Helicopter Fractional Order PID Controller Based the Technique of Bacterial Foraging

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Abstract – The theory of algorithm for improving bacterial feed is considered one of the important theories in advanced research and has been widely accepted for a global improvement algorithm to solve problems of control in improvement research in non-linear systems, which have become among the interests of researchers in this field. In our work, a new method for design of a bacteria foraging algorithm principle based on Proportional-integral-derivative controller (PID) for three degree of freedom (3DoF) helicopter system. This paper presents a method to stabilize pitch, roll and travel angle of the helicopter system using optimization technique based on bacterial foraging (BF) algorithm is used to tune the fractional order PID controller parameters by reducing the objective performance parameters. Transient and constant case responses are found to be appropriate. The result reveals that BF provides a good synthesis algorithm. In addition, BF-FOPID works better than BF-PID controller for the 3DoF helicopter model.

Keywords: Bacterial Foraging Optimization (BFO) algorithm, Fractional Order Proportional-integral-derivative controller (FOPID), Three degree of freedom (3DoF) helicopter system

1. INTRODUCTION

The Control of multiple input and output systems (MIMO) is almost somewhat difficult in helicopters because of its non-linear dynamics and unstable open rings and also high coupling between the control channels. Reference [5] present a study to suggest an optimal multi-objective fuzzy fractional order $PI\lambda D\mu$ controller (MOFFOPID) for controlling the electric vehicles (EVs) systems with time-dely. A new multi-objective stochastic optimisation is used for the online adjustment of the parameters of MOFFOPID controller to assess its efficiency. The experimtal results of the study are based on a TMS320F28335 DSP and implemented on a DC motor to verify the effectiveness of the proposed controller in controlling the speed of the non-linear feature DC motor.

An adaptive multi-objective Fractional-Order (FO) Fuzzy PID controller is proposed by [6] for the load frequency control (LFC) of islanded Microgrids (MGs). In this research a modified black hole optimizaition algorithm an adaptive tuning of the noninteger fuzzy PID controller coefficient is accomplished through a modified black hole optimization algorithm.

A novel fuzzy PID controller is suggested by [7] with filtered derivative action and fractional order integrator (fuzzy $PI\lambda DF$ controller) to solve the automatic generation control (AGC) problem of a power systems. Cuckoo optimization algorithm (COA) is used to make optimization for the controller parameters. The time domin simulation of the prposed controller provides an acceptable performance level and stability in comparison with other exisiting strategies as well as sensitivity analyses are accomplished to explor the robustness of the considerd technique.

The Takagi - Sugeno (T-S) fuzzy system was proposed by [8] to find the contribution factor of variable speed wind turbines so that the variable wind turbines share the maximum value of their inertia to compensate for the decrease in output energy of the grid. According to the proposed system, the optimum values of the wind turbine contribution factor proportional to the load are obtained based on the particle Swarm Optimization (PSO) algorithm without passing the minimum speed restrictions.Based on the obtained optimal values for the contribution, the initial T-S fuzzy system is extracted using the subtractive clustering algorithm.

The Least Squares Support Vectors Regression (LS-SVR) method is used to approximate the nonlinear uncertainties that must be constrained. The nonlinear electric vehicle (EV) system is assumed a case study. The goal is to force an EV's speed to follow a desirable reference for both (structured and unstructured) uncertainties.The second order EV simulation results demonstrated the effectiveness of the proposed method with fast versus slow and large against small disturbances [9].

The system of relative derivative control devices (PID) has been dealt for a long time, due to its ease of design, high efficiency and its ability to implement easily in any field of control [10,11]. The implementation of the system (PID) is continuing in control engineering due to its effectiveness in organizing the main time behavior of many different

applications [12], but some control unit (PID) applications are manually tuned in practical applications, which requires difficulty in controlling, and controlling performance as it needs to Lots of time to implement [28]. In very complex anarchic systems requires the PID system to provide the simplest useful solutions, the least time, the simplest implementation, and the easiest design [13, 14].

