Cognitive architecture based on the functional systems theory

A.V. Demin[a], E.E. Vityaev[b,c]

a) Institute of Informatics Systems, SB RAS, Novosibirsk 630090, Russia
b) Sobolev Institute of Mathematics, Novosibirsk 630090, Russia
c) Novosibirsk State University, Novosibirsk 630090, Russia

Abstract. In this paper the cognitive architecture based on the Functional Systems Theory (TFS) by P.K.Anokhin is presented. This architecture based on the main notions of this theory: goal, result, anticipation of the result. This theory is described on physiological and informational level. The logical structure of this theory was analyzed and used for the control system of the purposeful behavior development. This control system contains the hierarchy of functional systems that organize the purposeful behavior. The control system was used for the agents modeling that are solving the foraging task. The computer experiments are presented that compare this control system with the control systems based on the reinforcement learning.

1. Introduction

In section 3, we analyze the notion of goal in cognitive sciences and physiology. A goal cannot be attained without having a criterion of its attainment; otherwise we can always assume that the goal has been already attained. The definition of goal is paradoxical (produces a goal paradox), since it does not imply knowledge of how, by what means, and when can it be attained. A definition of the goal allows us to define the result, attained through the goal, as that which meets some criterion. We drink water to quench thirst, eat to ease hunger, etc. Actions are always goal-directed. If an action does not have a goal, it is unclear when and how it should be terminated. The goal of an action is to change the current state and/or some external stimulus. Goal-directed activity consists in organizing the activities that will satisfy some of the organism's needs.

The theory of functional systems (TFS) developed by P.K. Anokhin and many other distinguished scientists of his school is, at the moment, one of the few known theories in which the concepts of goal, purpose, result, and goal-directed activity are principal ones and which exposes the physiological mechanisms that implement these concepts. In TFS, it is studied in detail how the brain constantly solves the goal paradox during goal-directed activity, by defining by what means, when, and how goals can be attained. For the paradox solution we need an experience, based on the «principle of anticipatory reflection of reality» by P.K. Anokhin [5]. Therefore, TFS is a physiological theory of the brain in which goal-directness, based on the anticipatory reflection, is a principle of brain activity. Goals are desirable future. Functional systems are organizing the goal-directness behavior for attaining these goals. Hereupon, functional systems are anticipatory systems in accordance with the definition of Robert Rosen: «an anticipatory system is one in which present change of state depends upon future circumstances, rather than merely on the present or past» [6].

2. Goal and Goal-directed Activity

Desire is not passive. It makes no sense to desire if there is no possibility to get closer to satisfying the desire by some actions or activity. There are some organisms – corals and plants – that have very limited possibilities to display their own activity, and thus to somehow actively approach the moment of satisfying desires. Do they have awareness of desires or needs, or they are just processing what occurs to them naturally?

Desire is active, but meaningless without purposefulness – it causes the organism to be active and display some behavior in order to satisfy it. Thus the concept of goal emerges. Activity and actions are always goal-directed. If there is no goal for an action, it is unclear when (and by what means) it should be terminated. The goal cannot be attained without having a criterion of its attainment; otherwise we can always assume that it has already been attained.

Let us define the *goal* as such an activity/behavior that is aimed at satisfying certain criteria. Setting a goal is meaningless without having a criterion of its attainment, since we have to make sure that this criterion is not already fulfilled. Hence, it only makes sense to set as a goal something that is not already attained and that we wish to attain. Such a definition of goal allows us to define the *result of attaining the goal* as that, what we obtain by meeting the criterion and attaining the goal (fulfilling the desire). Between the concepts of goal and result, the following relationship holds: the result is obtained when the goal is attained and the criterion of its availability is "triggered". But when the goal is being set, we have the goal but not the result.

The definition of goal is paradoxical since the activity/behavior of satisfying some criteria does not essentially presuppose knowledge of how to attain the goal; you can set a goal without defining either how it can be attained, or by what means, or when. This paradoxicality of the goal concept we call the goal paradox. For the paradox solution we need an experience, based on the «principle of anticipatory reflection of reality».

As will be seen latter on, in the framework of the theory of functional systems, brain activity during goal-directed behavior is seen as being constantly occupied by solving the goal paradox, and determining by what means, when, and how to attain goals.

Let us proceed to outline the theory of functional systems, in which the concepts of goal, result, and goal-directed activity are principal ones, and which analyzes the physiological mechanisms of these concepts.

3. The Theory of Functional Systems of Brain Function

The theory of functional systems (TFS) is a theory of systems, whose function is to attain goals (satisfy needs) by solving the goal paradox. Therefore, we will outline the theory of functional systems as a theory of solving goal paradoxes, and describe how the brain determines by what means, when, and how goals can be attained.

Such definitions of the goal and result are the fundamental achievements of TFS, which distinguish it from other known theories. “#[1]Perhaps one of the most dramatic moments in the history of research on the brain as an integrative formation involves the focus of attention on the action itself, but not on action results ... we can consider that the result of a “grasp reflex” is not the action of grasping itself, but rather the totality of afferent impulses corresponding to features of the “grasped” object (the action result)#” [8-10].

“In our opinion, the most important milestone (in the history of the development of the concept of functional systems – E.V.) is the formulation of the “action result” concept (in 1966). P.K. Anokhin now considers action results as an independent physiological category” [10]. Understood this way, the action result itself reflects if the criterion of attaining the goal (of grabbing an object) has been satisfied, as signaled in the “totality of afferent impulses corresponding to features of the “grasped” object” [10]. Thus, the notion of action results establishes in physiological terms the criterion for assessing goal attainment. The dramatic moment in brain research on which P.K. Anokhin writes is still pertinent, as no other theory explores the mechanisms of attaining results in the given sense.

Let us briefly outline the theory of functional systems. First of all, let us consider what physiological mechanisms are used by the organism to set goals. “#By a *functional system* we refer to a system of neural components with their corresponding peripheral working organs, combined on the grounds of performing some well delineated and specific organismic functions. Such delineated functions include, for instance, locomotion, breathing, swallowing, swimming, etc#”. And further: “#The composition of a functional system cannot be determined by any anatomical principle. On the contrary, a variety of “anatomical systems” can participate and can be banded together on the basis of simultaneous excitation while performing a particular organismic function#” [8-10]. Thus, the units of an organism’s activity are not separate organs, but rather different functions of the organism. Performing these functions is exactly the task of the organism’s activity.

[1] Among quotations from [8] we will distinguish those of P.K. Anokhin with the # symbol.

As we know, the goal (task) makes sense only if there is a criterion of attaining it. Organism's functions should also lead to attaining particular goals, which are registered by corresponding results. "The main postulate of the theory of functional systems consists in a provision stating that the *result* that is useful for the organism and adaptive for the whole system acts as the leading system-defining factor for organizing functional systems at any level of the organism. It is namely the result which, due to constant reverse afferentation of its state, produces a kind of "mobilization" of the central and executive components to form a functional system" [10]. Thus, the units of organism's activity – functional systems – are dynamic assemblies of various organs, combined in order to attain particular useful results.

