# Simulation of PID-Regulator Tuning Using Genetic Algorithm on Multi-Criteria Objective Function for Controlling Unstable Objects

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### Abstract

The paper discusses the problem of a popular industrial controller tuning in automatic control systems. This controller is named after their components: proportional, integral, and differential units. The problem with using such a controller is its configuration, which must consider the contradictory properties of the individual units' behavior. In practice, the approximate manual tuning technique proposed by Ziegler and Nichols is usually used. This technique is based on the system's response to a typical impact. The approximate tuning is not the best and can be improved. The proposed study proposes an improved methodology using transient endpoints such as overshooting, mean squared reference deviation error, and transient settling time. The proposed indicators create a criterion for the quality of tuning. Since analytical methods in this formulation of the problem are not suitable, it is therefore proposed to use a genetic algorithm that searches for the best parameters of the PID controller. A feature of the proposed algorithm is the introduction of restrictions on the desired parameters of the controller and the principle of elitism to eliminate losses of the best sets from previous search iterations. The proposed approach showed satisfactory results for stabilizing unstable control objects.

### Keywords

Genetic algorithm, PID controller, multi-criteria objective function

## 1. Introduction

In automatic control systems, controllers of different types are used to increase productivity. These controllers directly influence the coordinates of the control object, generating a control signal that ensures the execution of the task with the required quality indicators. The best quality indicators are achieved in systems with feedback, where the controller is located in a forward circuit, and its input receives an error signal or deviation from the value on the system input generated by the feedback and input circuit signals. Since the input signal can change, it can be an additive mixture of desired and interfering signals, and the controller must ensure the stability of the control system, minor processing errors, and compensate for changes in the input signal. These properties have relatively simple PID controllers, which contain proportional and integral control elements that reduce errors in the static mode and differentiating units that affect the error in the dynamic mode.

Despite the existence of various types of control algorithms, the PID controller has found practical application in industrial production. According to Astrom and Hagglund [1], more than 95% of process controllers are PIDs, and their popularity is growing. Results from testing hundreds of plants [2] showed that about 30% of regulators used manual tuning; 65% of regulators with automatic tuning did not provide a minimum variance error compared to manual mode. These results highlight the need to find effective tuning methods.

ITS-2023: Information Technologies and Security, November 30, 2023, Kyiv, Ukraine
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CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073
CEUR-WS.org/Vol-3887/paper10.pdf

The PID controller automatic tuning assumes that the mathematical model of the control object is known, and the weak point of these methods is that it can correspond to the object only in a narrow range of controller parameters [3]. The actual control object is nonlinear; its parameters can change depending on time and operating conditions; there are time delays in the control circuits, which complicate the adjustment of the controller parameters. As a result, manual methods for tuning PID controller parameters are superior to complex calculations based on a given mathematical model.

Currently, a sufficient number of algorithms have appeared that use the properties of "reasonableness" in the parameter selection, which are based on adaptation, fuzzy logic, and neural networks. These approaches also include heuristic methods, which use the search for the best sets of parameters when solving a multi-criteria problem. These methods are borrowed from observations of natural selection, which occurs in nature when mechanisms of random selection, crossing, and mutation are involved and are called genetic algorithms [3].

Tuning PID controllers based on genetic algorithm (GA) has been widely reflected in publications. However, the main problem of genetic algorithms is convergence, which can be both premature convergence, which leads to falling into a local minimum, and low convergence speed, which may not lead to obtaining the desired result within the specified time.

The genetic algorithm simulation for tuning a PID controller for an unstable object using a multi-criteria objective function that ensures sufficient convergence in an acceptable time is paper objective.

Further, the paper is organized as follows: Section 2 presents a review of the well-known literature in the area of research; Section 3 formulates the research problem; a general approach to finding a solution using a genetic algorithm is given in Section 4; Section 5 is devoted to the simulation of the search for PID controller parameters for objects with zero and imaginary roots of the characteristic equation; and at the end of the paper, a discussion of the results obtained is given.

## 2. Paper review

Whitley presents canonical and experimental forms of the genetic algorithm in the handbook [4]. Here, we can be acquainted with the theoretical foundations of GA, including the design theorem and some precise models of the canonical GA.

Most publications devoted to tuning PID controllers use GA. Thus, A. Mirzal et al. [5] implemented a genetic algorithm (GA) in the canonical form to determine the parameters of a PID controller to compensate for the time delay in a first-order system. However, the work notes that the genetic algorithm does not always give the desired result. The studies performed in the Matlab environment showed negative results that exceeded 4% of all completed studies.

