Synthesis of the State-Feedback Controllers by the Genetic Algorithm According to the Maximum Stability Degree Criterion

Irina Cojuhari, Ion Fiodorov, Bartolomeu Izvoreanu, Dumitru Moraru
Technical University of Moldova
Chisinau, Republic of Moldova
irina.cojuhari@ati.utm.md, ion.fiodorov@ati.utm.md, bartolomeu.izvoreanu@ati.utm.md, dumitru.moraru@ati.utm.md

***Abstract*—The synthesis algorithm of state-feedback controllers is proposed in this paper. It was improved the procedure of finding the tuning parameters by the maximum stability degree criterion, using the genetic algorithm. Based on the genetic algorithm it is calculated the value of the maximum stability degree, according to witch it is calculated the control vector of the state-feedback controller. The proposed algorithm was verified by the computer simulation and there are presented some case studies. The case study was done for the situation when the control object is approximated with model of object with inertia and inertia with astatism.**

Keywords—automatic control system, maximum stability degree, state-feedback controllers, genetic algorithm

I. Introduction

Control problem is one of the most important problem in the designing of the automatic control systems. The automatic control systems are designed to stabilize the system that may be unstable, to ensure the settled performance of the system, or to maintain the desired output.

The inevitable part of any control problem is mathematical modelling of the process or control object, where the goal is to obtain a mathematical equation that describes the process with high precision range, based on the analytical or experimental identification procedure [1-2].

Dynamics of many linear systems can be described by the ordinary differential equations or difference equations and their equivalent Laplace or Z domain transfer functions, however these models are used for systems with single-input, single-output (SISO). The more general and efficient characterization of the system can be obtained, if the mathematical model in addition to the functional information (input-output), also includes the structural information through the state variables. The state variables is the set of variables $x(t) = [x_1(t), x_2(t),... ,x_n(t)]$, that fully describes the system and its response to any given set of inputs and permits prediction of the future development of a system. Mathematically, the knowledge of the initial values of the state variables at moment t_0, together with the knowledge of the system inputs for the moment of time $t \geq t_0$ are sufficient to predict the behaviour of the system and output variables for moment $t \geq t_0$ [1-2].

For state space realization of the system it is need to be satisfied the condition of controllability and observability [2-3], these concepts were introduced by Kalman in 1960 and play an important role in the designing of state feedback control systems.

The basic notions of the automatic control system design include feedback of different types [4]:

- Feedback control system, where the most useful control algorithm in industrial applications is PID, due to its simplity, robustness and possibility to establish the high performance to the control system. PID controllers are widely used in many control applications, especially for the case then parameters of the system are time invariant, system dynamics are favourable and the performance requirements are moderate. In case of design the complex automation control systems are used more specific control algorithms, that are based on optimization techniques, artificial intelligence algorithms etc. [5].

- State-feedback control systems, where the state variables of a system are available and the controller is tuned based on its [6].

The synthesis method for state-feedback controllers is based on the pole-placement method. The pole placement method is similar to the root-locus method, where is imposed the dynamic behaviour according to the desired performance by choosing the eigenvalues of the system matrix in the closed loop.

In [7-8], it is proposed the new synthesis method of the controller in the state space by the maximum stability degree (MSD) criterion to the model of object with inertia and astatism. This method offers to the designed systems the high performance and good robustness, where the feedback vector is calculated in dependency of the maximum stability degree value.

In this paper, the MSD criterion was proposed to be improved, namely the procedure of finding the tuning parameters in concordance with the variation of the maximum stability degree value, based on the genetic algorithm, that permits to set the different objective functions and promote the solution diversity.

II. Synthesis of the State-Feedback Controllers Based on the Maximum Stability Degree Criterion

It is considered given a structure of SISO system with representation in the state space (Fig.1)

$$\begin{cases} \dot{x} = Ax + bu, \\ y = c^T x, \end{cases} \tag{1}$$

and control algorithm

$$u(t) = -k^T x(t) = -\begin{bmatrix} k_0 & k_1 & \cdots & k_{n-1} \end{bmatrix} \cdot \begin{bmatrix} x_1 & x_2 & \ldots & x_n \end{bmatrix}^T, \quad (2)$$

where A is the state matrix with dimension $(n \times n)$; x - the vector of the state variables, $(n \times 1)$; u – the control value; b - the vector of control values, $(n \times 1)$; c - the vector of output values, $(n \times 1)$; k - the feedback vector (tuning parameters), $(n \times 1)$; n - the order of the system; y - the output value.