The helicopter has a special design and because of this design possesses a complex flight attribute and the dynamic characteristic which somewhat difficult to explain [1]. These characteristics differ among the aircraft due to a difference in the flight condition like the angles of attack, inclination, climbing, as well as the height of the plane .etc. of the many variables in flight [15]. Therefore, most of these flight variables are non-linear and multivariable couple. But the problems with flying a plane can be processed easily and simply [16]. Therefore, in mechanical engineering, it is very difficult to obtain a formulation helicopter model and consider it an accurate model [26]. It is possible to apply some ideas and studies to control the flight situation and simplify the flight situation, and among these ideas is the idea of (3DOF-three degree of freedom) [27, 29].

The FOPID control has shown its potential prove the system performance than conventional PID controller in the recent year [17]. The bacterial is a heuristic search technique developed passion [18, 30]. A group of synthesis bacterial collaborate to looking for the high possible solutions in the "D" search space. The BFOA was assumed a factor to solving various problems due to the presence of elimination and dispersion techniques that help them to looking for a suitable place for them. Especially when a small number of her participants involved in the appropriate space. These rare qualities make the (BFOA) high level of the rest of the systems in terms of efficiency and more than this is a suitable tool as a system to improve control systems [19, 20].

2. MATHEMATICAL MODELLING

The overall system of the Helicopter is nonlinear Multiple input, multiple output (MIMO) system. Three degree of freedom helicopter (3DoF) has been used in the current work. The aim of the control is to stabilize the desired roll, pitch position beside the angle travel speed of the helicopter. Figure 1, illustrates the helicopter bodes system which consist of propellers, balancing block and the base [21].

From figure 1, the system consist of one shaft installed with slip ring, one block for balancing, and two DC motors installed on the shaft with sensor positions. If one of the motor supplied with positive power causes to move to positive pitch and if a positive power applied to second motor causes to back pitch (or negative pitch). The arm is provided with electrical signals via the slip ring. This reduces friction, deletes crosslinks and freedom of movement without problems.

The three assumptions simplify the dynamic model of 3-DoF helicopter system [22]. Linear approximation will be valid when the angles are sufficiently small.
- Neglect the coupling dynamics.
- Neglect the gravity torque.
- Neglect the frictions forces.
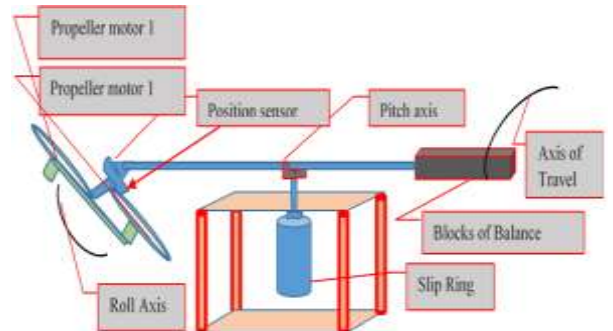
Fig. 1. 3-Degree of Freedom (3DoF) Helicopter System

According to the above proposals, the equations below illustrate the effectively decreasing the total Helicopter movement:

$$\begin{cases} J_\epsilon \ddot{\epsilon} = K_c l_1 V_s \\ J_p \ddot{p} = K_c l_p V_d \\ J_t \dot{r} = G l_1 p_c \end{cases} \qquad (1)$$

where, ϵ, ρ, and, r are respectively, the angles of pitch, angle of roll, and the travel rate, V_s and V_d are the applied voltages to the rear and front motors, J_r is the travel axis moment inertia, J_p is the roll axis moment inertia, $J\epsilon$ is the pitch axis moment inertia, l_p its distance between the roll axis and other motor, and l_1 its distance between the axis point and the propeller motor.

