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# A NOVEL APPROACH FOR OPTIMIZATION OF NOZZLE ANGLE AND THRUST VECTORING CONTROLLER VIA A SUB-MUTATION GENETIC ALGORITHM

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Abstract. *In this paper, we present a method for a proportional-integral-derivative (PID) controller design via new and improved genetic algorithm approach. This method provides for determining optimal controller parameters about ballistic missile systems. The relationship between thrust vector and angle of the nozzle is examined. This relationship is vital for controlling the movements of ballistic missiles. PID controller system provides sufficient success as observed in the results. In this study, optimal PID controller parameters are obtained by a new approach which is called as a sub-mutation genetic algorithm. The sub-mutation genetic algorithm provides more successful and robust results than that of the traditional genetic algorithm.*
**Keywords:** Optimization, Genetic algorithm (GA), Ballistic missile, Thrust vectoring, Nozzle, Optimal controller design

1. **Introduction.** The optimization of PID controller is one of the most popular topics in the area of control theory. The realization process of optimal PID controller is generally performed via metaheuristic optimization algorithms [1-3] such as genetic algorithm (GA), particle swarm optimization (PSO), and artificial bee colony (ABC). In addition to these, the application areas of controller optimization are very diverse. Some of the application areas of controller optimization can be listed as follows: power system [4], robotic arms and movements [5], unmanned aerial vehicle (UAV) [6], conditioning system [7], etc. In this paper, a novel approach is proposed to design optimal PID controller system. This designed system ensures that the ballistic missile movement is correctly performed on certain conditions. This study involves applying an innovative approach to a new field. The design of control system for the movement of the missile is a new area and we aim to merge this area with an innovative approach of GA [8]. It is aimed that the proposed approach will have more successful performance according to traditional GA. The process of controlling the ballistic missile is investigated within the context of this study because it is a rarely studied field in the literature.

Control systems of ballistic missiles are one of the most popular topics in the control systems field. The system of ballistic missiles is more complex and has advanced structures when compared with the other missile systems such as surface-to-surface missile (SSM). The key advantages of the ballistic missile are having long range and carrying nuclear warheads. Neutralization of ballistic missiles is tough to expect first launching process [9]. They can reach to very high speed (7 km/sec), and this speed provides an advantage in wars or space researchers. Furthermore, ballistic missile system has a modular structure providing versatile purpose such as carrying satellite or spacecraft out of atmosphere [10].

Research on ballistic missiles gives a great momentum on wireless communications, space research, and space odyssey [11]. In another way, the authorities who called cell phones have been one of the biggest phenomena on invention technology in last decade, and ballistic missiles systems have helped to these devices [12].

Operation processes of ballistic missiles are routing out of the atmosphere after free fall from outside of the air. These trajectories provide very high speed to ballistic missiles. The gravity force is only active on a ballistic missile of free fall sequence, and the ballistic missile can reach to very high speed on free fall course. These high speeds provide nearly invisibility to the ballistic missile from anti-missile defense system. Essential parts of a rocket engine are shown in Figure 1 [13-15].

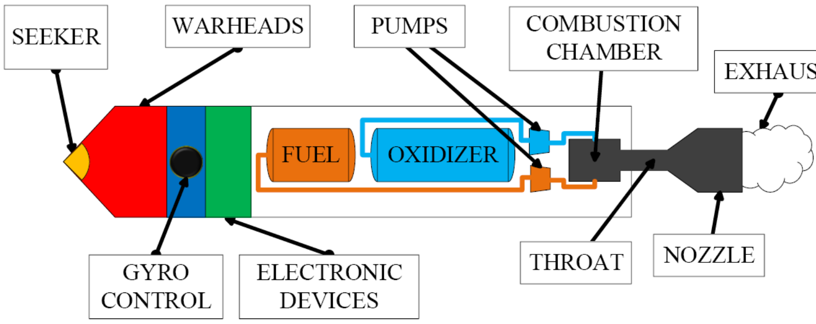


Figure 1. The parts of liquid rocket engine

The controlling process of a ballistic missile is critical in that respect. Ballistic missiles have three-dimensional movements like other aircraft [16]. Thrust vector or thrust vector control (TVC) is a generic term of the relationship between the orientation of aircraft created from driving force at the engine of plane and missile or similar structures. Users can change angular velocity or movement characteristic by this relationship which is one of the most important parameters for aircraft, missiles, and similar structures.

The design of aerodynamic surfaces on ballistic missile and rockets is not affected in outside of the atmosphere. For this reason, main movement characteristic of ballistic missiles and rocket is highly related to thrust vector control. Thrust vector control is highly effective at first state on ignition. At initial condition, thrust vector of ballistic the missile nozzle structure effect line is passed from the center of gravity ($c_g$) on missile and this condition shows zero moments at the center of gravity and this has not any effect on thrust. The main purpose of flight dynamics is to model three-dimensional movements of aircraft. These terms are defined as pitch, yaw, and rolls. Aircraft's movements are defined by light of three parameters [17]. Pitch, yaw, and roll terms are shown in Figure 2 [18].