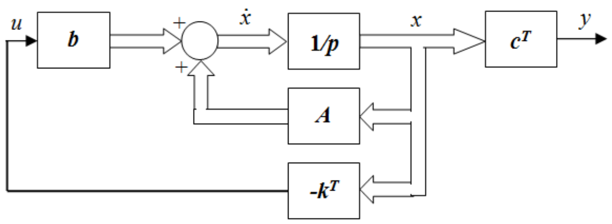

Fig. 1. The block scheme of a dynamic system in the state space.

According to the MSD criterion, the parameters of the feedback vector should be determinate, so as to be satisfied the condition [7-8]

$$J = \max_{k_i} \eta(k_i), i = (1, \ldots, n), \quad (3)$$

where J is the maximum stability degree; η - the stability degree of the system; k_i - the components of the feedback vector; n - the degree of the characteristic polynomial of the control system.

A. Synthesis of the State-Feedback Controllers to the Model of Object with Inertia and Astatism

In concordance with the MSD criterion [7-8] for determinate the feedback vector, the tuning procedure consists from the following steps:

1. The transfer function of control object with inertia and astatism is given in the following form:

$$H_F(s) = \frac{k}{a_0 s^n + a_1 s^{n-1} + \ldots + a_{n-1} s}, \quad (4)$$

where k is the transfer coefficient; $a_0, a_1, \ldots, a_{n-1}$ - the coefficients of the transfer function of control object, n - the order of control object.

2. The transfer function (4) is converted into the state space representation, namely controllable form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 1 \\ 0 & -\alpha_1 & \cdots & -\alpha_{n-2} & -\alpha_{n-1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-1} \\ x_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} u, \quad (5)$$

$$y = \begin{bmatrix} \beta_0 & 0 & 0 & \ldots & 0 \end{bmatrix} x = \beta_0 x_1.$$

where $\alpha_0 = \frac{a_n}{a_0}; \alpha_1 = \frac{a_{n-1}}{a_0}; \ldots; \alpha_{n-1} = \frac{a_1}{a_0}; \beta_0 = \frac{k}{a_0}$.

3. It is verified, if the condition of controllability is satisfied

$$rangU = rang[b, Ab, \ldots, A^{n-1}b] = n,$$

than it is passed to the next step, otherwise this control algorithm is not applied.

4. It is designed the structure of the controller

$$u(t) = -[k_1, k_2, \ldots, k_{n-1}] \cdot [x_2, x_3, \ldots, x_n]^T + k_0 \varepsilon, \quad (6)$$

where $\varepsilon = r - y$, r and y are the error, reference value and output value. To amplify the error signal, in direct connection it is included the proportional element k_0.

5. The value of the maximum stability degree J is determined by the following expression

$$J = \frac{\alpha_{n-1}}{n}. \quad (7)$$

6. The values of the feedback vector are calculated by the following relations:

$$k_0 = \frac{J^n}{\beta_0} \quad k_i = \frac{\prod_{l=1}^{i} (n - l + 1)}{i!} J^{n-i} - \alpha_i \quad i = 1, \ldots, (n-1). \quad (8)$$

B. Synthesis of the State-Feedback Controllers to the Model of Object with Inertia

According to the MSD criterion [7-8] in case of the model of object with inertia, the tuning procedure consists from the following steps:

1. The transfer function of control object with inertia is:

$$H_F(s) = \frac{k}{a_0 s^n + a_1 s^{n-1} + \ldots + a_{n-1} s + a_n}, \quad (9)$$

where k is the transfer coefficient; $a_0, a_1, \ldots, a_n$ - the coefficients of the transfer function of control object, n - the order of control object.

