Incorporation of Duality into the Computational Processes of Neural Network Decision-Making Components within Mobile Robotic Systems

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Abstract. The article suggests and investigates the method for optimization of the reliability of mobile robotic systems developed using neural network decision-making components. This method is based on the idea of incorporating duality in the processing of information by artificial neural networks. As a result of the incorporation of duality, the system initiates the implementation of operations that direct the system to autonomous provision of effective functioning and maintenance of specified reliability indicators, and not exclusively to processing the information that can be distorted by external and internal destabilizing influences. The computer model of the robotic system was used as an object of the experimental research, where the neural network decision-making component provided the execution of three basic functions: control of the motion along a given trajectory, reaction to the presence of obstacles on the trajectory of motion and determination of stopping points on the route with the purpose to perform a useful action. The conducted research confirmed the effectiveness of using the proposed method for solving the task of ensuring maximum reliability indicators (accuracy of functioning under external and internal destabilizing influences) of neural network decision-making components in mobile robotic systems belonging to the class of intelligent systems.

1. Introduction

In the modern world, the level of development of robotic systems (RS) is conditioned by the use of artificial intelligence (AI) technologies [1]. Objects of this class enable to solve tasks, which hitherto relate to purely human ones, with different degrees of efficiency, which is often the highest possible [2-4]. In particular, one of the most promising tasks at the intersection of two scientific fields - AI and modern robotics - is the creation of autonomous mobile RSs capable of orientation in space and independent decision-making in a precarious real situation. As a rule, such systems are based on decision-making components that can effectively perform difficult-to-formalize operations. The main means of constructing such components are artificial neural networks (ANN) [5-10]. Technologies of parallel processing of information provide for the application of a fundamentally new approach to the synthesis of computational methods in the algorithmic sense. This technology provides the RS with the opportunity to learn by examples and to adapt the process of the system functioning, while maintaining the consistently high technical performance of the system under external conditions not considered at the training stage. There appears the possibility of constructing effective RSs without laborious and often impossible creation of analytical descriptions, the ability to operate with fuzzy concepts.

However, with hardware implementation, the use of these means affects negatively the reliability of the RS [11-15]. This is due to the fact that the accuracy of functioning obtained at the training stage is not always ensured automatically in the course of further work. This is associated with the production and operational variations in the values of parameters of the system elements, which must be taken into account when forming an autonomous system with signs of artificial intelligence. The existing mechanisms for providing specified reliability indicators cannot be applied to new generation computing systems built with the use of fundamentally new architectures, applying different principles of information processing and requiring the use of other electronic element base.

Thus, it is necessary to perform experimental studies, which are aimed at formation of the foundations of AI in mobile RSs as a means of autonomous provision of effective functioning, maintaining specified values of reliability and life support of these systems used in solving the applied problems.

2. Analysis of the current state of research in the field of the use of AI in robotic systems

AI technologies existing today in most cases are associated with such statistical methods of analysis and information processing as machine learning, deep learning, genetic algorithms, etc. A wealth of experience has been accumulated in terms of successful solution of practical problems in many fields of science and technology [16-25].

However, AI tools did not become widely used for solving tasks of provision of effective functioning and life support of technical data processing objects. The most promising direction of application of this type of cognitive activity is robotics. Construction of mobile intelligent RS capable of adaptation, self-learning and self-development is a logical application of AI technologies.

Scientific and technical sources analysis [16-25] showed high relevance but low intensity of research in the field of creating technologies for self-maintenance of the process of functioning and ensuring RS maximum technical characteristics through AI. Existing results of interdisciplinary empirical studies [16-23] lying at the intersection of scientific fields of AI and robotics contributed to the accumulation of important knowledge revealing the fundamental principles forming the RS construction and functioning base, however, they did not allow achieving the end results. The study of these materials provided additional insight that at the given moment of time there existed only common theoretical developments that allow only partial solution of the stated tasks and which have a large number of disadvantages. In particular, the degree of self-sufficiency in decision-making by robots lies solely in the field of execution of the stated task and does not affect the processes of self-analysis and life support of the system within the given limits reflecting the true meaning of the “AI” term.