The user can change the moments via nozzle angle. The change of nozzle angle can provide a controllable moment when it does not pass over the gravity center of a ballistic missile. These differences provide a moment related with $c_g$ on aircraft and aerial vehicle. In attrition to that, these generated moments are provided by pitch and yaw moments on ballistic missiles. Therefore, there is a relationship between the moment of thrust vector and angle of the nozzle. The guidance application of ballistic missile is used in this relationship [19].

The sections are arranged as follows. The second section gives the definition of optimal controller system via transient systems parameters. The relationship between nozzle angle and thrust vector which are the most significant parameters for ballistic missile movement is explained in Section 3. The sub-mutation based genetic algorithm which is the novel part of the work is briefly explained in Section 4. The results of experimental work

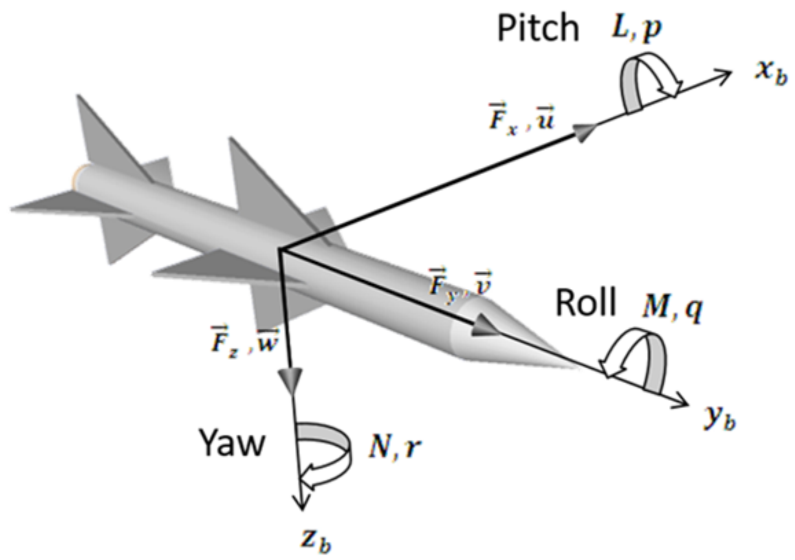


Figure 2. The illustration of pitch, yaw, and roll

are explained in Section 5 and the contribution of the work is explained briefly in the conclusion part as Section 6.

2. **The Generic Definition of Optimal PID Controller Design.** In this paper, we design a PID controller system to control the relationship between thrust angle and nozzle angle [20,21]. The nozzle element is intended to control the direction or the movement of fluid flow. Besides, nozzle elements can change the velocity of aircraft or missiles via the amount of fuel flow. In this work, an optimal proportional-integral-derivative (PID) controller system is designed to control this relationship with high performance. For this reason, metaheuristic optimization algorithms such as genetic or particle swarm algorithm are investigated. The genetic algorithm is selected since it is suitable for our new approach and modification. In initial process of the optimization problem, the users have to determine reasonable and effective parameters for controller optimization. These parameters must have directly or indirectly related to desired results. In this regards, step responses parameters of systems are examined due to the success of similar optimization problems. In this particular way, researchers use some of the important step response parameters such as peak time ($t_p$), settling time ($t_s$), and rise time ($t_r$).

The aim of our paper is to determine optimal PID coefficients which are $K_p$ (proportional constant), $K_i$ (integral constant), and $K_d$ (derivative constant) for desirable system responses. The selection of this parameter is vital for the optimization problem, and this parameter is equal to the quality of our cost functions. Some of the parameters of the transient response are highly correlated to each other. The use of these parameters together while defining the cost function reduces the efficiency of the optimization method. Therefore, we have to eliminate these parameters. As a result of our research, the parameters of the settling time ($t_s$), rise time ($t_r$), and maximum overshoot ($M_p$) are minimum correlated parameters with each other [22-24]. In this regard, the selection of these three parameters is very reasonable for the solution of the PID controller optimization problem. One of the most important parts of the optimization problem is the correct definition of problem space. Constraint continuous optimization problems are optimization problems where a function on real-valued variables should be optimized for a given set of constraints. Restrictions are usually given by a set of inequalities and equalities. The objective function can be defined as $S \rightarrow R$, with $S \subseteq R^n$. The constraints impose a feasible subset $F \subseteq S$ of search space $S$ and the goal is to find an element $x \in S \cap F$ that minimizes $f$. The problem can be represented by Equation (1) [25].

$$\text{Minimize } f(x), \quad x = (x_1, \ldots, x_n) \in \mathbb{R}^n \tag{1}$$

such that $x \in S \cap F$.

The feasible region $F \subseteq S$ of the search space $S$ is shown by Equation (2).

$$l_i \leq x_i \leq u_i \quad 1 \leq i \leq n \tag{2}$$

where $l_i$ and $u_i$ are lower and upper bounds on the variable $x_i$, $1 \leq i \leq n$.