2. The transfer function (9) is converted into the state space representation, standard controllable form:

$$\begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \\ \dot{\varepsilon} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & \ldots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & 1 & 0 \\ -\alpha_0 & -\alpha_1 & \ldots & -\alpha_{n-1} & 0 \\ -\beta_0 & 0 & \ldots & 0 & 0 \end{bmatrix}}_{\hat{A}} \cdot \begin{bmatrix} x_1 \\ \vdots \\ x_{n-1} \\ x_n \\ \varepsilon \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \end{bmatrix}}_{\hat{b}} u + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 0 \\ 1 \end{bmatrix} r, \quad (10)$$

$$y(t) = \begin{bmatrix} \beta_0 & 0 & 0 & \ldots & 0 \end{bmatrix} x,$$

where $\alpha_0 = \frac{a_n}{a_0}; \alpha_1 = \frac{a_{n-1}}{a_0}; \ldots; \alpha_{n-1} = \frac{a_1}{a_0}; \beta_0 = \frac{k}{a_0}$.

3. It is verified, if the condition of controllability is satisfied

$$rangU = rang[\hat{b}, \hat{A}\hat{b}, \hat{A}^2\hat{b}, \ldots, \hat{A}^n\hat{b}] = n+1,$$

than it is passed to the next step, overwise this control algorithm is not applied.

4. It is designed the structure of the controller

$$u(t) = -[k_1, k_2, ..., k_n] \cdot [x_1, x_2, ..., x_n]^T + k_0\varepsilon, \quad (11)$$

where ε=*r*-*y*.

5. The value of the maximum stability degree *J* is determined by the following expression

$$J = \frac{\alpha_{n-1}}{n+1}. \quad (12)$$

6. The values of the feedback vector are calculated by the following relations:

$$k_0 = \frac{J^{n+1}}{\beta_0} \; k_i = \frac{\prod_{l=1}^{i}(n-l+2)}{i!} J^{n+1-i} - \alpha_{i-1} \; i = 1,...,n. \quad (13)$$

III. Synthesis of the State-Feedback Controllers Based on the Genetic Algorithm

The classical methods for synthesis the controllers can met difficulties for the case of complex systems, and nowadays the artificial intelligence approaches such as evolutionary algorithms, fuzzy logic, neuronal network are widely used in control problems.

One of the particular type of evolutionary algorithms is genetic algorithm, that was for the first developed by John Holland in the 1960s, as a search technique based on the principles of Darwinian evolution, where are applied the genetic operators such as selection, crossover and mutation, for generation of the new population. Genetic algorithm is a population based algorithm, where every solution represents a chromosome and each parameter represents a gene, where is evaluated the fitness of each individual in the population using a fitness (objective) function [9].

Genetic algorithm consists from the following steps:

1. Random creation of the new population.

2. Analysis of each chromosome by applying the fitness function.

3. Generation of a new population by applying the genetic operations as:

- Selection – the use of the solutions with high fitness to pass on to next generations.

- Crossover – selection of two chromosomes from a population, which mate and recombine to create offspring for the next generation.

- Mutation - individual chromosome support the small random changes of genes that lead to the generation of new chromosomes.

4. The above-mentioned steps are repeated until the swarm converges to an optimal or sub-optimal solution [10].

The genetic algorithm demonstrated so good performances in synthesis of the typical controllers and in this paper it was proposed to tune the state-feedback controller to the system with imposed performance, by the genetic algorithm [10, 11, 12].

According to the genetic algorithm and MSD criterion, it was proposed the following algorithm for synthesis the state-feedback controller to the model of object with inertia and astatism:

1. It is obtained the mathematical state-space representation of the control object in controllable form.
2. It is verified, if the system is controllable.
3. It is generated the new populations, in concordance with maximum stability degree value of the system - *J*.
4. According to the analytical expressions (8) for model of object with inertia and astatism or (13) for model of object with inertia there are calculated the values of the feedback vector.
5. Based on the settled objective function, it is verified the obtained solutions, where the objective function is settled according to the imposed performance to the automatic control system.
6. New population generation, applying the genetic operators as: selection, crossover and mutation.
7. The 4th-6th steps should be realized until the solutions tend to an optimal values according to the fitness function.