A. A. Aly [6] presented setting up the PID controller GA in the SIMULINK environment for an electrohydraulic servo drive described by a system of four first-order differential equations and two control inputs. A feature of the controller tuning is the fitness function in the form of a mix of the integral of time multiplied by the absolute value of the error, overshoot, and steady-state error. Suyanto et al. [7] studied GA for tuning the PID controller in a water level control system in a mini-plant with a three-phase oil separator. Lambora et al. [8] present the GA basic processes discussion, their features, and applications. T. A. F. K. Yusoff et al. [9], Meena, and A. Devanshu compared the performance of Ziegler-Nichols and GA tuning methods in [10]. GA for tuning fractional order PID controllers in an automatic voltage regulation (AVR) system, we use these controllers proposed by Sun et al. [11].

Recently, intellectual approaches to attunement have been developing. Katoch et al. present a review of recent advances in GAs and a discussion of future research directions in the genetic operators' area, fitness functions, and hybrid algorithms [12]. An adaptive GA for adjusting the parameters of the PID controller, which is based on the operations of crossing and mutation according to adaptive probability algorithms, was proposed by Zhao J. and Xi M [13]. A machine-learning algorithm for a PID controller for optimal tuning is presented in [14].

Integrating a GA with an artificial immune system via a scheme incorporating diversity functions, distributed computing, adaptation, and self-control for tuning a PID controller is presented in the paper by Khoie et al. [15]. Yunan and Qu presented a combination of GA and iterative learning algorithms in [16]. Kawecki and T. Niewierowicz [17] proposed a hybrid algorithm based on genetic and classical algorithms for synthesizing time-optimal speed control of asynchronous motors. Flores-Morán et al. [18] present a combination of genetic and Fuzzy algorithms for tuning PID controllers in a DC motor control problem. Anh [19] proposes the Fuzzy Nonlinear ARX model for modeling, identification, and adaptive tracking of the angular position of the joint of a nonlinear robot manipulator in the article. The combination of the ant colony algorithm and GA for optimizing FID parameters is proposed in [20]. Bajarangbali et al. [21] show the integration of particle swarm optimization methods with GA for second-order objects.

Zhou et al. [22] proposed a scenario approach based on a genetic algorithm for investigating the events of entry and car tracking. Meng and B. Song [23] presented the improvement of genetic algorithms regarding population, selection, crossover, and mutation compared to simple genetic algorithms. A comparison of the structure and performance of a nonlinear variable PID controller (NL-PID) and a genetic algorithm (GA) PID controller is performed by Korkmaz et al. in [24]. Zhang et al. proposed the self-organization of genetic algorithms, in which new operators of dominant selection and cyclic mutation are introduced to optimize the PID controller parameters [25].

An analysis of the presented literature showed that the problem of controlling unstable objects is not well studied, which is of interest for constructing a genetic algorithm for tuning the PID controller of these objects.

## 3. Problem formulation

Some object with unstable dynamics is considered. Instability is characterized by the impossibility of establishing the output coordinates of an object to the required values in an acceptable time. The object is in the initial state. This state is known and characterized by these coordinates: state, speed, and acceleration of its changes.

To stabilize this object coordinates to a given position, a closed-loop controller with a proportional-integral-derivative (PID) controller in a feedback loop is used (shown in Figure 1).

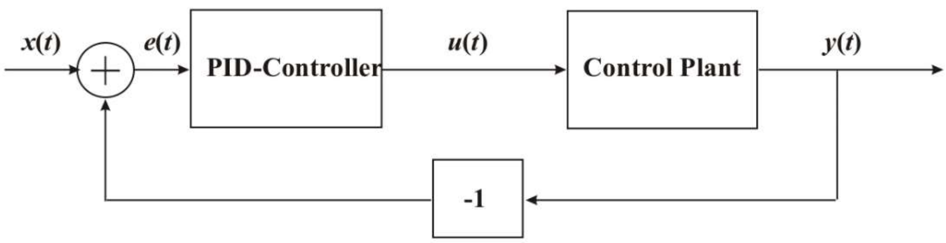


**Figure 1**: PID controller in an object control system

The PID controller generates a control signal from the error signal using proportional, integral, and differentiating units in the form:

$$u(t) = k_p e(t) + k_i \int_0^T e(t) + k_d \frac{de(t)}{dt}. \quad (1)$$

In (1) $k_p$, $k_i$, and $k_d$ are the transmission coefficients of the proportional, integral, and differential units, respectively; $e(t)$ is the error signal,

$$e(t) = x(t) - y(t), \quad (2)$$

where $x(t)$ is the input signal, $y(t)$ is the output signal, $t$ is a variable that has the sense of time, and $T$ is the observation time of the process.

We assumed that the parameters of the PID controller are subject to restrictions in the form:

$$\underline{k_p} \le k_p \le \overline{k_p},\ \underline{k_i} \le k_i \le \overline{k_i},\ \underline{k_d} \le k_d \le \overline{k_d}. \quad (3)$$

In (3), values $\overline{k}, \underline{k}$ are indicated as the upper and lower values of the controller parameters.

