Factors that determine the level of intelligence of cybernetic systems

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***Abstract*—In the article, a hierarchical system of properties of cybernetic systems that determine their quality and allow formulating the requirements, that a cybernetic system with strong intelligence must satisfy, is considered. The quality level of cybernetic systems is determined by a sufficiently large set of parameters of cybernetic systems. Each of the parameters determines the quality level of the cybernetic system in the corresponding aspect, indicating the level of development of specific abilities and capabilities of the cybernetic system. The obtained results will allow assessing the quality level of cybernetic systems, as well as determining the direction for development of a cybernetic system to increase the level of intelligence.**

***Keywords*—cybernetic system, cybernetic system intelligence, cybernetic system quality level, multi-agent system, computer system**

I. Introduction

At present, the usage of intelligent systems in various fields is becoming more and more relevant. The modern technology of Artificial Intelligence is represented by a variety of technologies focused on developing and maintaining various types of components of intelligent computer systems. Along with all their advantages, they have a number of serious drawbacks associated with the laboriousness of their development and maintenance. In particular, these disadvantages include the following ones:

- lack of a metric to assess the current level of intelligence of a particular system;
- lack of a standardized method for comparing the level of intelligence of different systems;
- lack of understanding of how to increase the level of intelligence of a cybernetic system.

To further increase the efficiency and level of practical significance of intelligent computer systems in increasing the level of automation of human activity [1], [2], it is necessary to clarify possible directions for improving the quality and level of intelligence in modern intelligent computer systems.

This work is dedicated to clarifying the criteria and relevant parameters that determine the quality of cybernetic systems, their level of intelligence. Quality criteria are touched upon not only for artificial cybernetic systems (computer systems of various types) but also for natural cybernetic systems, as well as various kinds of symbioses of natural and artificial cybernetic systems.

II. Problem definition

Intelligence is not defined in terms of matching human reaction times, error rates, or exact responses, but instead, the purpose is to build computer systems that exhibit the full range of the cognitive capabilities we find in humans [3]. From a formal point of view, intelligence is a set of classes of cybernetic systems, each of which includes cybernetic systems that are equivalent in terms of the level and nature for the manifestation of intelligent properties (including abilities). Thus, the nature of intelligent properties and the level of their development may be different for different cybernetic systems. Accordingly, cybernetic systems can be compared with each other.

The main property of a cybernetic system is the level of its intelligence. Intelligence is an integral characteristic that determines the level of efficiency during interaction of a cybernetic system with the environment of its existence. The process of evolution of cybernetic systems should be considered as a process of increasing the level of their quality in a number of properties and, first of all, as a process of increasing the level of intelligence of these cybernetic systems. At the same time, we can talk about the evolution of each specific cybernetic system in the course of its “life activity”, as well as the evolution of a whole class of cybernetic systems, when new instances of this class are more intelligent than their predecessors. In this aspect, the evolution of computer systems (artificial cybernetic systems) can be considered.

Various system metrics have been proposed for measuring the quality of computer-based systems. As computer-based systems grow in complexity with many subsystems or components, measuring their quality in multiple dimensions is a challenging problem [4]. Quality metrics involve a set of measures that can describe the attributes of a system in terms that are independent of the structure which leads to these attributes; these measures should be quantified numerically and should have a significant level of accuracy and reliability [5].

Researchers of artificial intelligence have traditionally defined intelligence as an inherent property of a machine

[6]. At the moment, there are no standardized metrics that allow assessing the level of intelligence of a cybernetic system, therefore, there is no way to compare different systems. The problem of identifying criteria for the intelligence of systems is considered in a number of works [7], [8], [9], [10], [11]. Nevertheless, for the practical implementation of intelligent computer systems, it is necessary to detail and refine these properties, trying to reduce them to more constructive, transparent, and understandable properties for implementation. It is important to clarify what other properties of cybernetic systems determine the level and nature of their intelligence. It is essential to clarify the point by which the level of intelligence of a cybernetic system can be increased.

III. Proposed approach

As part of this work, it is proposed to use an *OSTIS Technology* [12] as a basis, the principles of which make it possible to formally clarify and agree on the interpretation of such concepts as *cybernetic system*, *quality of a cybernetic system*, *multi-agent system*, and others within the corresponding set of ontologies. Based on the results obtained, it is necessary to clarify properties that affect the level of intelligence.

The OSTIS Technology is based on a universal way of semantic representation of information in the memory of intelligent computer systems, called an *SC-code*. SC-code texts are unified semantic networks with a basic set-theoretic interpretation. The elements of such semantic networks are called *sc-elements* (*sc-nodes* and *sc-connectors*, which, in turn, depending on orientation, can be *sc-arcs* or *sc-edges*). The *Alphabet of the SC-code* consists of five main elements, on the basis of which SC-code constructions of any complexity are built, including more specific types of sc-elements (for example, new concepts). The memory that stores SC-code constructions is called semantic memory, or *sc-memory*.

Within the technology, several universal variants of visualization of *SC-code* constructions are proposed, such as *SCg-code* (graphic variant), *SCn-code* (nonlinear hypertext variant), *SCs-code* (linear string variant).

The basis of the knowledge base within the OSTIS Technology is a hierarchical system of subject domains and ontologies. Based on this, in order to solve the above problems, it is proposed to implement a complex *Subject domain of cybernetic systems* and the corresponding *Ontology of the quality of cybernetic systems*.

Within this article, fragments of structured texts in the SCn code [13] will often be used, which are simultaneously fragments of the source texts of the knowledge base, understandable both to a human and to a machine. This allows making the text more structured and formalized, while maintaining its readability. The symbol ":=" in such texts indicates alternative (synonymous) names of the described entity, revealing in more detail certain of its features.

The development of the specified family of sc-models of subject domains and ontologies will allow:

- explicitly linking the class of the system and the parameters corresponding to this system;
- assessing the intelligence level for a system of a particular class;
- comparing systems of different classes in terms of the level of intelligence, i.e. providing an ability to solve more complex problems;
- making automation tools for assessing the intelligence level for the system.

