a result of processing a corpus of texts, where these connections are clearly indicated; 2) obtained during the processing of the agent's experience; 3) be part of the input information along with the relationship itself, information about the situation and the question. These interrelations are also represented as causal matrices.

Also, in the working memory, a sign is created corresponding the reflection of the agent over their own reasoning, and a sign corresponding to the stage of reasoning. The agent begins the reasoning “by focusing attention” on the active sign-instance in the working memory.

The algorithm for implementing the mechanism of reasoning in the sign-based world model listed in Table 3. Currently, this algorithm is being implemented on the basis of the library “map-core” developed at FRC CSC RAS [22].

Table 3. Algorithm for implementing the mechanism of reasoning in SBWM

Algorithm	
0	**INPUT:** Description of the situation D, question Q
1	Creation of signs-instance of the objects and relations specified by D
2	Creation of signs-instance of question and answers “Yes”, “No”

```
Activation of signs in working memory
WHILE question sign is not active AND
        (there are not considered active signs OR not applied actions)
    Choose one of the sign from set of active signs
    Choose one of the possible mental actions for the sign and apply to it
    Update set of active signs due to the spread of activity
END
IF question sign is active THEN
    Activate the "Yes" sign
ELSE
    Activate the "No" sign
```

4 Model example

We briefly illustrate the above algorithm without following formalities and omitting the technical details. We will consider the problem of modeling reasoning in a modified world "World of cubes". The objects will be cubes and tables with specified identifiers. An example of the environment configuration is shown in Fig. 1.

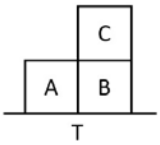

Fig. 1. Possible configuration of the "World of cubes" environment.

The environment has the following relationships: On (x, y), Left (x, y), Right (x, y), Above (x, y), Below (x, y), Near (x, y), Far (x, y). A complete description of the situation depicted in Fig. 1, as mentioned above, will be redundant.

Two obvious extreme cases where the question is contained in the description or when the description does not contain the object of the question are not considered.

The following example is of greater interest: a description $D = \{On(A,T), On(B,T), Left(A,B), On(C,B)\}$ is given and a question $Q = Right(B,A) \cdot Above(C,T)$ is asked – the answer is not presented clearly in the description, but all objects appearing in the question are contained in it.

In this case, at some stage of the reasoning, the agent will select a sign-instance of block "A", denote it $\hat{S}_A$, apply a mental action $obj2act(S)$ to it: $obj2act(\hat{S}_A) = \hat{S}_{Left1}$ and proceed to the sign-instance of the corresponding relation "Left", we denote it as $\hat{S}_{Left1}$. Next, applying to the $\hat{S}_{Left1}$ action $inst2prot(\hat{S})$ will go to the sign-prototype of the relationship "Left": $inst2prot(\hat{S}_{Left1}) = \dot{S}_{Left}$. On the significance network at the sign $\dot{S}_{Left}$ there is a causal matrix $Z_{Left \leftrightarrow Right}$, encoding that if the object X is to the left of the object Y, then the object Y to the right of the object X, i.e. if $Left(X,Y)$, then

$Right(Y, X)$. Using this interrelation of relations, the agent will replenish the description of the situation with a new fact: $D := D \cup Right(B, A)$. The relation $Above(C, T)$ is derived in a similar way using the rule: if $On(X, Y)$ and $On(Y, Z)$, then $Above(X, Z)$. Thus, the final description of the situation will be $D = \{On(A,T), On(B,T), Left(A,B), On(C,B), Right(B,A), Above(X,Z), \ldots\}$ where the dots correspond to other facts obtained in the course of the reasoning. This description contains a question and, therefore, the agent will give a "Yes" answer.

5 Conclusion

The article considers the cognitive architecture SBWM and proposes an algorithm that simulates a particular case of reasoning in it. The concept of long-term and working memory, as well as signs-prototype and signs-instance are introduced. A model example of the use of reasoning in a modified world "World of cubes" is given. However, all the capabilities of this algorithm will be fully revealed in more complex examples, which will be considered in subsequent works. The results will form the basis for the further development of reasoning algorithms in the SBWM.

Acknowledgements. The reported study was supported by RFBR, research Projects No. 18-07-01011 and No. 18-29-22027.

