Radioelectronic and Computer Systems, 2022, no. 2(102) ISSN 1814-4225 (print) ISSN 2663-2012 (online)

UDC 519.712.7:004.415.532.2 doi: 10.32620/reks.2022.2.02

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ALGORITHM FOR THE SYNTHESIS OF DUAL NON-PARAMETRIC CONTROL OF "BLACK BOX" TYPE DYNAMIC OBJECT WITH USE STATE MATRIX DIAGONALIZATION METHOD

The subject *of the article is a variant of an efficient algorithm for synthesizing a dual discrete model and controller for tracking a given trajectory of a dynamic nonlinear, nonstationary black box object, using standard procedures for diagonalizing the state matrix, which makes it possible to simplify obtaining control values in numerical form and reduce the number of calculations.* ***The current article presents*** *one the possible solutions to the problem of regulator synthesis to ensure stable development of a given trajectory of motion of a nonlinear, non-stationary object of "black box" type using the concept of dual control.* ***The task*** *was set to simplify the previously proposed synthesis algorithm for the adaptive control of dynamic nonlinear, non-stationary objects using the example of first-order object of the "black box" type, using standard procedures for the diagonalization of the state matrix. An extended state matrix is the basis for obtaining a control model and predicting the behavior of a nonlinear non-stationary object, which in turn makes it possible to effectively use the concept of dual control.* ***Methods*** *used in the work are based on concept of dual control, nonlinear dynamic models, matrix theory, difference equations. Obtained* ***results*** *of this work consist of the development of a version of a dual nonparametric controller of nonstationary nonlinear processes, which has adaptive properties, does not require knowledge of the physics of functioning of the control object, is presented in the form of a simple algebraic formula that does not contain coefficients that require adjustment.* ***Conclusion.*** *Scientific novelty lies in the application of each interval matrix operator control for the diagonalization of the state submatrix. This operator is used for subsequent calculation of the control action. This approach enables the use of a standard diagonalization procedure using mathematical applications. The results are presented in the form of a final formula that does not require use of matrix operations during control, which makes it possible to simplify the synthesis of the controller using standard mathematical procedures.*

Keywords: *"black box"; dual control; extended state matrix; diagonalization; local model; global model; deterministic chaos.*

Introduction

In principle, all technological processes are non-linear dynamic with non-stationary parameters. It is customary to describe them using models in the form of linear or nonlinear differential equations, difference equations with parameters and nonlinear characteristics, neuro models, etc. It is important to note that the use of a linear apparatus requires the implementation of the principle of superposition. Non-linear systems do not meet this principle. For this reason, linear equations, transfer functions, frequency characteristics, correlation images of processes, for example, of Wiener-Hopf, most statistical methods and integral models are not suitable for obtaining models of nonlinear processes. The linear apparatus, in principle, cannot take into account such phenomena as deterministic chaos and bifurcations, which also take place in the processes of ore disintegration. Real production processes are non-stationary and depend on a large number of physical parameters. The description of models of such processes based on the physical laws of their functioning can be extremely difficult or impossible. In many cases, direct measurement of the technological processes parameters is not possible with a sufficient degree of accuracy. Non-linear characteristics of processes are often obtained as static. However, in reality, these characteristics are built into the dynamics of the process. Dividing them into "dynamics" and "statics" requires proof and for this reason, looks artificial.

A large number of methods for solving the problem of dynamic objects control synthesis are known. These methods are well known to professionals. This raises some problems. Let's consider some of them.

To obtain a mathematical model of an object, it is not always possible to use the knowledge of its physical nature. For example, it is very difficult to obtain an analytical model of the ore disintegration process with bifurcation properties. The problem may be the provision of a given temperature inside the heating well when loading or unloading ingots with different initial temperatures, and different grades of steel.

The problem of choosing mathematical models' class arises (linear, nonlinear, stationary, nonstationary, etc.). If these are differential equations, then it is necessary to choose their order and form. The construction of a non-stationary process global model is meaningless. Nevertheless, attempts of this kind continue.

In the case of neuroregulators, despite successes, the issues of choosing a network, the number of layers, and the number of neurons in a layer are still insufficiently defined. In addition, the structure of the neural network is quite complex and its operation is not always available to the user. In some cases, a training sequence of considerable length is required. The resulting settings remain relevant only within the training sequence. In the case of control non-stationary processes, these settings become meaningless. The use of adaptive neuroregulators significantly complicates the algorithms of even relatively simple control objects. The synthesis of controllers based on fuzzy logic involves the so-called fuzzification and defuzzification procedures, which complicate the synthesis problems and reduce the accuracy of obtained results. The use of neuro-fuzzy technologies to tune three coefficients of PID controller is most likely of academic interest. It would be possible to further enumerate methods for the synthesis of controllers, but it is important to emphasize that in the case of objects close to linear, stationary, there is no need to use complex controllers. Practically ideal in this case are PI and PID controllers with constant, pre-calculated settings.