In addition, the main modern mass approach to creation and improvement of AI tools in robotics consists in the development of methods and algorithms, as well as in software implementation thereof on the basis of classical computing systems with von Neumann architecture [24-25]. The theory and methods for AI tools practical application in most cases are being developed without taking into account the possibility of their hardware implementation in the form of specialized electronic computing machines, which operating principles are comparable to the AI algorithms.

When comparing the results of analysis of the current state of research in the field of the use of AI in robotics with the results expected within the framework of this study, it may be concluded that the proposed approach will allow creating a research and practice base for creation of AI and RS machine consciousness focused on the support and achievement of maximum technical characteristics, including provision of the specified reliability indicators, that will have the edge over the existing base.

Expected results of the experimental research of the method for incorporation of duality into the computational processes of neural network decision-making components within mobile RSs have an innovative potential, as they are aimed at the emergence of new and universal fundamental principles of the RS cognitive activity. These principles form the strive to the robots self-sufficiency and represent a platform for developing the system intelligence generated on the basis of its existence under contradicting conditions.

From this perspective, the solution of the given scientific task contributes to further development of the AI theory and will allow creating mobile intelligent RSs having the maximum technical characteristics.

3. Methods

3.1. Theoretical aspects of the proposed method

The linearity of the algorithmic form of the AI behavior in RSs means the certainty factor *I* for each subsequent step *a* driven by the effect of information received from the system of primary sensors (the sensor system). If we express definiteness in terms of the probability of the action, we get $I_a=1$. This value *I* determines the absence in the neurobionic system of truly intelligent activities, including cognitive ones, which make it possible to ensure the viability of this system by studying the equilibrium state of the system when it interacts with the environment (homeostasis). If in the process of functioning of such a system an uncertainty $I_a<1$ will appear, then the appearance of duality in decision-making and the stimulus for the system to perform additional independent cognitive operations is possible in theory subject to the appropriate training of this system. Thus, we must obtain a system by means of which every action can be performed within a system upon condition that an uncertainty equals to one. At the same time, before the action is carried out, a duality is initiated that brings this uncertainty out of the equilibrium state, which results in the system having to return to the state of certainty by performing additional cognitive actions that are not related to the solution of the general practical problem.

In particular, consider the elementary operation (1) of information conversion inside a neuromorphic system - deliberation of the signal carrying information *x* with the use of the weight coefficient of the synaptic connection *w*.

$$y = w \cdot x \tag{1}$$

Equation (1) is one of many operations performed inside a computing system with parallel architecture, and the certainty of its execution for a known variable x and a known constant w equals to one. Figure 1 shows the structure and mathematical explanation of duality in the process of information conversion when this operation is being performed.

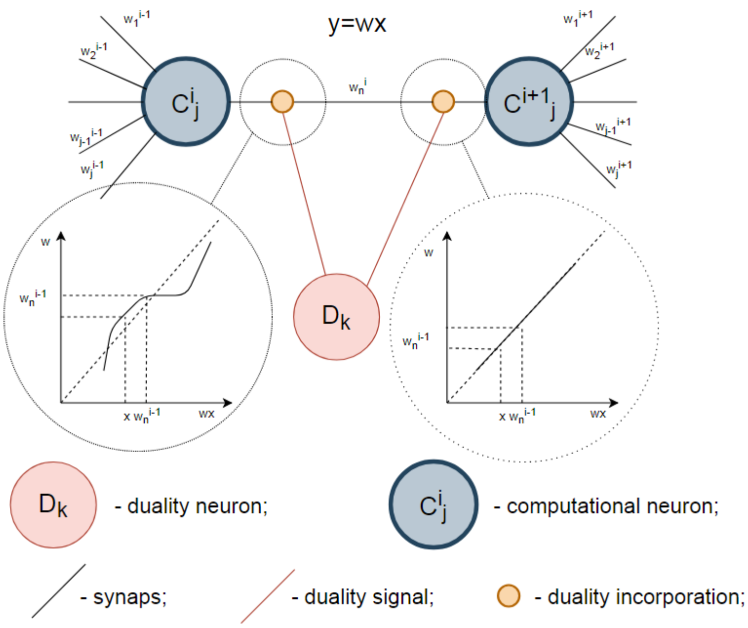

Figure 1. The explanation of the process of incorporating the duality in information conversion by elements within neural network decision-making component.

