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Designing an Optimal PID Controller for Control the Plan's Height, Based on Control of Autopilot by using Evolutionary Algorithms

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Abstract

The dangers of poor pilot performance as well as time and place conditions, and such as low altitude and climate, damage critical aircraft control system. Mentioned factors, caused damage in control of sensitive military and research aircraft. So researchers had to find a solution for this problem. Therefore, the use of Unmanned Aircraft Vehicle or (UAV) in sensitive and important Operation is required. Furthermore, designing the controller system is one of the main discussed Dynamic issues in Flying Objects. Here, has been attempted to determine the optimal coefficients of PID[1] controller in Autopilot based on Optimization Algorithm such as Evolutionary Algorithms in order to regulate and desired control on height of an Unmanned Aircraft Vehicle (UAV). The proposed Cost Function simultaneously optimized the system performance specifications. Optimization done by using Evolutionary Algorithms such as GA[2], PSO[3] and Social Policy Optimization Algorithm or ICA[4]. Finally, the system response based on Evolutionary Algorithms compared with the advantages of Classic method Optimization based on Constraints design, then you can easily decide on the superiority and being optimized of the proposed system.

Keywords: Unmanned Aircraft Vehicle (UAV), Autopilots, Height Control, Controller, Evolutionary, Biological and Social Optimization.

1. Introduction

Here With the advancement of Science and Technology, increased costs, today is tries, before Proceeding to Construction and Industrial Production, prepared accurate Simulations of the proposed system and plan. This is just to avoid spending costs exorbitant in testing and increase reliability of production. One of the main problems in the design of Autopilot is result of uncertainly in

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[1] Propriety Integrated Derivative
[2] Genetic Algorithm
[3] Particle Swarm Optimization
[4] Imperialist Competitive Algorithm

Aerodynamic Parameters with low precision. With this condition, designed controller shouldn’t be sensitive to change of values. On the other hand, the Equations of Motion and UAV behavior is non-linear and Varies with time. In summary, taking into account three factors is causing to complexity in the designing of Height Autopilot (controller). Three factors such as: 1 - uncertain of the Aerodynamic Coefficients (uncertainly parametric), 2 - Nonlinear Dynamics and not eliminate Coupling effects (not modeled Dynamics) and final: 3 - non-minimum height dynamics phase [1]. Several adaptive techniques have been introduced to solving the problem of uncertainly that they solve by parametric linear method [2, 3]. In [3], an adaptive controller is used to improve the strength High Classic Controller's parameter (Resistance compared with the Aerodynamic coefficients) of an UAV. Feedback linearization [4], is another popular technique that has many applications in designing of flight control system [5-8]. So far fuzzy controllers [9] have variety applications [10-15], because it is independent of the dynamics of the system and it is able to give control commands based on system behavior. In [12], for Autopilot, only considered uncertainly compared to Aerodynamic Coefficients. They are trying to improve the resistance parameter. In [14] a fuzzy PID Controller for linear non-minimum phase systems has been designed. In this reference, just trying to remove the Under Shot in the non-minimum phase systems. In this paper, we attempt to design an optimal PID controller, based on the optimal coefficients by the optimization algorithms that has been designed to pilot in [1], so that improve control of the height, in the introduced pilot. Firstly, for this purpose, the Mathematical Model (Dynamic) UAV will be explained, the Classic Pilot will be studied and next, we turn to description of PID controllers. Finally, the optimization algorithms, the results of simulations and discussion or conclusions will be shown.