1. Related works

It was previously noted that, as a rule, only input and output data are available for measurement. It should be noted once again that the influence of factors inaccessible for direct measurement affects the external object behavior [1]. Thus, the "input-output" accounting, strictly speaking, contains complete information about the control object. This was first noticed by W. Ross Ashby [2], who posed the problem and introduced the "black box" concept - an object about which only input-output data are known. Recently, this approach has become more widespread.

The well-known concept of dual control, put forward by A. A. Feldbaum, is in good agreement with this concept of a “black box” [3, 4]. The dual control problem, as you know, consists of three parts:

1) on each discreteness interval, the working control actions are simultaneously considered as testing;

2) the object model is being built;

3) the optimal control is calculated.

We will not discuss optimization for now, since A.A. Feldbaum is credited with the opinion that this task is very difficult. And this is perfectly true. In this paper, we consider the problem of calculating control to ensure given trajectory tracking. Tracking error is minimized by updating the model at each discreteness interval. This approach fits well with the concept of dual control.

There are relatively rare attempts to solve, at suitable level for practical use, at least the first two parts of the set by A. A. Feldbaum problem. These include, for example, work [4].

The paper [5] presents the use of machine intelligence to solve complex problems. An important property of the proposed metric is the universality, as it can be applied as a black-box method to intelligent agent-based systems (IABSs) generally, not depending on the aspect of IABS architecture. But this approach is quite difficult to implement for technical systems with distributed parameters.

In the work [6], it has been proposed the synthesis method of a fuzzy adaptive control system with variable structure for uncertain and nonstationary dynamic objects. Since the proposed fuzzy control system constructed regarding to bynar-coordinate and parametrically feedback, it is also not suitable for our case when considering the enrichment and grinding processes.

In [7, 8], implicit dual control methods are considered by systematic approximation of Bellman's stochastic dynamic programming equations. The very formulation of the problem is beyond doubt, however, the mathematical apparatus used is rather complicated and cumbersome to implement.

At the moment, much attention is paid to research on identifying systems for more accurate creation of their models. So, for example, in research [9] it is considered a novel approach to system identification that allows accurate models to be created for both linear and nonlinear multi-input/output systems. In addition to conventional system identification applications, the method can also be used as a black-box tool for model order reduction. A nonlinear Kalman filter is extended to include slow-varying parameter states in a canonical model structure. Interestingly, despite all model parameters being unknown at the start, the filter can evolve parameter estimates to achieve 100% accuracy in noise-free test cases and is also proven to be robust to noise in the measurements.

Also, article [10] investigation is devoted a novel guidance scheme based on the model-based deep reinforcement learning (RL) technique. With the model-based deep RL method, a deep neural network is trained as a predictive model of guidance dynamics which is incorporated into a model predictive path integral control. However, the traditional method assumes the actual environment similar to the training dataset for the deep neural network which is impractical in practice with different maneuvering of the target, other perturbations, and actuator failures.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

In [11], it is proved that the extended state matrix of the control object, which includes, following the concept of a "black box", the values of input and output variables at some discrete time interval preceding the calculation of the control action, is control object, discrete model. The results of this work, even before its publication, were successfully used in works [12, 13]. This serves as a rationale for obtaining the results of this work.

For example, the paper [13] develops a sampling-based approach to implicit dual control. Implicit dual control methods synthesize stochastic control policies by systematically approximating the stochastic dynamic programming equations of Bellman, in contrast to explicit dual control methods that artificially induce probing into the control law by modifying the cost function to include a term that rewards learning.

It should be especially emphasized that, at short discreteness intervals, the behavior of even complex objects is close to linear law. The foundations of mathematical analysis are based on this, which are also confirmed by the practice of approximating the behavior of high-order objects on small discreteness intervals. Taking this property into account makes it possible to significantly simplify the control object model on separate discreteness intervals, even in the case of high-order control objects.

Nonlinear deterministic models are widely used in completely different areas. For example, at work [14] explores a fast and efficient method for identifying and modeling ship maneuvering motion.

Separately, we note the work [15], which deals with the synthesis of dual nonparametric controllers. There are interesting formulations of problems, for example, the accounting for gaps in measured data, synthesis of controllers for multiply connected systems, and systems with delay. Numerous sales are quite good. However, the use of weight functions (linear concept), bell-shaped functions, blur parameters requiring verification of convergence conditions, parametric models, and statistical methods lead to complications in the controller synthesis technique. The technique proposed in this work makes it possible, in several cases, to simplify the synthesis of controllers.