A master action of a known type is applied to the input of the object, for example, a unit step function $x(t) = 1(t)$, generating the output signal $y(t)$ in the form of a transient process. Sensors record the following indicators of the control process: overshooting $OS$, settling time $t_{st}$, and steady-state error $e_{min}$. Noise-free sensors measure object parameters.

The task is posed to configure the parameters of the PID controller that satisfy constraints (3) and ensure system stability with minimal values of overshooting, establishment time, and steady-state error of the transient process. This problem we can represent by a complex criterion in the form:

$$I = \alpha \cdot OS + \beta \cdot MSE + \gamma \cdot T_p, \quad (4)$$

where OS is calculated by the formula

$$OS = \frac{y_{max} - y_{st}}{y_{st}} \cdot 100\%, \quad (5)$$

MSE (mean squared error) is the mean squared error, which is calculated as follows

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - y_{st})^2, \quad (6)$$

$T_p$ is the duration of the adjustment process, i.e. when the output value $y$ reaches the set value $y_{st}$. Other designations: $y_{max}$ is the maximum value of the initial value; α, β, and γ are weighting coefficients that determine the contribution of each term to the overall productivity of the GA;

$$I \le I_{min}, \quad (7)$$

where $I_{min}$ is the minimum value of criterion (4).

## 4. Solution

At the first step of applying the GA procedure, a random set of chromosomes is introduced, which are associated with the parameters of the PID controller, the effect of which on the system is further evaluated. After the simulation, the manipulated variable is immediately returned to the GA, and the selected error criterion is used to assess the performance and determine the fitness value of this chromosome for further search for PID controller parameters that can satisfy the system designer.

GA performance is evaluated by the objective function $I$ (4).

Traditionally, GA includes the following steps: selection, crossing, mutation, and quality assessment of the resulting chromosome set. If the stopping criterion is not met, the GA procedure is repeated the given number of times.

In the developed algorithm, the maximum number of generations of the new generation $P$ is set. A considerable number of iterations leads to an unjustified increase in the operating time of the algorithm when obtaining a repeated result, which can be interpreted as looping in a local minimum.

After the initialization of a chromosome set consisting of $N$ randomly selected individuals, the selection procedure is. This procedure is necessary for sampling the most successful generation of individuals according to the objective function (2). Since the initial data are given by real numbers, those data that correspond to the minimum value of the objective function rounded to the nearest larger whole get into the new chromosome set. It allows you to preserve the best generation of parameters and guarantees the asymptotic convergence of the GA.

The crossing operation was carried out according to the principle of arithmetic crossing, which is the most successful for finding the optimum of the function of many real variables. According to this principle, two offspring $h_{1s}$ and $h_{2s}$ are created based on the values of the genes of the parent chromosomes $h_1$ and $h_2$. Values of genes of offspring $h_{1si}$ and $h2_{si}$ are calculated according to the formulas:

$$h_{1_{si}} = kh_{1i} + (1-k)h_{2i}, \quad (8)$$

$$h_{2_{si}} = kh_{2i} + (1-k)h_{1i}, \quad (9)$$

where $k \in [0; 1]$ is some real coefficient. The geometric interpretation of this process is shown in Figure 2.


**Figure 2**: Scheme of arithmetic crossing

In Figure 2 $w_{min,i}$ and $w_{max,i}$ denote the minimum and maximum value of the $i$th parameter.

Mutation of selected chromosomes consists in changing the values of genes by some impurities $\Delta h_{ij}$ according to the rule

$$h'_{ij} = h_{ij} + \Delta h_{ij}, \quad (10)$$

where $h_{ij}$ is the gene before the mutation; $h'_{ij}$ is the gene after the mutation.

The algorithm uses an uneven mutation for the $i$th gene. According to [8], the new gene values in case of uneven mutation are calculated according to the formula

$$h'_{ij} = \begin{cases} h_{ij} + \Delta h(t, w_{max,i} - h_{ij}), if\ r \le 0.5, \\ h_{ij} - \Delta h(t, h_{ij} - w_{min,i}), if\ r > 0.5, \end{cases} \quad (11)$$

where $\Delta h(t, y) = y(1 - r^{(1-p/P)^k})$; $r$ is a random number from the interval [0; 1]; $p$ is the current iteration number; $k$ is a non-uniformity parameter. All chromosomes that do not meet the specified level of objective function are subject to mutations.

At the last stage of the algorithm, a new generation is formed. To prevent the best chromosomes from being lost, they are guaranteed to be included in the new population.

The specified sequence of operations is repeated until the algorithm is considered converged. The algorithm terminates when the specified performance is satisfied or all assigned generations are completed. In the latter case, the chromosome set with the best performance is chosen.

## 5. Simulation

In the interests of modeling, we use a mathematical model described by a differential equation of the second or third order, which will reproduce the dynamics of the controlled process with sufficient accuracy.

