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Development of an Intelligent Control System for Hybrid Stepper Motor as a Tool for Increasing the Efficiency of the Drive

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ABSTRACT An example of the organization of intelligent systems is presented as a further generalization of multi-level network projects implementing modes, measurement, calibration, monitoring, and correction of the control signal. The structure of executive means of intelligent control based on a vector-indicator and recurrent sequences in the form of a transformed expansion into a Taylor series is proposed. It is demonstrated that the exponential representation of the Euler sine with the recurrent expansion and the Laplace transform reduce the nonlinear model to an analytical one for the hybrid stepper motor. Angular movement of the rotor, currents in the phase windings and the transfer function are presented in the image of voltage drops. Five samples of existing hybrid stepper motor models were obtained and statistically investigated in the Matlab Simulink environment. Two experimental research methods of non-contact rotation angle measurement by a mirror-reflected laser beam and a laser rigidly connecting with a rotating shaft are presented. Research of the experimental models for full-step and half-step settings of the motor driver demonstrates the need for intelligent correction of the model for an adequate response of the executive means of the intelligent systems.

KEYWORDS intelligent system; executive means; structure; stepper motor; analytical model; experimental methods; non-contact measurements; laser beams; Simulink model; correction.

I. INTRODUCTION

Achievements in creating highly productive single-board computers together with a new model based on the essence of concept intelligence: knowledge, methods, goals, and criteria widen the ability to use large amounts of long-term and short-term memory [1]. The modifications of distributed information systems essentially open new ways of developing [1]. The expansion needs of automation in industry increasingly demonstrate the compensation of errors in an intelligent sensing instrumentation system in the new applications of mechatronic devices [2]. The analysis of several projects shows the tendency to search for means that use devices suitable for analyzing, changing conditions and intelligent restructuring [2]. The experience of multi-layer network projects functioning [3], implementation of calibration modes [4], observation, measurement through the use of a vector-indicator [5]. The recurrent sequences in the form of transformed Taylor expansion open new analytical opportunities for intellectual analysis and decision-making [5]. The need for fast parallel processing of large arrays of information with simultaneous directed activity and the use of knowledge bases stimulate the creation of intelligent systems [6]. By intellectualization, we will understand the process that, based on tasks, information, training, and knowledge synthesizes a decision about an effective action or a sequence of actions. Under the intelligent system (IS), we will understand the combined structure of technical, methodological, algorithmic, and software tools for decision-making and executive actions that are interconnected with the operator or do not depend on him. Such tools are capable of synthesizing decisions about an effective sequence of actions on the basis of information and knowledge.

Further development and detailing of the generalized structure of the IS for individual cases, due to the application databases of measured with tolerance estimation [7] knowledge, and algorithm based on parallel calculations in the task of tolerance ellipsoidal estimation [8], will further expand their capabilities. However, when implementing the tasks of practical implementation of the defined concept of intellectualization, theoretical problems arise related to the state and development of computerized systems and practical difficulties in their implementation [9]. The desire to solve them by developing the structure and improving the elements as a universal system quantitatively increases and complicates its structure and reduces reliability, but at the same time, it will increase the cost.

In this regard, it is important to search for innovative ideas that could simplify the structure due to the unification of modules. The principle of intellectualization and its tools for the peripheral level, which can reduce the overall cost and make the system socially accessible, is relevant.

II. ANALYSIS OF RELATED WORKS

Due to the spread and achievements of hardware capabilities and the openness of the code of single-board computers, conditions have been created to develop further and implement IS. Work [3] presented an analysis of the development of scientific and technical progress and social changes that require the use of the latest scientific solutions and tools for the further development of society. Robotics, automation, transition to a continuous digital format of information data streams are defined as distinguishing features of society. Intellectual technologies are a prerequisite for the active development of all spheres of human activity. Neural networks and artificial intelligence with its tools of express analysis and automatic inference are an artificially organized parallel component to human activity in the fields of design, construction, medicine, business, communication, and so on [3]. Credibility and reliability as a basis for people and industry covers the main aspects of the application of the Internet of Things (IoT) and systems based on it [4]. The global problem of reliability of applications, modeling, development for the implementation of reliable actuators based on hybrid stepper motors (HSM) for various human and industrial domains is also relevant and important [4]. In this regard, the problem of structuring reliability and continuous control of the hardware used is extremely important for processing experimental data and requires the isolation of the influence of hidden failures during the formation of the model [4]. Determining and forming a list of factors influencing the value of the model error for hybrid models of IS is an important informational component [5]. The applied functional analysis methods give an analytical estimations suitable for express calculation [5]. In work [6], it was demonstrated that the use of a recurrent network as a tool, which also allows calibration in automated systems, is no less important for the further improvement of IS. Calibration together with recurrent approximation (RA) as a tool expands the functionality of the network [6]. Another problem is the need to estimate methodical and instrumental error components [7]. The error, being a complex value of multifactorial influences, ensures the informational completeness of experimental data [7]. The evaluation of the quantitative interval of the influence of each of the factors separately for problems of radio electronic circuits, carried out by the method of ellipsoidal evaluation, was presented in paper [8]. However, the full benefits of using the method, which opens up the possibility of parallelization [8], cannot be realized as a result of the quantization problem.

The theoretical application of RA is the operation of forecasting the state of systems [9]. No less important for the further development of IS is the application to the description of qualitative quantities [9]. The joint application of normalization and transformation of the operations of union, intersection and addition over membership functions opened opportunities for applying mathematical analysis methods to solving problems of optimizing process parameters using IS [9]. The use of the state forecasting as an integral part of the IS functions was discussed in [10]. Predictive evaluations as criteria for correcting procedures allow controlling the process taking into account the actual response of the automated control system (ACS) [10].