IV. Applications and Computer Simulation

It was proposed to tune the state-feedback controller to the model of object with inertia third order and astatism and to the model of object with inertia forth order.

A. Synthesis of the State-Feedback Controller to the Model of Object with Inertia and Astatism

It is considered the control object described by the transfer function with third order inertia and astatism

$$H_F(s) = \frac{5}{s(0,7s+1)(1,5s+1)(2s+1)} = \frac{5}{2,1s^4 + 5,45s^3 + 4,2s^2 + s}, \quad (14)$$

where $k = 5; T_1 = 0,7\,s; T_2 = 1,5\,s; T_3 = 2\,s;$

$a_0 = 2,1; a_1 = 5,45; a_2 = 4,2; a_3 = 1; a_4 = 0.$

It is formulated the problem to synthesis the controller in the state space realization to the model object (14).

It is obtained the normalized transfer function

$$H_F(s)=\frac{\beta_0}{s^4+\alpha_3 s^3+\alpha_2 s^2+\alpha_1 s+\alpha_0}=$$
$$=\frac{2,3809}{s^4+2,5952s^3+2s^2+0,4762s},$$

where $\alpha_0=0;\alpha_1=\frac{a_3}{a_0}=0,4762;\alpha_2=\frac{a_2}{a_0}=2;$

$$\alpha_3=\frac{a_1}{a_0}=2,5952;\beta_0=\frac{k}{a_0}=2,3809.$$

It is determined the vector-matrix equation in the standard controllable realization

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & -0,4762 & -2 & -2,5952\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}+\begin{bmatrix}0\\ 0\\ 0\\ 1\end{bmatrix}u,$$
$$y(t)=\begin{bmatrix}2,3809 & 0 & 0 & 0\end{bmatrix}x.$$

It is verified the condition of controllability

$$rangU=rang\begin{bmatrix}b & bA & bA^2 & bA^3\end{bmatrix}=4.$$

Because the rank of matrix U is equal with order of the system, then the system is controllable.

The control algorithm is presented by the following form

$$u(t)=-[k_1,k_2,k_3]\cdot[x_2,x_3,x_4]^T+k_0\varepsilon.$$

The synthesis of state-feedback controller is done based on the maximum stability degree criterion, in concordance with expressions (8), where the value of the MSD J is finding according to the genetic algorithm and the fitness function is settled based on steady-state error. The genetic algorithm was implemented in MATLAB using the Optimization Toolbox.

The obtained result were compared with results obtained for the case of tuning the state-feedback controller by the maximum stability degree criterion, genetic algorithm, the pole-placement method and parametrical optimization from MATLAB Simulink. The obtained results are presented in the Table I.

TABLE I. THE RESULTS OF SYNTHESIS THE CONTROLLER

No.	The synthesis methods	k_0	k_1	k_2	k_3	k_4
1	Maximum stability degree	*J*=0,6488				
		0,0744	0,616	0,525	0	0,0744
2	MSD with genetic algorithm implementation	*J*=1.535				
		2,3318	13,99	12,13	3,544	2,3318
3	Genetic Algorithm	2,414	5,033	6,25	0,065	2,414
4	The domination poles	0,038	0,304	0,29	0,005	0,038
5	Parametrical optimization	0,115	0,77	0,461	-0,01	0,115

The step responses of the designed control system are presented in the Fig. 2 and the performance are given in the Table II ($\varepsilon_{st}=\pm5\%$ from y_{st}). The numbering of curves correspond to the numbering of the methods from the Table I.

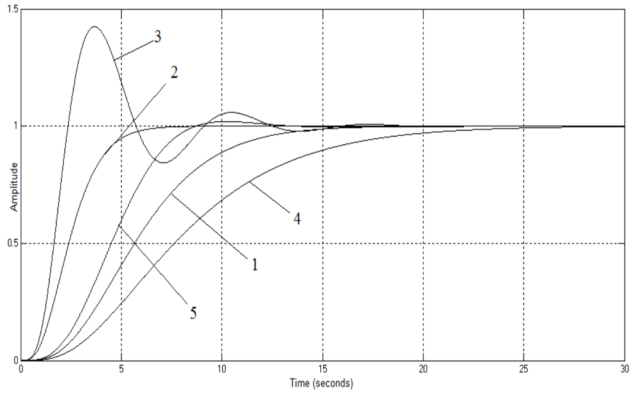

Fig.2. The step responses of the designed control system.