As achieving results consists in satisfying some criteria, this achievement should be registered in some way. In the physiological sense, what constitutes a criterion for registering the attainment of a result? According to P.K. Anokhin, this is physiologically realized by a "special receptor apparatus". "Every *need* is immediately perceived by a special *receptor apparatus,* even if there is a slight deviation of a vital function from the optimal level of metabolism" [10]. "The existence of these receptors, which "stand on guard" for the final adaptive result, is the starting point for the mechanism of self-regulation in each functional system. Smaller deviations from the optimal level of metabolism lead to a lesser excitation of receptors and, consequently, to a lower level of signaling in the nervous system" [10].

Thus, the result consists in attaining the optimal level of some physiological constant, as registered by a special receptor apparatus. The signaling of this receptor apparatus about obtaining a result (i.e., on the lack of deviation from the optimal level of metabolism) and attaining the goal is called *reverse afferentation*.

"...The signaling about a need has a dual function. On the one hand, it plays the role of a trigger, stimulating a special self-regulation mechanism, and on the other hand, it constantly informs these same centers about the results of actions performed by a functional system. This was called the *reverse afferentation*, since this signaling contains information on the final result – and on whether there is a deviation from the optimal level of metabolism, or whether this level has been restored…" [10].

Now we can explain, within the framework of TFS, how goals are being physiologically set by the organism. An organism need constitutes a goal in TFS. "The dual function of needs" means, firstly, that a goal is set in the organism to restore disturbed metabolism and, secondly, that an energy supply is provided for goal attainment. The criterion of goal attainment consists in obtaining reverse afferentation about the fact that a normal level of some physiological constant is restored. If, on the other hand, the normal level is disturbed and reverse afferentation indicates the criterion is not satisfied at the moment, then a need emerges, which sets the goal for the organism to satisfy the corresponding need. In this case, the goal (and its attainment criterion): firstly, signals by means of reverse afferentation that there is a lack (that some constant is not on the normal level), which essentially means there is a need; secondly, it sets a goal to wait for a signal, indicating that the normal levels of variables have been restored and that the results have been attained; and thirdly, it provides energy and actually forces the organism to attain the goal. Thus, the physiological mechanism of goal-setting in fact consists of the emergence of a need. Consequently, it is precisely the need that constitutes the goal that is being set to the organism. In TFS, the concepts of need and result are related to each other. In our definition, the notions of need and result are connected by the notion of the goal, where the result consists simply of registering that the goal has been attained and the need has been satisfied.

The interaction of different goals and results is organized in several ways according to TFS: by the "principle of the dominant", by the "hierarchy of results" and by "result models".

Let us consider the "principle of the dominant". This principle states that two goals that satisfied by some behavioral acts cannot be attained simultaneously. "Since the organism's metabolism is always multifaceted, the organism's total metabolic need is often multi-parametric, reflecting various aspects of metabolism ... But there is always the leading parameter of the total metabolic need – i.e. the dominant need which is the most important one for the survival of the individual, its genus or species. It stimulates the dominant functional system and builds a behavioral act aimed at satisfying it. When the main need is satisfied, than another need, important for the survival of the species or its genus, becomes dominant" [10].

Thus, the behavioral goals of the organism – i.e. the dominant needs – are always linearly ordered in time. Let us consider now how functional systems interact with each other at some moment of time. With respect to the dominant functional system, the remaining systems are arranged in a hierarchy by the principle of the "*hierarchy of results*". "In relation to each dominant functional system, all other functional systems are arranged in a certain hierarchical order, beginning with the molecular level and leading up to the organismic, social and public levels. The hierarchy of functional systems ... includes primarily hierarchical interaction of their action results – i.e., results of activity of one functional system are included as components in the result of another one" [10]. "Thus, the dominant functional system of a hungry rabbit is the one which involves searching for food. At that moment, all other functional systems that regulate, for example, blood pressure, respiration and excretion, are assigned to provide the best support for the dominant functional system" [10].

Let us consider in more detail how the hierarchy of results is formed. If searching for food forms the dominant functional system in a hungry rabbit, then during its activity oxygen consumption increases, the amount of nutrients in the blood decreases, the amount of harmful substances produced during metabolism and requiring removal from the organism increases, etc. All this leads to a shift from the normal level of a number of organism's physiological constants, and this fact is registered by the receptors of a number of other functional systems. This automatically "triggers" functional systems, whose goal is to ensure the normal levels of these physiological constants, and the results of these systems consist in reaching the corresponding normal level. Thus, the dominant need activates a hierarchy of functional systems whose goals are mutually coordinated (and subordinated) to ensure the normal level of physiological constants involved in satisfying the dominant need.

4. Central mechanisms of functional systems

"According to P.K. Anokhin, the central mechanisms of functional systems that support goal-directed behavioral acts have a similar structure" [10]. Let us examine in detail the architecture of goal-directed activity, as well as the physiological mechanisms of solving the goal paradox.

4.1 Afferent synthesis

The afferent synthesis, which includes the synthesis of motivational excitation, memory, contextual and triggering afferentation, constitutes the initial stage of a behavioral act of any complexity.

4.1.1 Motivational Excitation

As we know, the goal is set by an emerging need. But in case of goal-directed behavior, it transforms into a motivational excitation. "The leading stimulus… which determines goal-directed activity even for animals is the *motivational excitation*, which is formed on the basis of the leading internal need" [10]. "The dominant need is always perceived by a complex of specific receptors which are located both in the periphery and directly in the central nervous system. With their participation, a crucial moment arises in forming goal-directed behavior – the process of transforming internal needs into corresponding stimuli in the brain. Thus the dominant motivation emerges. The latter is always accompanied by a certain emotional sensation. In other words, during the process of forming a motivational stimulus, the material metabolic need is transformed into an excitation process of brain structures" [10]. But a motivational stimulus does not consist in the excitation of receptors which stand 'on guard' for some physiological constant – it is rather an excitation of 'central brain structures' initiated by the arising need. It is the motivational stimulus that constitutes the goal set in the organism in case of goal-directed behavior. As in the case of needs, the motivational stimulus not only sets a goal but also energetically supports its attainment. "Negative emotions accompanying motivation have essential biological significance. They mobilize the animal's effort to satisfy the emerging need. Negative emotional sensations that accompany the motivational stimulus facilitate an animal's search for a supporting agent" [10].

The attainment of the result and the activity of the reinforcing stimulus are subjectively perceived in goal-directed activity as positive emotions (elimination of negative emotions). As goal-directed behavior must be learned, it's necessary to memorize the sequences of stimuli which have led to the attainment of a result. Therefore, positive emotions (elimination of negative ones) also have a reinforcing (authorizing) role, which retains in memory the entire sequence of actions that led to goal attainment.