The helicopter state space model was formulated as below [22]:

$$\frac{d}{dt}\begin{bmatrix} \epsilon \\ P \\ \dot{\epsilon} \\ \dot{P} \\ r \\ \xi \\ \gamma \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{Gl_1}{J_t} & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} \epsilon \\ P \\ \dot{\epsilon} \\ \dot{P} \\ r \\ \xi \\ \gamma \end{bmatrix} +$$

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K_c l_1}{J_e} & \frac{K_c l_1}{J_e} \\ \frac{K_c l_1}{J_e} & -\frac{K_c l_1}{J_e} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} \epsilon \\ P \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} \epsilon \\ P \\ \dot{\epsilon} \\ \dot{P} \\ r \\ \xi \\ \gamma \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \qquad (3)$$

The table 1 illustrate the values of the physical parameter's value of equation 1.

Table 1. The values of the physical parameters

Symbol	Numerical values	Physical unit
$J\epsilon$	1.8145	kg.m2
J_t	1.8145	kg.m2
J_p	0.0319	kg.m2
G	4.2591	N
l_1	0.8799	m
l_2	0.3499	m
l_p	0.1699	m
K_c	12	N/V

2.1 Fractional Calculus

The non-integer order differentiation represents the fundamental operator of the fractional order calculus. The Integration is given by aD_t^r where (a) and (t) are the limits of the process and the integration or differentiation order is $\alpha \in \Re$, and define as [25, 26].

$$aD_t^r = \begin{pmatrix} \int_\alpha^t (d\tau)^{-r} & r < 0 \\ 1 & r = 0 \\ \dfrac{d^r}{dt^r} & r > 0 \end{pmatrix} \qquad (4)$$

The control algorithm realization need more equivalent definitions, these definitions are commonly used in the general differ-integral of fractions. They are the Riemann-Liouville (RL), Grünwald-Letnikov (GL), and Caputo definitions.

The Riemann-Liouville definition is:

$$aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \frac{d^n}{dt^n} \int_\alpha^t \frac{f(\tau)}{(t-\tau)^{r-n+1}} d\tau \qquad (5)$$

The Grunwald – Letnikov definition is:

$$aD_t^r f(t) = \lim_{h\to 0} \frac{1}{h^r} \sum_{j=0}^{\left[\frac{t-r}{h}\right]} (-1)^j \, j^r f(t-jh) \qquad (6)$$

The Caputo definition can be can be expressed as:

$$aD_t^r f(t)$$
$$= \frac{1}{\Gamma(n-r)} \int_\alpha^t \frac{f(\tau)^n}{(t-\tau)^{r-n+1}} d\tau \qquad (7)$$

Differential equations in fractional order (Caputo) and differential equations for integers are similar in the fundamental conditions. As explained in the definition above, the factorial function (m) can be described as positive real term, and as follows:

$$\Gamma(m) = \int_0^\infty z^{m-1} e^{-m} \, dz \qquad (8)$$

$$\Gamma(m+1) = m! \qquad (9)$$

Laplace Transform of Differ integral operator aD_t^α

$$L[aD_t^r f(t)] = \int_0^\infty e^{-st} aD_t^r \, f(t) dt \qquad (10)$$

$$L[aD_t^r f(t)] = s^r F(s) - \sum_{m=0}^{n-1} s(-1)^j \, {}_0 D_t^{r-m-1} f(t) \qquad (11)$$

The n comes between n-1< r ≤ n

For simplification, assume all the essentials value are zero, so:

$$L[aD_t^r f(t)] = s^r F(s) \qquad (12)$$

3. BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

The application of any algorithm to improve the non-linear system is based on a clear understanding and modelling of the search for food in any type of evolutionary types of genes. Bacteria find their food in two ways: swimming and tumbling, where the movement of bacteria swimming during movement in a predetermined direction and tumbling during movement in random directions. Bacteria always attract other bacteria so that they converge together in the desired place in order to reach the place of food very quickly during the recycling stage (this means the algorithms converge at the point of solution). Passion Explain the idea of the action of the mechanism of feed Escherichia Coli bacteria in the human body, especially in the intestines. They are in four types: chemical poisoning, agglomeration, reproduction, elimination of dispersion as follows [23, 24].