2. Objectives

The work aims to simplify the previously proposed synthesis algorithm for dual control of dynamic nonlinear, non-stationary objects [11,16] using the example of a first-order object of the "black box" type, using standard procedures for diagonalization of the state matrix, which makes it possible to simplify obtaining control values in numerical form and to reduce the calculations.

The main approach to the synthesis of the controller is outlined in [11]. However, this approach requires additional analysis and recommendations for its application. In addition, the following will show the possibility of simplifying the transformations to obtain the final controller formula.

3. The main provisions of the synthesis method for the "black box" model

Let us consider the main provisions of the synthesis method for the "black box" model as an example of a nonlinear nonstationary discrete object with scalar input and output in the form of a difference first-order equation,

$$\begin{aligned} x[n+1] &= a(n,\ x[n-1],\ u[n-1], \Delta t)\cdot x[n] + \\ &+ b(n,\ x[n-1],\ u[n-1], \Delta t)\cdot u[n], \end{aligned}$$

where Δt – is the discreteness interval (polling sensors and issuing control); n – is the number of the discrete-time interval; x[n] – output reaction of the object; u[n] – control action; a(n, x[n-1], u[n-1], Δt), b(n, x[n-1], u[n-1], Δt) – coefficients functions of discrete-time, output reaction of the object and control action.

Obviously, under the condition of physical realizability, these coefficients can be determined no later than on the [n-1] - th interval. Further, we simplify the designation of the coefficients, keeping their meaning as functions of discrete time, control action, and output response. Taking this into account, the equation of motion of the object takes the form:

$$x[n+1] = a\cdot x[n] + b\cdot u[n]. \quad (1)$$

However, the discreteness interval affects not only the values of output quantity x[n + 1] and x[n], but also the coefficient a(n, x[n-1], u[n-1], Δt), b(n, x[n-1], which determines the stability of the object. The root of the characteristic polynomial is equal to:

$$\text{root} = a(n, x[n-1], u[n-1], \Delta t), b(n, x[n-1]), \quad (2)$$

and the condition for stability of the object`s discrete model has the form as:

$$|\text{root}| < 1 \cdot$$

It is assumed that the parameters of the object, including the discreteness interval, are unknown. The output response and the input action (control) calculated by the controller are available for measurement. This is a typical black box case. Control actions u[*] at the initial stage of the object start-up are set in the range of admissible control values, and then, in the course of normal operation, are calculated by the controller. Hereinafter, the symbol "*" is used in the sense of "for any moment of discrete time".

Following the concept of dual control, the coefficients of the model equation (1) must be determined on a limited interval of discrete time. Then these coefficients must be calculated at each next interval. On limited time intervals, even complex processes can be approximated by a low-order equation. In principle, all calculus is based on neglecting values above the first order of magnitude over a short time interval. In addition, higher-order equations are always reduced to a system of first-order equations. Then each equation is processed separately.

Let's compose equations for two unknown coefficients of a and b model (1) on discrete time interval: [n], [n-1], [n-2]:

$$\begin{aligned} x[n] &= a \cdot x[n-1] + b \cdot u[n-1], \\ x[n-1] &= a \cdot x[n-2] + b \cdot u[n-2]. \end{aligned} \qquad (3)$$

To determine the coefficients of the model (3), we use Cramer's method:

$$a = \frac{\Delta_a}{\Delta} = \frac{\begin{vmatrix} x[n] & u[n-1] \\ x[n-1] & u[n-2] \end{vmatrix}}{\begin{vmatrix} x[n-1] & u[n-1] \\ x[n-2] & u[n-2] \end{vmatrix}},$$

$$b = \frac{\Delta_b}{\Delta} = \frac{\begin{vmatrix} x[n-1] & x[n] \\ x[n-2] & x[n-1] \end{vmatrix}}{\begin{vmatrix} x[n-1] & u[n-1] \\ x[n-2] & u[n-2] \end{vmatrix}}, \qquad (4)$$

where Δ, Δ_a, Δ_b – are determinants of the system (3).

Equation (1) is represented in an equivalent form:

$$x[n+1] - a \cdot x[n] - b \cdot u[n] = 0.$$

Then, taking into account (4), we obtain the equation of model (1) in the form:

$$x[n+1]\begin{vmatrix} x[n-1] & u[n-1] \\ x[n-2] & u[n-2] \end{vmatrix} - \begin{vmatrix} x[n] & u[n-1] \\ x[n-1] & u[n-2] \end{vmatrix} x[n] - \begin{vmatrix} x[n-1] & x[n] \\ x[n-2] & x[n-1] \end{vmatrix} u[n] = 0. \qquad (5)$$

This is the sought difference equation of the black-box model, in which only the measured output data and the calculated control action are used. This model is almost continuously adapting to changes in the control object. Input and output data are continually being processed. The impression that the model does not take into account the internal parametric and structural, as well as external, not measurable perturbations is not entirely true. The point is that the indicated perturbations inevitably affect the output data and determine the x[*] result. Numerical and field tests of the model of this kind of perturbed object gave positive results.