4.1.2 Memory

Memory constitutes the second component of afferent synthesis. The whole sequence of stimuli that has led to goal attainment is recorded during reinforcement, starting with the motivational stimulus. "...Extracting past experience from memory follows the same neurochemical path on which it was recorded at the time of acquiring this experience" [10]. Extraction of past experience from the memory is based on the "principle of anticipatory reflection of reality" [5]. Thus, the emergence of a motivational stimulus is enough to "extract from memory" all previous sequences of actions which have led to attaining the respective result and reinforcement. Moreover, motivational stimuli possess chemical specificity, allowing them to "extract from memory" all ways of attaining a particular goal set by a given motivational stimulus. "Each motivation is built by a chemical metabolism specific to it, and ascending activating stimuli of the corresponding subcortical centers to the cerebral cortex. This leads to the fact that animals, with the help of motivational stimuli, perform active selection of only specific environmental stimuli to satisfy their dominant needs" [10].

4.1.3 Situational Afferentation

While recording a memory trace, the situation in which the result is attained is also being recorded. This situation is registered, along with the motivation, as a necessary precondition for attaining the result. Thus, the motivational stimulus in this situation "extracts from memory" only those ways of attaining the goal that are possible in the given situation. Therefore, while interacting with experience extracted from memory, situational afferentation determines how and what can be done in the given situation to attain the goal.

4.1.4 Triggering Afferentation

The fourth component of afferent synthesis is the triggering afferentation. It is essentially the same as the situational afferentation, with the difference that it involves the time and place of attaining the result, rather than the stimuli of a situation. "...Special stimuli reveal the so-called pre-triggering motivation, which is formed on the basis of interaction between motivational and situational excitation and memory mechanisms. These triggering stimuli, therefore, attribute certain time and place to the goal-directed activity" [10]. Thus the triggering afferentation answers the questions when and where can the result be attained.

Consequently, the goal paradox is solved for the most part during afferent synthesis, as it's here that the what, how, and when of goal attainment are determined. "Thus at the stage of afferent synthesis, a number of points are determined: what to do (based on the comparison of internal and external stimuli), how to do it (based on memory), and when to do it (based on the effect of triggering stimuli)" [10].

Therefore, taking experience and environment into account, the motivational excitation as a goal automatically solves the goal paradox and determines by what means, how, and when can the goal be attained. By "extracting" from memory all relevant experience, the motivational excitation – when regarded as a goal – transforms into a *particular goal*, which determines the ways of attaining the result. This particular goal is called the "*higher motivation*" in TFS.

4.2 Decision-making

At the stage of afferent synthesis, motivational excitation can extract from memory several ways of attaining the goal. «Anticipation is not prediction, but rather driven by the evaluation of possibilities» [11] – different ways for the goal attainment. At the stage of decision making, only one of them is selected – thus forming the *"program of actions"*. "At the stage of decision making, in accordance with the initial need, only one particular line of behavior is selected" [10].

Decision making is a delicate process that should take into account [12-13]:

– The likelihood of attaining the goal in a given situation;

– The total energy consumption of a particular method of attaining the goal, taking into account the informational certainty of whether the goal can be really attained;

– The amount of experience extracted from memory, including dominant (genetically defined) forms of behavior in case current experience is insufficient for decision making.

4.3 Acceptor of Action Results

Suppose a program of actions is chosen. At that point, there is no guarantee yet that the final result will necessarily be attained, nor even intermediate ones. The goal can only be attained if each of the intermediate results of the current program of actions will be attained. Motivational excitation "extracts from memory" the entire sequence and the hierarchy of results that should be attained during the program of actions. This sequence and hierarchy of results are defined in TFS as the *acceptor of action results*. "It is exactly the dominant motivation that "extracts" into the acceptor of action results all available experience to determine the final result. This will satisfy the underlying need by creating a particular *model* or program of behavior. From this standpoint, the acceptor of action results is a transformation of the organism's dominant need into anticipatory neural excitation, into a complex "receptor" of corresponding reinforcement" [10]. "...It should be noted that in the acceptor of action results, not only the continuum of behavioral results is programmed, but also the whole mosaic of actions aimed at attaining every result" [10].

Therefore, while being transformed into a particular goal, the motivational excitation extracts from the memory a *particular criteria* of this goal attainment. This consists of the whole sequence and the hierarchy of criteria of results which must be attained in the process of attaining the goal and performing the program of actions, i.e. the acceptor of action results. Thus, the acceptor of action results anticipates the particular criteria of attaining a particular goal and attainment of a *particular result*. "The formation of a "goal" in the central architecture of a behavioral act involves constructing the next stage in the systemic organization of a behavioral act. This relies on a mechanism for predicting the future result (of the entire sequence and hierarchy of results) that satisfies the dominant need, i.e., on the mechanism of the acceptor of action results" [10]. "Thus, forming prognosis of future results in functional systems – i.e., in the acceptor of action results – constitutes the physiological mechanism of setting a goal" [10], setting a "particular goal", in terms employed here.

The definitions of a "goal" by P.K. Anokhin and our definition of a "particular goal" differ: firstly, motivational excitation according to P.K. Anokhin is not involved in the process of determining a goal; secondly, by a goal P.K. Anokhin understands not only the result and the "entire mosaic of actions", but also its prognosis. Prognosis is understood in two senses: firstly, as the expectation of attaining the result (corresponding to reverse afferentation), based on the "principle of anticipatory reflection of reality" [5] and, secondly, as a prediction of attaining the final result. In our definition of the acceptor of action results as a particular goal, the second meaning of prognosis as a prediction is not necessary.

Transforming motivational excitation as a goal into a particular goal, the criteria of the result attaining into acceptor of action results, and the program of actions into the model of a particular result also transforms the original paradoxical goal – for which it is not determined by what means, how, and when it can be attained – into a non-paradoxical particular goal, for which the final goal (and result) is divided into sub-goals (and sub-results), so that for each sub-goal it is already known by what means, how, and when it can be attained.

4.4 Neurophysiologic mechanisms of the acceptor of action results.

On neurophysiological level formation of the acceptor of action results is executed by special collateral branches of performed actions, which enter for the «input» of the brain, by converging with the afferentation of input stimuli: «We are referring to the collateral branches of the pyramidal tract, which allocate to a large number of mediate neurons "copies" of those efferent parcels that exit on the pyramidal tract... Thus, the

moment of decision-making and beginning of out coming of working efferent excitation starting to exit the brain is accompanied by a formation of an extensive complex excitations consisting of afferent criteria of future results and of collateral "copies" of efferent excitations that pass through the pyramidal tract to the periphery of working bodies» [14 c. 97].