It is assumed that the neural network decision-making component within the RS consists of two parts: computational part and duality part. The structure and mathematical description of the first is individual for each particular task being solved and depends on the chosen basic computing architecture. The computational part is formed at the stage of engineering design of the neural network component. The basic computing architecture is synthesized, and hyperparameters are selected (number of layers, number of neurons in each layer, neuron activation functions, etc.). The next step in creating these systems is the training process. After its completion, we obtain a computational structure (qualitative and quantitative set of elements and interrelations between them) capable of solving the defined decision-making task.

The second is universal and invariant in relation to the first one and implies the complication of the neurons that make up its composition. The principle of functioning of such neurons will correspond to the neurobionic approach. The duality part will act as an analog of the biological proprioceptive system in a technical facility. This task of controlling and correction is more adequate for a structure with complex neurons.

3.2. Set of methods of experimental research

The basis for the set of methods to be used in this research is the scientific hypothesis that the process of studying specialized neural network decision-making components within intelligent RSs should be based on an experimental examination of the set of structural and functional properties of the software and hardware implementation of the system.

The advantage of this set of methods, ensuring its effectiveness in the solution of research problems, is that it allows to take into account all the basic properties of complex and non-trivial systems that affect the state of these systems and are not taken into account by other methods:

- Integrity (irreducibility of the properties of the system to the sum of the properties of its constituent elements).
- Structuredness (the system consists of certain elements and their interrelations).
- Consideration of structural elements as independent systems (subsystems) proceeding from their functional belonging.
- Dependence of the system on the influence of the external environment.

On the basis of the proposed structural and functional approach to investigating a neural network decision-making component within RS, we have developed a specific methodology. The methodology comes down to the following successive actions:

- Decomposing the system according to the functional features and defining the structural characteristics at the element level inside the system and at the level of the system’s interrelation with the ambient environment.
- Modeling the subsystem’s operation that ensures the learning of the system with a successive analysis of the variations of qualitative values of the subsystem’s parameters and an analysis of the impact of these variations on the system’s operation as a whole.
- Modeling the subsystem’s operation that ensures the input information processing with a successive analysis of the variations of qualitative values of the subsystem’s parameters and an analysis of the impact of these variations on the system’s operation as a whole.
- Modeling the subsystem’s operation that characterizes the physical processes related to the use of nanoscale elements with a successive analysis of the variations of qualitative values of the subsystem’s parameters and an analysis of the impact of these variations on the system’s operation as a whole.
- Building the structural and functional model of the system that helps to reveal cause and effect relations while forming the fault tolerance index of the system.
- Forming the process of fault-tolerant operation of the computing system in question at the design engineering stage.

At the core of the proposed set of methods lies the scientific idea, which has an absolute novelty and differs from other ideas related to hardware engineering of AI tools on the basis of the following provisions:

- The process of experimental research of AI tools within RSs, performed on the basis of the set of structural and functional methods, is invariable to the structure of the system being created and the type of the task being solved.
- When using the set of structural and functional methods, all the factors that predetermine values of quality, reliability, fault tolerance and functioning accuracy indicators for any AI tools within RSs are taken into account.
- The set of structural and functional methods allows to track the provision of specified indicators of the main technical characteristics of the system during the testing stage without complicating the computing system being created.
- The set of structural and functional methods allows us to consider the formation of the indicators in question as a change in the quantitative value of the system parameters, as a result of which all processes are maximally formalized, and their interpretation is justified.
- The set of structural and functional methods requires the study of the dynamics of processes occurring in the system (in particular, in the event of hardware implementation the accuracy may gradually decrease during system operation).

3.3. The description of object of the experimental research

As an object of experimental research it was chosen an industrial mobile RS in which the neural network component of decision-making generates, based on the input information from the primary sensors, three types of controlling influences: control of the RS movement along a given trajectory, reaction to obstacles on the trajectory and determination of stopping points on the route. Figure 2 shows the conceptual design of the RS.