Further, fragments of sc-models of the specified subject domains and ontologies are considered in more detail.

IV. Typology of cybernetic systems

The term "cybernetic system" has a clear quantitative definition. It is a system that dynamically matches acquired information to selected actions relative to a computational issue that defines the essential purpose of the system or machine [14]. A cybernetic system is a system that is able to control its actions, adapting to changes in the state of the external environment, the environment of its "habitat". The purpose of such adaptation can be both self-preservation (preserving own integrity and "comfort" of existence by keeping own "vital" parameters within certain limits of "comfort") and the formation of certain reactions, influences on the external environment in response to certain stimuli, situations, or events in the external environment.

The cybernetic system is able to evolve in the direction of:

- studying its external environment at least to predict the consequences of its own influences on the external environment, as well as to predict changes in the external environment that do not depend on its own influences;
- studying oneself and, in particular, its interaction with the external environment [15];
- creating technologies, methods, means, that ensure a change in their external environment, the conditions of their existence in their own interests.

The cybernetic system is an adaptive, purposeful system, an active subject of the independent life. The functioning of such a system is based on the processing of information about the environment in which this system exists. It is able to monitor, analyze, and actively influence its state and the state of the environment.

The classification of cybernetic systems on the basis of naturalness or artificiality is given bellow.

A feature of computer systems is that they can play the "role" not only of the products of the corresponding actions for the implementation of these systems, but they themselves are subjects capable of performing (automating) a wide range of actions. At the same

cybernetic system

⇒ *subdividing**:

Attribute of naturalness or artificiality of cybernetic systems

= {• *natural cybernetic system*

⊃ *human*

• *artificial cybernetic system*

• *symbiosis of natural and artificial cybernetic systems*

⊃ *community of computer systems and humans*

}

time, the intellectualization of these systems significantly expands this spectrum.

The structural classification of cybernetic systems is given bellow.

cybernetic system

⇒ *subdividing**:

Structural classification of cybernetic systems

= {• *simple cybernetic system*

• *individual cybernetic system*

• *multi-agent system*

}

The development level for a simple cybernetic system is below the level of individual cybernetic systems. It is a specialized means of information processing, a specialized problem solver that most often implements (interprets) one problem-solving method and, accordingly, solves only problems of a given class of problems. A simple cybernetic system can be a component built into an individual cybernetic system, and it can also be an agent of a multi-agent system, which is a collective of simple cybernetic systems.

An individual cybernetic system is a cybernetic system with a level of development based on the transition from a specialized problem solver to an individual solver that provides the interpretation of an arbitrary (non-fixed) set of problems-solving methods (programs), provided that these methods are introduced (loaded, recorded) in memory of a cybernetic system. Such a system is capable of being independent, able to "survive" on its own. The features of individual cybernetic systems are:

- the presence of memory designed to store at least interpreted methods, programs and provide correction of stored methods, their deletion from memory, and the introduction of new methods into memory;
- the ability to "re-program" a cybernetic system easily to solve other problems, which is ensured by the presence of a universal problem-solving model and, accordingly, a universal interpreter of any models represented in the corresponding language;
- the presence of even simple means of communication, information exchange with other cybernetic systems (for example, with humans);
- the ability to enter into various collectives of cybernetic systems.

A multi-agent system is a collective of interacting autonomous cybernetic systems that have a common operation environment [16]. The classification of multi-agent systems is given bellow.

multi-agent system

⇒ *subdividing**:

{• *single-level multi-agent system*

• *hierarchical multi-agent system*

}

A single-level multi-agent system implements either one model of parallel (distributed) problem solving of the corresponding class or a combination of a fixed number of different and parallel implemented problem-solving models. A hierarchical multi-agent system consists of agents, which can be individual cybernetic systems, collectives of individual cybernetic systems, as well as collectives consisting of individual cybernetic systems and collectives of individual cybernetic systems.

V. Structure of a Cybernetic System

The generalized decomposition of the cybernetic system is represented in Figure 1:

cybernetic system

⇒ *generalized decomposition**:

{• *information stored in the memory of a cybernetic system*

• *abstract memory of a cybernetic system*

• *problem solver of a cybernetic system*

• *physical shell of a cybernetic system*

}

The information stored in the memory of a cybernetic system is an information model of the environment in which this cybernetic system operates, exists, and functions.

The abstract memory of a cybernetic system is the internal abstract information environment of a cybernetic system, which is a dynamic information construction. Each state of such an information structure is nothing but the information stored in the memory of the cybernetic system at the appropriate moment in time.

The problem solver of a cybernetic system is a combination of all the skills and abilities acquired by a

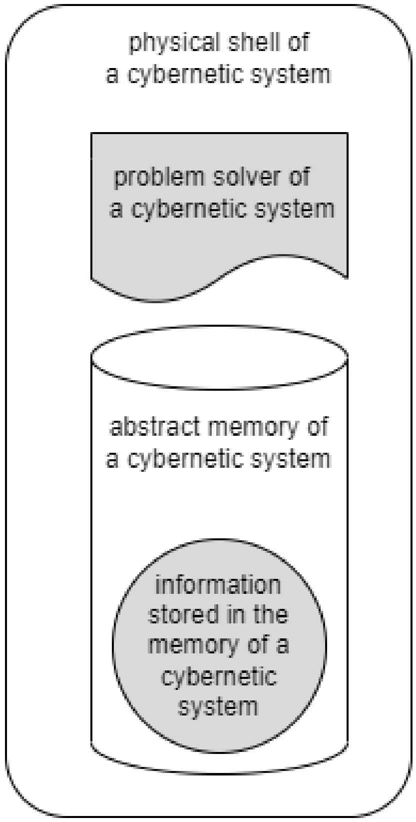

Figure 1. The structure of the cybernetic system

cybernetic system by the moment in question. A problem solver is a subject built into a cybernetic system that is capable of performing purposeful, “conscious” actions in the external environment of this cybernetic system, as well as in its internal environment (in abstract memory). The classification of actions of a cybernetic system is represented below:

action of a cybernetic system
⇒ *subdividing**:
{• *external action of a cybernetic system*
• *action of a cybernetic system performed in its own physical shell*
• *action of a cybernetic system performed in its own abstract memory*
}

Each complex action performed by a cybernetic system outside its own abstract memory includes sub-actions performed in the specified abstract memory. This means that all external actions of a cybernetic system are controlled by its internal actions (actions in abstract memory).