References

1. Ng, G. W., Tan, Y. S., Teow, L. N., Ng, K. H., Tan, K. H., Chan, R. Z.: A Cognitive Architecture for Knowledge Exploitation. In: 3rd Conference on Artificial General Intelligence AGI-2010, pp. 1–6. Atlantis Press, Lugano (2010).
2. Ng, K. H., Du Z., Ng, G. W.: DSO Cognitive Architecture: Unified Reasoning with Integrative Memory Using Global Workspace Theory. In: 10th International Conference, AGI 2017, pp. 44–57. Springer, Melbourne (2017).
3. Ng, K. H., Du Z., Ng, G. W.: DSO Cognitive Architecture: Implementation and Validation of the Global Workspace Enhancement. In: 11th International Conference, AGI 2018, pp. 151–162. Springer, Prague (2018).
4. MacLean, P.D.: The triune brain in evolution: Role in paleocerebral functions. New York, Plenum Press (1990).
5. Baars, B.J.: A Cognitive Theory of Consciousness. Cambridge University Press, Cambridge (1993)
6. Baars, B., Franklin, S., Ramsoy, T.: Global workspace dynamics: cortical "binding and propagation" enables conscious contents. Front. Psychol. 4, 200 (2013)
7. Goertzel B.: From Abstract Agents Models to Real-World AGI Architectures: Bridging the Gap. In 10th International Conference, AGI 2017, pp. 3–13. Springer, Melbourne (2017).
8. Goertzel, B., Pennachin, C., Geisweiller, N.: Engineering General Intelligence, Part 1: A Path to Advanced AGI via Embodied Learning and Cognitive Synergy. Atlantis Thinking Machines, Springer, New York (2013).

9. Goertzel, B., Pennachin, C., Geisweiller, N.: Engineering General Intelligence, Part 2: The CogPrime Architecture for Integrative, Embodied AGI. Atlantis Thinking Machines, Springer, New York (2013).
10. Goertzel, B.: Probabilistic growth and mining of combinations: a unifying metaalgorithm for practical general intelligence. In: Steunebrink, B., Wang, P., Goertzel, B. (eds.) AGI - 2016. LNCS, vol. 9782, pp. 344–353. Springer, Cham (2016). doi:10.1007/978-3-319-41649-6 35
11. Potapov A., Zhdanov I., Scherbakov O., Skorobogatko N., Latapie H., Fenoglio E.: Semantic Image Retrieval by Uniting Deep Neural Networks and Cognitive Architectures. In 11th International Conference, AGI 2018, pp. 196–206. Springer, Prague (2018).
12. George, D., Hawkins, J.: Towards a mathematical theory of cortical micro-circuits. PLoS Computational Biology, 5(10), (2009). https://doi.org/10.1371/journal.pcbi.1000532
13. George, D.: How the Brain Might Work: a Hierarchical and Temporal Model for Learning and Recognition. Stanford University. (2008).
14. Samsonovich, A. V.: Emotional biologically inspired cognitive architecture. Biologically Inspired Cognitive Architectures, 6, 109–125. (2013). https://doi.org/10.1016/j.bica.2013.07.009
15. Newell, A.: Unified Theories of Cognition. Cambridge, MA: Harvard University Press (1990).
16. Aitygulov, E., Kiselev, G., Panov, A.I.: Task and spatial planning by the cognitive agent with human-like knowledge representation. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11097 LNAI(16), 1–12. (2018). https://doi.org/10.1007/978-3-319-99582-3_1
17. Kiselev G, Kovalev A., Panov A.I.: Spatial reasoning and planning in sign-based world model, in: Artificial Intelligence / Ed. by S. Kuznetsov, G. Osipov, V. Stefanuk., pp.1-10. Springer, Moscow (2018).
18. Osipov G.S., Panov A.I.: Relationships and Operations in a Sign-Based World Model of the Actor // Scientific and Technical Information Processing. Vol. 45, № 5. pp. 317–330 (2018.)
19. Panov A.I.: Behavior Planning of Intelligent Agent with Sign World Model // Biologically Inspired Cognitive Architectures. Vol. 19. pp. 21–31 (2017).
20. Osipov, G.S., Panov, A.I., Chudova, N.V.: Behavior control as a function of consciousness. II. Synthesis of a behavior plan. J. Comput. Syst. Sci. Int. 54, 882–896 (2015)
21. Kiselev G.A., Panov A.I.: Synthesis of the Behavior Plan for Group of Robots with Sign Based World Model // Interactive Collaborative Robotics / ed. Ronzhin A., Rigoll G., Meshcheryakov R. Springer, pp. 83–94 (2017).
22. Map-core library, https://github.com/cog-isa/map-planner/tree/map-core