The discrete model of (5) contains coefficients depending on control and output variables on a limited discrete time interval. A model of (4) must be obtained based on the latest data on the state of the control object. The problem of "data aging" is practically eliminated.

At the same time, the form of a model does not differ from the form of the equation of the (1) object, which makes it possible to assess the significance of the Lyapunov exponents, which means that the current state of the control object belongs to the basin of attraction or repeller.

4. Practical application of the method

The purpose of further research within the framework of this work is to find another, possibly simpler and more convenient, the algorithm for synthesizing the model of the form of (5).

Let's compose an extended matrix of the object state, which includes both the measured values of the output x[*], the calculated and realized values of the u[*] control at discrete times [n + 1], [n], [n-1], [n-2]

$$M(X,U) = \begin{pmatrix} x[n+1] & x[n] & u[n] \\ x[n] & x[n-1] & u[n-1] \\ x[n-1] & x[n-2] & u[n-2] \end{pmatrix}, \qquad (6)$$

where X, U – is column vectors, respectively output and control.

In [11], the following theorem holds: that

$$\det(X, U) = 0,$$

is a discrete equation of the control object of the form (5). The essence of the theorem can be represented as follows: expand the determinant of matrix (6) along the leftmost column and equate it to zero. We get:

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

$$x[n+1]\begin{vmatrix} x[n-1] & u[n-1] \\ x[n-2] & u[n-2] \end{vmatrix} - \begin{vmatrix} x[n] & u[n-1] \\ x[n-1] & u[n-2] \end{vmatrix} x[n] + \\ + \begin{vmatrix} x[n] & x[n-1] \\ x[n-1] & x[n-2] \end{vmatrix} u[n] = 0.$$

Comparing it with the (5), we notice that after rearranging the columns in the last determinant, we get an expression that exactly coincides with the equation of the discrete model of the "black box" (5).

Let us note an important property of the described method. Model (5) is dual. This means that it can be used both to predict the future value of the output quantity x[n + 1] and to determine the control action u[n], to estimate the signature of Lyapunov exponents.

The presented approach in various final forms was successfully used in the numerical simulation of various objects, the state of which changed from stable to unstable in the example of the pendulum with a lower suspension point [16]. Such an object is considered one of the best test objects for checking the quality of regulators. In addition, a model of a multi-zone furnace was created using a dual regulator. Each zone has its damper, which is controlled by software with the ability to open the heat outflow channels throughout the layout of the furnace to create perturbations. The first version of the test was to calculate the angle of rotation of the damper separately in time for each zone. In the second variant, the calculation of the gate angle was performed using parallel computing technology. In both cases, the task schedules were worked out with sufficient accuracy. Also, this approach was implemented and processed in the forecast mode on the data of real operation of the processes of disintegration of ore raw materials, which is described in detail in [17].

The tests indicated earlier were based on obtaining the controller model by a purely algorithmic method and were analytically substantiated in [11].

An important result is proof that the extended object state matrix is the basis for obtaining a regulator or predictor. This allowed us to develop different approaches to obtaining specific formulas of the regulator.

The presented work shows how it is possible to synthesize the same dual regulator in another way, obtaining some savings at the stage of regulator synthesis using matrix algebra. The coincidence of the results obtained in different ways confirms that these results are not accidental. In addition, we consider it important that in each case of testing, the physical nature of the control object did not matter. The learning sequence consisted of only 4 steps. Then, during the entire period of operation, the regulator adapted to the disturbances.

5. Implementation of an adapted method

Let's consider a method of forming an extended state matrix (6) using the auxiliary matrix and the inverse state submatrix. The input of the object receives control actions at different moments of discrete time *n*. The result is the reaction of the object at the appropriate times. Divide the matrix (6) into two submatrices. There are two lower lines of (6):

$$\begin{pmatrix} x[n] & x[n-1] & u[n-1] \\ x[n-1] & x[n-2] & u[n-2] \end{pmatrix}$$

we present in the form of two sub-matrices: a square submatrix of outputs and a matrix-vector of control actions.

$$X_n = \begin{pmatrix} x[n] & x[n-1] \\ x[n-1] & x[n-2] \end{pmatrix}, \\ U_{n-1} = \begin{pmatrix} u[n-1] \\ u[n-2] \end{pmatrix}. \qquad (7)$$

Similarly, we define the extended matrix on the next (n + 1)-th, not yet implemented, discreteness interval.