The fitness function for this problem can be defined by Equation (3). The fitness function constants ($a$, $b$, and $c$) may be modified according to the priorities (4). The boundaries are given by Equation (5).

$$\text{Minimize } f\left(K_p, K_d, K_i\right) = at_r + bt_s + cM_p \tag{3}$$

$$a = b = c = 1 \tag{4}$$

$$-128 \leq Kp,\ Kd,\ Ki \leq 127 \tag{5}$$

These parameters are very efficient on the generic system. The transfer function characteristic of nozzle angle and thrust vector is usually unstable due to the location of roots in this work. Thus, traditional transient response parameters are not worked properly. As we mentioned before, the cost function parameters are selected for simplicity and efficiency. The rise and peak time parameters are highly correlated with each other. The selection of cost parameters is related to statistical analysis [26]. We selected one of the highly correlated transient parameters of transient response for optimal and efficient cost function design. Our approach is compared with the traditional genetic algorithm for the success of controller design. Due to the nature of the genetic algorithm, we have to use binary base numbers, and optimal coefficients of PID controller system may have a negative sign. For this reason, fixed-point arithmetic binary encoding is used in this study [27]. Also, the derivative filter coefficient is selected as $N = 100$ [28]. The reason for this selection is that pure derivative is not suitable for controlling system and practical application and only derivative gain can strengthen the noise on the system. Therefore, derivative filter parameter ($N$) is used on PID controller additionally.

3. **Relationship between Nozzle Angle and Thrush Vector.** In this section, we explain the importance of the relationship between nozzle angle and thrust vector. This relationship can be represented by a transfer function for the guidance of ballistic missile. The main parameters and axis of the ballistic missile are shown in Figure 3. On the rocket at the left in Figure 3, the nozzle has been deflected to the left, and the thrust line does not pass through the missile's center of gravity ($c_g$). The angle between thrust line and the center line is called as the *gimbal angle* [29].

The trajectory of a ballistic missile is protected by zero angles of attack in the process of approaching the target. This process is obtained by changing pitch angle or pitch ratio at zero-gravity ($zero_g$) environment. These conditions are only obtained at the boundary of atmosphere or outside the air. The zero angle of attack is obtained in difficulty due to the flow rate of fuel and some conditions of the environment. For these reasons, the relationship between nozzle and thrust angle is critical for missile control systems. Hence, the aim of missile control system is to protect the relationship between nozzle angle and thrust angle on ballistic missiles [30]. Any difference in nozzle angle must directly affect the angle of thrust vector, and this is critical due to maneuver of rockets.

The success of controlling this relationship is equal to the performance of hitting the target with a minimum error or optimal maneuvers. This relationship can be represented

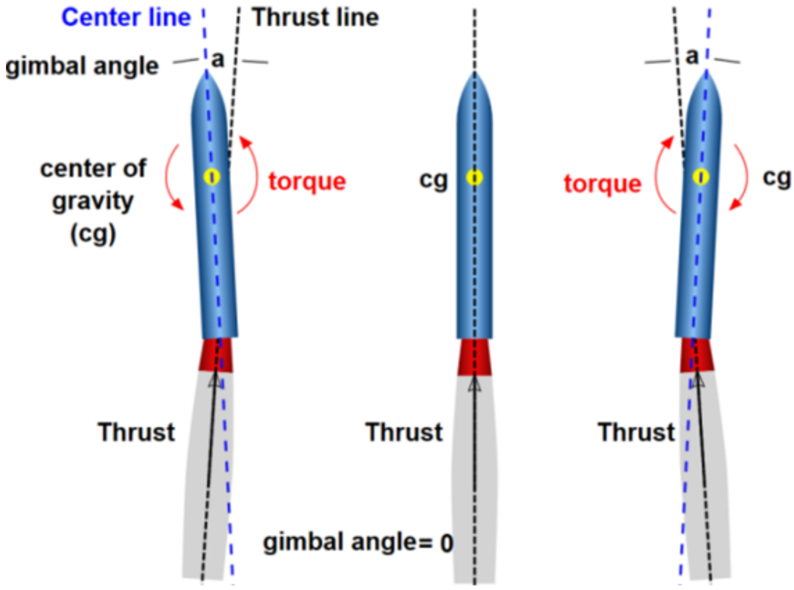


FIGURE 3. Representing of nozzle angle, gimbal angle, and other parameters

by a transfer function with several assumptions. Firstly, the axis of $X$ is equal to the longitudinal axis of a ballistic missile, and this axis provides stability of ballistic missile on thrust vector. The axis of $Z$ is equal to the orbital plane of it, and all the pitch movement is defined on the axis of $Y$.