To study the dynamics of such a model, the space of states is usually linked to the phase coordinates of a dynamic system [7]. At the same time, the differential equation of the object model is represented by a system of differential equations, which for a stationary object is convenient to present in matrix form:

$$\begin{gathered} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t), \end{gathered} \quad (12)$$

In (12), $x(t)$, $y(t)$, and $u(t)$ are vectors of phase variables, output coordinates, and control, respectively, depending on time $t$. Vectors dimensionality are $x \in R^n$, $y \in R^m$, and $u \in R^p$. Matrices $A$, $B$, and $C$ have these forms $A \in R^{n \times n}$, $B \in R^{n \times p}$, and $C \in R^{m \times n}$.

A system with feedback provides the given dynamics of an object. A PID controller in the feedforward circuit of the system is installed in series with the object.

### 5.1. Double integrator

#### 5.1.1. Math model

As an unstable control object, a double integrator is chosen, which has a double zero root and is described by a system of differential equations in the first-order form:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= ku(t), \end{aligned} \tag{13}$$

where $x_1(t)$ and $x_2(t)$ are the phase variables of the integrator containing its output and its derivative, $u(t)$ is the control signal, and $k$ is the amplification factor of the control system. The variable $t$ is a time. At the control start ($t$=0), the initial state of integrators is unexcited, i.e. $x_1(0) = x_2(0) = 0$.

The object can be stabilized by applying a control device. Such a device is a PID controller, which at the space of phase variables, can be represented by a system of equations

$$\begin{aligned} u(t) &= y_1(t) + y_2(t) + y_3(t), \\ y_1(t) &= k_p e(t), y_2(t) = k_i \int_0^t e(\tau)d\tau\,,\ y_3(t) = k_d \frac{de(t)}{dt}. \end{aligned} \tag{14}$$

In (10), $y_1(t)$, $y_2(t)$, and $y_3(t)$ are the outputs of the proportional, integral, and differential units, respectively. Values $k_p$, $k_i$, and $k_d$ are the parameters of the corresponding units of the PID regulator, and variable $e(t)$ is the error signal at the input of the PID regulator. Restrictions (3) are applied to the parameters of the PID controller.

A standardized single signal in the form of a step, i.e. $r(t)=1(t)$, is applied to the input signal of the system.

In the interests of modeling and to prevent complex integration algorithms, we present the considered system in the extended phase space $X_{ext} \in R^5$, which takes into account the phase coordinates of the considered objects, which allows us to present the system in the form of a matrix differential homogeneous equation of the first order of the form:

$$\dot{X}_{ext}(t) = A_{ext}X_{ext}(t). \tag{15}$$

with the initial vector $X_{ext}(0) = (0, 0, 0, 0, 1)^T$. The system of equations in (14) has the form:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -k(k_p + 1)x_1(t) - kx_3(t) + kx_4(t) + k(k_p + 1)x_5(t), \\ \dot{x}_3(t) &= k_d x_1(t) - kx_3(t) + k_d x_5(t), \\ \dot{x}_4(t) &= -k_i x_1(t) + k_i x_5(t), \\ \dot{x}_5(t) &= 0 \end{aligned} \tag{16}$$

In (16), $x_1$ and $x_2$ are the phase coordinates that coincide with (12), $x_3$ and $x_4$ are the outputs of the differential and integral links of the PID controller, respectively, and $x_5$ is the input signal.

Limit parameters (3) of the PID controller are given by inequalities:

$$\begin{aligned} 10^{-5} &\le k_p \le 1, \\ 10^{-5} &\le k_i \le 1, \\ 10^{-5} &\le k_d \le 1. \end{aligned}$$

#### 5.1.2. GA parameters

GA parameters are given in Table 1.

**Table 1**
Genetic algorithm parameters

| Parameter | Value |
|---|---|
| Coefficients of the objective function α, β, γ | 0.1 |
| The number of generations of the new generation | 10 |
| Initial chromosomal set | 20 |
| Arithmetic crossover coefficient | 1/3 |
| Coefficient r mutation | Median of the generated random series |

The PID controller's initial and final parameters are given in Table 2. The PID controller parameters, at the beginning of the study, were selected according to the Ziegler-Nichols method.

**Table 2**
PID controller setting parameters

| Parameter | before GA | after GA |
|---|---|---|
| $k_p$ | 0.001 | 0.1883 |
| $k_d$, s | 0.3 | 0.5044 |
| $k_i$, $s^{-1}$ | 0.0004 | 0.0181 |
| $k$, $(V \cdot s)^{-1}$ | 2 | 2 |
| $I$ | 8.3561 | 7.8674 |

### 5.1.3. Simulation results

Transient processes in the system according to Table 2 are presented in Figures 2 and 3.