For this purpose, we will use the first two lines of the matrix of (6). For brevity, we immediately represent the square matrix of outputs X_{n+1} and the vector of control actions U_n in the form

$$X_{n+1} = \begin{pmatrix} x[n+1] & x[n] \\ x[n] & x[n-1] \end{pmatrix}, \\ U_n = \begin{pmatrix} u[n] \\ u[n-1] \end{pmatrix}, \qquad (8)$$

where x[n + 1] is a given (hence known) value of the output quantity in the next interval; u[n] is the desired control on the n-th interval, which should provide the given x[n + 1].

Let us pose the problem: find the matrix operator S for transforming the square submatrix (7) at the previous and current intervals into the square submatrix (8) at the next one containing a given output value. After that, the obtained operator S is applied to the column vector (7).

Let us reduce the square submatrix X_{n+1} to some diagonal matrix X_{diag}

$$X_{diag} = \begin{pmatrix} x[n+1] & 0 \\ 0 & x[n] \end{pmatrix}. \qquad (9)$$

The transformation operator S is obtained from the sequence of relations

$$SX_n = X_{diag},$$
$$S = \left(X_{diag}\right)\left(X_n\right)^{-1}.$$

The control vector U_{n-1} must be processed by the same algorithm as the square submatrix Xn. Then, it will be obtained the vector as:

$$U_n = \left(X_{diag}\right)\left(X_n\right)^{-1} U_{n-1}. \quad (10)$$

In [3, 20], the essence of the algorithm was reduced to reducing the square submatrix (7) to a submatrix, the top row of which coincides with the sum of rows of the submatrix (8). Using a diagonal matrix simplifies the transformations, allowing you to get the same result.

We add all the elements of the vector Un in formula (10), we take the obtained value for the control u [n]. After transformations, we get

$$u[n] = ((x^3[n+1]\cdot x[n-2] - x[n-1]\cdot x[n])\cdot \cdot u[n-1] + (x[n]\cdot x[n] - x^3[n+1]\cdot x[n-1])\cdot \cdot u[n-2]) / (x[n-2]\cdot x[n] - x[n-1]\cdot x[n-1]). \quad (11)$$

This result coincides with those previously obtained using other algorithms in numerical and physical experiments and published in [3, 17-19]. However, the use of a sparse inverse matrix allows reducing the number of calculations in the case when the control controller is programmed considered matrix transformations. This is especially felt with the increasing order of the extended matrix. In this case, you can do only numerical transformations of matrices (7), (8), without using symbolic transformations of matrices and further programming by numerical methods. In this case, the symbolic transformations of the matrices were performed and a ready-made simple form of the (11) controller was obtained.

To start the controller, which implements the formula of (11) regulator, it is necessary to set the training sequence by feeding to the object (1) by (11) a sequence of arbitrary admissible controls u[n-2], u[n-1] with the discrete interval of the sensors and actuators set for the given object. The obtained values serve as initial (starting) data for filling in part of the formula (11). Then in the formula of the regulator (11) enter the first set value of the output $x^3[n + 1]$ and by calculation receive the first operating control action u [n] to ensure the value of the output x[n + 1] in the next interval. This value in the process tends to the given $x^3[n + 1]$. This completes the learning process. The regulator then automatically adapts to the control object. In case of maintenance work at the facility, it is recommended to save the training sequence, and then use it to restart the process. Although this is not necessary. The learning process, in this case, is short and can be repeated with a new arbitrary admissible control sequence after the object is prevented.

The performance of any product must be verified through testing at the limit of capability. Therefore, the coefficient in the object model of (1) was changed in such a way that the root of the characteristic polynomial of (2) during the tests slid near the stability boundary. The coefficient a [n] was specified as: a = 0.1sin(n). Thus, the amplitude of the root (2) varies smoothly according to the harmonic law within the limits (1 ± 0.1). In this case, root (3) smoothly migrates across the boundary of the stability region in both directions.

In fig. 1 it is shown the result of the regulators' operation when given trajectory according to the law of quadratic parabola was working out. In this case, the root of characteristic polynomial (3) slides along the stability boundary. The first three intervals are training.

Fig. 1 it follows that the proposed dual nonparametric controller successfully controls the object that smoothly crosses the stability boundary on both sides. The stability indicator is the ratio for the root of the characteristic equation. In the figure, the root modulus value fluctuates, on average, about one (stability boundary). The regulation error is about zero on average.

More detailed studies have shown that, in contrast to the PID controllers widely used to date, the increase in the degree of reference polynomial does not lead to complications of the controller structure and does not reduce the accuracy of the task processing [20].

In fig. 2 the results of the regulator's operation when processing more complex tasks and abrupt changes in the root of characteristic polynomial shows and are on the border of sustainability. The process remained stable and then settled at the given value. The first three intervals are training.