However, the analyzed works do not establish a connection between methodical, instrumental and random errors, which hampers the determination of the reliability of experimental data. In this regard, the presented results [11] of the development and production experience with the new HSM, are important. Significantly improved torque characteristics of the HSM ensure its application, in particular in robotics and units of automatization. Theoretical and experimental research presented the results of the impact of design improvements of combs and magnets on the characteristics of two types of HSM. However, during modeling, the model error was not estimated, and comparisons were made only based on experimental data, the reliability of which was not presented. The work [12] is devoted to the development of a simplified mathematical model of SM. A mathematical model of a two-phase HSM was constructed, in which the basic physical assumption is to ignore the spatial harmonics of the permeability. This paper derives simple voltage, current, and torque equations, but Simulink models are used for comparison. The fact that the reliability of the proposed model is checked by comparison with the results of the Simulink model in the Matlab library is contradictory and methodologically wrong. Therefore, despite the good coincidence of the obtained simulation results for both models, it is only possible to assert that their samples are not statistically different. For the transparency of the process of creating a model, a SM working with an open control loop, was considered in [13], and feedback was used to increase the efficiency of work. A highly effective angle position regulator of the shaft and a speed chain are used to correct the nonlinear characteristics taking into account external loads. It was shown that the programmable logic matrix (FPGA) was an alternative for the implementation of the SM drive system. The proposed steps compensate for the lack of accuracy of the SM models for different voltage drop growth laws, which will require an assessment of the accuracy of the Simulink model as one of the possible options for prelaunch settings and tests. Paper [14] presented complex results of model formation, experimental data, and simulation in the Matlab environment using the Simulink model. The simulation oscillograms presented graphically were provided, but numerical data, root mean square errors, or other quantitative parameters of the experimental results and comparison of the mathematical model and Simulink models were not provided. In [15], it was proposed to use PC for a disturbance observer and a micro-step current control. The improvement of tracking the shaft position when working in the micro-step mode, which is achieved in the current feedback mode, is experimentally shown. The main idea of increasing the accuracy of shaft rotation is to track the resulting EMF and error compensation in the estimation of the back EMF without improving the model. However, the implementation of such an approach for HSM of manipulator links, where speeds and accelerations reach significant values, remains unsuitable. Another approach is observed for powerful motors of the main links, such as manipulators or autonomous robots, where the power of the motor reaches several kVA [16]. Simultaneous control of hybrid, parallel applications with multiple converters reduces transient time and power loss by 28.6%–78.3%. However, the lack of accurate models leads to the need for experimental studies of the compensation processes of the motor fixed frequency, determination of the dominant voltage converter, and adjustment of programs. The need to establish accuracy characteristics for Matlab/SimMechanics, which models hand movements to describe the kinematics of an anthropomorphic robot, was especially emphasized in [17]. Kinematic and dynamic models using Matlab parameters provide motion control, but they do not establish their accuracy, which limits their application. Analogous tasks were defined in work [18] in the process of modeling and analysis of the application of the inverse kinematics method of an anthropomorphic manipulators. As shown in [19], attempts to use reference control models to avoid collisions of an operator-controlled manipulator also require models with known positioning errors to predict the next position [19]. The need for an accurate model is also observed when modeling and controlling the torque of the well-known robot Puma 600, which is carried out using fuzzy logic [20]. Speed as one of the characteristics of the robot is determined by the accuracy of the predicted position, which also largely depends on the model accuracy of individual joints for robot links [21].

Along with an overview of the latest works demonstrating the success of the development of SM and HSM models it needs to present an analysis of the trends in the improvements of drive systems built on the experience of their use. The rapid prototyping of Matlab programs is a simple tool, but they do not have proper hardware support [22]. The target controller is connected via a serial port to the host computer. Such a structure is an integrated toolkit of the distributed principle that meets the requirements for real-time operation [22]. Another example of an SM model with a permanent magnet is software in the Matlab environment with Simulink tools [23]. Its SM drive hardware structure and software are designed and tested for different types of SM movements, which proves the possibility of coherent operation [23]. Another group of works that captures the trend of wireless remote control using wireless network services is described below. Thus, work [24] demonstrated SM control using a smart mobile phone application. A Blynk web application for the IoT was developed to control the step size of an SM remotely [24]. An extension of brushless DC motor control examples as a growing network of physical objects that have an IP address to connect to the Internet and the communication that occurs between these objects and other Internet-enabled devices and systems was presented in [25]. Other examples of remote control of the SM using radio frequency modules of the STT-433 MHz transmitter, the STR-433 MHz receiver, the HT640 radio frequency coder, and the HT648 radio frequency decoder were given in article [26]. Further development of digital control systems HSMs with high-precision positioning becomes more attractive for robotics and numerically controlled machines [27]. Using an embedded NodeMcu microcontroller and Wi-Fi enables control of actuators such as an SM via IoT [27]. The growing needs for modeling in Matlab are presented as an advantage of the environment, which allows the use of a real SM for smartphone control [28]. Equally important are the results of work in a simulator, based on linearized equivalent circuits with a variable reactive and permanent magnet or a HSM [29]. The capabilities of the BlueSteps system were shown in [30]. The wireless control of SM is implemented through an FPGA connected to a Bluetooth module and a special assembly driver circuit [30]. The SM driver controls the angle and direction of the SM, while the magnetic sensor is for positioning control [31]. Universal asynchronous receiver/transmitter (UART) is used in this work to exchange data with ZigBee module, byte conversion needs to be developed in FPGA using Verilog HDL. The prototype created and tested for its various functions is an aid to the user [31]. An automation system that plants seeds, waters crops, controls air production, monitors plant health, and forms a plant database using applications and algorithms for crop detection is an example of controlling by Arduino and Raspberry PI manipulator in agriculture using IoT applications [32]. The IoT integration with a three-degree-of-freedom robotic arm with a mechanical gripper enables the implementation of smart industry tasks [33]. Experience with its control using an Android mobile device to perform the pick-and-place operation and graphical display of movements as feedback in Matlab confirms a steady trend toward integration [33]. The results of using Arduino as a control board presented in [34] demonstrate distance measurement to objects and implement the intellectualization of manipulator movement. The latter confirms the feasibility of creating socially accessible IS and stimulates further research. Peculiarities of data transmission from the sensors of a controlled robotic arm using Arduino via Wi-fi or Bluetooth module to a smartphone were realized and presented in [35].

Thus, the analysis of trends and component achievements that reflect the development and possible signs of innovative improvements and examples for justifying the review of decisions presents an IS as an object of research. The structure of technical, methodological, algorithmic and software tools, which synthesizes and presents an alternative solution based on knowledge, as a result of training, parallel to human activity, needs improvements at various levels of universality. Intellectualization and modularization of functions at the peripheral level of the structure is key in creating socio-economically accessible intelligent devices and general-purpose robotic systems.

The main unsolved problem is the improvement of the general purpose HSM drive with a non-changing hardware structure of the driver.

III. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of the study is to improve the efficiency of drivers by justifying and building intelligent drive systems at the peripheral level. To achieve the goal, the following objectives are formulated:

- Substantiate the generalized structure of intelligent drive systems at the peripheral level;
- Improve the mathematical model;
- Conduct an experimental study of the drive and establish the adequacy of the Simulink model in the Matlab library

IV. RATIONALE AND DEVELOPMENT OF INTELLIGENT DRIVE SYSTEMS AT THE PERIPHERAL LEVEL

A. JUSTIFICATION OF THE GENERALIZED STRUCTURE OF INTELLIGENT DRIVE SYSTEMS

The IS proposed and studied in [3] was taken as a prototype. Based on the analysis of the advantages and disadvantages of the structure and experience with hybrid architecture decision support systems in underwater technology [5], conclusions were drawn as innovative improvements:

- a division of knowledge base in the structure of the prototype on the independent two structure's elements: knowledge base and database - is needed;

- a process of developing the knowledge base and database and their list correction is an undivided part of the life cycle of an automated control system with the elements of intellectual processing.

The proposed IS as a new generalized structure is presented in Fig. 1. In comparison with the prototype [3], IS with the following novelty is proposed:

- Firstly, the knowledge base is divided into the knowledge base and the database;
- Secondly, each of these bases is connected by a bidirectional ware link with block executive means with intelligent control;
- Thirdly, each of these systems is using means of Wi-Fi communication with a cloud manufacturing environment;
- In addition, it is provided that the unit for executing means of intellectual control as a complex of blocks will contain electric drivers, sensors, microcontrollers, and single-board computers, each of which is part of intellectualized means at the peripheral level.

To substantiate the proposed innovative improvement all of them are provided with means of two-way information exchanges with the database and knowledge bases which are divided into models, tools for estimation, and algorithms of the ACS hybrid architecture. The drives themselves can be made according to the modular with integral principle. Their functioning involves a two-way connection between databases, knowledgebase and algorithms, and the block of forecasting results. Changes in the state of the control object and drivers are recorded by feedback sensors. Note that it is part of the conditional block of executive means of intelligent control, which is noticed by a dashed line. It includes several blocks for various executive mechanisms. According to its structure, together with connected blocks: analysis, forecasting, and comparison of results, and synthesis of control influence [5] are realized as elements of training, calibration, and correction of the control signal [6]. This analysis can be done only with the analytical mathematical model corrected by an experimental study.

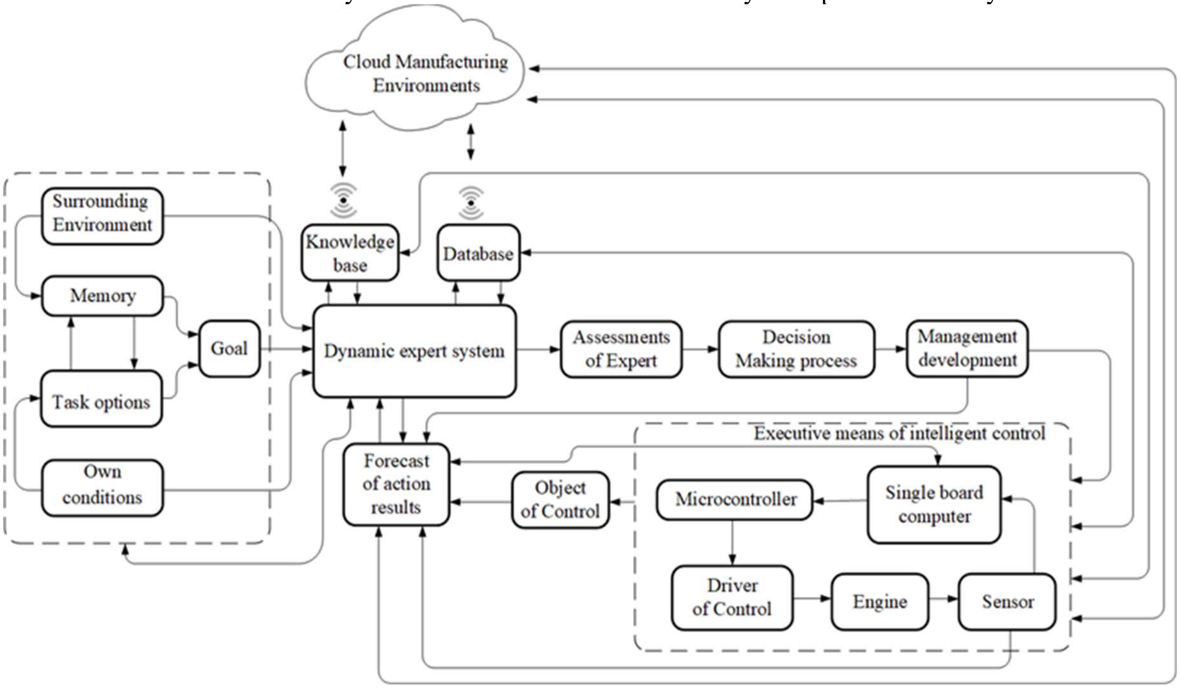


Figure 1. Schematic representation of the generalized structure of the intelligent system [3], which has been improved

A schematic representation of the generalized structure of the assembled block of executive means of intelligent control and information flows is presented in Fig. 2. Under these conditions, we will generally consider the structure of the control unit in two variants. The first variant is a single-board computer. Second is a one-board computer with an additional controller with a radio channel or Bluetooth for data exchange functions.

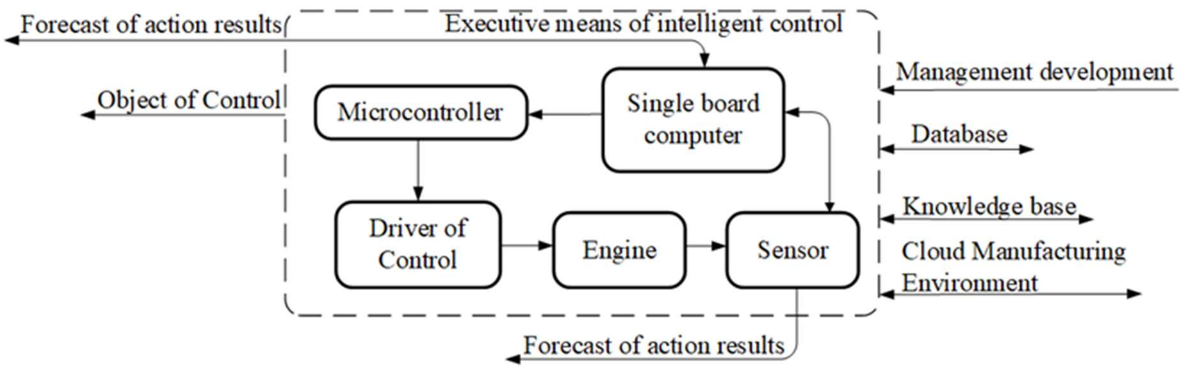


Figure 2. Schematic presentation of the generalized structure of executive means of intelligent management and information flows.