2. Mathematical models of Unmanned Aircraft Vehicle (UAV)

In extraction of the Motion Equations we used from reasonable assumption that in the Unmanned Aircraft Vehicle (UAV) mass and moment of inertia are constant. Motion Nonlinear Equations of UAV was showed at below [1]. (They obtained Aerodynamic Coefficients by using DATKOM® software):

$$\dot{U} = -9.8\sin\theta - QW + RV - 0.0125U - 16.36\alpha + 16.6\delta_E + 4.5 \tag{1}$$

$$\begin{gathered}\dot{V} = 9.8\sin\phi\cos\theta + PW - RU - 263.7\beta - 0.0053P + 1.64R - 0.0032 \\ \delta_A - 58.2\delta_R\end{gathered} \tag{2}$$

$$\dot{W} = 9.8\sin\phi\cos\theta + QU - PV - 0.069U - 259\alpha - 1.3Q + 57.5\delta_E + 21 \tag{3}$$

$$\dot{P} = -1.51QR + 0.04PQ + 76.7\beta - 1.9P - 0.68R + 149\delta_A + 105\delta_R \tag{4}$$

$$\dot{Q} = 1.03PR - 0.017(P^2 - R^2) - 988\alpha - 8.9Q + 1362\delta_E - 0.284 \tag{5}$$

$$\dot{R} = -0.038QR - 0.85PQ + 306\beta - 0.044P - 2.82R + 2.27\delta_A + 434\delta_R \tag{6}$$

$$\dot{\alpha} = \frac{\dot{W}\cos\alpha - \dot{U}\sin\alpha}{V_t\cos\beta} \tag{7}$$

$$\dot{\beta} = \frac{1}{V_t}[-\dot{U}\cos\alpha\sin\beta + \dot{V}\cos\beta - \dot{W}\sin\alpha\sin\beta] \tag{8}$$

$$\dot{\phi} = P + Q\sin\phi\tan\theta + R\cos\phi\tan\theta \tag{9}$$

$$\dot{\theta} = Q\cos\phi - R\sin\phi \tag{10}$$

$$\dot{\psi} = (Q\sin\phi + R\cos\phi)\sec\theta \tag{11}$$

$$\dot{h} = V_t\sin\gamma \tag{12}$$

$$V_t = \sqrt{U^2 + V^2 + W^2} \tag{13}$$

$$\gamma = \theta - \alpha \tag{14}$$

$$\delta_E = \delta_{E\min} + \delta_e \tag{15}$$

(1-15, are Motion Nonlinear Equations)

This parameter such defined δ_E is Elevator angle, $\delta_{E\min}$ is Elevator angle in trim condition, δ_e is Elevator angle Compared to amount of trim, δ_R is Rudder angel, δ_A is Aileron angle, **h** is height, ϕ is Roll angle, θ is Pitch angle, ψ is Side angle, P is Rate of Roll angle, Q is Rate of pitch angle, R is Rate of yaw angle, U Longitudinal velocity, **W** is Vertical velocity, **V** is Lateral velocity, $\mathbf{V_t}$ is the total Rate, α is Attack angle and β is lateral movement angle. Some variables of UAV are defined in the Figure 1. The purpose is design the Autopilot for height, which is capable to control the height of Aircraft by using the elevator height. Equation 1-15, showed nonlinear behavior UAV. By linearization the nonlinear Equations around trim flight Cruise condition, nominal linear model for height be made in the Transfer Function or Equation 16.

$$\frac{h(s)}{\delta_e(s)}=\frac{-57.3(s-24.6)(s+21)(s+0.008)}{s(s^2+0.011s+0.022)(s^2+2.12s+98.4)} \tag{16}$$

It is assumed that the nominal linear model is a mathematical model, so that it developed based on Autopilot. The relationship between height output variable and input Elevator variable has unstable zero. Moreover flight characteristics in short period and Phugoid mode are undesirable.