1. Chemotaxis:

Chemotaxis; where an organism reacts to the chemical stimulation through rapid movement. Single-cell, bacteria, Somatic cells, and other multicellular organisms have ability to direct their actions according to specific chemicals respectively through swimming and tumbling by flagella. Figure 2 illustrate the bacteria swimming and tumbling, and it's verified it by mathematically expression:

$$\theta^i(l,k,j+1) = c(i) \frac{\Delta(i)}{\sqrt{\Delta(i)\,\Delta^T(i)}} + \theta^i(l,k,j) \qquad (13)$$

The code Δ means a vector in the irregular direction whose elements occur in (-1, 1).

The connexion between swimming behaviour and rotation of flagellar in E- coli

Fig. 2: bacterium swimming and tumbling.

2. Swarming:

When nutrients, surface area and temperature are provided, wide range of bacterial types will rapidly grow and spread which can be defined as swarming. So such pattern of movement usually directs the new cells towards the edge of the colony. This action of swarming would positively reduce the emulation between cells for nutrients, accelerating growth. When bacteria even the site of the richest foods in the research period try to attack the other bacteria so that they converge together at the desired location.

3. Reproduction

Reproduction refers usually to the binary fission, a single cell bacteria can be divided into two new daughter cells, it

begins when cleavage of the DNA occur and migrate the sides of the cell forming the new DNAs of the identical daughter cells.

4. Elimination and Dispersal

In BFO and from frequent reproduction processes, a dispersion event occurs. A number of selected bacteria are then killed based on a predetermined probability of Ped or relocated to another location within the environment [28]. To simulate this phenomenon in BFOA, some bacteria are randomly filtered with very low probability while new alternatives are randomly configured on the search space.

The flow chart of the complete algorithm in figure 3, and the semi- random code is presented below:

4.2. parameters

The Initialize parameters are as follows, S, Nc, Ns , Nre , Ned , Ped, C(i)(i=1,2…S) and θi

p: Search space Dimension.

S: Total population bacteria number,

Nc: The chemotactic steps number.

Ns: The length of the swimming.

Nre: The reproduction steps number.

Ned: The number of elimination-dispersal events.

Ped: probability of the elimination-dispersal.

C (i): step size based in the random direction which determined via the tumble

4.3. Algorithm

1. The loop of the elimination-dispersal: $l=l+1$

2. The loop of the reproduction: $k=k+1$

3. The loop of the Chemotaxis: j =j+1

3.1. For i =1, 2, 3, 4, 5, S take a chemotactic step for bacterium i as below.

3.2. Calculate the cost function, J (i, j, k, l).

3.3. Suppose = (i,) keep this value so we could find a better cost through a run.

3.4. Update position

$$\theta^i(l, k, j + 1) = c\ (i) \frac{\Delta\ (i)}{\sqrt{\Delta(i)\ \Delta^T\ (i)}} + \theta^i(l, k, j) \quad (14)$$

This consequents a step of the size (i) in the tumble direction for bacteria i.

3.5. Evaluate the cost function $(i, +1, k, l)$

3.6. Swimming

3.6.1. Let m=0 (initial counter for length of the swim).

3.6.2. When $Ns > m$ (if it is not decrease more), so we can say that:

3.6.2.1. m = m + l.

3.6.2.2. J (i, j + 1, k, l) < st (when the performance is good)

3.6.2.3. Assume that $st = J$ (i, j +1, k, l) and let

3.6.2.4. Update the position and the cost function

$$\theta^i(j + 1, k , l) = \theta^i(j, k, l) + c(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (15)$$

The parameter [(j+1, j, k)] utilize to calculate the J (i, j +1, k, l) which it is a new cost function

3.5.2.5. Else, let it be m = NS. End statement.

3.7. Go to the next bacterium (i+1) if i ≠ S (i.e., go to [B] to process the next bacterium).

4- If j < NC, go to 3. In this situation continue chemotaxis, while the bacteria her life is not over.