The simplicity of the regulator formula is reduced by replacing the formula of the PID controller or other controller with the formula of (11). In this case, the training sequence in the form of permissible control actions u[n-1], u[n-2] is given to fill the initial data of the formula of the (11) controller only at the beginning.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

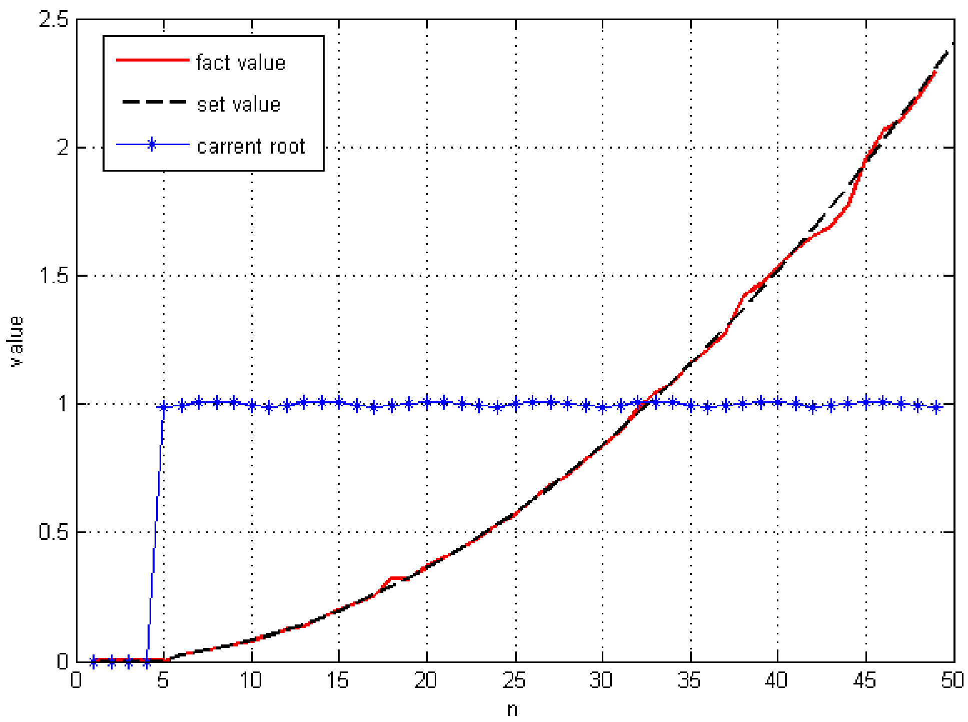

Fig. 1. Results of controller operation on quadratic specified trajectory near the stability boundary. Designations: set value=x^3[n + 1], fact value=x[n+ 1], current root=root

Then the regulator itself learns (adapts). Any work sequence is at the same time instructive, which exactly corresponds to the concept of dual control. This eliminates the need for classical experiments to obtain transient characteristics, which is acceptable only for linear, stationary objects. In real production conditions, such experiments are in most cases unacceptable or impossible.

Conclusion

In this paper, one of the options for using the matrix operator is shown, which allows diagonalizing the state submatrix at the previous control intervals, and then calculating the control to achieve a given state at the next discreteness interval. The proposed method for the synthesis of the controller in the form of a simple formula that does not require significant calculations allows one to adapt to changes in the parameters and characteristics of a non-stationary nonlinear control object.

Based on the obtained results, the following conclusions can be drawn:

− the presented controller (11) combines at each discreteness interval the identification of the control object according to the input-output data and the definition of u[n] control. From (11), we can also easily obtain forecast of x[n + 1] output value for given u[n] control;

− for the controller synthesis no knowledge of the physics of the control object is required;

− the training sequence is only set at the start of operation. Then the regulator learns itself (adapts). Any working sequence is at the same time teaching, which exactly corresponds to the concept of dual control;

− abrupt changes in the parameters (characteristic polynomial) do not lead to emergency modes, even in the most unfavorable case with bilateral sliding on the stability limit;

− beyond stability, the controller also copes with the tasks. Relatively large fluctuations that occur are found. However, this property is inevitably characteristic of any regulator in the case of control of an unstable object;

− the regulator formula is invariant to the value of discreteness interval, the frequency of data collection and the issuance of control actions;

− the regulator's formula is extremely simple compared to most studies in this area. The results were tested on a model of the heating furnace. Such simple adaptive regulators are most necessary for the management of real production processes;

− the property of regulator invariance for discreteness interval and data sampling frequency has many advantages: it frees from the analytical determination of specified parameters; at the same time, in the course of the real control process, by changing the sampling interval and the frequency of data collection