It should be noted that the conventionally allocated component of the cybernetic system problem solver is the interface of the cybernetic system. It provides a solution to interface problems aimed at the direct implementation of the interaction of a cybernetic system with its external environment. Such an interface should be distinguished from the physical provision of the interface of a cybernetic system.

The physical shell of a cybernetic system is a part of a cybernetic system that is an “intermediary” between its internal environment (memory in which information of a cybernetic system is stored and processed) and its external environment. The generalized decomposition of the physical shell of a cybernetic system is given bellow.

physical shell of a cybernetic system
⇒ *generalized decomposition**:
{• *cybernetic system memory*
• *cybernetic system processor*
• *physical provision of the cybernetic system interface*
• *cybernetic system physical shell*
}

In this context, the memory of a cybernetic system is understood as a physical shell, the implementation of the abstract memory of a cybernetic system, within which the cybernetic system forms and uses, processes an information model of its external environment.

Not every cybernetic system possesses memory. In cybernetic systems without memory, information processing is reduced to the exchange of signals between the components of these systems. The occurrence of memory in cybernetic systems as a medium for “centralized” storage and processing of information is the most important stage in their evolution. The fact of the occurrence of memory in a cybernetic system significantly increases the level of adaptability of a cybernetic system to various changes in its environment. The principles of organizing the memory of a cybernetic system can be different (associative, addressable, structurally fixed/structurally adjustable, non-linear/linear). Its quality largely depends on the organization of memory.

The cybernetic system processor is a hardware-implemented interpreter of the methods and programs stored in the memory of a cybernetic system, corresponding to the problem-solving model basic for this cybernetic system.

An example of the physical shell of artificial cybernetic systems is a computer. A computer for intelligent computer systems must be an effective hardware interpreter of any problem-solving models, both intelligent problems and fairly simple ones, since an intelligent system should be able to solve any problems.

VI. Complex of properties that determines the overall quality level of cybernetic systems

The quality of a cybernetic system is an integral, comprehensive assessment of the development level for a cybernetic system. This is a property, a characteristic of cybernetic systems, a sign of their classification, which allows placing these systems along the "steps" of some conditional "evolutionary ladder". Each such "step" includes cybernetic systems that have the same level of development, each of which corresponds to its own set of values of additional properties for cybernetic systems that refine (detail, specialize) the corresponding development level of cybernetic systems. Such an evolutionary approach to the consideration of cybernetic systems makes it possible, firstly, to detail the directions for evolution of cybernetic systems and, secondly, to clarify the place of this evolution, where and due to which the transition from non-intelligent cybernetic systems to intelligent ones is carried out.

The evolutionary approach to considering the diversity of cybernetic systems is based on the position that ideal cybernetic systems do not exist, but there is a constant striving for the ideal, for greater perfection. It is important to clarify what specifically in each cybernetic system should be changed in order to bring this system to a more perfect form.

So, for example, the development of computer system design technologies should be aimed at the transition to such new architectural and functional principles underlying computer systems that provide a significant reduction in the complexity of their development and reduce development time, as well as provide a significant increase in the level of intelligence and, in particular, the level of learnability of the developed computer systems, for example, by moving from supporting learning with a teacher to implementing effective self-learning (to automating the organization of self-study).

To refine the concept of the cybernetic system quality, it is necessary to set a metric of the cybernetic system quality and build a hierarchical system of properties, parameters, features, that determine the quality of cybernetic systems.

cybernetic system quality

⇒ *prerequisite property**:
- *quality of the physical shell of a cybernetic system*
- *quality of information stored in the memory of a cybernetic system*
- *quality of the problem solver of a cybernetic system*
- *hybridity of a cybernetic system*
  - ⇒ *private property**:
    {
    - *variety of knowledge types stored in the memory of a cybernetic system*
    - *variety of problem-solving models*
    - *variety of types of sensors and effectors*

    }
- *adaptability of the cybernetic system to its improvement*
- *cybernetic system performance*
- *reliability of the cybernetic system*
- *cybernetic system interoperability*

A. Complex of properties that determine the quality of the physical shell of a cybernetic system

The quality of the physical shell of the cybernetic system is the integral quality of the physical, hardware basis of the cybernetic system. The selected set of properties that determine the quality of the physical shell of a cybernetic system is given below:

quality of the physical shell of a cybernetic system

⇒ *prerequisite property**:
- *memory quality of a cybernetic system*
- *cybernetic system processor quality*
- *quality of cybernetic system sensors*
- *quality of cybernetic system effectors*
- *adaption of the physical shell of a cybernetic system to its improvement*
- *ease of transportation of the cybernetic system*
- *reliability of the physical shell of a cybernetic system*

It is essential that the memory provides a high level of flexibility to the specified information model. It is also important that this information model should be a model not only of the external environment of the cybernetic system but also a model of this information model itself – a description of its current situation, prehistory, regularities.

memory quality of a cybernetic system

⇒ *prerequisite property**:
- *ability of the memory of a cybernetic system to provide storage of high-quality information*
- *ability of a cybernetic system memory to provide a high quality problem solver*
- *memory size*

The fact of the occurrence of memory in a cybernetic system is the most important stage in its evolution. Further development of the cybernetic system memory, which ensures the storage of more and more high-quality information stored in memory and more and more high-quality organization of the processing of this information, i.e. the transition to supporting more and more high-quality information processing models, is the most important factor in the evolution of cybernetic systems.