5- Reproduction:

5.1. k and l are given, and for each i = 1,2,3,4,5,..., S , so

$$J_{health}^i = \sum_{j=1}^{N_c+1} J\ (i, jk, l) \quad (16)$$

If we consider the equation (14) as the bacterial health i (i.e the amount of nutrient required by the bacteria to avoid noxious substances during her life successfully). Sorting bacteria in an ascending cost pattern J health, (lower health that means higher cost).

5.2. with the highest value die of Jhealth ,the Sr equal to halfe of S bacteria , and this process can be implemented through copies were made in the same place as the parents' place

6- If k < Nre, go to 2. This status, the number steps of specified reproduction are not reached, so start to the next generation of the chemotactic loop.

7- With the probability Ped, elimination and dispersal, For i= 1,2,3,4,5,…., S, each bacterium, this leads to keeping the number of bacteria in the population constant. To do this, if a bacterium is eliminated. This can be done, when if the bacteria is eliminated, probably, one of bacteria disperse on the untidy location on the optimization zone.
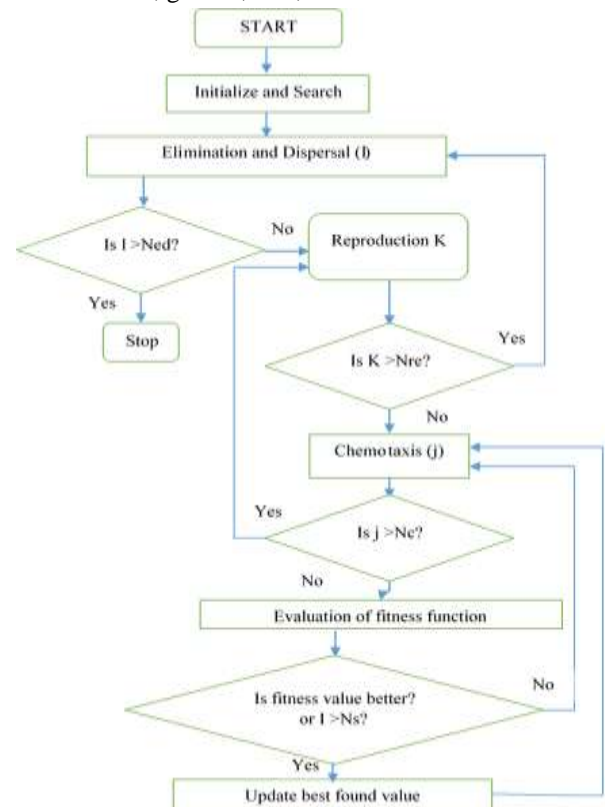
8- If l < Ned, go to 2, else, END.

Fig. 3. Flow chart for BF Optimization Algorithm

## 5. FOPID CONTROLLERS DESIGN USING BF

Fractional-order PID (FOPID) controller is a classical PID controller in general that uses fractional calculus. In comparison with traditional PID, the order of derivative section and integral segment is non integer that gives additional dynamic in getting the control objectives [23, 24].

The goal of BF-based optimization is to specify a set of PID and FOPID parameters so that the performance indicator is decreased. The PID has a parameters KD, KI and KP, also the FOPID has got a parameters KD, KI, KP, μ and λ. An appropriate optimization algorithm is essential to the parameter tuning of FOPID controller. The equations (17) and (18) respectively with a usual symbols are the dynamic equations of PID and FOPID system controller. The derivative and integration parameter codes are μ and λ respectively. Figure 4 shows the BF-FOPID controller tuning [4, 25].

$$u(t) = K_i \int_0^t K_d \frac{de(t)}{d(t)} + e(t)d(t) + e(t) K_p \qquad (17)$$

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \qquad (18)$$
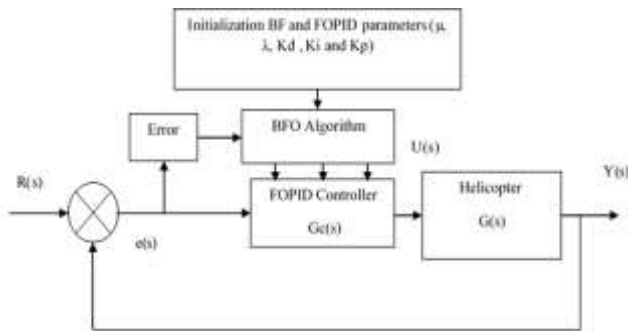
Fig. 4 The BF-FOPID controller tuning