The mass of ballistic missiles is constant, and it also has a rigid body during the entire flight. The initial condition of the missile is the surface of the earth, and there is a petite amount of change on $c_g$ point. In Equation (1), $d$ (1.143 meters) represents the diameter of a ballistic missile, $C_{m\dot{\alpha}}$ is represented as time lag due to the aerodynamic effect of air created from wings to tails and assume, there is not any structure of wing or horizontal stabilizer system on a ballistic missile, $C_{m\dot{\alpha}} = 0$. $\delta$ is represented by an angle between nozzle angle and $X$ axis. The highest pressure value on a ballistic missile is affected after 75 seconds from the ignition and a cruise altitude of the ballistic missile is 10973 meter, the velocity of the cruise ($U$) is 391.67 meter/second and mass ($m$) of the ballistic missile is 6500 kg. Pitch moment created from pitch rate and defined by the mass center of the missile is represented by $C_{m\dot{\alpha}}$. The moment of $X$ axis and nozzle angle difference created is represented by $C_{m\delta}$. The angle of attack is shown by $\alpha$ and $q$ (24.651 kg.m$^2$) which is equal to pitch rate. The distance between nozzle and gravity center of a ballistic missile, the reference area, and initial moment of the ballistic missile are illustrated by $l$ (8.229 meters), $S$ (1.026 m$^2$) and $I_y$ (155919 kg.m$^2$), respectively. The aerodynamic lifting coefficient is represented by $C_{z_\alpha}$ [31]. The difference between $X$ axis and center of mass is defined as $\Theta$ and the transfer function between nozzle angle and thrust vector is obtained by means of this information for this specified circumstances and the suitable transfer function is obtained for optimization with the PID controller via in light of the above-mentioned assumptions.

The equations of this system are given below.

$$C_{z_\delta}\delta = \beta_1 + \beta_2 \tag{6}$$

$$\beta_1 = \left(\frac{mU}{Sq}s - C_{z_\alpha}\right)\alpha(s) \qquad \beta_2 = \left(-\frac{mU}{Sq}s - C_w \sin(\Theta)\right)\theta(s) \tag{7}$$

$$C_{m_\delta}\delta = \gamma_1 + \gamma_2 \tag{8}$$

$$\gamma_1 = \left(\frac{d}{2U}C_{m_{\dot\alpha}}s - C_{m_\alpha}\right)\alpha(s) \qquad \gamma_2 = \left(-\frac{I_y}{Sqd}s^2 - \frac{d}{2U}C_{m_\alpha}s\right)\theta(s) \tag{9}$$

$$C_{m_\delta} = \frac{-Tl}{Sqd} = -34.25 \quad C_{z_\delta} = \frac{-T}{Sq} = -4.63 \tag{10}$$

The parameters of the ballistic missile are also shown in Figure 4.

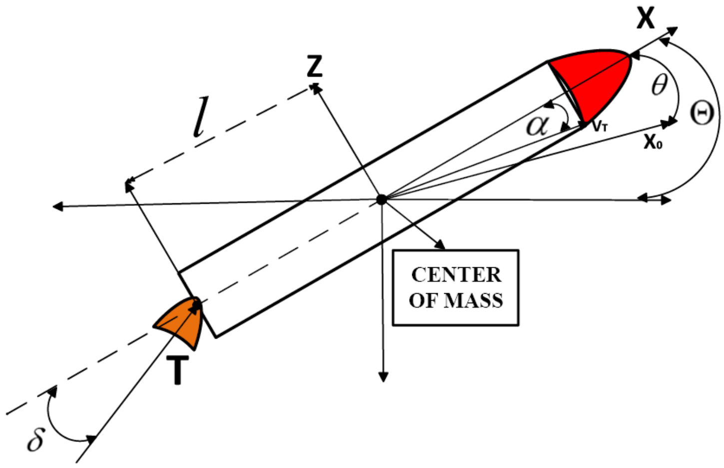


FIGURE 4. The missile parameters

The transfer function of the angle of nozzle and thrust vector is shown in Equation (14). Several assumptions have been made in this transfer function as shown.

$$C_{z_\alpha} = -3.13 \quad C_{m_\alpha} = 11.27 \qquad \frac{mg}{Sq} = C_w = 2.22 \tag{11}$$

$$-11.27\alpha(s) + \left(4.75s^2 + 0.312s\right)\theta(s) = -34.25\delta(s) \tag{12}$$

$$(88.5s + 3.13\alpha(s)) + (-88.5s + 2.06)\,\theta(s) = -4.636\delta(s) \tag{13}$$

$$G(s) = \frac{\theta(s)}{\delta(s)} = \frac{-7.21(s + 0.0526)}{(s + 1.6)(s - 1.48)(s - 0.023)} \tag{14}$$

4. **Sub-Mutation Based Genetic Algorithm and Optimal Controller Design.** In this section, we explain the basic definition of a genetic algorithm which is represented by natural selection process on nature. Genetic algorithm based optimization method is invented by John Henry Holland [32] and provides global maximum or minimum like other optimization algorithms. It is a metaheuristic algorithm such as ant colony optimization. It means that nature inspires it. The aim of the genetic algorithm is to determine optimal or most robust genes and transfer these genes to next persons. At first point of initials is selected randomly or by the users. These initial points represent our first persons for the genetic algorithm. These genetic codes or initial points are represented in binary form. In the second step, most suitable genes from persons are a crossover with each other. This crossover is provided by a more appropriate person or gene code for a solution or optimal gene code. The common problem of optimization algorithms is stacked to local minimums or maximum points, and genetic algorithm eliminates this issue with the process of mutation [33].