The ability of the memory of a cybernetic system to ensure the functioning of a high-quality problem solver is based on the quality of access to information stored in the cybernetic system memory, the logical and semantic flexibility of the memory of a cybernetic system, the ability of the memory of a cybernetic system to provide interpretation of a wide variety of problem-solving models.

The quality of a cybernetic system processor is determined by its ability to provide a high quality problem solver.

ability of the cybernetic system processor to ensure the functioning of a high-quality problem solver
⇒ *prerequisite property**:
- *variety of problem-solving models interpreted by the cybernetic system processor*
- *simplicity and quality of interpretation by the system processor of a wide variety of problem-solving models*
- *providing high-quality control of information processes in memory by the cybernetic system processor*
- *cybernetic system processor speed*

The maximum level of quality of the cybernetic system processor in terms of the variety of problem-solving models interpreted by the cybernetic system processor is its universality, i.e. its fundamental ability to interpret any model for solving both intelligent and non-intelligent problems. Simplicity is determined by the degree of proximity of the interpreted problem-solving models to the "physical" level of organizing the cybernetic system processor. High-quality control of information processes in memory implies a competent combination of such aspects of process management as centralization and decentralization [17], synchrony and asynchrony, sequence and parallelism.

The quality of sensors and effectors of a cybernetic system is reduced to the variety of types of sensors and effectors in a cybernetic system, i.e. to the variety of means of perception and influence on information about the current state of the external environment and its own physical shell. The adaption of the physical shell of the cybernetic system to its improvement is determined by the flexibility and stratification of the physical shell of the cybernetic system.

B. Complex of properties that determine the quality of information stored in the memory of a cybernetic system

The quality of the information model for the "habitat" of a cybernetic system, in particular, is determined by:
- the correctness of this model, the absence of errors in it;
- the adequacy of this model;
- completeness, sufficiency of the information contained in it for the effective functioning of the cybernetic system;
- structuredness and systematization.

The most important stage in the evolution of the information model for the environment of a cybernetic system is the transition from an insufficiently complete and unsystematized information model of the environment to a knowledge base.

The correctness/incorrectness of information is the level of adequacy of the stored information of the environment in which the cybernetic system exists and the information model of which this stored information is. The consistency/inconsistency of information means the level of presence in the stored information of various types of contradictions and, in particular, errors. Errors in the stored information can be syntactic and semantic, contradicting some rules that may not be explicitly represented in memory and are considered true.

The completeness/incompleteness of information is the degree to which the information stored in the memory of a cybernetic system describes the environment of existence of this system and the methods used by it for solving problems sufficiently fully so that the cybernetic system can actually solve the entire set of problems corresponding to it. The more complete the information stored in the memory of a cybernetic system is, the more complete the information support of the activity of this system, the more effective (of higher quality) this activity itself is. The completeness is determined by the structuring of information and the variety of knowledge types stored in the memory of a cybernetic system.

The unambiguity/ambiguity of information is determined by the variety of forms of information duplication and the frequency of information duplication.

The integrity/non-integrity of information is the level of meaningful informativeness of information, the level of how semantically coherent the information is, how fully all the entities described in memory are specified (by describing the necessary set of relations of these entities with other entities being described), how rarely or often information holes occur within the stored information corresponding to the apparent insufficiency of some specifications. Examples of information holes are:
- missing method for solving common problems;

quality of information stored in the memory of a cybernetic system

⇒ *prerequisite property*:*

- *semantic power of the language for representing information in the memory of a cybernetic system*
- *amount of information immersed into the memory of a cybernetic system*
- *degree of convergence and integration of various types of knowledge stored in the memory of a cybernetic system*
- *stratification of information stored in the memory of a cybernetic system*
- *simplicity and locality of performing semantically integral operations on information, stored in the memory of a cybernetic system*
- *correctness/incorrectness of information stored in the memory of a cybernetic system*
- *unambiguity/ambiguity of information stored in the memory of a cybernetic system*
- *integrity/non-integrity of information stored in the memory of a cybernetic system*
- *compliance/incompliance of information stored in the memory of a cybernetic system*
- *reliability/unreliability of information stored in the memory of a cybernetic system*
- *accuracy/inaccuracy of information stored in the memory of a cybernetic system*
- *clarity/fuzziness of information stored in the memory of a cybernetic system*
- *certainty/uncertainty of information stored in the memory of a cybernetic system*

- missing definition of the concept being used;
- insufficiently detailed specification of frequently considered entities.

The compliance/incompliance of information means the variety of forms and the total amount of information garbage that is part of the information stored in the memory of a cybernetic system. Information garbage is understood as an information fragment that is part of information, the removal of which will not significantly complicate the operation of a cybernetic system. Examples of information garbage are:

- information that is not frequently needed but can be easily inferred, when necessary;
- information that has expired.

The semantic power of the language for representing information in the memory of a cybernetic system is determined by the hybrid nature of the information stored in the memory of a cybernetic system. A language whose information constructions can represent any configuration of any relations between any entities is a universal language. The universality of the internal language of a cybernetic system is the most important factor in its intelligence.

The hybridity of information stored in the memory of a cybernetic system is determined by the variety of knowledge types and the degree of convergence and integration of various knowledge types.

Stratification of information is the ability of a cybernetic system to allocate such sections of information stored in the memory of this system that would limit the areas of action for the agents of the problem solver of the cybernetic system, which are sufficient to solve the given problems. Stratification is determined by the structuredness and reflexivity of information stored in the memory of a cybernetic system. The reflexivity of information stored in the memory of a cybernetic system, i.e. the presence of meta-linguistic means, is a factor that provides not only the structuring of stored information but the possibility of describing the syntax and semantics of the most diverse languages used by a cybernetic system.