TABLE II. THE PERFORMANCE OF THE DESIGNED CONTROL SYSTEM

No.	The synthesis method	The performance of control system			
		t_c, s	t_r, s	σ, %	λ
1	Maximum stability degree	9,25	11,95	-	-
2	MSD with genetic algorithm implementation	11,27	21,12	-	-
3	Genetic Algorithm	2,86	9,99	9,54	
4	The domination poles	14,55	17,95	-	-
5	Parametrical optimization	5,38	7,68	2	-

From the Fig. 2 and Table II it can be observed, that for the case of tuning the state-feedback controller by the maximum stability degree criterion with genetic algorithm implementation, it was obtained the aperiodic transient process with the best performance.

B. Synthesis of the State-Feedback Controllers to the Model of Object with Inertia

It is considered the control object described by the following transfer function

$$H_F(s)=\frac{6}{(0,5s+1)(s+1)(2s+1)(4s+1)}=\frac{6}{4s^4+15s^3+17,5s^2+7,5s+1}, \quad (15)$$

where $k=6$, $a_0=4,a_1=15,a_2=17,5,a_3=7,5,a_4=1.$

It is formulated the problem to synthesis the controller in the state space to the model object (15).

It is obtained the normalized transfer function by the a_0

$$H_F(s)=\frac{\beta_0}{s^4+\alpha_3 s^3+\alpha_2 s^2+\alpha_1 s+\alpha_0}=$$
$$=\frac{1,5}{s^4+3,75s^3+4,375s^2+1,875s+0,25},$$

where $\alpha_0 = \frac{a_4}{a_0} = 0{,}25; \alpha_1 = \frac{a_3}{a_0} = 1{,}875; \alpha_2 = \frac{a_2}{a_0} = 4{,}375;$

$$\alpha_3 = \frac{a_1}{a_0} = 3{,}75; \beta_0 = \frac{k}{a_0} = 1{,}5.$$

It is determined the vector-matrix equation in the standard controllable form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -0{,}25 & -1{,}875 & -4{,}375 & -3{,}75 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u,$$
$$y(t) = \begin{bmatrix} 1{,}5 & 0 & 0 & 0 \end{bmatrix} x.$$

The stationary error of the control system will be null if in the structure of controller is connected an integrator element, which raises the order of the designed system and the above equation is transformed in the following form [13]

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{\varepsilon} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -0,25 & -1,875 & -4,375 & -3,75 & 0 \\ -1,5 & 0 & 0 & 0 & 0 \end{bmatrix}}_{\hat{A}} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ \varepsilon \end{bmatrix} +$$

$$+ \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}}_{\hat{b}} u + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} r,$$

$$y = \begin{bmatrix} 1{,}5 & 0 & 0 & 0 & 0 \end{bmatrix} x.$$

It is verified the condition of controllability

$$rangU = rang[\hat{b}, \hat{A}\hat{b}, \hat{A}^2\hat{b}, \hat{A}^3\hat{b}, \hat{A}^4\hat{b}] = 5 .$$

Because the rank of matrix U is equal with order of the system, then the system is controllable.

The control algorithm is presented in the following form

$$u(t) = -[k_1, k_2, k_3, k_4] \cdot [x_1, x_2, x_3, x_4]^T + k_0 \varepsilon .$$

The synthesis of state-feedback controller is done based on the maximum stability degree criterion, in concordance with expressions (13), where the value of the MSD J is finding according to the genetic algorithm. The obtained results were compared with results obtained for the case of tuning the state-feedback controller by the maximum stability degree criterion, the pole-placement method and parametrical optimization from MATLAB Simulink. The obtained results are presented in the Table III.