Usually, we can check up the performance of a controller for a PID or FOPID controlled system by the quantitative measure of Performance index. In this paper, ISE has been taken as performance index, which is given in (19), for all optimization algorithms.

$$ISE = \int_0^T e^2(t)dt = \int_0^T [r(t) - y(t)]^2 dt \qquad (19)$$

The bacteria select behaviour, which resort to get better successful foraging strategies, and eliminate poor foraging strategies. This behaviour of bacteria makes the researchers to utilize it as an improvement process.

Table 2 give the parameters of initialization of BF

Table 2. Initialization Parameters of BF

Search space distance: $p = 5$	Chemo-tactic steps: Nc= 5
Population size: s = 20	Reproduction steps: Nre = 4
Length of a swim: Ns = 4	Reproductions rate :Sr = s/2
Elimination-dispersal: Ned =	3 (PID) , 5 (FOPID)
Elimination probability of each bacteria: Ped = 0.25	

6. SIMULATION AND RESULTS

The initial paramerters of BFPID controller shown in table 2. The helicopter system has an axis model of the travel angle,

the Roll angle, and the Pitch angle, which if they are bounded in input signal make an unstable in unbounded output signal as shown in figure 5.

6.1. The equation (1) in section 2 gives an axis model of pitch, as below:

$$J_e \ddot{\epsilon} = K_c l_1 V_s$$

Now, Taking Laplace transform of we get:

$$J_e \epsilon(s). s^2 = K_c l_1 V_s(s)$$
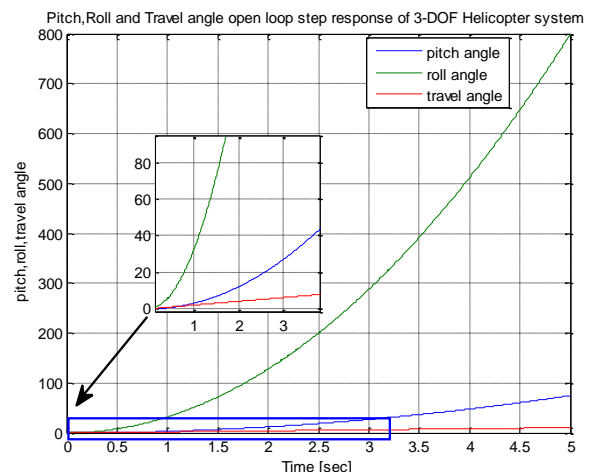
$$\frac{\epsilon(s)}{V_s(s)} = \frac{K_c l_1}{J_e s^2}$$

Substituted the physical parameter's value K_c, l_1 and J_e from Table 1.we get the transfer function in open loop for angle of pitch is $\frac{\epsilon(s)}{V_s(s)} = \frac{10.56}{1.815 \, s^2}$.

Similarly,

6.2. The transfer function in open loop for angle of roll is

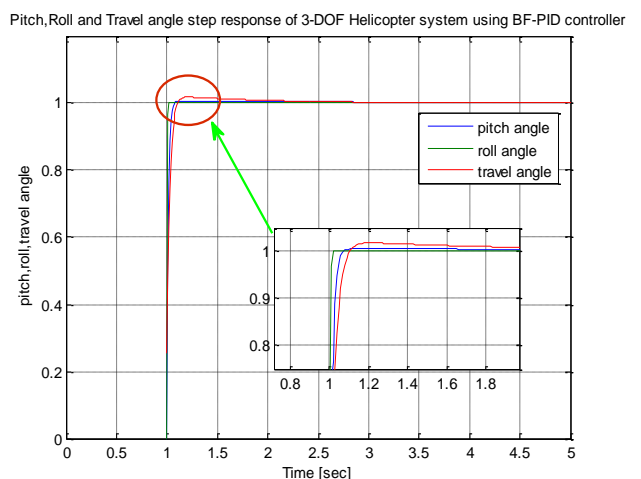$$\frac{p(s)}{V_d(s)} = \frac{2.04}{0.0319 \, s^2}$$