The main hypothesis was put forward in the following formulation: Modern single-board computers can simultaneously control three executive drivers and collect information about their state according to functional requirements, parametric and economic indicators, and open code. Also, according to its structure, the block of executive means of intelligent control functions is shown in Fig. 2. The single-board computer selects the appropriate control algorithm depending on the information from the feedback sensors and the state of the control object and executive drive. As a single-board computer, it is possible to choose an Arduino Uno Rev2 or Raspberry Pi 4 or a laptop equipped with radio communication. Digital control signals synthesized by a single-board computer are transmitted either directly to the electric driver or via a microcontroller. The microcontroller unit uses ATmega or NodeMCU developers' processors, such as ATmega328 or ESP8266. This unit forms time sequences of signals according to those synthesized by a single-board computer. The control signals go to the control driver unit. The control driver unit uses a TB6600 driver that generates the appropriate power for the motor windings, driving the HSM rotor. Rotor parameters of movement are measured by sensors and transmitted to the control system for further analysis and correction of control influences in a block of forecast of action results.

B. IMPROVEMENT OF THE MATHEMATICAL MODEL

Stepwise jump-like changes in angular positions form the basis of all operating modes of the SM and are essentially its only, but important, feature. Fig. 3 shows a fragment of the stator and rotor of the SM, which graphically represents the relationship between the angle Θ and the angular length of the step λ.

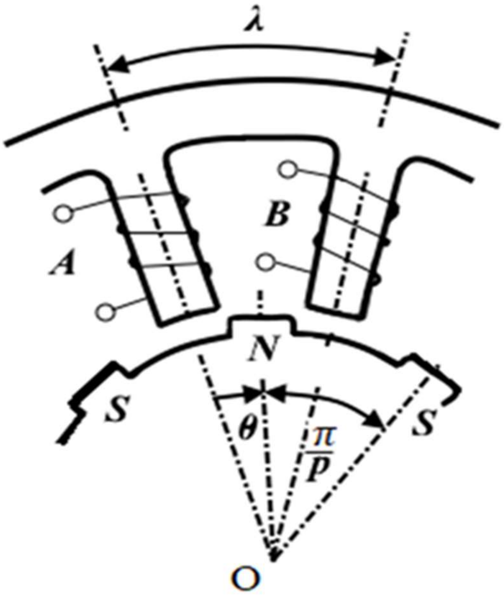


Figure 3. Structural model of a SM.

Therefore, all the parameters to be measured are also changed accordingly as Stepwise jump-like changes of time function. This will become obvious after developing the mathematical model, modeling and experimental investigation of the SM. The mathematical model is described as a system of non-linear differential time-dependent equations based on two fundamental laws:

$$\begin{cases} J\dfrac{d^2\theta}{dt^2}+D\dfrac{d\theta}{dt}+pn\Phi_m i_A\sin\left(p\theta\right)+pn\Phi_m i_B\sin\left(p\left(\theta-\lambda\right)\right)=0, \\ V_{gA}-r\cdot i_a-L\cdot\dfrac{di_A}{dt}-M\dfrac{di_B}{dt}+\dfrac{d}{dt}\left[n\Phi_m\cos\left(p\theta\right)\right]=0, \\ V_{gB}-r\cdot i_b-L\cdot\dfrac{di_B}{dt}-M\dfrac{di_A}{dt}+\dfrac{d}{dt}\left[n\Phi_m\cos\left(p\left(\theta-\lambda\right)\right)\right]=0, \\ M_{em}=-nN_r\Phi_M\cdot\left[i_A\cdot\sin\left(N_r\cdot\theta\right)+i_B\cdot\cos\left(N_r\cdot\theta\right)\right], \end{cases} \quad (1)$$

where: *VgA, VgB* – supply voltage, respectively phases A and B;

L – is the inherent inductance of each winding of phase;

M – mutual inductance of winding of phases;

r – is the resistance of the stator winding circuit;

Nr – is the number of rotor teeth;

J – moment of inertia of rotor;

D – is the coefficient of viscous friction;

θ – is the rotation angle of the SM rotor relative to the stator;

p –is the number of pole pairs of the SM stator;

n – the number of winding turns;

Φ_m – coefficient of mutual induction;

i_A, i_B – current in the windings of phases A and B, respectively;

λ – is the pitch of the SM stator teeth.

It is generally known that to synthesize the control influence of electromechanical executive mechanisms of robot kinematic pairs it is necessary to have their analytical transfer functions. The use of the numerical Simulink modeling tool in the Matlab environment made it possible to carry out only numerical modeling [15]. However, the numerical data set [16] does not provide opportunities for solving problems of optimal design for intelligent correction and bringing the characteristics to the required laws for analytical prediction of action results.

The next reason the demand for an analytical solution is necessary is that Matlab`s mathematical model of SM does not estimate the value of its error. For this reason, it becomes impossible to find the error and preevaluate the adequacy of the obtained model. Therefore, we will solve system (1) for a two-phase SM type by analytical methods.

In this regard, based on the main law of dynamics for rotational motion of absolutely a rigid body, Kirchhoff's second law, and the interaction of currents with the field of a permanent magnet, we will consider the model in the differential form of a system (1). The first equation of system (1) is a differential form nonlinear model, that is not suitable for direct application of the Laplace transform. We proposed to apply the method of recurrent approximation [6] simultaneously with dynamic programming for the solution of this problem. Let us decompose the first nonlinear equation into a recurrent series of analytic functions with the linear scheme of approximation, the speed convergence of which is determined by the value of its second derivative maximum:

$$J\frac{d^2\theta_n}{dt^2}+D\frac{d\theta_n}{dt}+pn\Phi_m\left(i_A-i_B\right)\sin p\theta_n+p^2n\Phi_m\left(i_A-i_B\right)\left(\theta_{n+1}-\theta_n\right)\cos p\theta_n+M_{fr}=0. \quad (2)$$