Due to the collateral branches the acceptor of action results is formed by elaborating the conditioned (causal) relations between actions (efferent excitation) and the subsequent perception of the results of these

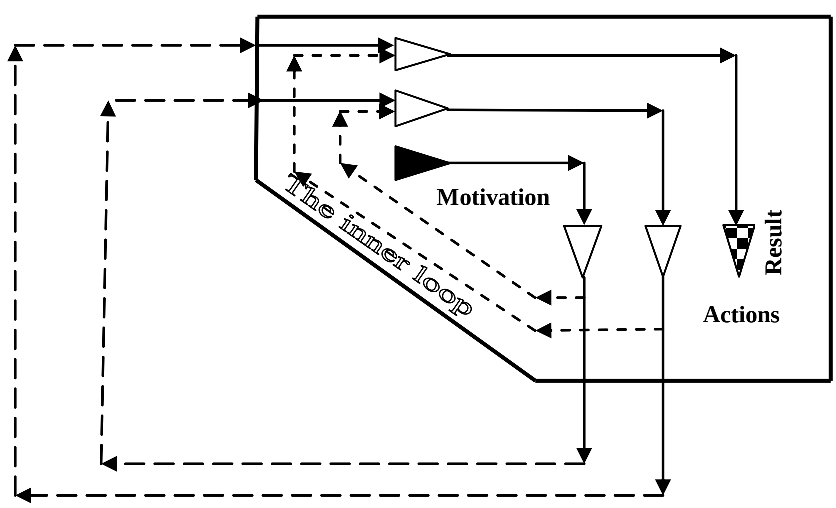

Fig. 1. Acceptor of action results formation.

actions represented by their afferent criteria fig. 1. While carrying out an action, we immediately sends using collaterals conditional signal that we will now receive afferentation on the results of these actions. This leads to the development of conditioned connections between actions and theirs results. These conditional connections executed by the brain on the inner contour fig. 1 that allow us to predict the results of actions taking place in the external world, even before the results themselves are obtained. When various sequences of actions to attain the given goal are activated by the motivational excitation, the whole sequence and hierarchy of results, which will be achieved in the process of attaining the goal, is being predicted on the «inner contour». And when a decision is made for the concrete plan of actions, the attainment of all intermediate results, which constitute the acceptor of action results, is simultaneously anticipated on the «inner contour».

4.5 Efferent Mechanisms of Functional Systems

How is the action program executed? "The stage where the acceptor of action results is formed is dynamically and gradually replaced by the formation of goal-directed action itself. However, this is preceded by a stage where the action, while not being externally realized yet, has already been formed as a central process ... It seems that the name "stage of efferent synthesis" reflects the semantic meaning of this stage most successfully. The dynamic association of somatic and vegetative functions into a holistic behavioral act is performed at this stage with the help of central nervous excitations" [10].

Since the real situation always differs somewhat from situations that have been extracted from memory and accounted in acceptor of action results, some "disagreements" will inevitably occur between the expected results and the actual reverse afferentation about the results of performed actions. "Action results are evaluated with the help of *orienting/search activity* [15] and emotional sensations. Orienting/search reaction occurs and is strengthen in all cases when the result of a performed action unexpectedly does not agree with the properties generated based on efferent synthesis of the acceptor of action results, i.e., when "disagreements" occur in the behavioral activities. When such a reaction happens, the efferent synthesis is immediately rearranged, a new decision is made, and a new program of actions created" [10].

Note that when a disagreement occurs between the "reverse afferentation" and the afferentation expected by the acceptor of action results, a rearrangement of efferent synthesis is carried out and a new decision is made – which means setting a new particular goal and acceptor of action results, although both the motivational excitation and the corresponding final result remain the same.

"The goal-directed behavioral act is completed therefore by the last authorizing stage. At this stage, while influence of the stimuli satisfying the leading need – the reinforcement in the conventional sense – the parameters of the attained result ... cause, through excitation of the corresponding receptors, the flow of reverse afferentation, which has all the previously programmed properties of supporting stimulus in the acceptor of action results” [10].

During reinforcement, a “trace” is recorded of all stimuli which have led to the attainment of the result, and thus the realized action program is registered in memory.

5. Formal model of TFS

Let us define a formal model that also takes into account «sensory corrections» as described in N.A. Bernstein’s works: «...as soon as the body under the influence of external and reactive forces as well as some additional internal muscle forces will deviate in its resulting movement from those intended by the central nervous system, the latter will get a comprehensive signalization about this deviation, which will be sufficient for adding to the effector process adequate corrections. The whole outlined principle of coordinating thus deserves the name of the principle of sensory corrections» [14]. From the principle of sensory corrections it follows that it is impossible to plan a sequence of actions in advance, we can only plan a sequence of attained results, while the choice of a particular action should be made in real time on the basis of sensory corrections, based on the flow of backward afferentation.

Now let us assume that our model constitutes the control system of some animat that operates in discrete time $t = 0, 1, ...$ as it was done in [27].

Suppose the animat has a set of sensors $S_1, ..., S_n$, which characterize both the state of the animat itself and of external environment. Each sensor S_i has a set of possible indications VS_i. The animat also has a set of available actions in the environment $A = \{a_1, ..., a_m\}$. Any action that animat performs at a moment t_i may result at a moment $t_i + 1$ in some changes in the environment, and consequently, in his sensors indications.

Since the animat «perceives» the world only through its sensors, then from its point of view the system's state at any given point in time can be written as a vector of all sensors indications $V(t) = (v_1, ..., v_n)$, where $v_i \in VS_i$ is the indications of the the *i*-th sensor at the moment *t*, and the states with same sensor indications are indistinguishable for it. The set of all possible states of the system is denoted by $S = (VS_1 \times VS_2 \times ... \times VS_n)$.

Now, from the general model «animat – environment» we will move to a more specific discrete model. On a set of states of the system $S = (VS_1 \cup VS_2 \cup ... \cup VS_n)$ we define a set of predicates $PS = \{P_1, ..., P_k\}$, each of which is calculated on the basis of sensors indications. Each state of the system can thus be written as a vector $s = (p_1, ..., p_k),\ p_i \in \{0,1\}$ of predicates values from PS, where 1 means validity of a predicate, and 0 – its falsity. The state may be described by a subset of predicates $s = (p_{i_1}^e, ..., p_{i_e}^e),\ p_{i_1}^e, ..., p_{i_e}^e \subseteq p_1, ..., p_k$.

The animat's task is to attain a certain goal. Let us define a goal *Goal* as a state of the system $s_{Goal} = (p_{i_1}^{goal}, ..., p_{i_{goal}}^{goal})$, which it is required to attain. A notation $(p_{i_1}^{goal}, ..., p_{i_{goal}}^{goal})$ means that predicates $p_{i_1}^{goal}, ..., p_{i_{goal}}^{goal}$ should be true when the goal is attained.

Let us clarify concepts of event and history. By an event $e = (s_0, s_e, a)$ we will understand a singular fact of transferring the system from the state $s_0 = (p_1^0, ..., p_k^0)$ into a state $s_e = (p_1^e, ..., p_k^e)$ as a result of an action a, and by a history of events – a set of pairs (e_t, t), where $e_t = (s_t, s_{t+1}, a)$ is an event and *t* is a moment in time when this event has occurred.