The knowledge base is an example of information stored in the memory of a cybernetic system and that has a high quality level in all respects and, in particular, a high level of:

- semantic power of the language for representing information stored in the memory of cybernetic systems;
- hybridity of information stored in the memory of a cybernetic system;
- variety of knowledge types stored in the memory of a cybernetic system;
- formalization of information stored in the memory of a cybernetic system;
- structuredness of information stored in the memory of a cybernetic system;

The transition of information stored in the memory of a cybernetic system to a quality level corresponding to knowledge bases is the most important stage in the evolution of cybernetic systems.

C. Complex of properties that determine the quality of a problem solver of a cybernetic system

The quality of the problem solver of a cybernetic system is an integral qualitative assessment of the set of problems that a cybernetic system is capable of performing at a given moment. The main property and purpose of the problem solver of a cybernetic system is the ability to solve problems based on various types of skills accumulated and acquired by the cybernetic system using the cybernetic system processor, which is a universal interpreter of all kinds of accumulated skills. The quality of this ability is determined by a number of additional factors.

The total volume of problems solved by a cybernetic system is determined by the power of the language for representing problems solved by a cybernetic system. The power of the problem representation language is primarily determined by the variety of types of problems represented (the variety of types of described actions). Each problem is a specification of the corresponding (described) action. Therefore, consideration of the variety of types of problems solved by a cybernetic system is fully consistent with the variety of activities carried out by this system. It is important to note that there are activities of a cybernetic system that determine the quality and, in particular, the level of intelligence of a cybernetic system.

The ability of a cybernetic system to analyze the problems to be solved involves assessing the problem for:

- achievement difficulty;
- expediency of achievement (need, importance, priority);
- compliance of the purpose with the existing norms (rules) of the relevant activity.

A problem-solving method is a type of knowledge stored in the memory of a cybernetic system and containing information that is sufficient either to reduce each problem from the corresponding class of problems to a complete system of subproblems, the solution of which guarantees the solution of the initial problem, or to finally solve this problem from the specified class of problems. As problem-solving methods, not only algorithms can act but also functional programs, production systems, logical calculations, genetic algorithms, artificial neural networks of various types. Problems, for which there are no methods corresponding to them, are solved using problem-solving meta-methods (strategies) aimed at:

- generating the necessary initial data (the necessary context) for solving each problem;
- generating a plan for solving the problem, which describes the reduction of the initial problem to subproblems (down to those subproblems whose solution methods are known to the system);
- narrowing the problem solution area (to the context of the problem sufficient for its solution).

The quality of the solution of each problem is determined by:

- the time of its solution (the faster the problem is solved, the higher the quality of its solution);
- completeness and correctness of the result of solving the problem;
- memory resources spent to solve the problem (the extent of a fragment of stored information used to solve the problem);

general characteristics of the problem solver of a cybernetic system
⇒ *prerequisite property**:
{
- *total volume of problems solved by a cybernetic system*
- *variety of types of problems solved by a cybernetic system*
- *ability of a cybernetic system to analyze the problems being solved*
- *ability of a cybernetic system to solve problems, methods for solving which are currently known*
- *ability of a cybernetic system to solve problems, the methods for solving which it currently does not known*
- *set of skills used by the cybernetic system*
- *degree of convergence and integration of various types of problem-solving models used by a cybernetic system*
- *quality of organizing interaction between problem-solving processes in a cybernetic system*
- *performance of the problem solver of a cybernetic system*
- *ability of a cybernetic system to solve problems involving the usage of information that has various kinds of non-factors*
- *variety and quality of solving information retrieval problems*
- *ability of a cybernetic system to generate answers to questions of various types in case when they are completely or partially absent in the current state of the information stored in memory*
- *ability of a cybernetic system to reasoning of various kinds*
- *quality of goal-setting*
- *quality of implementation of own action plans*
- *ability of a cybernetic system to localize such an area of information stored in its memory, which is sufficient to provide a solution to a given problem*
- *ability of a cybernetic system to identify the essential in the information stored in its memory*
- *cybernetic system activity*

}

- the resources of the problem solver used to solve the problem (amount of used internal agents).

Thus, improving the quality of the process of solving each specific problem, as well as each class of problems (by improving the corresponding method, in particular, the algorithm) is an important factor in improving the quality of the problem solver as a whole.

A promising option for building a problem solver for a cybernetic system is the implementation of an agent-based information processing model, i.e. construction of a problem solver in the form of a multi-agent system whose agents process information stored in the memory of a cybernetic system and are controlled by this information (more precisely, by its current state). A special place among these agents is occupied by sensory, receptor, and effector agents, which, respectively, perceive information about the current state of the external environment and influence the external environment, in particular, by changing the state of the physical shell of the cybernetic system.

The indicated agent-oriented model for organizing the interaction of problem-solving processes in a cybernetic system is, in fact, nothing more than a model of situational control for the problem-solving processes solved by a cybernetic system both in its external environment and in its memory.

The speed of the problem solver of a cybernetic system is reduced to the speed of solving problems, the speed of the problem solver, the speed of reaction of the cybernetic system to various problem situations. In many ways, the property is determined by the speed of the processor of the cybernetic system.

Examples of problems involving the usage of information that has various kinds of non-factors are the problems of design, recognition, goal-setting, prediction, etc. Most often, these are:

- vaguely formulated problems;
- problems that are solved in conditions of incompleteness, inaccuracy, inconsistency of the source data;
- problems belonging to classes of problems for which it is almost impossible to build corresponding algorithms.

These problems are characterized by:

- the inaccuracy and unreliability of source data;
- the lack of result quality criterion;
- the impossibility or high complexity of algorithm development;
- the need to take into account the context of the problem.

The ability of a cybernetic system to generate (build, synthesize, derive) answers to a variety of questions and, in particular, to questions like "what is it", to why-questions, means the ability of a cybernetic system to explain (justify the correctness) of its actions.