Let us set the problem of finding a solution to the system as a problem of dynamic programming. Additionally, we will put forward the condition that the search for the next approaches of θ_{n+1} - time depended function at ends when:

$$\theta_{n+1}-\theta_n=0\,. \quad (3)$$

We will rewrite and transform the first equation of system (1) taking into account condition (3) and bring it to the solution of the system as a whole by the methods of operational research:

$$J\frac{d^2\theta_n}{dt^2}+D\frac{d\theta_n}{dt}+pn\Phi_m\left(i_A-i_B\right)\sin p\theta_n+M_{fr}=0. \quad (4)$$

We will enter the notation for the current strength of both the original and the image, respectively, and we will use the lower index to denote the phase, of since we will reduce the sine to one phase reading. Let us present the product of the functions in the third term, taking into account the exponential representation of the sine and Euler's formulas:

$$\sin p\theta=\frac{e^{jp\omega t}-e^{-jp\omega t}}{2j}.$$

Then, according to the image shift property, we will have Laplace transform multiplication of the function of the third term in (4):

$$\left(i_A-i_B\right)\sin\left(p\theta\right)\div\frac{1}{2j}\left\{\left[\tilde i_A\left(s-jp\theta\right)-\tilde i_B\left(s-jp\theta\right)\right]-\left[\tilde i_A\left(s+jp\theta\right)-\tilde i_B\left(s+jp\theta\right)\right]\right\}.$$

Let us expand the right-hand side of the Laplace transform around the point s into a Taylor series, then write:

$$\left(i_A-i_B\right)\sin\left(p\theta\right)\div-p\omega\frac{d}{ds}\left[\tilde i_A\left(s\right)-\tilde i_B\left(s\right)\right].$$

For our case $\theta=\omega t$, taking into account the differentiation property of the image, we received in Laplace transform model of HSM:

$$\left(i_A-i_B\right)\sin\left(p\theta\right)\div p\omega\left[\tilde i_A\left(s\right)-\tilde i_B\left(s\right)\right]s.$$

Using the subtraction method, we combine the second and third equations and apply the Laplace transform to it and reduce the system to form:

$$\begin{cases} Js^2\tilde\theta_{n+1}+Ds\tilde\theta_{n+1}+p^2n\Phi_m\omega s\left(\tilde i_A-\tilde i_B\right)+\tilde M_{fr}=0;\\ \tilde V_{gA}-\tilde V_{gB}-2p^2n\Phi_m\frac{d\theta_{n+1}}{dt}\tilde\theta_{n+1}=\left(L-M\right)\cdot\frac{d\left(\tilde i_A-\tilde i_B\right)}{dt}+r\cdot\left(\tilde i_a-\tilde i_b\right).\end{cases}$$

If we simplify the problem and neglect the moment of friction forces, then its solution will be the image and the transfer function:

$$\begin{cases} \tilde\theta_{n+1}=-\frac{p^2n\Phi_m\omega s}{\left(Js^2+Ds\right)}\left(\tilde i_A-\tilde i_B\right);\\ \tilde V_{gA}-\tilde V_{gB}=2p^2n\Phi_m\omega\tilde\theta_{n+1}+\left(L-M\right)\cdot s\left(\tilde i_A-\tilde i_B\right)+r\cdot\left(\tilde i_a-\tilde i_b\right);\\ W\left(s\right)=\frac{\tilde\theta_{n+1}}{\tilde V_{gA}-\tilde V_{gB}}=\frac{p^2n\Phi_m\omega}{\left[\left(M-L\right)\cdot s-r\right]\left(Js+D\right)-2\left(p^2n\Phi_m\omega\right)^2}.\end{cases} \quad (5)$$

Thus, it is possible to make a transition from images to originals using the algorithm of one of the methods of inverse Laplace transformation. The latter is implemented by a single-board computer and transferred to the forecast block, where it is used in the learning and decision-making algorithms of the recurrent network according to a five-point scheme [6].

C. EXPERIMENTAL STUDY OF THE DRIVE AND ADEQUACY OF THE SIMULINK MODEL IN THE MATLAB LIBRARY

To solve the third problem, it is decided that for the Simulink SM model, five measurements should be made for each given angle value, for sixteen angles. The data of these measurements are presented in Table 1.

Table 1. The value of the variant of the rotation angles of rotor shaft of the SM of the Simulink model

Simulink model, angle αi, degree					
№	α1	α2	α3	α4	α5
1	1,8795	1,8795	1,87956	1,87955	1,80015
2	3,6484	3,64847	3,64847	3,65	3,59932
3	5,4737	5,47374	5,47372	5,4737	5,4005
4	7,2505	7,25056	7,25055	7,25055	7,19915
5	9,0879	9,08791	9,08791	9,08791	8,99508
6	10,8478	10,8478	10,8478	10,8478	10,8004
7	12,6765	12,6766	12,6766	12,6765	12,5993
8	14,4687	14,4687	14,4687	14,4687	14,3992
9	1,87954	1,87954	1,87956	1,87954	1,80015
10	3,64847	3,64798	3,64847	3,64847	3,59932
11	5,47372	5,47372	5,47374	5,47374	5,4005
12	7,25055	7,25053	7,25055	7,25055	7,19915
13	9,08791	9,08785	9,08791	9,08791	8,9995
14	10,8478	10,8478	10,8478	10,8478	10,8004
15	12,6766	12,6766	12,6766	12,6766	12,5993
16	14,4687	14,4687	14,4687	14,4687	14,3992

The data of the first column of Table 1 shows lists of the numbers of experimental trials. The data into columns from the second to the fifth show the results of measuring the angle of rotation of the shaft for the Simulink SM model in degrees. Data from the first to the eighth line, we define the first series of experiments. Data into lines from 9 to 16 present the second series of experiments. The results of the statistical analysis of the data of the first series of experiments are presented into Table 2. In Table 3 statistical processing data for the second series of experiments are shown. Into this

Table 2. Statistical parameters of the first dependence

№	$\bar{X}_1$	σ_1	Δ_1	ε_1
1	1,863652	0,035498	0,015875	1,904781
2	3,638933	0,022154	0,009908	0,608817
3	5,459073	0,032744	0,014643	0,5998
4	7,240261	0,022982	0,010278	0,317414
5	9,069344	0,041515	0,018566	0,457748
6	10,83831	0,021185	0,009474	0,195468
7	12,66109	0,034521	0,015438	0,272653
8	14,45481	0,031078	0,013898	0,214998