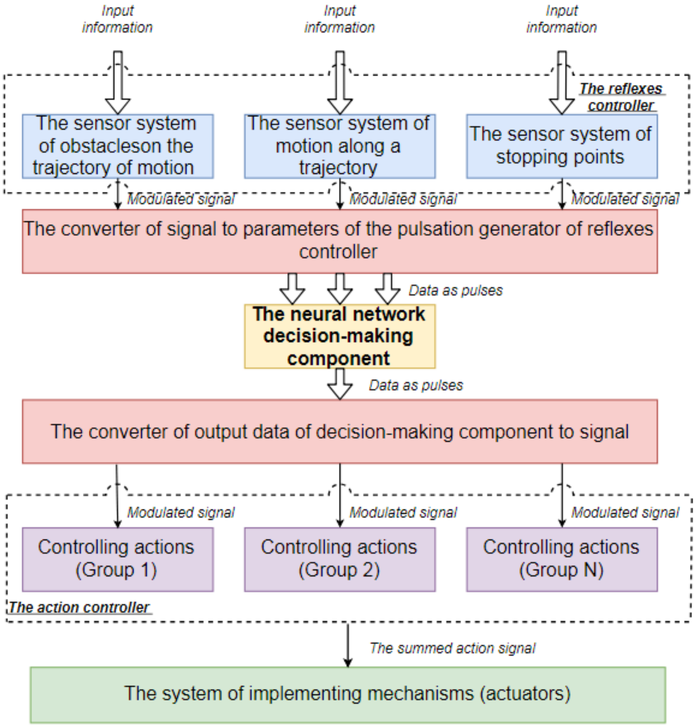

Figure 2. The conceptual design of the RS developed using neural network decision-making component.

In the system "MATLAB" a computer model of this neural network component of the RS was developed. This component is a trained three-layer, fully connected feedforward artificial neural network (ANN) with 55 neurons in the first layer, 30 in the second and 3 output neurons for information providing from which impulses are received, which generate the controlling influences for the three types of execution units. The activation function of the first and second layers is tangential, the function of the third layer is linear. The tangential function satisfies the condition of the range of input data (-1; 1), and the oddness of this function makes it convenient for solving decision-making tasks. The ANN training algorithm is the Levenberg-Markquardt algorithm with Bayes regularization (TRAINBR function in "MATLAB"). The training of the synthesized ANN was carried out until the maximum accuracy (minimum error) was reached by the sum of squares of errors (SSE), the total value of which was $7.79 \cdot 10^{-13}$. Figure 3 show the results of training, validating and testing the correctness of operation of the computer model of the research object.

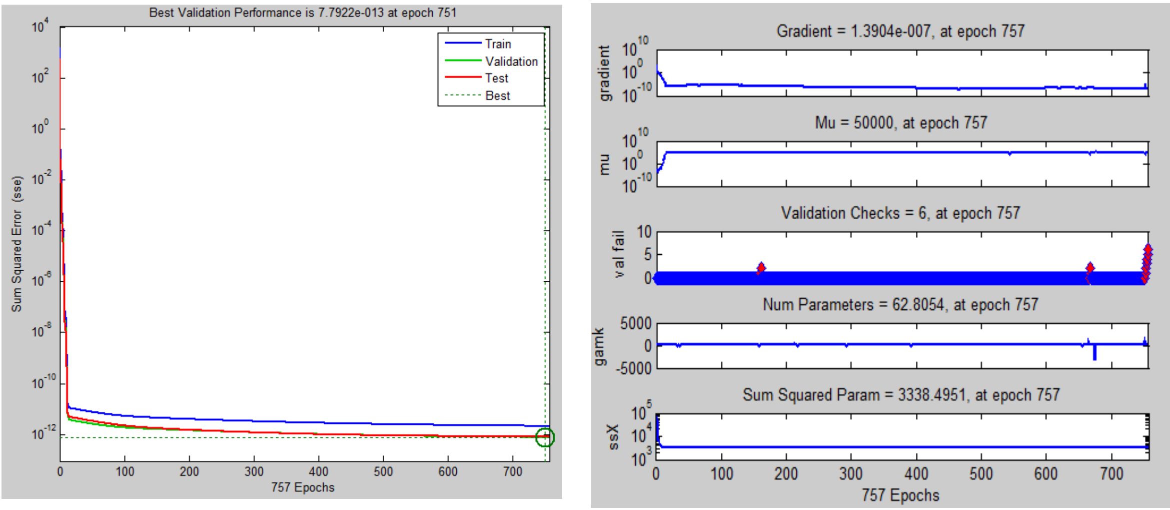

Figure 3. The results of training, validating and testing the correctness of operation of the computer model of the research object.