6.3. The transfer function in open loop for angle of travel is

$$\frac{r(s)}{p_c(s)} = \frac{3.748}{1.815 \, s}$$

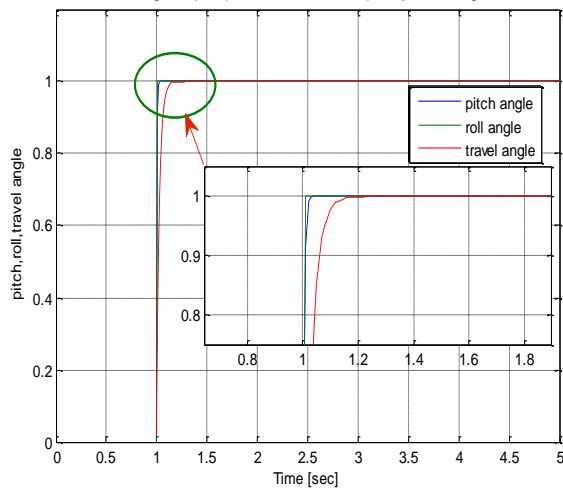**Fig. 5**: Open loop response of pitch, roll and travel angle.

Figure 6 and 7 show the travel, pitch, and roll angles axis model response of Helicopter system with BF-PID controller, and BF-FOPID controller respectively.

**Fig. 6:** BF-PID Controller response of pitch, roll and travel angle.

Pitch,Roll and Travel angle step response of 3-DOF Helicopter system using BF-FOPID controller
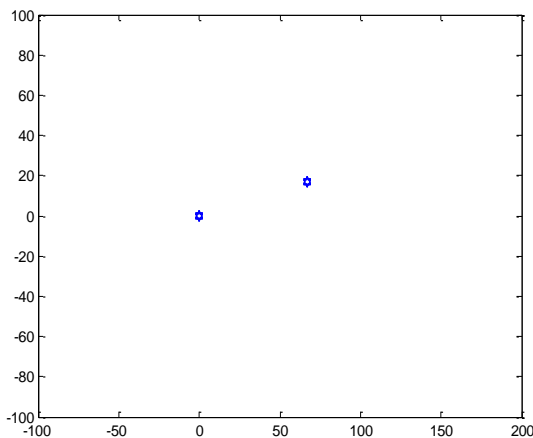

Fig.7: BF-FOPID Controller response of pitch, roll and travel angle.

Figure 8 (a and b) shows the bacteria movements in search space with population size 20 for pitch angle FOPID controller of Helicopter system at first and final iteration respectively.
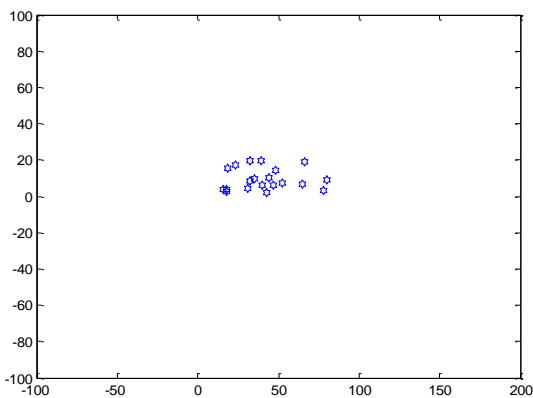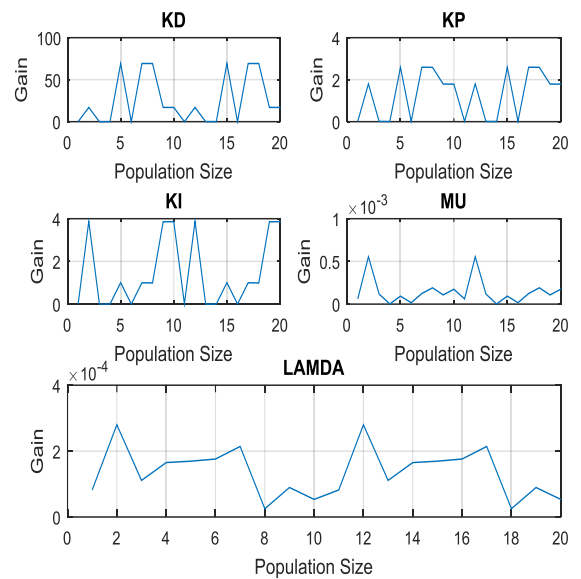