Table 3. Statistical parameters of the second dependence

№	$\bar{X}_2$	σ_2	Δ_2	ε_2	t
1	1,863652	0,035498	0,015875	1,904781	0,000641
2	3,638933	0,022154	0,009908	0,608817	0,028035
3	5,459073	0,032744	0,014643	0,5998	0,000512
4	7,240261	0,022982	0,010278	0,317414	0,000365
5	9,069344	0,041515	0,018566	0,457748	0,034022
6	10,83831	0,021185	0,009474	0,195468	0,000269
7	12,66109	0,034521	0,015438	0,272653	0,001428
8	14,45481	0,031078	0,013898	0,214998	0,000875

two tables (2 and 3) statistically processed data are displayed. In columns from the second to the fifth accordingly, the arithmetic mean value of the rotor rotation angle $\bar{X}_1$ **and** $\bar{X}_2$, mean square value σ_1 and σ_2, representativeness error Δ_1 and Δ_2, relative error ε_1 and ε_2 are shown, respectively. Lower index in the notation denotes series of experiments number. Comparative statistical analysis of data from Tables 2 and 3 made it possible to calculate Student's *t* test, column 6 of Table 3. For significance *p* = 0.05; 0.01; 0.001 standard Student's test for samples of five options: 2.3; 3,4; 5.0 respectively. The calculated Student's criterion for each angle of the two samples is significantly smaller than the standard one. The latter allows us to claim that the samples do not statistically differ. However, the absence of a statistical difference proves that the Simulink model does not change its properties in the range of the experimentally studied angles. Such a conclusion theoretically confirms the practical attractiveness of modeling in the Matlab environment with Simulink tool, but does not establish its accuracy. Methodology to study the models and determine their adequacy, by non-contact experimental measurement of turning angles according to two metrological schemes was proposed. The first is the laser which acts as a source of light rays and emits onto a mirror, from which it is reflected directly to the measuring ruler, where the coordinates of its position are fixed on the scale before and after the rotation. The second is the laser that is attached to the motor shaft, and the beam is directed to the measuring ruler, where the coordinates of its position are similarly fixed on the scale. This decision to measure linear displacement is taken as an alternative because the error value of the direct measurement of the rotation angle is critically large. The photo of the experimental stand is shown in Fig. 4. The stand includes a rotary table 1, a single-board computer 2, HSM 3, a mounting traction 4, an MPU 6050 sensor - 5, a driver 6, and a controller 7.

Work experience was taken into account for conducting experimental studies. Also, as in the series of work tests, stable values of the specified rotation angles of the HSM shaft were established. Next, the signals for controlling the stepper motor are defined, i.e., rotation to an angle that is a multiple of the minimum rotation step of the motor shaft in the Simulink tool. After that, the created model is converted into program code and sent to the Arduino Uno board through a USB port connected to a single-board computer.

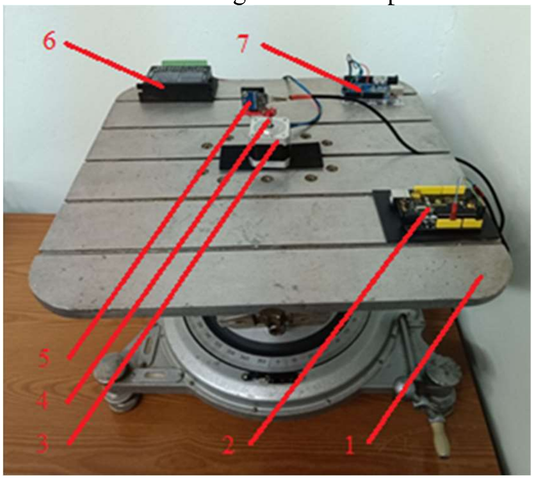
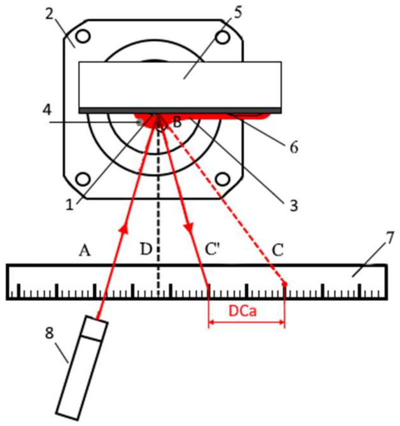
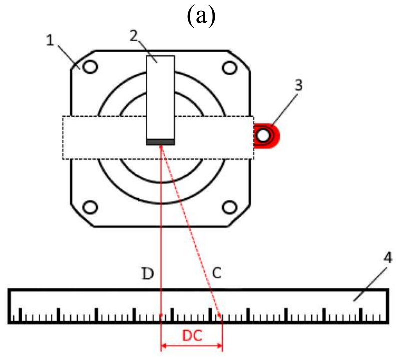


Figure 4. Photo of the stand for testing the intelligent drive

The error of any indirect measurement is determined by methodological, instrumental and random components. To find ways to reduce it, the first and second metrological schemes for measuring turning angles were studied. The schematic representation of the first and second metrological schemes is shown in Fig. 5.



(a)

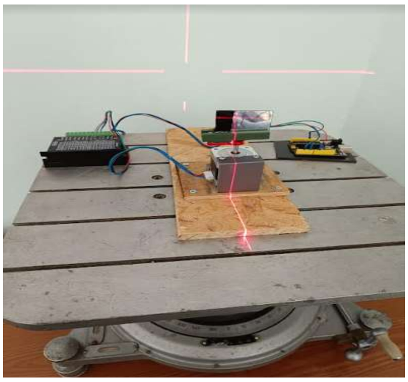


(b)

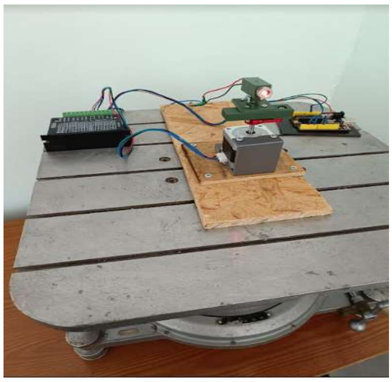
Figure 5. Schematic representation of the stand measurement principle (Mountain View) The first scheme for measuring the

shaft rotation angle - (a). The second measurement scheme - (b).