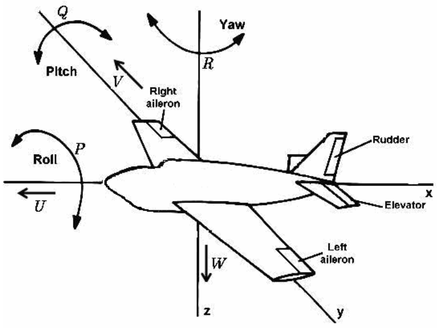

Figure 1: Flight Parameters of Unmanned Aircraft along the three coordinate

To investigate the strength parameter of autopilot, we used the linear non-nominal model. In linear non-nominal model we assume an important stability derivative such as C_{Du}, C_{ma}, C_{mq} and C_{Lu}, shows as Table 1. With applying the change, the nominal non-linear Transfer Function model obtained as follows; by Equation 17.

$$\frac{h(s)}{\delta_e(s)}=\frac{-57.3(s-25.5)(s+21.6)(s+0.0017)}{s(s^2+0.0055s+0.021)(s^2+1.82s+64)} \tag{17}$$

Table 1: The impact of derivatives on the stability characteristics in dynamic mode [15]

Stability derivatives		The method of impact on parameter
C_{mq}		*Increasing of this parameter increases the damping parameter in the short period.*
C_{ma}		*Increasing of this parameter increases the normal frequency parameter in the short period.*
C_{Du}		*Increasing of this parameter increases the damping parameter in the short Phugoid.*
C_{Lu}		*Increasing of this parameter increases the normal frequency parameter in the short Phugoid.*

3. Design of Classic Autopilot

In common, designed Autopilot for Height based on special structures that have three-ring. In this structure, the Rate of pitch angle, Pitch Angle and Height measured, such that Autopilot (Controller) for Pitch Angle is the inner loop for Height Autopilot, and the Rate controller of Pitch Angle is inner loop for pitch Autopilot. This makes the structure to be Robust against the complex parametric uncertainty. So should be designed **3** controllers and measured **3** variables. In this paper, the Pitch Angle and rate of Pitch – Angle becomes removed and we used a single-loop structure. In this simple structure, height measured just by the altimeter. In this section, the Angle and Height classic Autopilot, will designed for the nominal linear model. By using a nominal linear model and root locus method, the Compensator Transfer Function will design, it's Equation 18.

$$G_{C_b} = \frac{0.012(s+0.05)(s^2+2.12s+98.4))}{(s+20)(s^2+6s+15.25)} \tag{18}$$

In Compensator designing, a lot of efforts reduce the effects of an unstable zero. Phugoid and short period modes improved. In [3] and [12] also used this method to design compensator, by given $\xi = 0.6,\ \omega_n = 2.31$ in Figure 2.

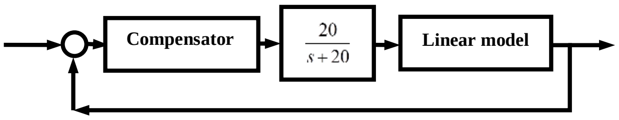

Figure 2: Control modes for design the height compensation.

To evaluate the Autopilot, it is necessary to be applied the following command on nominal linear model. Commands are height is 10 meters, and the side angle is between 0 to10. The simulation result is shown in Figure 3. According to this Figure, there is a good response time for the linear model. These are desired response time characteristics, speed response such as; Time Rise, Over Shot, Under Shot and Steady State Error. As is known, the response was not good for linear nonlinear. This shows the Compensator, against uncertainly hasn't any resistance for defined parameters of system. Whatever increased the command angle, nonlinear effects become severe and the weakness of compensator is obvious [1].

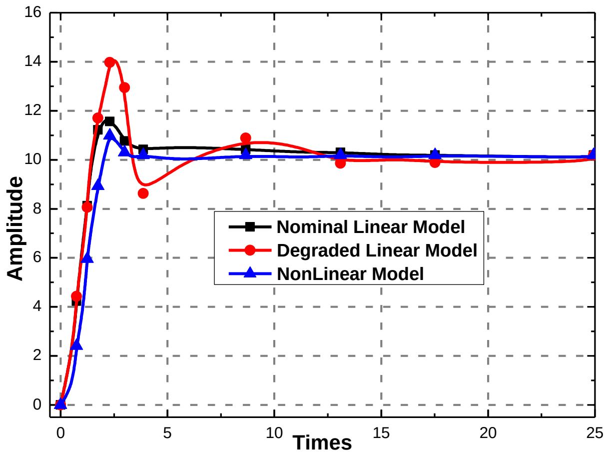

Figure 3: Response time for nominal linear model, non-linear model and compensator linear mode