In this section, we explain how to design a PID controller for ballistic missile systems. PID controller is designed for a relationship about the angle of nozzle and thrust vector. As mentioned before, there are some assumptions when the transfer function (11) is obtained. The poles of system transfer function are $s_1 = -1.6$, $s_2 = 1.48$, and $s_3 = 0.023$. In this regard, this system has an unstable characteristic due to the location of poles. At the beginning of the optimization problem, a cognitive cost function is created for optimization [34,35]. This cost function should improve the system response and make stable the system with the structure of PID controller. As explained before, the parameters of the settling time ($t_s$), rise time ($t_r$), and maximum overshoot ($M_p$) are selected due to the efficiency and success of optimization process. These parameters are obtained by step response for each iteration. These results are compared with previous results and optimal PID controller parameters are obtained by the algorithm. The parameters of transient response are very important for the system of missile control. For example, a parameter of maximum overshoot is generated in the very unsafe situation on aircraft or ballistic missile system. This means that there will be an oscillation at direction change or little bias at the movement. In this work, optimal parameters of PID controller system are designed by genetic algorithm for satisfied transient response parameters and change the character of the transfer function from unstable to stable. The optimization process is performed by resolution of 8 bit for each part, and there are two parts which are integer and fraction for each controller coefficient. As a result, decoding the resolution of optimization algorithm can be accepted as 16 bit for each controller coefficient. We define a new approach for better convergence to the global minimum, and this sub-mutation approach is called on genetic algorithm. The initial conditions of the genetic algorithm are selected randomly, and iteration number is selected as 500 for each sequence. The result of the algorithm is obtained after 1000 random initial points. The result of the genetic algorithm is also obtained using 1000 random process. Fixed-point arithmetic represents the parameters of PID controller. The reason for selection for fixed-point arithmetic is flexibility and usefulness for this application. Besides, the fractional part of fixed-point arithmetic is defined for better converge at the optimal point of the solution. Fixed points of controller coefficients such as $K_p$, $K_i$, and $K_d$ parameters are shown in Figure 5.

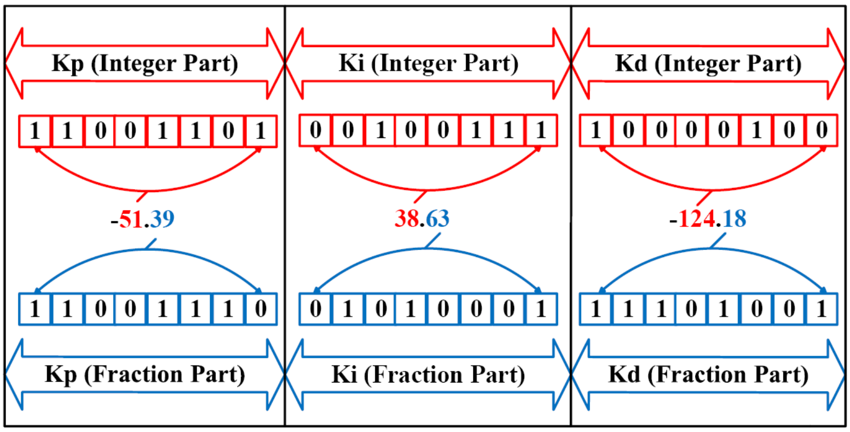


FIGURE 5. Binary representation of controllers

As shown in the figure, the numbers are separated into two parts including integer and fraction. Furthermore, two mutation parameters which are common mutation and sub-mutation are defined for the genetic algorithm. The new mutation parameter provides better convergence about solutions, and it also avoids getting stuck to local minima. The parameters of normal mutation ($p_{mutation}$) and sub mutation ($p_{sub\text{-}mutation}$) are defined as integer part and fraction part, respectively. In this optimization problem, the number of normal mutation is selected smaller than sub mutation number. The crossover process is applied between integer parts and fraction parts. The flowchart about sub-mutation based genetic algorithm is shown in Figure 6.