Further, the processing of information from the originally synthesized ANN was modified according to the methodology developed in the framework of this study. In Table 1 we can see the recorded variations in the accuracy of the functioning of the ANN under study for different types and degrees of influence of destabilizing influences.

4. Results and Discussion

The experimental research consisted of several stages. At the first of them, an earlier-described computer model of a neural network decision-making component, which is capable of functioning within the limits of specified tolerances on the accuracy of information processing without the influence of destabilizing factors, was synthesized. The obtained quantitative values of the functioning accuracy are presented in Table 1. Then, possible external and internal destabilizing influences were created programmatically, which are an integral part of the information processing process in the hardware implementations of computing devices. These influences represent various changes in the numerical values of the parameters of neurons, namely weight coefficients and threshold displacements functioning as the components of an artificial neuron, as well as changes in input information that can be caused by a distortion of the electrical signal carrying this information. At the next stage, duality, which consists in the creation of an adaptive subsystem with a constant global goal, was incorporated into the processes of information processing by the elements of the neural network component. This goal is the achievement of a balance between the search for new, unpredictable stimulation and the striving for predictability of the results of own behavior. After the incorporation of the duality, the study object was deeply trained, which is necessary for separating the functions of the neurons and dividing the information flows. After the deep training of the system, the accuracy values of its functioning were calculated. Then the experiment was repeated under the influence of external and internal destabilizing values similar to those applied prior to incorporation of duality. All the data obtained are presented in Table 1.

Table 1. The results of an experimental investigation of the duality incorporation method.

Parameters of the computing elements, from 10 to 20 random parameters	Errors Values of the Parameters, %	Functioning Accuracy of the Neural Network Component, SSE	After incorporating the duality	
			The amount of changes in decisions, %	The amount of correctly changed decisions, %
The weight coefficients of the synapses	10	$8.56 \cdot 10^{-9}$	91	84
	20	$1.97 \cdot 10^{-8}$	89	86
	30	$9.66 \cdot 10^{-7}$	92	90
	40	$9.21 \cdot 10^{-4}$	90	86
	50	$1.14 \cdot 10^{-1}$	91	89
The threshold displacements of neurons	10	$6.08 \cdot 10^{-9}$	89	89
	20	$2.09 \cdot 10^{-8}$	92	88
	30	$9.83 \cdot 10^{-8}$	92	87
	40	$5.87 \cdot 10^{-5}$	92	92
	50	$2.01 \cdot 10^{-1}$	91	86
The distortion of inputs data	10	$1.25 \cdot 10^{-8}$	92	90
	20	$5.02 \cdot 10^{-6}$	85	88
	30	$1.13 \cdot 10^{-4}$	85	91
	40	$4.04 \cdot 10^{-3}$	90	90
	50	$2.38 \cdot 10^{-1}$	92	82

The results of the analysis of the data presented in Table 1 indicate the efficiency of the proposed method for solving the task of ensuring maximum reliability indicators (accuracy of functioning under external and internal destabilizing influences) of neural network decision-making components in mobile robotic systems belonging to the class of intelligent systems. When applying these effects to the system prior to making structural changes in it, according to the proposed method, the accuracy of functioning critically decreased. As the performed experiment shows, after the incorporation of duality, we can observe the reaction of the system to artificially created destabilizing influences. This confirms the possibility of formation of the AI foundations in mobile RSs as the means of autonomous provision of effective functioning and life support of these systems, using the proposed method of duality incorporation.

5. Conclusions

As a result of the performed experimental research, the target goal was achieved. The main scientific and practical results include the results of approbation of a new method for optimizing the reliability of mobile RSs developed using neural network decision-making components. The experimental researches performed confirm the effectiveness of the application of this method under conditions of influence of external and internal destabilizing factors on the process of RS functioning.

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