The schematic representation of the stand shows that traction 3 is mounted on shaft 1, which is fixed with screws 4. Holder 5 for fixing mirror 6 is attached to traction 3. To ensure accurate measurement of the rotation angle of shaft 1 of the SM 2 and experimental determination of the rotation error of the output shaft 1, traction 3 is rigidly fixed. Clip-holder 5 and mirror 6, the plane of which coincides with the axis of shaft 1 of SM 2, are also rigidly fixed on traction 3. The latter ensures the rotation of shaft 1 and mirror 6 at the same angle. To accurately measure a small angle, ruler 7 and laser 8 are placed at a long distance from the mirror. The amount of linear displacement of the laser beam depends on the amount of angular displacement. Increase in the distance to the ruler proportionally increases the linear displacement and improves the metrological properties of the measurement scheme.



(a)



(b)

Figure 6. Photo of the experimental stand. The first scheme for measuring the angle of rotation of the shaft with fixed mirror - (a). The second scheme of measurement with fixed laser on the shaft - (b).

The diagram of the measurement principle implemented in the stand is shown in Fig. 5. The photo of the stand itself is shown in Fig. 6. The stand works as follows: laser 8 emits a set of rays in the form of a line, so the rays form a red line on mirror 6. Rays of the line are reflected from mirror 6 at an angle of incidence. Then motor 2 rotates shaft 1 and traction 3 together with mirror 6 fixed on holder 5 counterclockwise. The latter changes the angle of incidence and reflection of the laser line. The distance before and after turning will practically not change and depends on the small angle of rotation of motor shaft 1. As a result, if the distance is known exactly, it is possible to calculate the angle to which the mirror will turn, and therefore shaft 1 SM 2. These results of samples of experimental modeling on control bench can be compared with the results of samples of the control model of the Simulink SM in the Matlab environment for the same angles in Fig. 6. The difference in results will be the experimental error, which characterizes the accuracy of the Simulink SM control model. The algorithm for measuring the angular displacement is based on the analysis of the beam's movement along line 7. Having fixed its initial and final position, we will find the initial angle of reflection of the beam and the new one.

To solve the third task of the research, experimental measurements were carried out in two alternative ways on the stands in Fig. 6 (a) and (b) with a fixed laser and a rotating mirror and with a moving laser as a fixed laser on traction 3. The results of experimental studies of five samples for each of the eight angles after statistical processing are presented in Table. 4. The angle number is given in the first column, and the rotation angle of the Simulink rotor of the SM model is presented in the second column.

Table 4. Experimental data of the angle of rotation shaft according to the scheme in Fig. 5 A

№	Simulink model, angle α, degree	DC_a, mm	Angle α, degree	Error of represen-tation Δ, degree	Ratio error $\mathcal{E}$, %
1	1,875	59,1	1,781673	0,187083	4,97744
2	3,75	115,4	3,475786	0,187083	7,3123733
3	5,625	171,8	5,16683	0,2	8,1452444
4	7,5	232,6	6,979665	0,367423	6,9378
5	9,375	290	8,678397	0,790569	7,430432
6	11,25	352,9	10,52231	0,458258	6,4683556
7	13,125	416,5	12,36459	0,790569	5,7936
8	15	486	14,34839	0,790569	4,3440667

Data from column 3 shows beam deflection, and column four gives, respectively, the mathematical expectation of the experimental value of the angle α. The error of representation of sample Δ and the relative error $\mathcal{E}$ are shown in columns 5 and 6 accordingly. As the analysis of data in Table 4 shows, the largest discrepancy between theoretical and experimental data is observed at the range of smallest angles of rotation. As the given angle increases, the relative error decreases significantly. The reason of this result as an additional source of error component can be explained as the uncontrolled rotation of the SM shaft. As a result of the termination of the current in the windings of the SM phases, the magnetic field of the stator becomes zero. Then the moment of interaction of the magnetic field of the coils and the rotor also becomes zero. Further, as a result of the interaction of the rotor magnets with the pole tips of the stator, the rotor, regardless of its position, returns to the nearest stable equilibrium position. The angular position of the rotor at the moment of zero current depends on the total moment of inertia. The moment of inertia of traction 3, screws 4, holder 5, mirror 6 and fastening elements are not taken into account, it is the source of terms of error.

Table 5. Experimental data of the rotation angle of the shaft according to the scheme of the laser on the traction

№	Simulink model, angle α, degree	DC_a, mm	Angle α, degree	Error of represen-tation Δ, degree	Ratio error $\mathcal{E}$, %
1	1,875	54	1,645321	0,316228	12,24954667
2	3,75	111,4	3,391204	0,244949	9,567893333
3	5,625	166,2	5,05219	1,067708	10,18328889
4	7,5	219,4	6,656605	0,244949	11,24526667
5	9,375	282,4	8,542912	0,244949	8,875605333
6	11,25	353,6	10,65232	0,244949	5,312711111
7	13,125	409,4	12,28559	0,244949	6,395504762
8	15	472,4	14,10543	0,244949	5,9638

To establish the validity of such an assumption, a second experiment was conducted according to the scheme in Fig. 6 (b). According to the measurement scheme, the laser was directly fixed to the rod of the SM. The results of measurements and comparison are presented in Table 5. The structure of the data in Table 5 is similar to Table 4. As evidenced by the analysis of the data in Table 5, the nature of the error is preserved, and its value does not decrease.

Thus, the conducted theoretical and experimental studies confirm the need to determine and increase adequacy by means of hardware and algorithmic additions to the computerized system. A similar conclusion applies to the application of simulation in the Matlab environment by means of Simulink.

Thus, the standard driver must be supplemented with additional controls to set the initial value of the angular position and correct the characteristics taking into account the moment of inertia of the rotor as a whole. To demonstrate the influence of the moment of inertia on the characteristics of the model, a simulation was carried out using a mathematical model (5). Data demonstrating the influence of the relative value of the moment of inertia on the characteristics of the JK42HS43-1334AC HSM model are presented in Table 6. Values of the angle of rotation - α, which is given for modeling in degree, are shown in column 3. Values of the angle of rotation received by the Simulink modeling, for three different ratios of inertia moment J, 1,05J, and 1,1J correspondingly are shown in columns 4, 5, and 6. Data in columns 7, 8 and 9 demonstrate the results of modeling by model (5) for ratios of inertia moment 1,01J, 1,05J, and 1,1J correspondingly. It shows the angle of rotation α in degree and relative accuracy compared to the execution angle from column 3 in percent %. The difference between the required and received angle is stable at 4,76-4,75% and 9,079 -9,074% for 1,05 J and 1,1 J of inertia moment correspondingly. Analysis of the results for Simulink modeling shows that increasing inertia moment increases the angle of rotation. This result is in contradiction with modeling by the received model (5) and also the inertia law which is physically proven.