Fig. 8-a: Bacteria movement in search space with population size 20 for pitch angle FOPID controller at first iteration.

Fig. 8-b: Bacteria movement in search space with population size 20 for pitch angle FOPID controller at final iteration.

Figure 9 shows the variation of parameters of the fractional order PID controller.

Fig. 9 FOPID controller´s parameters

The Pitch, Roll and Travel BF-PID and BF-FOPID Controllers parameters Helicopter system as shown in Table 3,4,5.

Table 3. Pitch BF-PID and BF-FOPID Controller Parameters.

Pitch Controller Parameters	BF-PID Controller	BF-FOPID controlling System
Settling Time in sec (t_S)	0.0516	0.0184
Rise time in sec (tr)	0.03	0.00875
Over shoot in % (MP)	0.561	0.0192
K_P	12.0267	106.8162
K_D	4.9945	1.9486
K_I	0.8288	4.1686
λ		0.0046
μ		0.0073

Table 4. Roll BF-PID and BF-FOPID Controller Parameters.

Roll Controller Parameters	BF-PID Controller	BF-FOPID controlling System
Settling Time in sec (t_S)	0.0136	0.0098
Rise time in sec (tr)	0.00862	0.008
Over shoot in % (MP)	0.187	0.0106
K_P	5.3133	73.1319
K_D	3.4313	3.1625
K_I	0.5878	9.1962
λ		0.0064
μ		0.0062

Table 5. Travel BF-PID and BF-FOPID Controller Parameters.

Travel Controller Parameters	BF-PID controller	BF-FOPID controlling System
Settling Time in sec (tS)	0.433	0.103
Rise time in sec (tr)	0.0578	0.0575
Over shoot in % (MP)	1.81	0.00241
K_P	0. 1656	0.02848
K_D	22.7773	18.6956
K_I	2.0280	1.8218
λ		0.0095
μ		0.0249

Based on the acquired simulation results (as it is given above) in this paper, the fractional order (FOPID) controller gives faster response, minimum overshoot and higher accuracy than PID controller under the normal condition and in the presence of uncertainties in the parameters of the model.

7. CONCLUSION

From the principle of gene mutation, the bacteria tends to be more dynamically influential. So, in this paper The BF-FOPID and BF-PID controllers regulate the angular travel speed, roll positions in addition to pitch positions of the 3-DOF helicopter model. The values of controller's parameters (μ, λ, K_I, K_D, and, K_P) have been acquired by using the Bacterial Foraging (BF). Then the closed loop system response performance was analysed. The obtained results of K_P in the Pitch, roll and travel are (106.8162, 73.1319, and 0.02848, respectively) are good and different from the BF-PID controller. The values of K_D in the Pitch, roll and travel are (1.9486, 3.1625, and 18.6956 respectively) show better behaviour than in the BF-PID system. Also the values of K_I in the Pitch, roll and travel are (4.1686, 9.1962, and 1.8218, respectively) also less compared to the BF-PID. So the time domain observe that the system is given better performance for the designed BF-FOPID over BF-PID controller considering the rising time, settle time, and maximum over shoot. These results agree with our expectations and the previous theories.

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