Independence of goal-setting is the ability of a cybernetic system to generate, initiate, and solve problems that are not subproblems initiated by external (other) subjects, as well as the ability, based on an analysis of its capabilities, to refuse to perform a problem initiated from outside, redirecting it to another cybernetic system, or on the basis of analysis of this problem itself to substantiate its inexpediency or incorrectness. Increasing the level of independence significantly expands the capabilities of the cybernetic system, i.e. the volume of those problems that it can solve not only in "ideal" conditions, but also in real, complicated circumstances. The ability of the system to adequately prioritize its purposes and not "disperse" to achieve non-priority (insignificant) purposes is the ability to analyze the expediency of activities.

The ability of a cybernetic system to identify the essential in the information stored in its memory is the ability to identify (detect, allocate) such fragments of information stored in the memory of the cybernetic system that are essential, important for achieving the corresponding purposes. The concept of an essential fragment of information stored in the memory of a cybernetic system is relative and is determined by the corresponding problem. Nevertheless, there are important permanently solved problems, in particular, the problems of analyzing the quality of information stored in the memory of a cybernetic system. The essential fragments of the stored information, allocated in the process of solving these problems, are relative not so much in relation to the problem being solved but in relation to the current state of the stored information.

The level of activity of a cybernetic system can be different for different problems being solved, for different classes of actions performed, for different types of activities. The higher the activity of a cybernetic system is, the more it manages to do, therefore, the higher its quality and efficiency. The inverse property is the concept of passivity of a cybernetic system.

D. Complex of properties that determine the level of learnability of a cybernetic system

The learnability of a cybernetic system is the ability of a cybernetic system to improve its quality, adapting to solving new problems, the quality of the internal information of its environment model, the quality of its problem solver, and even the quality of its physical shell. The ability of a cybernetic system to improve (evolve, increase its quality), to self-improve with varying degrees of independence.

The maximum level of learnability of a cybernetic system is its ability to evolve (increase the level of its quality) as quickly as possible and in any direction, i.e. the ability to quickly and without any restrictions to acquire any new knowledge and skills.

Realization of the ability of a cybernetic system to learn, i.e. to solve the permanently initiated superproblem of self-learning, imposes additional requirements on the information stored in the memory of the cybernetic system, on the problem solver of the cybernetic system, and in the future also on the physical shell of the cybernetic system.

The most important characteristic of a cybernetic system is not only what level of intelligence the cybernetic system possesses at the moment, what set of actions (problems) it is capable of performing, but also how quickly this level can be increased.

learnability of a cybernetic system
⇒ *prerequisite property**:
- *flexibility of a cybernetic system*
- *stratified cybernetic system*
- *reflexivity of a cybernetic system*
- *limited training of a cybernetic system*
- *cognitive activity of a cybernetic system*
- *self-preservation ability of a cybernetic system*

Since learning always comes down to making certain changes to the cybernetic system being trained, without a high level of flexibility of this system, there cannot be a high level of its learning. The flexibility of possible self-changes of a cybernetic system is determined by the simplicity and variety of possible self-changes of a cybernetic system.

If the cybernetic system is stratified, it becomes possible to clearly define the scope of various changes introduced into the cybernetic system, i.e. the possibility of clearly limiting those parts of the cybernetic system beyond which there is no need to take into account the consequences of the primary changes made to the system (to carry out additional changes that are the consequences of the primary changes).

The reflexivity of a cybernetic system is the ability of a cybernetic system to self-reflection. The constructive result of the reflection of a cybernetic system is the generation in its memory of the specification of various negative or suspicious features that should be taken into account in order to improve the quality of the cybernetic system. Such features (disadvantages) include identified contradictions (mistakes), identified pairs of synonymous signs, homonymous signs, information holes.

The limitation of learning a cybernetic system defines the boundary between the knowledge and skills that the corresponding cybernetic system in principle can acquire and those knowledge and skills that the specified cybernetic system will never be able to acquire. This property determines the maximum level of potential capabilities of the corresponding cybernetic system. The maximum degree of absence of restrictions in the acquisition of new knowledge and skills is the complete absence of restrictions, i.e. full universality of the capabilities of the corresponding cybernetic systems.

The cognitive activity of a cybernetic system is curiosity, activity, and independence in acquiring new knowledge and skills. It is necessary to distinguish the ability to acquire new knowledge and skills, as well as to improve them, from the desire to do so. The desire (target setting) to learn how to solve certain problems can be formulated by a cybernetic system either independently or from outside (by some teacher).

cognitive activity of a cybernetic system
⇒ *prerequisite property**:
- *ability of a cybernetic system to synthesize cognitive purposes and procedures*
- *ability of a cybernetic system to self-organize its own learning*
- *ability of a cybernetic system to perform experimental actions*

The ability of a cybernetic system to synthesize cognitive purposes and procedures is the ability to plan its own learning and manage the learning process, the ability to ask questions or purposeful sequences of questions, the ability to generate a clear specification of its information needs. The ability of a cybernetic system to self-organize its own learning is the ability to manage its own learning, the ability of a cybernetic system itself to play the role of its teacher. The ability of a cybernetic system for experimental actions is the ability to deviate from the prepared plans of its actions in order to improve the quality of the result or maintain the purposefulness of these actions, the ability to improvise.

The higher the level of security of a cybernetic system, the higher its level of learning. The ability of a cybernetic system to self-preserve means the ability of a cybernetic system to identify and eliminate threats aimed at reducing its quality and even destroying it, which means a complete loss of the required quality.

E. Complex of properties that determine the level of intelligence of a cybernetic system

The main property, characteristic of a cybernetic system is the level of its intelligence, which is an integral characteristic that determines the efficiency level of interaction of a cybernetic system with the environment of its existence. The process of evolution of cybernetic systems should be considered as a process of increasing the level of their quality in a number of properties and as a process of increasing the level of their intelligence.