4. Design of PID Controller

Industrial PID controllers are usually available as a packaged, and it's performing well with the industrial process problems. the PID controller requires optimal tuning. Figure 4 shows the diagram of a simple closed-loop control system. In this structure, the controller (Gc(s)) has to provide closed-loop stability, smooth reference tracking, shape of the dynamic and the static qualities of the disturbance response, reduction of the effect of supply disturbance and attenuation of the measurement noise effect [26].

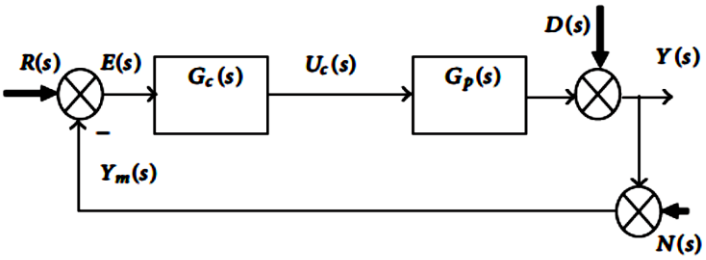

Figure 4: diagram of a closed-loop control system.

In this study reference tracking, load disturbance rejection, and measurement noise attenuation are considered. Closed-loop response of the system with set point R(s), load disturbance D(s), and noise N(s) can be expressed as Equations 19 and 20.

$$Y(s)=\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]R(s)+\left[\frac{1}{1+Gp(s)Gc(s)}\right]D(s)-\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]N(s) \tag{19}$$

$$Y(s)=[T(s)*[R(s)-N(s)]+(S(s)*D(s)] \tag{20}$$

Where the complementary sensitivity function and sensitivity function of the above loop are represented in 21 and 22, respectively.

$$T(s)=\frac{Y(s)}{R(s)}=\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right] \tag{21}$$

$$S(s)=\left[\frac{1}{1+Gp(s)Gc(s)}\right] \tag{22}$$

The final steady state response of the system for the set point tracking and the load disturbance rejection is given in (23) and (24), respectively:

$$y_R(\infty)=\lim sY_R(s)=\lim_{t\longrightarrow\infty} sx\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]\left(\frac{A}{s}\right)=A \tag{23}$$

$$y_D(\infty)=\lim_{t\longrightarrow\infty} sx\left[\frac{1}{1+Gp(s)Gc(s)}\right]\left(\frac{L}{s}\right)=0 \tag{24}$$

Where A is amplitude of the reference signal and L is disturbance amplitude. To achieve a satisfactory $yR(\infty)$ and $yD(\infty)$, it is necessary to have an optimally tuned **PID** parameters. From the literature it is observed that to get a guaranteed robust performance, the integral Controller gain "*Ki*" should have an Optimized value. In this study, a no interacting form of PID (*GPID*) Controller Structure is considered. For real control applications, the Feedback Signal is the sum of the measured output and Measurement noise Component. A low pass filter is used with the derivative term to reduce the effect of measurement noise. The PID structures are defined as the following or Equation (25):

$$G_{PID}(s)=K_p\,e(t)+K_d\,\frac{de(t)}{dt}+K_i\int_0^t e(\tau)d(\tau)+K_p\left[1+\frac{1}{T_i s}+\frac{T_d s}{\frac{T_d s}{N}+1}\right] \tag{25}$$

$Kp/Ti = Ki$, , $Kp * Td = Kd$, and N = filter constant

Cost Function In Optimization Algorithms as Equation 26 or: $O=w^1 T_r+w^2 M_p+w^3 T_s$ (26)

In Cost Function, w^1, w^2, w^3 respectively are the weight or important coefficient of system performance. T_r, M_p, T_s are the Rise Time, Maximum Over Shot and Settling Time. Suggested Cost Function makes all Coefficients and parameters be same, and caused more impact of characteristics [16].