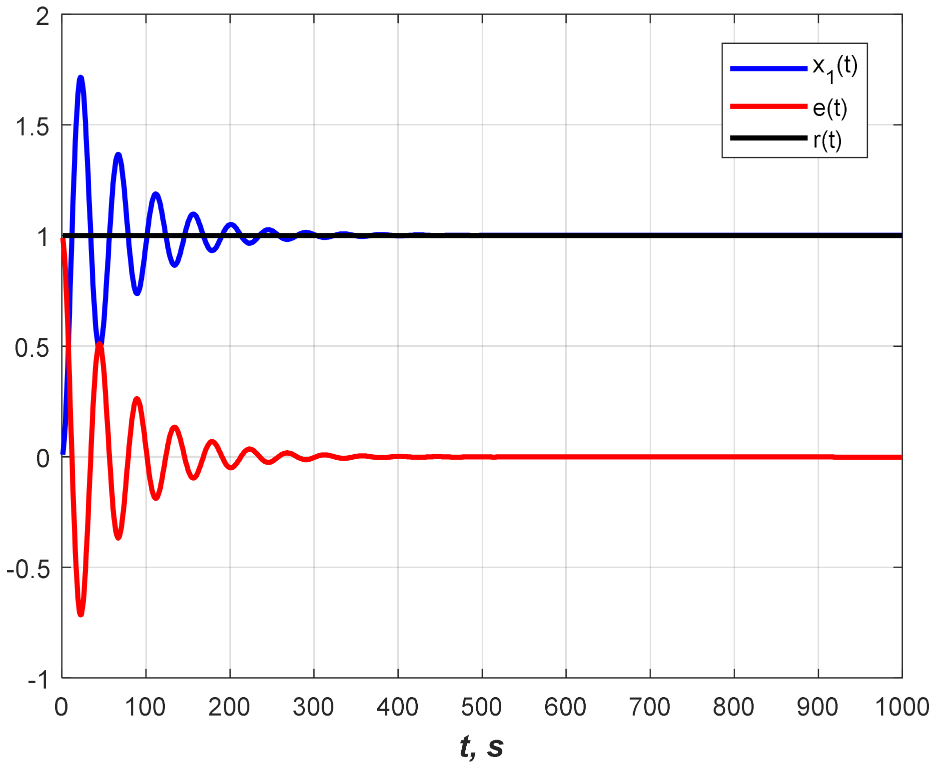


**Figure 2**: Functions $x_1(t)$, $e(t)$, and $r(t)$ for the PID controller and the double integrator before the GA start

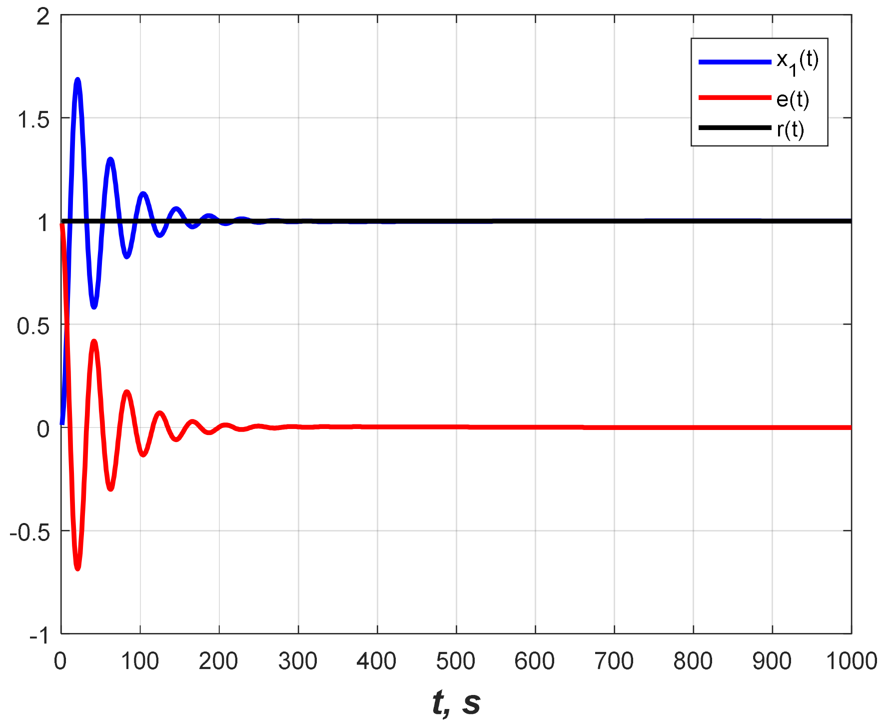

**Figure 3**: Functions $x_1(t)$, $e(t)$, and $r(t)$ for the PID controller and the double integrator after the GA start

Analysis of Figures 2 and 3 shows a general decrease in oscillations and transient transients. System performance increased by approximately 6%.