A cybernetic system can be both intelligent and non-intelligent. In turn, the intelligent system can be both low-intelligent and high-intelligent.

intelligence level of a cybernetic system
⇒ *prerequisite property**:
- *education of the cybernetic system*
- *learnability of a cybernetic system*
- *interoperability of a cybernetic system*

The level of education of a cybernetic system is the level of skills, as well as other knowledge acquired by a cybernetic system by a given moment.

education of the cybernetic system
⇒ *prerequisite property**:
- *quality of skills acquired by a cybernetic system*
- *quality of information stored in the memory of a cybernetic system*

Examples of an educated cybernetic system are:
- a knowledge-based cybernetic system;
- a knowledge-driven cybernetic system;
- a targeted cybernetic system;
- a hybrid cybernetic system;
- a potentially universal cybernetic system.

A learnable cybernetic system is a cybernetic system capable of knowing its environment, that is, building and constantly updating in its memory an information model of this environment, as well as using this model to solve various problems (to organize its activities) in this environment. Examples of a trainable cybernetic system are:
- a cybernetic system with a high level of stratification of its knowledge and skills;
- a reflexive cybernetic system;
- a self-learning cybernetic system;
- a cybernetic system with a high level of cognitive activity.

The intelligence of a cybernetic system, as well as the underlying cognitive process performed by a cybernetic system, has a social character, since it is most effectively formed and developed in the form of interaction of a cybernetic system with other cybernetic systems. A socially oriented cybernetic system has a sufficiently high level of intelligence to be a useful member of various, including human-machine communities. A certain level of socially significant qualities is a necessary condition for the intelligence of a cybernetic system. Examples of a socially oriented cybernetic system are:
- a cybernetic system capable of establishing and maintaining a high level of semantic compatibility and mutual understanding with other systems;
- a negotiable cybernetic system.

All properties inherent in cybernetic systems can have very different levels in different cybernetic systems. Moreover, in some cybernetic systems, some of these properties may not exist at all. At the same time, in cybernetic systems, which we will be conditionally called intelligent systems, all the above properties must be represented in a sufficiently developed form.

VII. Complex of properties that determine the quality of a multi-agent system

The transition from cybernetic systems to collectives of interacting cybernetic systems, i.e. to the social organization of cybernetic systems, is the most important factor in the evolution of cybernetic systems. A cybernetic system, which is a collective of interacting cybernetic systems with a certain degree of independence (self-sufficiency, freedom of choice), will be called a multi-agent system [18].

cybernetic system
⇒ *subdividing**:
{
- *individual cybernetic system*
- *cybernetic system, which is the minimum component of an individual cybernetic system*
- *cybernetic system, which is a complex of components of the corresponding individual cybernetic system*
- *community of individual cybernetic systems*
  ⇒ *subdividing**:
  {
  - *simple community of individual cybernetic systems*
  - *hierarchical community of individual cybernetic systems*
  }
}

The agents of a multi-agent system can (but do not have to) be intelligent systems. For example, agents of an intelligent problem solver with an agent-oriented architecture are not intelligent systems. An agent of a hierarchical multi-agent system may act as another multi-agent system [19].

In a multi-agent system with centralized control, there are specially allocated agents that make decisions in a certain area of activity of the multi-agent system and ensure the implementation of these decisions by controlling the activities of other agents that are part of this system.

In a multi-agent system with decentralized control [20], decisions are made collegially and “automatically” (decisions on recognizing new information proposed by someone including initiating a certain problem, decisions on correcting, clarifying previously recognized, agreed information) on the basis of a well-thought-out and constantly improved methodology, as well as on the basis of the active participation of all agents in the formation of new proposals to be recognized or agreed upon. In such a multi-agent system, all agents participate in the control of this system. An example of such a system is an orchestra capable of playing without a bandmaster.

The transition to multi-agent systems is the most important factor in improving the quality (and, in particular, the level of intelligence) of cybernetic systems, since the level of intelligence of a multi-agent system can be much higher than the level of intelligence of each agent included in it. This does not always occur, since the most important factor in the quality of multi-agent systems is not only the quality of the agents included in it but also the organization of the interaction of agents and, in particular, the transition from centralized to decentralized control. Quantity does not always become a new quality.

The quality of individual cybernetic systems is determined, among other things, by how much an individual cybernetic system contributes to improving the quality of the collectives to which it belongs. This property of individual cybernetic systems will be called the level of their interoperability [21].

A synergetic cybernetic system is a multi-agent system with a high level of collective intelligence, whose atomic agents are individual intelligent systems with a high level of interoperability [22] [23]. An example of a synergetic cybernetic system is a creative collective implementing a complex science-intensive project.

The effectiveness of the creative collective (for example, in the field of scientific and technical activities) is determined by:

- the consistency of motivation, goal-setting of the whole collective and each of its members (there should be no contradictions between the purpose of the collective and the creative self-realization of each of its members);
- the effective organization of decentralized control of the activities of collective members;
- the clear, prompt, and accessible to all documentation of the current state of the completed tasks and directions for its further development;
- the level of labor intensity of the efficiency for fixing individual results within a collectively created overall result;
- the level of structuredness and, above all, stratification of the generalized documentation (knowledge base);
- efficiency of associative access to documentation fragments;
- flexibility of a collectively created base;
- automation of analysis of the completed tasks and project control.

The intelligence level of a multi-agent system can be significantly lower than the intelligence level of the most "stupid" member of this collective, but it can also be significantly higher than the intelligence level of the most "intelligent" member of the specified collective. In order for the number of intelligent systems to turn into a significantly more intelligent quality of a collective of such systems, all intelligent systems combined into a collective must have a high level of interoperability, which imposes additional requirements on the information stored in memory, as well as on the problem solvers of intelligent systems, combined in a collective.

The interoperability of a cybernetic system is the ability of a cybernetic system to interact with other cybernetic systems in order to create a collective of cybernetic systems (multi-agent systems), the level of quality and, in particular, the level of intelligence of which is higher than the quality level of each cybernetic system that is part of this collective.