5. Optimization Algorithm

In this section it is tried to investigate the Optimization Algorithms from algorithms structure, Convergence Method, and Parameters Perspectives. First we deal with Genetic Algorithm investigation and function, then the Particle Swarm Optimization (PSO) Algorithm, then Imperialist Component Algorithm (ICA) is investigated, and finally the result and simulation for conclusion illustrated.

5-1 Genetic Algorithm (GA)

Today, the Genetic Algorithm is used for finding approximate answers in optimization and search problems. This algorithm is inspired from Natural concepts such as heredity, mutation, selection, and recombination. The main objective in this algorithm is to increase the chance of good samples to continue life in the next generation and to optimize generation by generation until an acceptable answer is obtained. The Pseudo Cod illustrates the procedure of this algorithm [17].

```
Procedure: Applied Genetic Algorithm
    Initialization
      t = 0;
      Set population size or pop size, number of generation or
      max_gen, probability of crossover $p_c$ and probability of mutation $p_m$
      Initialize parent population P (t):
      Evaluate P (t) and select the best solution $\sigma^*$ with the
      Optimum objective function among P (t)
      While (no termination criteria) do
      Regenerate C (t) from P (t) by applying the crossover  And mutation operations:
      Evaluate C (t) and select the current best solution $\sigma$
      With the minimum objective value among C (t)
      Update the best solution $\sigma^*$ solution, I, e, if $\sigma < \sigma^*$ , then $\sigma^* = \sigma$ ;
      Select P (t+1) from P (t) and C (t);
      t = t+1;
    End while;
End procedure
```

In the Genetic Algorithm used in this paper, n-gene chromosomes were used to illustrate the problem space. For example, if n = 8 is the number of cities, a chromosome is accidently like the shown chromosome.

1	8	5	2	6	4	7	3

This indicates an acceptable solution in which the salesman is first visiting the 1st city, then the 8th city so that in the end returns the 1st city [18]. In this paper the rotating selection (roulette wheel) is used for selecting chromosomes in order to combine and generate the next generation. In this method the chromosomes are mapped on continuous sections of a line, so that each chromosome's share is equal to the amount of its fitness. In order to do the selection, a random number is generated and the chromosome with that number in its section, is then selected [19]. The method applied for mutation is the inverse method. In this method, a sub-collection of chromosome's genes is selected and then its reverse is replaced. In order to combine chromosomes with above mentioned structure, the partially mapped cross over (PMX) method is used [20]. The combination operator keeps the talented genes and then relocates other genes to generate offspring. In this example, a gene is considered talented when leads to generation of the shortest path.

5-2 Particle Swarm Optimization (PSO)

The PSO Algorithm is one the parallel search algorithms based on population which starts with a set of accidental answers (birds). Then in order to find the optimized answer in problem's space, keeps searching by updating birds locations. Each bird is specified in multi-dimensions (depending on the problem type) with two vectors, $V_i[t]$ and $X_i[t]$, which represents current speed and location, respectively. In each stage of swarm, the location of each bird is updated with the best value. The first value is the best experience that the bird itself has encountered till now and is shown by p_best. The second value is the best experience that is achieved among all the birds and is shown with g_best. In each replication, the algorithm updates the new bird's speed and location using the equations (27) and (28).