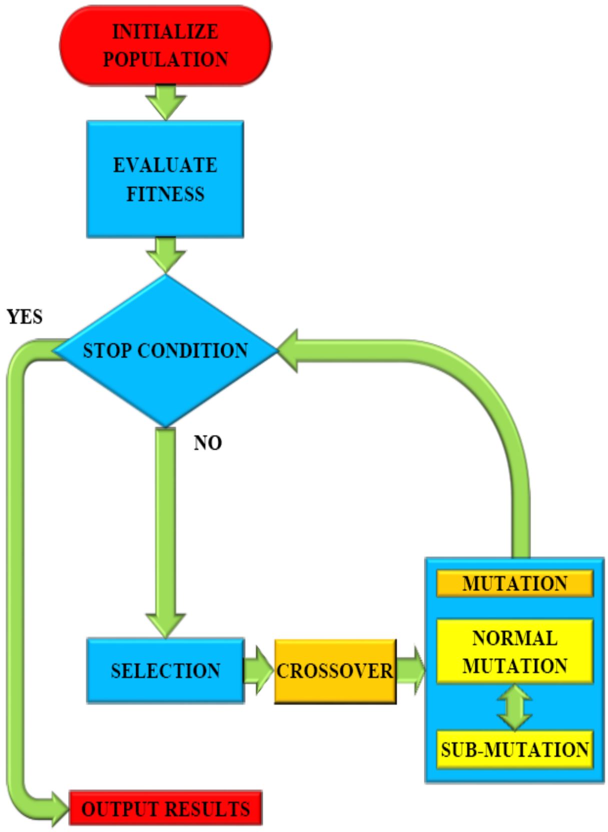


FIGURE 6. The flowchart of modified sub-genetic algorithm

For this study, the mutation process consists of two distinct parts. These are normal mutation and sub-mutation. The purpose of the sub-mutation described for this study is to avoid local minimum with much higher success according to traditional approaches. In this experiment, crossover and mutation parameters are selected as $p_{crossover} = 0.85$, $p_{mutation} = 0.15$ and $p_{sub\text{-}mutation} = 0.1$. The parameter of $p_{crossover}$ is defined as probability of crossover between chromosomes and the probability of mutation is defined as $p_{mutation}$ and the probability of sub-mutation which is defined as special for this work and main contribution of this work is represented via $p_{sub\text{-}mutation}$.

The representation of fixed-point arithmetic gives information about positive and negative for numbers. The ranges of signed integer are between $-128$ to 127. The important part of a selection of *normal mutation* and *sub-mutation* parameters is avoiding overlapping. Therefore, the probability of *sub-mutation* has to be much smaller than the probability of normal mutation. The optimal parameters of PID controller are found after 500 iterations. The iteration starts at random points for 1000 times. At the end of the process, the optimal PID controller parameters are obtained as $K_p = -7.034$, $K_i = -5.335$, and $K_d = -11.08$.

5. **Experimental Results.** The coefficients of PID controller versus total iteration are shown in Figure 7. As shown in the figure, all parameters are converged to a fixed number. The optimal or lowest cost function values provide information about optimal controller parameters for this system. The total cost about some iteration is shown in Figure 8.

The critical parameters for calculation of cost function process are shown in Table 1. As shown in the table, our new approach increases the success of convergence about optimal controller design called as sub-mutation. Moreover, the standard deviation of