TABLE III. THE RESULTS OF SYNTHESIS THE CONTROLLER

No.	The synthesis methods	k_0	k_1	k_2	k_3	k_4
1	MSD	*J*=0,75				
		0,158	1,33	2,344	1,25	0
2	MSD with genetic algorithm impleme ntation	*J*=19.57				
		1,9e+06	7.3e+05	7,4e+04	3,8e+03	94,10
3	The domi-nation poles	0,06	0,62	1,195	0,515	-0,15
4	Parametrical optimization	0,091	0,538	0,257	-0,962	-0,91
5	Genetic algorithm	3,262	7,769	7,323	5,177	-0,02

The step responses are presented in the Fig. 3 and the performance are given in the Table IV. The numbering of curves correspond to the numbering of the methods in the Table III.

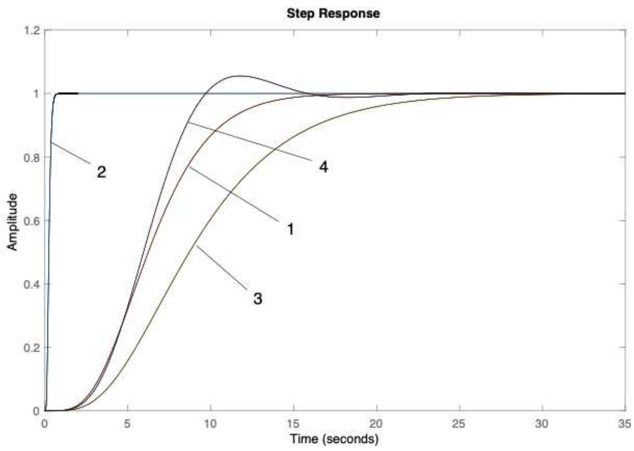

Fig.3. The step responses of the designed control system.

In the Fig. 4 it is presented the results for the case of tuning the state-feedback controller by the genetic algorithm, where the values of tuning parameters are found based on the imposed performance (steady-state error).

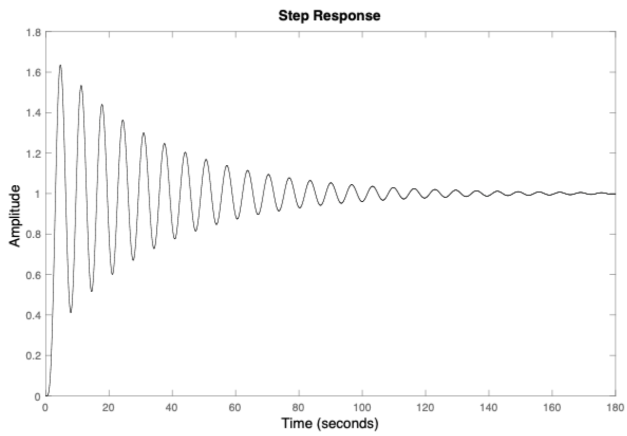

Fig.4. The step response of the designed control system.

TABLE IV. THE PERFORMANCE OF THE DESIGNED CONTROL SYSTEM

No.	The synthesis method	The performance of control system			
		t_c, *s*	t_r, *s*	*σ*, *%*	*λ*
1	Maximum stability degree	8,95	12,2	-	-
2	MSD with genetic algorithm implementation	0.28	0.54	-	-
3	The domination poles	15	19,2	-	-
4	Parametrical optimization	5,6	12,6	5,5	1
5	Genetic algorithm	1,49	123,1	63,57	19

From the Fig. 3 and performance presented in the Table IV, it can be observed that automatic control system with state-feedback controller tuned by the maximum stability degree criterion with genetic algorithm implementation gave the best results.

V. CONCLUSIONS

The process of synthesis the state-feedback controllers suppose the choosing of new eigenvalues values in concordance with imposed performance to the automatic control system and it can became complex problem, that requires to use the graph analytical design.

In this paper is presented an improved method of synthesis the state-feedback controller by the maximum stability degree criterion with implementation the genetic algorithm. Based on the genetic algorithm it is calculated the value of the maximum stability degree according to witch it is calculated the feedback vector.

The computer simulation demonstrated the good performance of the proposed algorithm. The algorithm was verified for the case of synthesis of the state-feedback controller to the model of object with inertia fourth order and inertia third order with astatism. The fitness function was designed based on the steady state error.