$$V_i[t+1]=W \times v_i[t]+C_1 r_1(x_{i,pbest}[t]-x_i[t])+ C_2 r_2(x^{gbest}[t]-X_i\,[t]) \quad (27)$$

$$X_i\,[t+1] = X_i\,[t] + V_i\,[t+1] \quad (28)$$

In Equation (27), W is the inertia coefficient which is linearly located between [0 – 1.25]. C_1 and C_2 are the value of the individual and group experience, which is selected from [0 – 1.5]. Generally, the 1.5 or 1.2 values are used for them [22, 23, and 24]. The numbers r_1 and r_2 are the accidental number in [0 – 1] range. Also the final value of bird's speed, in order to avoid algorithm's divergence, is limited to a given range and V is a member of [Vmin, Vmax] domain. Equation (28) also updates the bird's current location according to the new updated speed. The right part of equation (28) is consisted of three parts, the first part is a coefficient of bird's current speed, the second part is for changing bird's speed and rotation towards best individual experience, and the third part causes a change in bird's speed and rotation towards best group experience [25]. For the first time in [25], it was suggested that W signifies the movement coefficient in overall search. One of the known problems of PSO algorithm is that for a bird containing g_best information, the second and third parts of equation (27) becomes zero [26], thus the bird will continue to move along its last movement vector. The bird containing g_best will become immobile and the other birds will converge toward it [22]. To remove this problem, first in 2002, a new algorithm named GCPSO was introduced [27]. In this method a new parameter was added to the algorithm that causes accidental searches around optimized answer for the best bird. The second issue with standard PSO is its linear convergence which could be quite time taking [28].

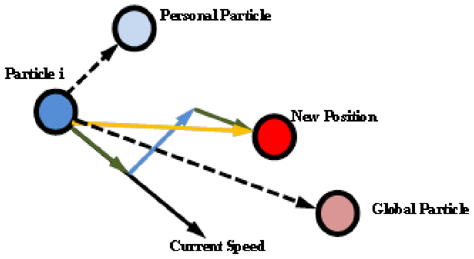

Figure 5: The optimization procedure of Particle Swarm algorithm

In discrete problems, such as traveling salesperson, the binary model of this algorithm is applied. The change in algorithm's updating Equation (29) is carried out in two steps, step one include the use of following equation to change speed,

$$V_{ij}[t+1] = W \times V_{ij}[t] + C_1 r_1 (X_{ji'}^{best}[t] - X_i[t]) + C_2 r_2 (X^{gbest}[t] - X_i[t]) \qquad (29)$$

And to apply the sigmoid function in Equation 30 in order to limit the speed to the [0, 1] range.

$$\text{If } (\text{rand}() < S(vij[t+1])) \ \text{ Then } X_{ij}[t+1] = 1 \qquad \text{Else } X_{ij}[t+1] = 0 \qquad (30)$$

and the second step is to obtain the particle's new location using equation

$$s\,(v_{ij}[t+1]) = \frac{1}{1+e^{-v_{ij}[t+1]}} \qquad (31).$$

Here, in order to optimize the traveling salesperson standard problem, due to the discrete space of problem answers, the Binary Particle Swarm Optimization (BPSO) algorithm was applied.

5.3 Imperialist Competitive Algorithm (ICA)

Imperialist Competitive Algorithm is a new evolutionary optimization method which is inspired by imperialistic competition and has been applied in some different fields [29-33]. Like other evolutionary algorithms, it starts with an initial population which is called country and is divided into two types of colonies and imperialists which together form empires. Imperialistic competition among these empires forms the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition converges to a state in which there exists only one empire and colonies have the same cost function value as the imperialist. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state which is based on assimilation policy. Figure 6 shows the movement of a colony towards the imperialist. In this movement, θ and x are random numbers with uniform distribution as illustrated in Equation 32 and d is the distance between colony and the imperialist.

$$X \sim U(0, \beta \times d),\ \theta \sim U(-\gamma, \gamma) \qquad (32)$$

Where β and γ are parameters that modify the area that colonies randomly search around the imperialist.