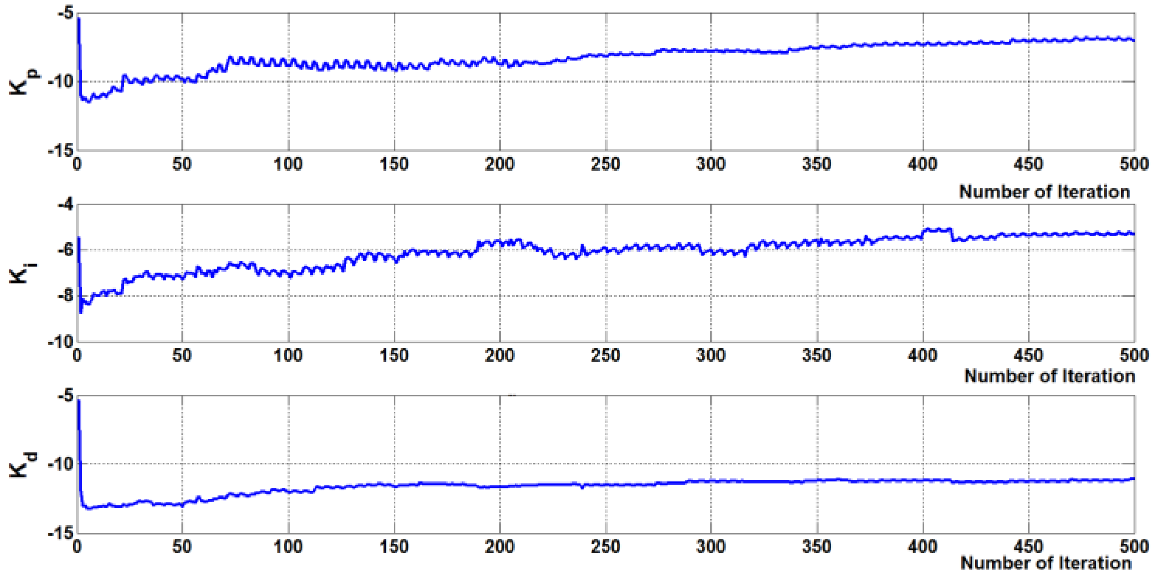


FIGURE 7. The change of controller parameters versus iteration

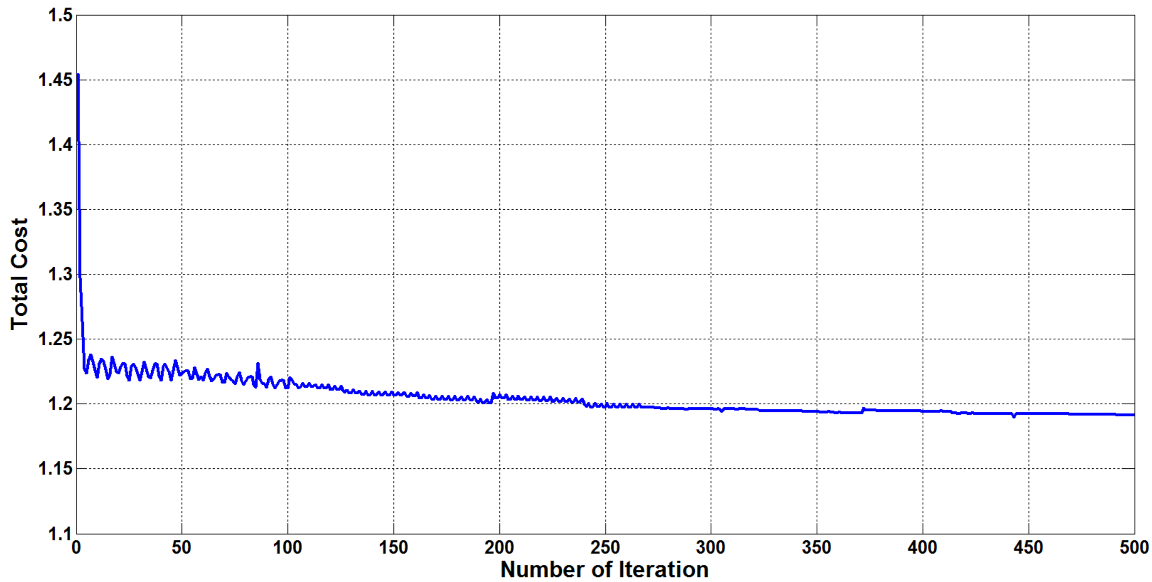


FIGURE 8. Total cost versus iteration for the proposed system

TABLE 1. Cost parameters of mutation types

| **Mutation System** | Cost Mean | Cost Standard Deviation |
|---|---|---|
| Normal Mutation | 1.348 | 0.0189 |
| Sub-mutation | 7.509 | 0.1054 |
| Normal & Sub-mutation | 1.204 | 0.0169 |

cost function decreases in high amount. Hence, this new parameter significantly increases the robustness of cost function calculation.

The coefficient calculation of PID controller is shown as 3D representation in Figure 9. As shown in the figure, PID parameters are converged to a specific location which is represented by solution point or global minimum for our optimization problem.