The obtained results were compared with results obtained for the case of tuning the state-feedback controller by the maximum stability degree criterion, genetic algorithm, the pole-placement method and parametrical optimization from MATLAB. The best results were obtained for the case of tuning the state-feedback controller by the maximum stability degree criterion with genetic algorithm implementation.

ACKNOWLEDGMENT

This work was supported by the project 20.80009.5007.26 „Models, algorithms and technologies for the control, optimization and security of the Cyber-Physical systems”.

REFERENCES

[1] Aliyu Bhar Kisabo, Aliyu Funmilayo Adebimpe, Odooh Clement Okwo and Sholiyi Olusegun Samuel, “State-Space Modelling of a Rocket for Optimal Control System Design,” in Journal of Aircraft and Spacecraft Technology, Volume 3: 128.137, 2019, pp.128-137.

[2] I. Dumitrache, S. Dumitru, I. Mihu, F. Munteanu, Gh. Muscă, C. Calcev, Automatizări electronice (Electronic automation). Bucureşti: Editura Didactică şi Pedagogică, 1993.

[3] C. Pozna, Teoria sistemelor automate (Theory of automatic control systems). Bucureşti: MATRIX ROM, 2004. 329.

[4] K. M. Hangos, J. Bokor, G. Szederkényi, State Feedback Controllers. In: Analysis and Control of Nonlinear Process Systems. Advanced Textbooks in Control and Signal Processing. Springer, London, 2004.

[5] América Morales Díaz and Alejandro Rodríguez-Angeles (September 6th 2011), “A PI_2D Feedback Control Type for Second Order Systems,” in Advances in PID Control, Valery D. Yurkevich, IntechOpen, 2011, DOI: 10.5772/10660.

[6] M. Huba and D. Vrančič, "State-Space Controller as a FOTD Based Generalization of ADRC," 2020 21th International Carpathian Control Conference (ICCC), High Tatras, Slovakia, 2020, pp. 1-6, doi: 10.1109/ICCC49264.2020.9257211.

[7] I. Fiodorov, “Sinteza Regulatorului în Spaţiul Stărilor după Criteriul Gradului Maximal de Stabilitate,” In proceedings of the 8th International Conference on Microelectronics and Computer Science ICMCS-2014, UTM, Chişinău, 22-25 October 2014, pp. 251-256.

[8] I. Fiodorov, I. Cojuhari, B. Izvoreanu and D. Moraru, “Analytical Algorithms for Synthesis of Modal Controllers by the Maximum Stability Degree Criterion,” in Annals of the University of Craiova, Electrical Engineering Series, No. 39, 2015. pp. 36-42.

[9] S. Mirjalili, Evolutionary Algorithms and Neural Networks. Springer International Publishing AG, 2019.

[10] I. Cojuhari, I. Fiodorov, B. Izvoreanu and D. Moraru, "Synthesis of PID Controller for the Automatic Control System with Imposed Performance based on the Multi-Objective Genetic Algorithm," 2020 International Conference and Exposition on Electrical And Power Engineering (EPE), Iasi, Romania, 2020, pp. 598-603, doi: 10.1109/EPE50722.2020.9305638.

[11] Qu Zhi, Xu Kai, He Xin, Lin Lu-chao, “Design of Wind Pendulum Control System Based on Improved Genetic PID Algorithm,” in IOP Conf. Series: Materials Science and Engineering 439(2018) 032095, 2018. pp. 1-7.

[12] Huu Khoa Tran, Hoang Hai Son, Phan Van Duc, Tran Thanh Trang and Hoang-Nam Nguyen, “Improved Genetic Algorithm Tuning Controller Design for Autonomous Hovercraft,” in Journal Processes, 2020; 8(1):66, https://doi.org/10.3390/pr8010066.

[13] В. В. Григорьев, Н. В.Журавлёва, Г. В. Лукьянова, К. А. Сергеев, “Синтез систем автоматического управления методом модального управления (Synthesis of control systems by the modal control method),” С-Пб: СПбГУ ИТМО, 2007. 108 с.