### 5.2. Oscillating object

An oscillating object is chosen as an unstable control object, the characteristic equation of which has conjugate imaginary roots $\pm j\omega$ and is described by a system of first-order differential equations of the form [26, 27]

$$\begin{gathered}\dot{x}_1(t) = x_2(t),\\ \dot{x}_2(t) = -\omega^2 x_1(t) + \omega^2 k u(t),\end{gathered} \tag{17}$$

where $x_1(t)$ and $x_2(t)$ are the phase variables of the object, which have the content of its output and its derivative, $u(t)$ is the control signal, $k$ is the parameter of the control object, and $\omega$ is the oscillation frequency. The initial state of the control object ($t$=0) is not excited, as in the case of the previous object $x_1(0) = x_2(0) = 0$.

The system response to a standardized unit signal is in the step form, i.e. $r(t)$=1($t$). The initial values of the coefficients of the PID regulator are set according to the Ziegler-Nichols algorithm and have the values $k_p$ = 0.31, $k_d$ = 1.023 s, and $k_i$ = 0.021 $s^{-1}$, performance $I$ = 4.027. The graphs of the functions $x(t)$, $r(t)$, and $e(t)$ before and after setting the PID controller by GA have the form shown in Figures 4 and 5. After the GA action, the following values of the coefficients of the PID regulator were obtained: $k_p$ = 0.0548, $k_d$ = 0.6446 s, $k_i$ = 0.0222 $s^{-1}$, and $I$ = 3.9434. A productivity increase of 2.1% was obtained.