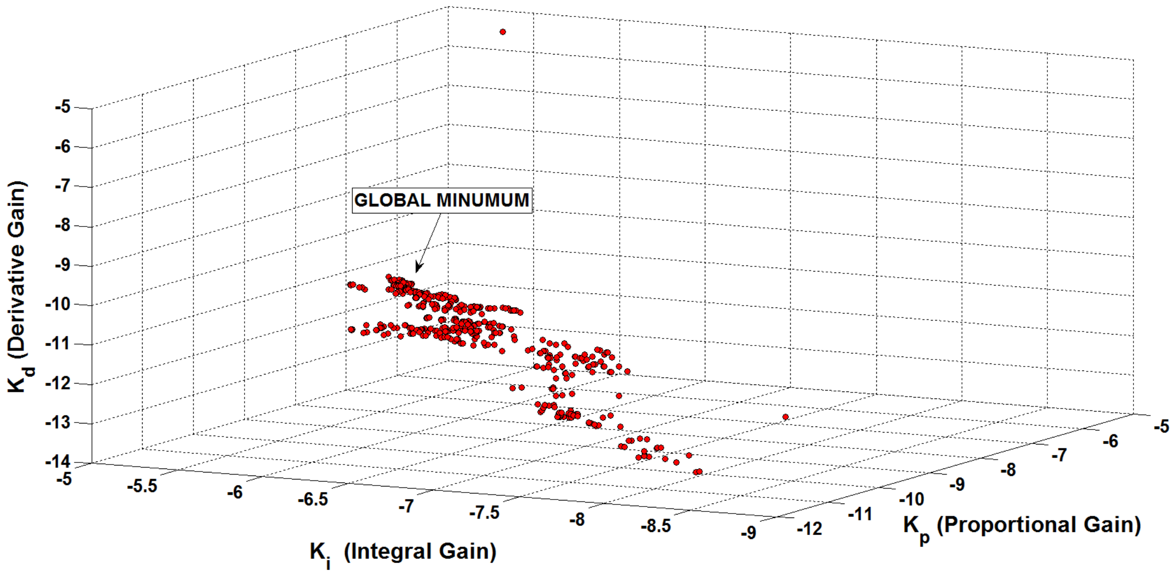


Figure 9. The change of controller parameters in 3D space

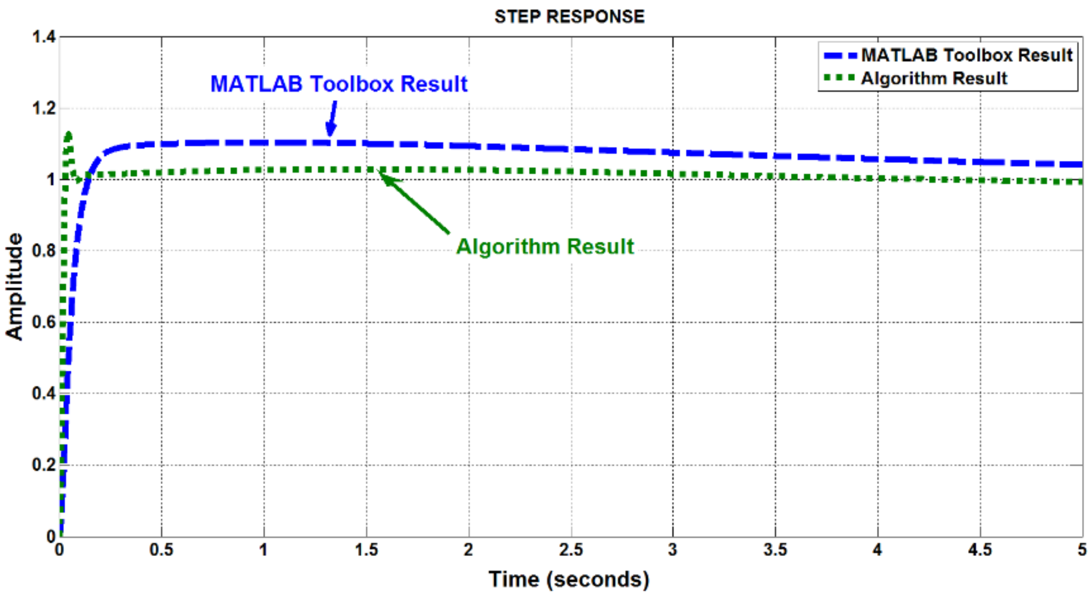


Figure 10. Comparison of step response

The step responses of the controlled system are shown in Figure 10. Normally, step response of the system has an unstable characteristic due to the location of poles. The feature of an optimized system with PID controller has stable and acceptable result for step response. Also, our algorithm results are compared with that of MATLAB toolbox. It is observed that our algorithm results are much more acceptable than MATLAB control toolbox results.

The transfer function of nozzle angle and thrust vector is unstable. The designed PID controller changes this system to stable. Besides, the product of the algorithm is more suitable than MATLAB PID toolbox. The poles of our optimized system are shown in Table 2.

The generic form of PID controller with $N$ (filter coefficient) is shown in Equation (15). PID controller is shown in Equation (16) by optimal controller parameters. The open

TABLE 2. Closed loop poles about optimized system

| Poles | Locations |
|---|---|
| $S_{1,2}$ | $-49.72 \pm j74.23$ |
| $S_{3,4}$ | $-0.3023 \pm j0.6267$ |
| $S_5$ | $-0.0523$ |

form of PID controller is shown in Equation (17). The last form and coefficients of the transfer function with optimized PID controller for missile system are shown in Equations (19) and (20).

$$G_c(s) = \left(K_p + \frac{K_i}{s} + K_d \frac{N}{1 + \frac{N}{s}}\right) \qquad G_c(s) = \left(-7.304 - \frac{5.335}{s} - 11.08 \frac{100}{1 + \frac{100}{s}}\right) \tag{15}$$

$$G_c(s) = \frac{-1115s^2 - 708.8s - 533.5}{s^2 + 100s} \tag{16}$$

$$U(s) = E(s)\left(K_p + \frac{K_i}{s} + K_d \frac{N}{1 + \frac{N}{s}}\right) \tag{17}$$

$$\frac{\theta(s)}{\delta(s)} = \frac{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}{\beta_5 s^5 + \beta_4 s^4 + \beta_3 s^3 + \beta_2 s^3 + \beta_1 s^3 + \beta_0} \tag{18}$$

$$\alpha_3 = 8042.1 \quad \alpha_2 = 5533.3 \quad \alpha_1 = 4115.1 \quad \alpha_0 = 202.316 \tag{19}$$

$$\beta_5 = 1 \quad \beta_4 = 100.09 \quad \beta_3 = 8049.5 \quad \beta_2 = 5296.3 \quad \beta_1 = 4120 \quad \beta_0 = 202.3 \tag{20}$$

## 6. **Conclusion.**

In this paper, an optimal PID controller system is designed for optimizing the relationship between nozzle angle and thrust vector on a ballistic missile system. We propose a new approach which is called as a *sub-mutation* genetic algorithm to design optimal controller. This is a modified version of the traditional genetic algorithm for optimal controller design. When compared with this method, our approach has much more promising and robust results. The generic idea of our approach is to design a new mutation factor which is individual from normal mutation factor, and this parameter provides a small bias on solution process. This method prevents getting stuck on local optimum points for genetic algorithms. Also, the design of PID controller via metaheuristic optimization algorithms is explained for the general purpose. The process of creating a cost function for optimal PID controller is examined, and important things about the selection of transient response parameters are discussed for optimal controller design. Besides, the fundament of ballistic missile system and common terms about the movement of aerial vehicles are defined. It is briefly explained why the relationship between nozzle angle and thrust vector is necessary for the control of ballistic missile system.

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