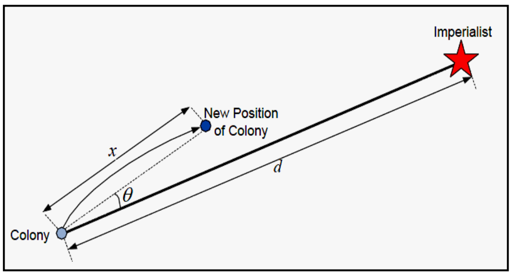

Figure 6: Motion of colonies toward their relevant imperialist

The total power of an empire depends on both the power of the imperialist country and the power of its colonies which is shown in Equation (33).

$$\mathbf{T.C.}_n = \mathbf{Cost}(\text{imperialist}_n) + \zeta * \mathbf{mean}\ \{\mathbf{Cost}(\text{colonies of impire}_n)\} \qquad (33)$$

Fig.4 shows a big picture of the modeled imperialistic competition. Based on their total power, in this competition, each of the empires will have a likelihood of taking possession of the mentioned colonies. The more powerful an empire, the more likely it will possess the colonies. In other words these colonies will not be certainly possessed by the most powerful empires, but these empires will be more likely to possess them. Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated.

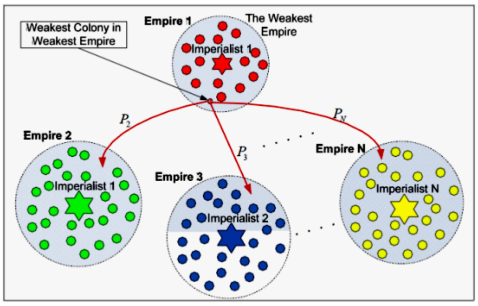

Figure 7: Imperialistic Competition adapted from [34]

With the implementation of optimization algorithms, the coefficients of the PID controller become optimal. In order to compare, based on cost function or Equation 33, we will display the performance (response) of these algorithm in Figure 8. According to the responses, Rise and Settle Time, easily we can select the ICA Algorithm has better performance and it will be Optimized Algorithm in PID Controller Designing [34].

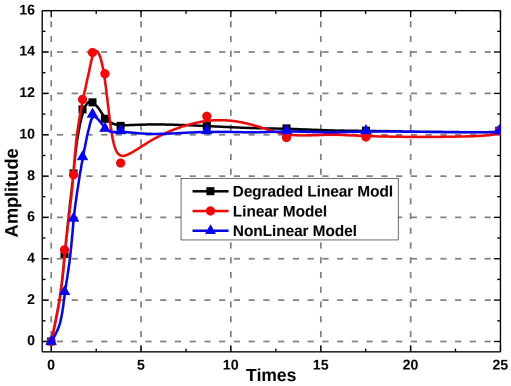

Figure 8: Step Response of Evolutionary Algorithms

In Table 2, other properties and values of ICA Algorithm have been determined. Easily, we can see, the ICA Algorithm is better Algorithm in compare with other Evolutionary Algorithm.

Table 2: Evolutionary Algorithm Result in PID Controller

Properties	GA Properties	PSO Properties	ICA Properties
Kp	**6.9867**	**2.2750**	**5.0377**
Ki	**25.4450**	**5.5669**	**16.3.57**
Kd	**7.9318**	**8.8306**	**5.0428**
Mp	**31.128**	**20.1099**	**27.9187**
Ts	**3.3848**	**0.8798**	**0.7044**
Rise Time	**0.1278**	**0.1317**	**0.1736**
Over shot	**31.1281**	**20.10**	**27.9187**
Peak	**1.3113**	**1.2011**	**1.2792**
Peak Time	**0.3133**	**0.448**	**0.29360**

According to Best Result of ICA Algorithm, in Figure 9 have been determined Time Responses of Dynamic models and Controlled Autopilot (by Optimal PID) by ICA model.