Let us define a rule *R* that predicting within the inner contour of the brain (fig. 1) a change of a state(s) after the execution of an action *a*, as a transformation $R = (s_0 \xrightarrow[p]{a} s_e)$, where:

s_0 – is the initial state of the system $(p_{i_1}^0, ..., p_{i_0}^0)$;

s_e – is the final state of the system $(p_{i_1}^e, ..., p_{i_e}^e)$;

a – is an action that transforms the initial state into the final one;

p – is the probability with which the action transforms the initial state into the final one.

The probability of a rule R is calculated as follows: if n is the number of cases in which the initial state was s_0 and an action a was executed, and m is the number of those n cases, in which the action a transform the state s_0 into the state s_e, then $p = m/n$. Probability of a rule R (which predicts transition from a state s_0 to a state s_e after the execution of an action a within the inner loop of the brain, fig. 1) and probabilities from the set P (which predict transition from the state s_0 to the state s_e as a result of action a and is calculated in accordance with the objective factors of execution of actions in the external world) are different values. One can say that the task of education is to maximize proximity between «subjective» probabilities of rules R measured by animat and objective probabilities characterizing the interaction of the animat with the external environment.

These rules may be discovered by neurons, which reveal conditioned connections within the inner loop of the brain, according to the semantic probabilistic inference and formal model of neuron [23].

Let us first define a functional system $FSC = (s_{Goal}, R_1, ..., R_n, p_{FSC})$ that realizes sensory corrections. Functional system FSC performs transformations $s_0 \xrightarrow[p_{FSC}]{R_1,...,R_n} s_{Goal}$, where $s_{Goal} = (p_{i_1}^{goal}, ..., p_{i_{goal}}^{goal})$ - is the target state of the functional system, $R_1, ..., R_n$ - are rules of the form $s_0 \xrightarrow[p]{a} s_{Goal}$, using which from various initial states s_0 and some action a the system can get to the target state s_{Goal} (fig. 2). The goal s_{Goal} of the

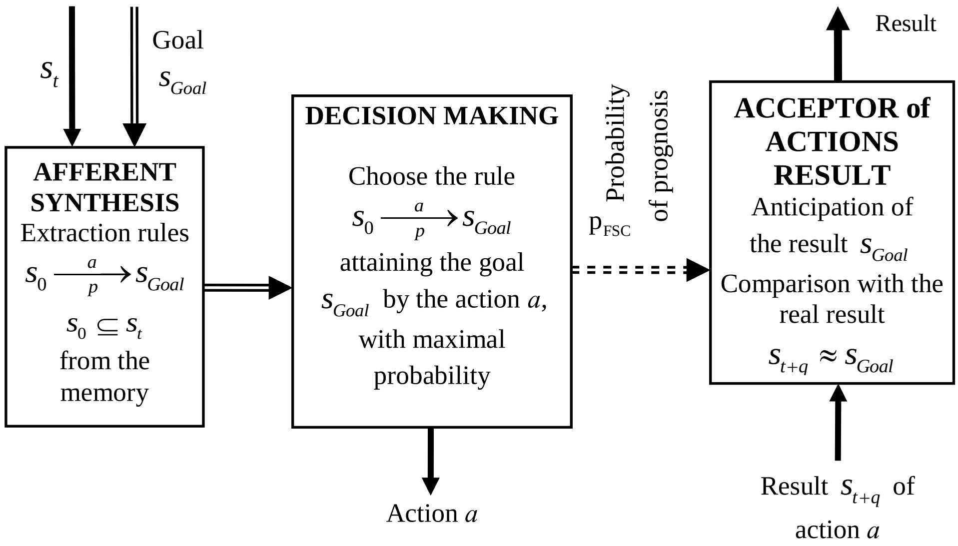

Fig. 2. functional system that realize sensory corrections.

functional system is assigned by the corresponding to s_{Goal} motivational excitation.

In accordance with the principle of sensory corrections, it is fundamentally impossible to know in advance the exact result of the previous action. Therefore, a functional system FSC can choose the most probable rule $s_0 \xrightarrow[p]{a} s_{Goal}$, which leads to attaining the goal, only after receiving afferentation $s_t = (p_1^t, ..., p_k^t)$ that constitutes the completion of the previous step. Then selected rule with the initial state $s_0 = (p_{i_1}^0, ..., p_{i_0}^0)$ can correspond to the received afferentation $\{p_{i_1}^0, ..., p_{i_0}^0\} \subset \{p_1^t, ..., p_k^t\}$ (we denote it as $s_0 \subseteq s_t$ on fig. 2).

When a functional system of a higher level that satisfies some need makes a decision and search various sequences/hierarchies of functional systems FSC to attain the goal, we also in principle cannot know which states s_t will arise as a result of the actual execution of actions of a given sequence/hierarchy. It is also impossible to know which rules will be chosen to achieve the goals for each functional system FSC in this sequence/hierarchy. Nevertheless, the prognosis of probability of attaining the goal is necessary for decision-making. An estimate of the probability of attaining a goal by a functional system can be calculated based on the statistics of attaining goals as follows: if n is the number of cases in which a request to attain a goal s_{Goal} was received and m is the number of cases in which the selected rules and sequences/hierarchies of actions led to attaining the goal s_{Goal}, then $p_{FSC} = m/n$.

When at a moment t a request comes to the functional system FSC to attain the goal s_{Goal} in the current state $s_t = (p_1^t, ..., p_k^t)$, it (fig. 2):

1. extracts from the memory all rules $s_0 \xrightarrow[p]{a} s_{Goal}$ from the set $R_1, ..., R_n$, which:
   a) is applicable in the current situation $s_0 \subseteq s_t$ (afferent synthesis);
   b) can attain the goal s_{Goal} with maximum probability p (decision making);
2. predict that the goal will be attained with probability p;
3. anticipates the attainment of the goal s_{Goal} in the acceptor of action results after the execution of an action a;
4. compares the state $s_{t+q} = (p_1^{t+q}, ..., p_k^{t+q})$ reached at a moment $t+q$ as a result of an action a with the goal $s_{Goal} \approx s_{t+q}$ using the acceptor of action results. If $s_{Goal} \subset s_{t+q}$ then the goal is attained and the rule $s_0 \xrightarrow[p]{a} s_{Goal}$ is rewarded (its statistics increase);
5. if for the current state s_t there is no suitable rules, then functional system FSC in response to the request returns that goal cannot be attained;
6. if the goal is not attained and this fact is registered by the acceptor of action results, then orienting-investigative reaction occurs, which selects another functional system to attain the goal s_{Goal} (activated rule is penalized, its statistics decrease);

In general case functional systems are sequences and the hierarchies of the functional systems FSC.