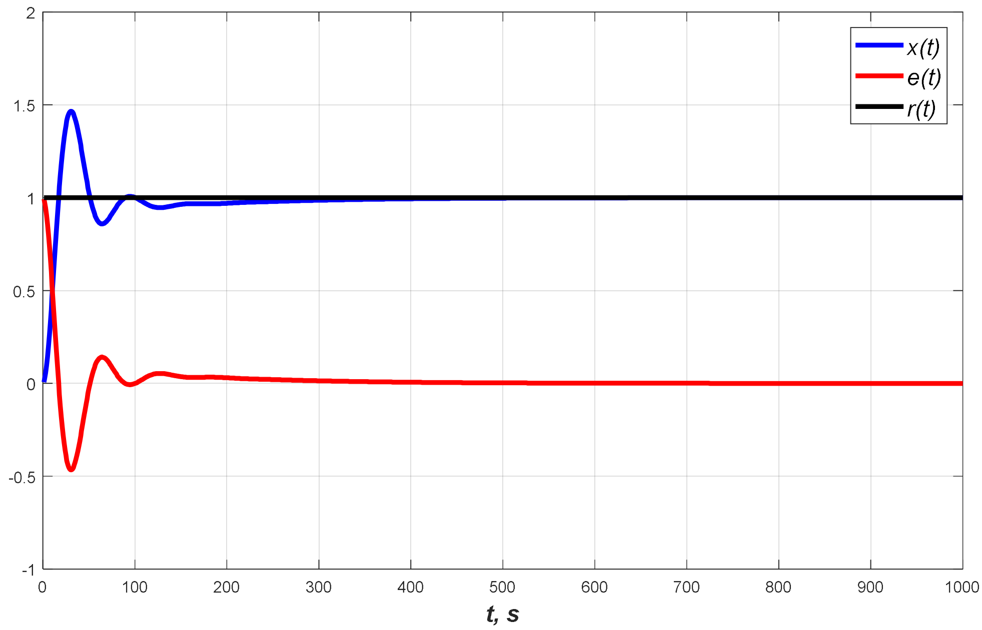


**Figure 4**: Functions $x(t)$, $e(t)$, and $r(t)$ for the PID controller and the oscillating object before the GA start

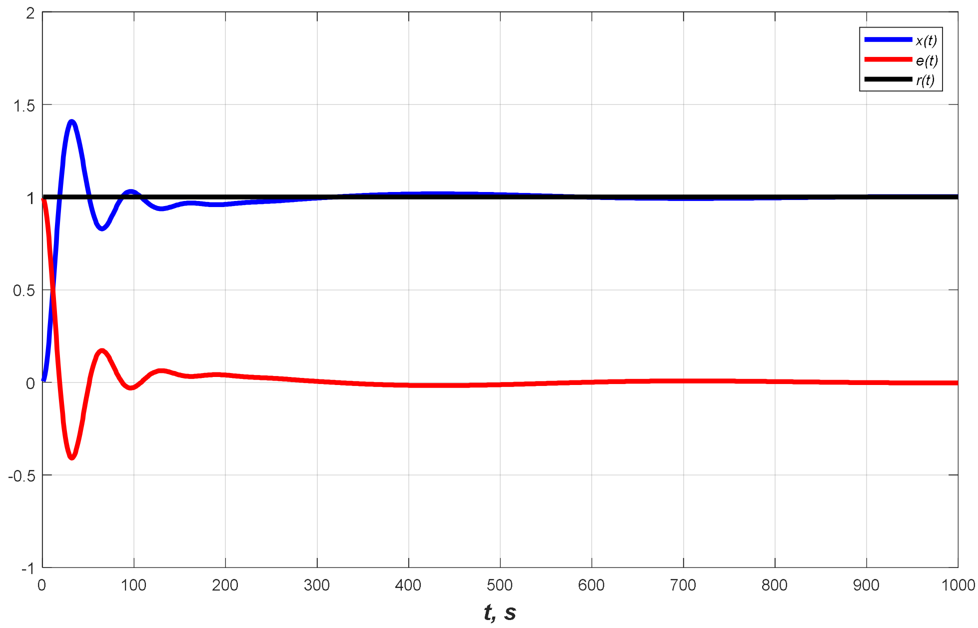


**Figure 5**: Functions $x(t)$, $e(t)$, and $r(t)$ for the PID controller and the oscillating object after the GA start

## Discussion

The paper presents the GA implementation technology for setting the PID controller parameters for an unstable object with multiple zero roots of the characteristic equation. A multi-criteria function was used as the objective function, which includes the overshooting, the root mean square error, and the duration of the transition process. The total increase in adjustment compared to the Ziegler-

Nichols algorithm is 6% for the double integrator and 2.1% for the oscillating object, which allows us to conclude the feasibility of using GA to improve the adjustment of the PID controller.

## Acknowledgements

The work has been carried out on an initiative basis. The authors thank both the authorities of the National Aviation University and the especially leadership of the Faculty of Computer Science and Technologies for their support during the preparation of this paper.

## References

[1] S. Anzaroot, A. McCallum, UMass citation field extraction dataset, 2013. URL: http://www.iesl.cs.umass.edu/data/data-umasscitationfield. K. Astrom, T. Hagglund, PID controllers: Theory, Design, and Tuning, 2nd. ed., Instrument Society of America, 1995. URL: https://www.amazon.com/PID-Controllers-Theory-Design-Tuning/dp/1556175167

[2] D.B. Ender, Process control performance: not as good as you think, Control Engineering, September (1993) 180-190. URL: https://api.semanticscholar.org/CorpusID:232712838

[3] H. O. Bansal, R. Sharma, P. R. Shreeraman, PID Controller Tuning Techniques: A Review, Journal of Control Engineering and Technology (JCET), 2, 4, (2012) 168–176. URL: https://www.academia.edu/11729116/PID_Controller_Tuning_Techniques_A_Review

[4] D. Whitley, A genetic algorithm tutorial. Stat Comput 4 (1994) 65–85. https://doi.org/10.1007/BF00175354

[5] A. Mirzal, S. Yoshii, M. Furukawa, PID Parameters Optimization by Using Genetic Algorithm. URL: https://arxiv.org/ftp/arxiv/papers/1204/1204.0885.pdf

[6] A. A. Aly, PID Parameters Optimization Using Genetic Algorithm Technique for Electrohydraulic Servo Control System Intelligent Control and Automation, 2 (2011) 69-76, doi:10.4236/ica.2011.22008

[7] Suyanto, P. A. Darwito, B. L. Widjiantoro, D. O. Pradana, S. A. Prananda, S. W. Sudrajat, Development Of PID Based On Genetic Algorithm As A Control Algorithm On A Three-Phase Mini Plant Separator Level Control System, in: Proceedings of the 2022 IEEE International Conference of Computer Science and Information Technology (ICOSNIKOM), Laguboti, North Sumatra, Indonesia, 2022, pp. 01-06, doi: 10.1109/ICOSNIKOM56551.2022.10034865

[8] A. Lambora, K. Gupta, K. Chopra, Genetic Algorithm- A Literature Review, in: Proceedings of the 2019 International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon), Faridabad, India, 2019, pp. 380-384, doi: 10.1109/COMITCon.2019.8862255

[9] T. A. F. K. Yusoff, M. F. Atan, N. A. Rahman, N. A. Wahab, S. F. Salleh, Optimization of PID Tuning Using Genetic Algorithm, Journal of Applied Science & Process Engineering, 2, 2, (2015) 97 – 106. doi: 10.33736/jaspe.168.2015

[10] D. C. Meena, A. Devanshu, Genetic algorithm tuned PID controller for process control, in: Proceedings of the 2017 International Conference on Inventive Systems and Control (ICISC), Coimbatore, India, 2017, pp. 1-6, doi: 10.1109/ICISC.2017.8068639

[11] J. Sun, L. Wu, X. Yang, Optimal Fractional Order PID Controller Design for AVR System Based on Improved Genetic Algorithm, in: Proceedings of the 2020 IEEE International Conference on Advances in Electrical Engineering and Computer Applications( AEECA), Dalian, China, 2020, pp. 351-355, doi: 10.1109/AEECA49918.2020.9213473

[12] Katoch, S., Chauhan, S.S. & Kumar, V. A review on genetic algorithm: past, present, and future. Multimed Tools Appl 80, (2021) 8091–8126. URL: https://doi.org/10.1007/s11042-020-10139-6