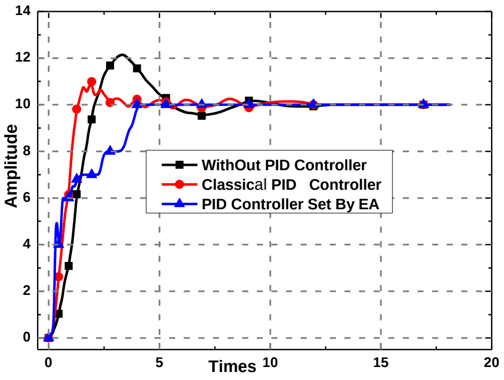

Figure 9: Time Response of nominal Linear Model, non-nominal Linear Model and non - linear mode that controlled by Proposed Algorithm

According to the nominal linear model response, good parameters achieved. In the responses time, the nominal nonlinear has desired characteristics, then it is accepted as an appropriate response. As shown in Figure 10, it is clear, the auto pilot which controlled by a PID controller, against designed compensator, has reduced impact of the non-linear terms as satisfactory.

6. Simulation Results

Terms of the objective function (performance profile system) in the paper are: Rise Time, Over Shot and Settling Time. Three parameters; K_p, K_i ,K_d belongs to the controller are considered as variables in the designing. Optimization is performed for the objective function and the results come in the form as curves. According to the simulation results, based on design constraints, Imperialist Competitive Algorithm (ICA) has the best performance. A curve belonging to the Imperialist Competitive Algorithm optimization method is noticeably superior. The results in figures 10, 11, and 12 have been determined.

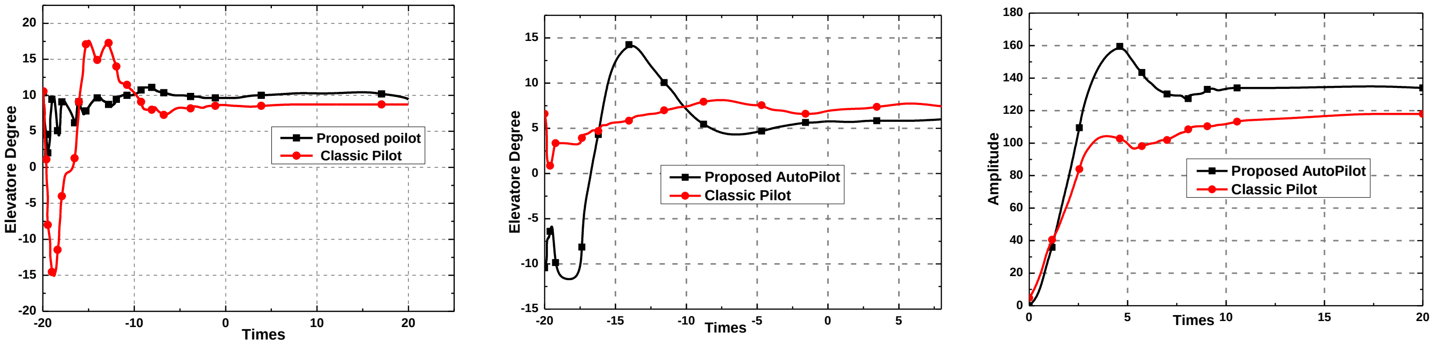

Figure 9, 10, 11: Left to Right: High Controller Time Response by Classic and Proposed Method, Angle Response (elevator) by Classic and Proposed Method, Acceleration Response (elevator) and Proposed Method

UAV constantly changes their height, because they fly close to ground surface, and not to deal with obstacles, they change their height. In Figures 10, 11 and 12, height, Lift angle and Acceleration Time Response, for 100 meters Command were shown. It is clear that the proposed method can be made in not far a future.

7. Conclusion

The PID controller is used, based on the model presented in this paper, in order to control the pitch angle in aircraft. Controller coefficients are obtained from the optimization procedure, based on Design Adverbs 21 by using MATLAB ® Simulink toolbox. Furthermore, the results of the coefficients are used in PID controller. In curves shown better results of the optimization based on design Adverbs. Achieve these results by using single-objective optimization is possible. Thus, by comparing between the results obtained from the two methods, it was found that the results obtained from the Evolutionary Optimization Algorithms and its Application in PID Controller, Can improve design parameters, performance and system specification.

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