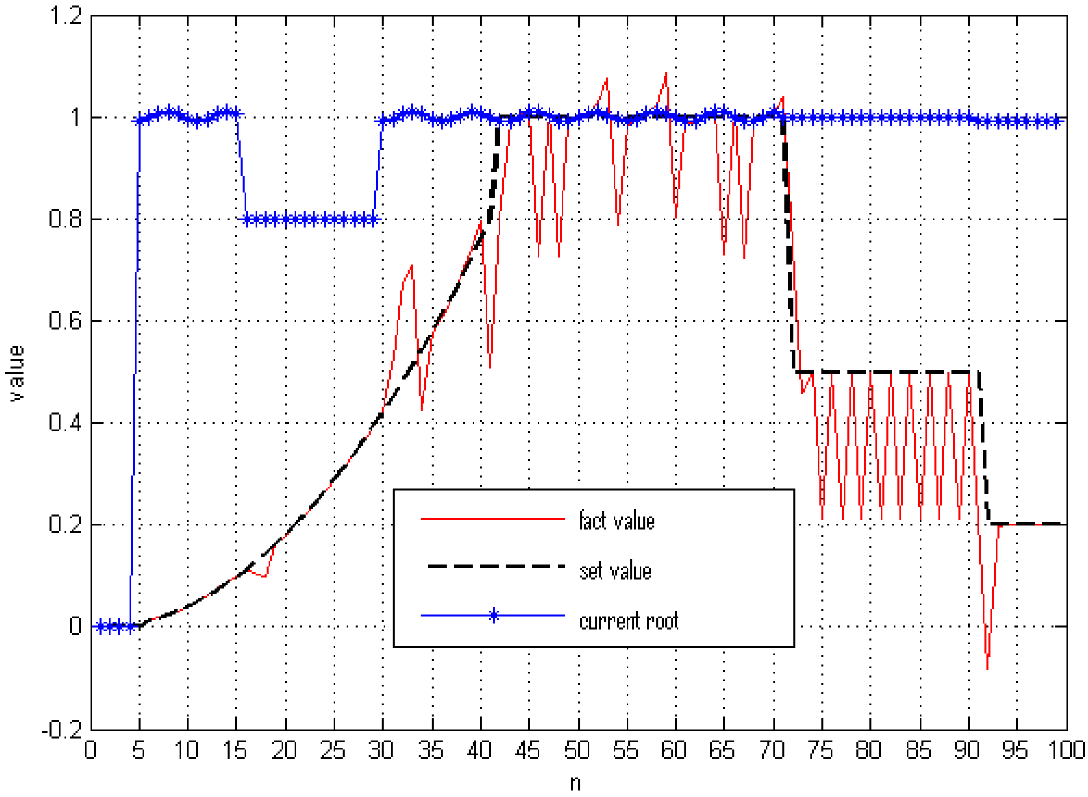

Fig. 2. The results of the regulator's operation when processing more complex tasks and abrupt changes in the root f characteristic polynomial. Designations: set value=$x^3[n + 1]$ – dotted line, fact value=$x[n + 1]$, current root=root

and control, it is possible to minimize the error in the regulator operates in the normal use. For nonlinear, and even more so for nonstationary objects, this must be done constantly, since the analytical determination of these parameters is impossible;

– the regulator of (11) does not require the definition of the parameter and, as a consequence, their setting. Therefore, it is called nonparametric. The process of identification and regulation are combined, which corresponds to the duality concept. This allows you to conduct the management process without interfering with the technological process.

As a direction for further research, one can single out the solution to such problems as:

– the development and testing of dual nonparametric controllers for multiply connected objects of "black box" type;

– the signature evaluation of the Lyapunov exponents of the "black box" type objects to identify bifurcation points of possible deterministic chaos;

– the use of sparse matrices in regulator synthesis to significantly reduce the computation time;

– the investigation of physical realizability of analytical expression structure of a controller of (9) type and the limiting values of output quantities and control actions, especially when the set initial value reaches the constant value, although numerous studies have not identified any problems.

Contribution of authors: statement of the research problem, the previously proposed synthesis algorithm for dual control of dynamic nonlinear, non-stationary object, adaptation of the algorithm and analysis of results, formulation of conclusions – **A. Zhosan**; implementation of developed algorithm and modeling, processing of obtained results, formulation of directions of further researches – **I. Marynych**; analysis of works according to the research topic, interpretation of obtained results and formulation of conclusions, translation and text editing – **O. Serdiuk**.