These results prove that to improve the metrological characteristics of measuring equipment, it is necessary to minimize additional and non-accounting inertia moments, which is also the problem of the miniaturized size of the mirror and its holder.

Table 6. The characteristics of the shaft rotation angle for SM JK42HS43-1334AC: Simulink and analytic model (5).

№	Modeling time, s	The angle of rotation is given, deg.	The rotation angle of the Simulink model (J), deg	The rotation angle of the Simulink model (1,05J), deg	The rotation angle of the Simulink model (1,10), deg	The rotation angle of the model (5) / Ɛ (1,01J), deg/ %	The rotation angle of the model (5) / Ɛ (1,05J), deg/ %	The rotation angle of the model (5) / Ɛ (1,10J), deg/ %
1	0.0019625	1,875	1,924	2,232	2,623	1,856439/0,9899	1,785731/ 4,761	1,704576/9,089
2	0.003925	3,75	3,757	4,089	4,359	3,712886/0,9897	3,571495/ 4,760	3,409213/9,088
3	0.005888	5,625	5,541	5,866	6,233	5,569339/0,9895	5,357293/ 4,759	5,11391/9,086
4	0.00785	7,5	7,335	7,723	7,971	7,4258/0,9893	7,143124/4,758	6,818668/9,084
5	0.009813	9,375	9,156	9,468	9,839	9,282268/0,9891	8,928988/4,757	8,523487/9,082
6	0.011775	11,25	10,944	11,33	11,668	11,13874/0,9889	10,71489/4,757	10,22837/9,081
7	0.013738	13,125	12,747	13,134	13,4	12,99523/0,9887	12,50082/4,756	11,93331/9,080
8	0.0157	15	14,546	14,94	15,238	14,85172/0,9885	14,28678/4,755	13,63831/9,079
9	0.017663	16,875	16,335	16,732	16,989	16,70821/0,9883	16,07278/4,754	15,34337/9,076
10	0.019625	18,75	18,155	18,537	18,834	18,56472/0,9881	17,85881/4,753	17,04849/9,047

When setting up the bench, the TB6600 driver was used to study the output characteristics of the SM. There are six switches on the driver body, the first three of them are used to set the micro-step mode of operation, and the others adjust the output current from the driver. The list of the TB6600 driver switch settings are shown in Table 7.

Table 7. Description of driver settings (Microstep Driver)

Microstep	Pulse/rev	S1	S2	S3
NC	NC	ON	ON	ON
1	200	ON	ON	OFF
2/A	400	ON	OFF	ON
2/B	400	OFF	ON	ON
4	800	ON	OFF	OFF
8	1600	OFF	ON	OFF
16	3200	OFF	OFF	ON
32	6400	OFF	OFF	OFF
Current(A)	**PK Current**	**S4**	**S5**	**S6**
0.5	0.7	ON	ON	ON
1.0	1.2	ON	OFF	ON
1.5	1.7	ON	ON	OFF
2.0	2.2	ON	OFF	OFF
2.5	2.7	OFF	ON	ON
2.8	2.9	OFF	OFF	ON
3.0	3.2	OFF	ON	OFF
3.5	4.0	OFF	OFF	OFF

Three series of experiments were also carried out in full step mode, when the SM makes 200 steps for one rotation of the motor shaft on 360 degrees, that is, the angle of rotation is proportional to the value of the rotation of the SM shaft by a step of 1.8 degrees. The picture of the change in the relative error was observed similar to Table 4 and Table 5. In the next series of tests, the driver was configured in micro-step 2/A mode on the TB6600 driver. For one rotation of the SM to an angle of 360 degrees in the half-step mode, 400 pulses were supplied, provided that the angle of rotation for two half-steps of the SM shaft is also 1.8 degrees. The results of the experiments in the 2/A micro-step mode shows a similar pattern of changes in the relative error.

Thus, simply changing driver settings does not provide the necessary changes to improve the accuracy of the actuator. Implementing an adjustable brake also does not improve the angle rotation accuracy. Experimental study and applying a knowledge base with a generalized structure of executive means of intelligent control is the way to compare and correct their characteristics. The structure of new proposals modified the IS realized in the experimental module according to Fig. 1 and Fig. 2 and it is the permissible direction for future implementation [36] and development in accordance with the requirements of the time [37]. This experimental study and its positive and negative results show, that the proposed executing means of intellectual control together with the analytical model (5) open up new possibilities. Application, for example, this model will be useful for experimental study, reformulation and correction of the assembled manipulator control system for people with disabilities [38]. Thus, in their totality, the mentioned proposes created the prerequisites for finding innovative ideas suitable for simplifying the structure due to the unification of modules and the application of intellectualization at the peripheral level. For future improvements of the IS based on the results of this research for intelligent unmanned vehicles [39] and transportation intelligent vehicles [40], the experimental measurement scheme needs to be improved. The mirror and its holder need to be designed with limited momentum of inertia. The ratio of the value of additional momentum inertia recommended should be less than 0,1% from the momentum inertia of the motor's shaft.

VI. CONCLUSIONS

The proposed generalized structure of the intelligent systems of electromechanical drivers at the peripheral level is substantiated. The proposed structure of the executive means of intellectual control allows, together with the related blocks, performing analysis, forecasting, and comparison of the results and implementing the synthesis of control influence as elements of training and calibration.

The control signal correction using the knowledge base and database will be done due to bidirectional ware link with block executive means with intelligent control, block forecasting results, and cloud manufacturing environment. The simulation results, received using Matlab and physical experiment established that the data difference is within 4-12% for small turning angles. Physically accurate accounting of the moments of inertia or correction of the characteristic allows for the reduction of error almost twice.

The simultaneous application of Euler's exponential representation, decomposition into a recurrent series, and Laplace transformation reduce the nonlinear model as the system of differential equations of the motion of a hybrid stepper motor to an analytical mathematical model. It describes the angular movement of the rotor, the current into the winding, and the analytical transfer function. The model's accuracy is less than 1% if a moment of inertia has an accuracy of less than 1%.

The drive's experimental studies establish large values of the relative errors for small angles of rotations and the need to increase the adequacy of the Simulink model in the Matlab library by accounting for the moments of inertia of the drive rotor as a whole.

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