In order for the number of members of the collective of a cybernetic system to turn into a higher quality of the collective itself, the members of the collective must have additional abilities, which we will call the properties of interoperability. The main such properties are the ability to establish and maintain a sufficient level of semantic compatibility (mutual understanding) with other cybernetic systems and negotiability (the ability to coordinate own actions with others) [24].

Purposeful exchange of information between cybernetic systems significantly accelerates the process of their learning (the process of accumulating knowledge and skills). Consequently, the ability to effectively use the specified channel for the accumulation of knowledge and skills significantly increases the level of learning of cybernetic systems. Increasing the level of interoperability of a cybernetic system is, on the one hand, an additional increase in the level of intelligence of this cybernetic system itself, as well as a factor in increasing the level of intelligence of those collectives, those multi-agent systems that include this cybernetic system.

cybernetic system interoperability
⇒ *prerequisite property**:
- *negotiability of a cybernetic system*
- *social responsibility of a cybernetic system*
- *social activity of a cybernetic system*

Properties-preconditions for the level of negotiability of a cybernetic system are represented below:

Understanding information coming from outside includes:

negotiability of a cybernetic system
⇒ *prerequisite property*:*
- *the ability of a cybernetic system to understand received messages*
- *the ability of a cybernetic system to form transmitted messages understandable to recipients*
- *the ability of a cybernetic system to provide semantic compatibility with partners*
- *communication skills of a cybernetic system*
- *the ability of a cybernetic system to discuss and agree on the purposes and plans of collective activity*
- *the ability of a cybernetic system to take on the solving of urgent problems within agreed plans for collective activity*

- translation of this information into the internal language of the cybernetic system;
- local verification of input information;
- immersion (convergence, placement) of the text resulting from the specified translation into the stored information (in particular, into the knowledge base).

The immersion of the input information into the knowledge base of a cybernetic system is reduced to the identification and elimination of contradictions that arise between the immersed text and the current state of the knowledge base. The complexity of the problem of understanding the input verbal information lies not only in the complexity of the consistent immersion of the input information in the current state of the knowledge base but also in the complexity of translating this information from the external language into the internal language of the cybernetic system, i.e., in the complexity of generating the text of the internal language, semantically equivalent the input text of the external language. For natural languages, this translation is a difficult problem, since at present the problem of formalizing the syntax and semantics of natural languages has not been solved.

The semantic compatibility of two given cybernetic systems is determined by the consistency of the concepts systems used by both interacting cybernetic systems. The problem of providing permanent support for the semantic compatibility of interacting cybernetic systems is a necessary condition for ensuring a high level of mutual understanding of cybernetic systems and, as a result, their effective interaction.

The sociability of a cybernetic system is the ability of a cybernetic system to establish mutually beneficial contacts with other cybernetic systems (including collectives of intelligent systems) by honestly identifying mutually beneficial common purposes, interests.

Properties-prerequisites for the level of social responsibility of a cybernetic system are represented below:

social responsibility of a cybernetic system
⇒ *prerequisite property*:*
- *the ability of a cybernetic system to fulfill its obligations in a quality and timely manner within the relevant collectives*
- *the ability of a cybernetic system to adequately assess its capabilities in the distribution of collective activity*
- *altruism/selfishness of a cybernetic system*
- *absence/presence of actions that, due to the illiteracy of the cybernetic system, reduce the quality of the collectives it is part of*
- *absence/presence of "conscious", motivated actions that reduce the quality of collectives, which include a cybernetic system*

Properties-prerequisites for the level of social activity of a cybernetic system are represented below:

social activity of a cybernetic system
⇒ *prerequisite property*:*
- *the ability of a cybernetic system to generate proposed purposes and plans for collective activity*
- *activity of the cybernetic system in the examination of the results of other participants in the collective activity*
- *the ability of a cybernetic system to analyze the quality of all the collectives it belongs to, as well as all members of these collectives*
- *the ability of a cybernetic system to participate in the formation of new collectives*
- *quantity and quality of those collectives in which the cybernetic system is or was a part*

The formation of a specialized collective of cybernetic systems comes down to the fact that in the memory of each cybernetic system included in the collective, the specification of this collective is generated, which includes:
- a list of all collective members;
- abilities of each member of the collective;
- their responsibilities within the collective;

- specification of the entire set of problems (type of activity) for the solution of which the given collective of cybernetic systems is formed.

Each cybernetic system can be part of a large number of collectives, while performing, in the general case, different "duties", different "business processes" in different collectives.

VIII. Conclusion

To increase the level of automation of human activity, it is necessary to automate more complex problems. The solution of such problems is reduced to the requirement to increase the level of intelligence of individual cybernetic systems. However, the individual intelligence of cybernetic systems has its limitations. It is possible to achieve a significant increase in the level of intelligence by forming collectives of cybernetic systems, i.e. move to multi-agent systems.

Thus, one of the most important factors determining the level of intelligence of a cybernetic system is interoperability, the ability to form collectives with individual cybernetic systems. At the same time, the level of quality of individual cybernetic systems of the entire collective should be quite high. This will allow the number of intelligent systems to be transferred into a significantly more intelligent quality of the collective of such systems.

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Факторы, определяющие уровень интеллекта кибернетических систем

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В работе рассмотрена иерархическая система свойств кибернетических систем, определяющих их качество и позволяющих сформулировать требования, которым должна удовлетворять кибернетическая система с сильным интеллектом. Уровень качества кибернетических систем определяется достаточно большим набором параметров кибернетических систем. Каждый из параметров определяет уровень качества кибернетической системы в соответствующем аспекте, указывая уровень развития конкретных способностей и возможностей кибернетической системы. Полученные результаты позволят оценить уровень качества кибернетических систем, а также определить направление развития кибернетической системы для повышения уровня интеллекта.

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