A functional system FS that combines a sequence of functional systems of the form FSC is a sequence $FS = (s_{Goal}, \langle FSC_1, ..., FSC_n \rangle, p_{FS})$ which executes a transformation

$$FS = s_0 \xrightarrow[\to s_1 \to s_2 \to ... \to s_{goal} \quad p_{FS} = p_{FSC_1} \bullet ... \bullet p_{FSC_n}]{FSC_1, ..., FSC_n} s_{goal}, \text{ where}$$

$$FSC_1 = (s_0 \xrightarrow[p_{FSC_1}]{R_1^1, ..., R_{v_1}^1} s_1), \; FSC_2 = (s_1 \xrightarrow[p_{FSC_2}]{R_1^2, ..., R_{v_2}^2} s_2) \; ... \; FSC_n = (s_{n-1} \xrightarrow[p_{FSC_n}]{R_1^n, ..., R_{v_n}^n} s_{goal})$$

are functional systems of the type FSC. The goal of the functional system FS is to successively attain goals $s_1 \to s_2 \to ... \to s_{goal}$ using functional systems $FSC_1, ..., FSC_n$ with a resulting probability $p_{FS} = p_{FS\tilde{N}_1} \bullet ... \bullet p_{FS\tilde{N}_n}$. Such functional systems may be automatically generated during the learning as described below. Such functional system corresponds to fulfillment of some sequence of actions.

Functional systems FS that attain some goal stated by motivation include different sequences and hierarchy of functional systems FSC. These sequences and hierarchy may be described by sequences of functional systems FS including both functional systems FS, FSC recursively. Then functional system $FS = (s_{Goal}, \{\langle FS_1^1, ..., FS_n^1 \rangle\}, p_{FS})$ is a set of sequences/hierarchies of functional systems that realize transformations

$$FS = s_0 \left\{ \xrightarrow[\to s_1 \to s_2 \to ... \to s_{goal} \quad p_{FS} = p_{FS_1^1} \bullet ... \bullet p_{FS_n^1}]{FS_1^1, ..., FS_n^1} \right\} s_{goal},$$

where FS_i^1 is either FS or FSC. For example, if $FS_i^1, FS_j^1 \in \langle FS_1^1, ..., FS_n^1 \rangle, i < j$ realizes transformations

$$FS_i^1 = s_{i-1} \left\{ \xrightarrow[\to s_1^i \to s_2^i \to ... \to s_{goal}^i \quad p_{FS_i^1}]{FS(i)_1^2, ..., FS(i)_{n_i}^2} \right\} s_i, \; FS_j^1 = s_{j-1} \left\{ \xrightarrow[\to s_1^j \to s_2^j \to ... \to s_{goal}^j \quad p_{FS_j^1}]{FS(j)_1^2, ..., FS(j)_{n_j}^2} \right\} s_j,$$

then functional systems $FS(i)_1^2, ..., FS(i)_{n_i}^2, FS(j)_1^2, ..., FS(j)_{n_j}^2$ are of the level 2 and the transformation realized by the functional system FS has the form

$$FS = s_0 \left\{ \xrightarrow[\to s_1 \to s_2 \to ... \to s_{i-1} \{\langle \to s_1^i \to s_2^i \to ... \to s_{goal}^i \rangle\} ... \to s_{j-1} \{\langle \to s_1^j \to s_2^j \to ... \to s_{goal}^j \rangle\} ... \to s_{goal} \quad p_{FS}]{FS_1^1, ... FS_{i-1}^1 \{\langle FS(i)_1^2, ..., FS(i)_{n_i}^2 \rangle\}, ..., FS_{j-1}^1 [FS(j)_1^2, ..., FS(j)_{n_j}^2], ..., FS_n^1} \right\} s_{goal}.$$

In accordance with the theory of the movement organization by N.A. Bernstein [14], the leading level of the organization of movements is the top level $FS = (s_{Goal}, \{\langle FS_1^1, ..., FS_n^1 \rangle\}, p_{FS})$ of rank 1, which corresponds to the domonant motivation. Functional systems of the lower levels are activated by the functional systems of the upper levels.

When functional system FS receives a request to attain a goal s_{Goal} in the current state $s_t = (p_1^t, ..., p_k^t)$ it:

1) extracts from the memory all sequences/hierarchies of the functional systems FSC that are applicable in the current situation $s_0 \subseteq s_t$, where s_0 - is the first state of the sequence/hierarchy (afferent synthesis);
2) from all these sequences/hierarchies it choose one that attain the goal s_{Goal} with the maximum probability p_{FS} (decision making);
3) generate a «specific goal» (the highest motivation) as a sequence and hierarchy of all goals of functional subsystems contained in the chosen sequence/hierarchy. For example, for the above mentioned functional system, it would be a sequence

$$s_0 \to s_1 \to s_2 \to ... \to [\to s_1^i \to s_2^i \to ... \to s_i]... \to [\to s_1^j \to s_2^j \to ... \to s_j]... \to s_{goal};$$

3) predicts that the goal s_{Goal} will be attained with probability p_{FS};
4) anticipates (using acceptor of action results) the achievement of the entire sequence/hierarchy of goals for all its functional subsystems after the corresponding actions;
5) successively activates execution of actions in functional subsystems FSC;
6) if the goal s_{Goal} is not attained by some functional subsystem and this fact is registered by the acceptor of action results, then orienting-investigative reaction occurs, which selects another sequences/hierarchies of the functional systems from the set $\{\langle FS_1^1, ..., FS_n^1 \rangle\}$ or selects another functional system FS to attain the goal s_{Goal}. Activated rule of the corresponding functional subsystem is penalized;
7) the goal s_{Goal} is attained and results for each functional subsystem is registered by the acceptor of action results and all activated rules for each functional subsystem are rewarded.

Let us describe all elements of the architecture of functional systems using definitions introduced above.

Afferent synthesis involves the synthesis of motivational excitation, memory, situational and triggering afferentation, as well as reverse afferentation on performed actions. All these afferentation are recorded by a set of sensors $S_1, ..., S_n$. Motivational excitation also sets a goal $Goal = (p_{i_1}^{goal}, ..., p_{i_{goal}}^{goal})$.

Memory. Each goal can be attained by various sequences of actions. Therefore motivation extracts from the memory all sequence/hierarchies $\langle FS_1^1, ..., FS_n^1 \rangle$ of functional subsystems of the functional subsystem $FS = (s_{Goal}, \{\langle FS_1^1, ..., FS_n^1 \rangle\}, p_{FS})$ that attain the goal.

Situational and launching afferentation specifies the current state of the system $s_t = (p_1, ..., p_k)$ at each instant of time *t*. The initial states $s_0 = (p_{i_1}^0, ..., p_{i_0}^0)$ of the first functional systems of each sequence/hierarchy $\langle FS_1^1, ..., FS_n^1 \rangle$ should correspond to the current state $s_0 \subseteq s_t$.

«Extracting» from the memory the whole experience, transforms motivational excitation as a goal into a «specific goal» of «higher motivation» that determines how it may be attained. A «specific goal» for a functional system $FS = (s_{Goal}, \{\langle FS_1^1, ..., FS_n^1 \rangle\}, p_{FS})$ is the entire set of sequence/hierarchies of functional systems $\{\langle FS_1^1, ..., FS_n^1 \rangle\}$.