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Надійшла до редакції 30.08.2021, розглянута на редколегії 15.04.2022

АЛГОРИТМ СИНТЕЗА ДУАЛЬНОГО НЕПАРАМЕТРИЧЕСКОГО УПРАВЛЕНИЯ ДИНАМИЧЕСКИМ ОБЪЕКТОМ ТИПА "ЧЕРНЫЙ ЯЩИК" С ИСПОЛЬЗОВАНИЕМ МЕТОДА ДИАГОНАЛИЗАЦИИ МАТРИЦЫ СОСТОЯНИЯ

А. А. Жосан, И. А. Маринич, О. Ю. Сердюк

Предметом статьи является вариант эффективного алгоритма синтеза дуальной дискретной модели и регулятора для слежения за заданной траекторией динамического нелинейного, нестационарного объекта типа "черный ящик", с использованием стандартных процедур диагонализации матрицы состояния, позволяющего упростить получение значения управления в численном виде, уменьшить количество вычислений. **Целью статьи** является представление одного из возможных вариантов решения проблемы синтеза регулятора для обеспечения устойчивой отработки заданной траектории движения нелинейного, нестационарного объекта типа "черный ящик" с использованием концепции дуального управления. Была поставлена **задача** упростить ранее предложенный алгоритм синтеза адаптивного управления динамическим нелинейным, нестационарным объектом на примере объекта первого порядка типа "черный ящик", диагонализацией подматрицы состояния с использованием стандартных матричных процедур. Расширенная матрица состояния является основой для получения модели управления и предсказания поведения нелинейного нестационарного объекта, что в свою очередь позволяет эффективно использовать концепцию дуального управления. **Методы**, использованные в работе, основаны на концепции дуального управления, нелинейных динамических моделей, теории матриц, разностных уравнений. Полученные **результаты** работы заключаются в разработке варианта дуального непараметрического регулятора нестационарных нелинейных процессов, который обладает адаптивными свойствами, не требует знания физики функционирования объекта управления, представлен в виде простой алгебраической формулы, не содержащей коэффициенты, требующих настройки. **Выводы.** Научная новизна заключается в применении на каждом интервале управления матричного оператора для диагонализации подматрицы состояния. Этот оператор используется для последующего вычисления управляющего воздействия. Такой подход обеспечивает использование стандартной процедуры диагонализации с помощью математических приложений. Результат представлен в виде конечной формулы, не требующей использования матричных операций в ходе управления, что позволяет упростить синтез регулятора с использованием стандартных математических процедур.

Ключевые слова: “черный ящик”; дуальное управление; расширенная матрица состояния; диагонализация; локальная модель; глобальная модель.

АЛГОРИТМ СИНТЕЗУ ДУАЛЬНОГО НЕПАРАМЕТРИЧНОГО КЕРУВАННЯ ДИНАМІЧНИМ ОБ'ЄКТОМ ТИПУ "ЧОРНИЙ ЯЩИК" З ВИКОРИСТАННЯМ МЕТОДУ ДІАГОНАЛІЗАЦІЇ МАТРИЦІ СТАНУ

А. А. Жосан, І. А. Маринич, О. Ю. Сердюк

Предметом статті є варіант ефективного алгоритму синтезу дуальної дискретної моделі і регулятора для стеження за заданою траєкторією динамічного нелінійного, нестаціонарного об’єкта типу "чорний ящик", з використанням стандартних процедур діагоналізації матриці стану, що дозволяє спростити отримання значення управління в чисельному вигляді, зменшити кількість обчислень. **Метою** статті є представлення одного з можливих варіантів вирішення проблеми синтезу регулятора для забезпечення стійкого відпрацювання заданої траєкторії руху нелінійного, нестаціонарного об’єкта типу "чорний ящик" з використанням концепції дуального управління. Було поставлено **завдання** спростити раніше запропонований алгоритм синтезу адаптивного управління динамічним нелінійним, нестаціонарним об’єктом на прикладі об’єкта першого порядку типу "чорний ящик", діагоналізацією підматриці стану з використанням стандартних матричних процедур. Розширена матриця стану є основою для отримання моделі управління і передбачення поведінки нелінійного нестаціонарного об’єкта, що в свою чергу дозволяє ефективно використовувати концепцію дуального управління. **Методи**, використані в роботі, засновані на концепції дуального управління, нелінійних динамічних моделях, теорії матриць, різницевих рівнянь. Отримані **результати** роботи полягають в розробці варіанту дуального непараметричного регулятора нестаціонарних нелінійних процесів, який володіє адаптивними властивостями, не вимагає знання фізики функціонування об’єкта управління, представлений у вигляді простої алгебраїчної формули, яка не містить коефіцієнти, які потребують настройки. **Висновки.** Наукова новизна полягає в застосуванні на кожному інтервалі управління матричного оператора для діагоналізації підматриці стану. Цей оператор використовується для подальшого обчислення керуючого впливу. Такий підхід забезпечує використання стандартної процедури діагоналізації за допомогою математичних додатків. Результат представлений у вигляді кінцевої формули, яка не потребує використання матричних операцій в ході управління, що дозволяє спростити синтез регулятора з використанням стандартних математичних процедур.

Ключові слова: "чорний ящик"; дуальне керування; розширена матриця стану; діагоналізація; локальна модель; глобальна модель.

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