[13] Zhao J. and Xi M., Self-Tuning of PID Parameters Based on Adaptive Genetic Algorithm, in: Proceedings of the 2020 IOP Conf. Ser.: Mater. Sci. Eng. 782 042028, doi: 10.1088/1757-899X/782/4/042028

[14] D. Kucherov, A. Kozub, V. Tkachenko, G. Rosinska, O. Poshyvailo, PID controller machine learning algorithm applied to the mathematical model of Quadrotor lateral motion, in: Proceedings of the IEEE 6th International Conference on Actual Problems of Unmanned Aerial Vehicles Development (APUAVD), 19-21 Oct. 2021, Kyiv, Ukraine, doi: 10.1109/APUAVD53804.2021.9615438

[15] M. Khoie, A. K. Sedigh and K. Salahshoor, PID controller tuning using multi-objective optimization based on fused Genetic-Immune algorithm and Immune feedback mechanism, in: Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, Beijing, China, 2011, pp. 2459-2464, doi: 10.1109/ICMA.2011.5986338

[16] H. Yunan, B. Qu, Application of Iterative Learning Genetic Algorithms for PID Parameters Auto-Optimization of Missile controller, in: Proceedings of the 2006 6th World Congress on Intelligent Control and Automation, Dalian, 2006, pp. 3435-3439, doi: 10.1109/WCICA.2006.1713006

[17] L. Kawecki, T. Niewierowicz, Hybrid Genetic Algorithm to Solve the Two Point Boundary Value Problem in the Optimal Control of Induction Motors, in: Proceedings of the IEEE Latin America Transactions, vol. 12, no. 2, pp. 176-181, March 2014, doi: 10.1109/TLA.2014.6749535

[18] E. Flores-Morán, W. Yánez-Pazmiño, J. Barzola-Monteses, Genetic algorithm and fuzzy self-tuning PID for DC motor position controllers, in: Proceedings of the 2018 19th International Carpathian Control Conference (ICCC), Szilvasvarad, Hungary, 2018, pp. 162-168, doi: 10.1109/CarpathianCC.2018.8399621

[19] H. P. H. Anh, Implementation of Fuzzy NARX IMC PID control of PAM robot arm using Modified Genetic Algorithms, in: Proceedings of the 2011 IEEE 5th International Workshop on Genetic and Evolutionary Fuzzy Systems (GEFS), Paris, France, 2011, pp. 54-59, doi: 10.1109/GEFS.2011.5949491

[20] Ant colony algorithm with genetic characteristic and its application in PID parameters optimization, in: Proceedings of the 2008 Chinese Control and Decision Conference, Yantai, China, 2008, pp. 5069-5074, doi: 10.1109/CCDC.2008.4598295

[21] Bajarangbali, Sujay H S, Suman R, Chaithanya S, Narayanan S, Shamanth U, Tuning and Analysis of PID Controllers Using Soft Computing Techniques, International Journal of Scientific Research in Science and Technology (IJSRST), 5, 3 (2018) 67-71. URL : https://ijsrst.com/IJSRST185312

[22] R. Zhou, Y. Liu, K. Zhang, O. Yang, Genetic Algorithm-Based Challenging Scenarios Generation for Autonomous Vehicle Testing, IEEE Journal of Radio Frequency Identification, 6 (2022) 928-933. doi: 10.1109/JRFID.2022.3223092

[23] X. Meng, B. Song, Fast Genetic Algorithms Used for PID Parameter Optimization, IEEE International Conference on Automation and Logistics, Jinan, China, (2007) 2144-2148. doi: 10.1109/ICAL.2007.4338930

[24] M. Korkmaz, Ö. Aydoğdu, H. Doğan, Design and performance comparison of variable parameter nonlinear PID controller and genetic algorithm based PID controller, in: Proceedings of the 2012 International Symposium on Innovations in Intelligent Systems and Applications, Trabzon, Turkey, 2012, pp. 1-5, doi: 10.1109/INISTA.2012.6246935

[25] J. Zhang, J. Zhuang, H. Du, S. Wang, Self-organizing genetic algorithm based tuning of PID controllers, Information Sciences, 179, 7 (2009) 1007-1018. https://doi.org/10.1016/j.ins.2008.11.038

[26] D. Kucherov, A. Kozub, O. Sushchenko, R. Skrynkovskyy, Stabilizing the spatial position of a quadrotor by the backstepping procedure, Indonesian Journal of Electrical Engineering and Computer Science, 23, 2, (2021) 1188-1199. doi: 10.11591/ijeecs.v23.i2.pp1188-1199

[27] D. Kucherov, T. Shmelova, O. Poshyvailo, V. Tkachenko, I. Miroshnichenko, I. Ogirko, Mathematical Model of Damping of UAV Oscillations in the Cargo Delivery Problem, in: Proceedings of the 2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, 2023, pp. 1-6, doi: 10.1109/KhPIWeek61412.2023.10312855