Decision making. At the previous stage of the afferent synthesis a set of sequences/hierarchies $\{\langle FS_1^1, ..., FS_n^1 \rangle\}$ of functional systems that attain the goal s_{Goal} is extracted from the memory. At the stage of decision making only one of these is chosen as a “program of actions”. The decision making is carried out by a switching function of emotions (see 5.2) [12-13].

Acceptor of action results. For the “program of actions” motivational excitation extracts from the memory a “particular criteria” of attaining the goal – i.e. *acceptor of action results*, which consists a full totality of criteria of attaining the whole sequence/hierarchy of goals, for example, the sequence/hierarchy of goals

$s_0 \to s_1 \to s_2 \to ... \to [\to s_1^i \to s_2^i \to ... \to s_i]... \to [\to s_1^j \to s_2^j \to ... \to s_j]... \to s_{goal}$.

Automatic formation of new functional systems. New functional systems FS can be formed automatically by combining a sequence of functional systems in case they implement some standard sequence of actions that is implemented always at the same way. The sequence of functional systems $\langle FS_1^1, ..., FS_n^1 \rangle$,

$$FS_1 = s_0 \left\{ \xrightarrow[\to s_1^1 \to s_2^1 \to ... \to s_{goal}^1 \ \ p_{FS_i^1}]{FS_1^1, ..., FS_{n_i}^1} \right\} s_1, \ldots, FS_n = s_{n-1} \left\{ \xrightarrow[\to s_1^n \to s_2^n \to ... \to s_{goal}^n \ \ p_{FS_i^n}]{FS_1^n, ..., FS_{n_i}^n} \right\} s_n,$$

automatically combines into a functional system $FS = (s_{Goal}, \{\langle FS_1, ..., FS_n \rangle\}, p_{FS})$ with one element in the set $\{\langle FS_1, ..., FS_n \rangle\}$ of the form:

$$FS = s_0 \left\{ \xrightarrow[\to s_1 \to s_2 \to ... \to s_{goal} \ \ p_{FS} = p_{FS_1} \bullet ... \bullet p_{FS_n}]{FS_1, ..., FS_n} \right\} s_{goal} .$$

If the sequence of actions is standard and not switched in the middle to the execution of a different sequence, then the probability p_{FS} of functional system will be equal to the product $p_{FS_1} \bullet ... \bullet p_{FS_n}$ of the probabilities of its constituent functional subsystems.

Automatic unification of functional systems occurs for the same reason as the elaboration of the conditioned relations for rules: the elaboration by the inner loop (fig. 1) the conditional connection between the execution of the first functional system FS_1 and the result of the entire sequence of actions if it always obtains a sequence of results $s_1 \to s_2 \to ... \to s_n$.

Automatic formation of new functional subsystems. Before learning the control system have fixed hierarchy of functional systems. In particular, it may have only one system. In the process of learning the control system may elicit new subgoals and form corresponding functional subsystems. Let us describe the process of the new functional subsystems formation. We define a subgoal as a state, which arriving significantly increases the probability of the upper goal attainment and the further actions from this state may be different.

For subgoals determination the set of functional system rules FS is analyzed. The state $s = (p_{i_1}, ..., p_{i_m})$, is a new subgoal $s_{SubGoal}$, if the following conditions are fulfilled:

1. For any rules $R_1 = s_1 \xrightarrow[p_1]{a} s_{Goal}$, such that $s \subseteq s_1$, and $R_2 = s_2 \xrightarrow[p_2]{a} s_{Goal}$, such that $s_2 \subset s_1$ и $s \not\subset s_2$, we have $p_1 - p_2 > \delta$.
2. There are exist different rules $R_1 = s_1 \xrightarrow[p_1]{a_1} s_{Goal}$, $R_2 = s_2 \xrightarrow[p_2]{a_2} s_{Goal}$, such that $s \subseteq s_1$, $s \subseteq s_2$ and $a_1 \neq a_2$.

The first condition claim that adding the state *s* to the promise of the rule must increase the conditional probability of that rule on more then δ, where δ is some threshold, for example δ = 0.2. It means that arriving of that state is significantly increases the probability of the upper goal attainment. The second condition means that after the state *s* achievement many different actions are possible for the goal achievement.

For every functional system FS its set of rules is analyzed and new subgoal determined. For every new subgoal $s_{SubGoal}$ a new function system is FS_{new} is form.

6. Experiments

For investigation of the control system behavior two experiments was setting. We explored the foraging task. In this task some agent moving on the plain and gathering pabulary objects. There are no subgoals in this task, so we complicated this task by introducing a «tablet» that is needed for the eating the pabulary object. In this case the subgoal is in the eating the «tablet» before the eating the pabulary object.

The virtual world was modeled in which the agent can gather the pabulary objects.

This world include the rectangular field with 25×25 cells. Each cell may be or empty, or include the «pabulary objects» or «barrier». Barriers are placed only on the perimeter of the field. Agent is placed on one of the cells and may be oriented in one of the four directions. The possible actions $\{a_1, a_2, a_3\}$ of the agent are: step on the one cell ahead, turn left, turn right.

In the first experiment some number of the «pabulary objects» are placed randomly on the field. To eat the «pabulary objects» agent need to take a step on the cell, where the «pabulary objects» is placed. In that case the «pabulary objects» disappear from the cell and randomly appear on some another cell.

Agent have sensors $S_1, ..., S_9$, in which $S_1, ..., S_8$ placed on the circle around the agent and inform the agent about the objects placed on this cells, and S_9 inform the agent about the object placed on the cell that agent occupied.

The second experiment is more complicated then the first. In the cells of the field a «tablet» objects may be placed, which are randomly distributed. To eat the «pabulary objects» agent needs to have a «tablet» object, which he need to gather on the field. When the agent eats a «pabulary objects» the gathered «tablet» object disappears and for eating a new «pabulary objects» the agent need to gather a new «tablet» object. The agent gather a «tablet» object if it placed on the cell with this object. The agent may gather only one «tablet» object. When agent gather a «tablet» object the cell became empty and a new «tablet» object is randomly appeared on the field.

In the second experiment agent have ten sensors $S_1, ..., S_9, S_{pill}$, where first nine is the same as in the first experiment and sensor S_{pill} inform the agent about availability of the «tablet» object.

For the estimation of the effectiveness of the control system we compared it with control systems based on the reinforcement learning, described in the work [4]. For comparison we used two control systems based on the Q-Learning. These algorithms consist in consecutive refinement of the estimation of the reward $Q(s_t, a_t)$ summary, if in the state s_t the system act as a_t:

$$Q^{(i+1)}(s_t, a_t) = Q^{(i)}(s_t, a_t) + \alpha(r_t + \gamma \max_A Q^{(i)}(s_{t+1}, a) - Q^{(i)}(s_t, a_t)) .$$

The first system (Q-Lookup Table) use table, which include Q-values of all possible states and acts. Initially, the table is fulfilled randomly. Then the system in each act specifies the Q-value.

The second system (Q-Neural Net) use approximation of the function $Q(s_t, a_t)$ using neural networks. In that case for each act a_i a special neural network used. In each time period the system choose the act, which neural network produces a greater value of the estimation Q-value. Then the act accomplished, and weighs of the neural nets are changed.

For the estimation of the systems the period of agent functioning was divided on stages for 1000 steps. The estimation consists of the volume of the «pabulary objects» gathered for a step of the work. After learning every system will reach some optimal value. During the experiment we can estimate the learning speed and corresponding optimal value.

6.1. The results of the first experiment

In the first experiment there were 24 predicates for sensors – three predicates ($S_i = empty$), ($S_i = block$), ($S_i = food$) for each sensor S_i, $i = 1,...,8$. At the beginning the control system contained only one functional system with purpose S_{Goal} = ($S_9 = food$), when sensor S_9 inform about «pabulary objects» in the central cell.

In this experiment there is no subgoals. The main task of this experiment is the estimation of the effectiveness of the functional system and its learning.

On the fig. 3 there are results of comparison for different control systems. For each control system the mean values for 20 experiments are presented. The duration of each experiment is 50,000 steps of the agent. The number of the «pabulary objects» on the field is 100.

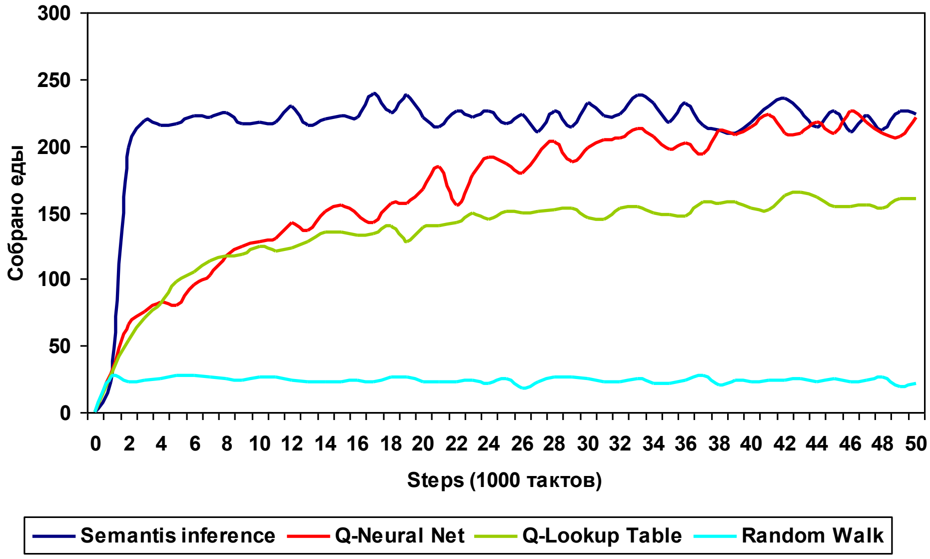

Fig 3. Amount of the food gathered by the agent with different control systems.

It is seen from the figure that the control system based on the semantic probabilistic inference is fully leaned during the 1000 steps. Control systems based on the neural nets (Q-Neural Net) is learning more slowly and become fully leaned after 10,000 steps. The slow leaning of the Q-Lookup Table is follow from the huge number 2496 of states with three possible actions.

The results of this experiment demonstrate that the control system based on the semantic probabilistic inference is working rather effectively and more effectively then that is based on the Reinforcement Learning.

The results of the second experiment.

This experiment is principally different in that the task may be divided in two parts: at first – to find a «tablet» object and then to find the «pabulary objects». The purpose of this experiment is to demonstrate the possibility of automatic subgoals formation.

The agent have 32 predicates – four predicates for each sensor S_i, $i = 1,...,8$: ($S_i = empty$), ($S_i = block$), ($S_i = food$) и ($S_i = pill$), and one predicate ($S_{pill} = yes$) for the state when the agent have a «tablet» object and one predicate $(S_9 = food)$ for the state, when the «pabulary objects» is in the central cell under the agent.

At the beginning the control system of the agent have only one functional system with the purpose $S_{Goal} = (S_{pill} = yes) \& (S_9 = food)$, when the agent have a «tablet» object and it find a «pabulary objects».

During the experiment the control system of the agent alwase found the subgoal $S^2_{Goal} = (S_{pill} = yes)$ and formed a corresponding functional system. When the agent had no the «tablet» object, the control system passed the control to the subsystem for the search a «tablet» object, and, after finding the «tablet» object and achieving the goal $S^2_{Goal} = (S_{pill} = yes)$, the control system of the upper system begun finding the «pabulary objects».

The results of experiment are presented on the figure 4. On the figure the mean values for 20 experiments are presented for each control system. In each experiment the agent had 100,000 steps. The number of «pabulary objects» and «tablet» objects on the field was 100 for each.

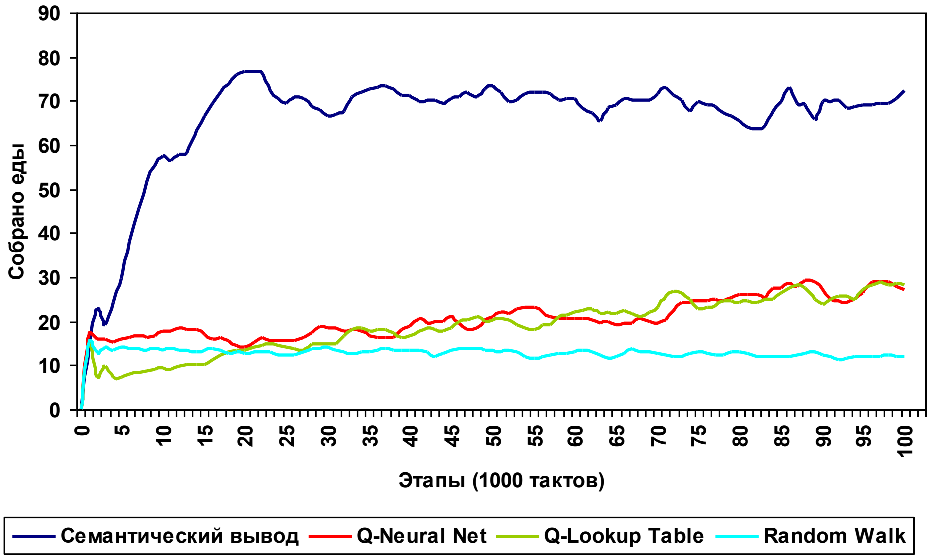

Fig 4. Amount of the food gathered by the agent with different control systems in the presence of the «tablet» objects.

As it seen from the figure, the control system, based on the semantic probabilistic inference where working more effectively then systems, based on the reinforcement learning. Control systems based on the reinforcement learning where not well learned and worked unstable. They cannot during the reasonable time to learn the need of the «tablet» objects for the goal achievement and passed by «tablet» objects after 100,000 steps of learning. Additional experiments demonstrated that control system (Q-Neural Net) can sometimes learn during the 300,000 – 500,000 steps.

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