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Design of PID Controller for Non-Linear Systems Using Lévy Flight Based Heuristic Algorithms

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ABSTRACT: In this work, tuning of classical PID controller is proposed for highly non-linear systems such as the benchmark bioreactor and Magnetic Levitation System (MLS)using Lévy flight based Cuckoo Search (CS)/Firefly Algorithm (FA). A weighted sum of cost function comprising the overshoot, settling time, integral square error (ISE) and integral absolute error (IAE) is considered to guide the heuristic search in order to discover three controller parameters such as K_p, K_i, and K_d. In the proposed work, the major aim is to compare the performance of the considered CS and FA on the controller design problem. The simulation work is implemented using the Matlab software and the performance of this study is validated by measuring the ISE and IAE values. This study confirms that, both the algorithms offers approximately similar result on the considered bioreactor and MLS systems.

KEYWORDS: Bioreactor, Magnetic levitation system, PID controller, Cuckoo search, Firefly algorithm.

I. INTRODUCTION

From control literature, PID and customized forms of PID controllers are still extensively used because of its structural simplicity, reputation and easy implementation, despite the significant developments in advanced process control schemes. It isalso observed that, heuristic algorithm based PI/PID controller design iswidely employed by the researchers to discover optimal solutions for a class of linear and non-linear systems [1-6]. Even though a substantialamount of algorithms are available in the literature, choice of a particular algorithm for an optimization problem mainly depends on : (i) Number of parameters to be optimized (dimension), (ii) Convergence speed, (iii) optimization accuracy , and (iv) Number of initial algorithm parameters to be assigned.

Controller design problem existing for the stable and the linear system are very simple compared with the unstable and the non-linear systems. The number of traditional controller design procedure existing for the unstable and non-linear systems are also very few [6]. Hence, in recent days, heusristic algorithm based PID [5,6], IPD [7], fractional order PID and setpoint weighted PID controller [8] design procedures are widely proposed by the researchers.

From the resent literature, it is noted that, Lévy flight based algorithm offers faster convergence and better result compared to other heuristic algorithms, which works on a random search []. In Lévy flight strategy, the agent will move quickly in a bounded search boundary, until it finds optimal solutions based on the problem. In this work, Cuckoo Search (CS) and Firefly Algorithm (FA) is considered to solve the PID controller design problem [9]. Recently, CS and FA are considered to solve a variety of engineering optimization problems [10-16]. In the proposed work optimal PID controllers are designed using the CS and FA algorithms and implemented on the non-linear model of the bioreactor and the state-space model of the MLS. The result confirms that, CS and FA algorithm offers approximately similar result because of its Lévy flight strategy.

II. PROCESS DESCRIPTION

In order to implement the CS/FA based PID controller, the following non-linear process models are adopted:

2.(a) Bioreactor

Bioreactor plays a vital role in chemical process industries to produce important chemical and biochemical compounds. In this system, living organisms, known as microbes are converted into marketable products such as beverages, antibiotics, vaccines and industrial solvents [17,18]. The quality of the final product from a bioreactor depends mainly on the control loop employed to monitor and control the microbial growth based on the reference input [19,20].

Bioreactor can be defined as a reactor system employed to execute a number of biological reactions in a liquid medium to form intermediate and final products. Fig.1 shows the schematic diagram of the bioreactor. The dynamic behaviour of the reactor is complex and a number of vital manufacturing processes belong to this group.

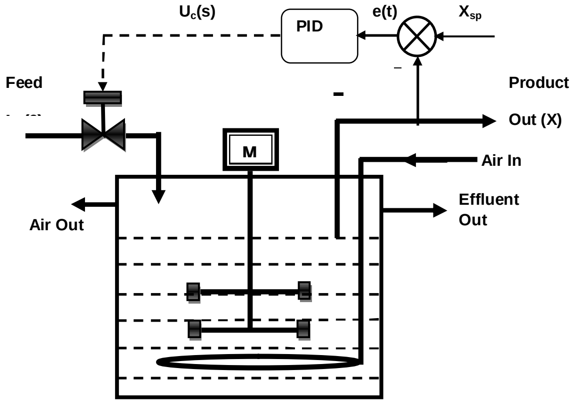

Fig.1 Scheme of a benchmark bioreactor

The basic reaction inside the bioreactor is $A \xrightarrow{k} P$ (1)
where 'A' is the reactant, 'k' is reaction rate constant and 'P' is the product.

Biosynthesis is widely utilized to convert the living cells (biomass / microbes) into marketable chemical, pharmaceutical, food and beverage products. Eqn.1 shows the operation performed during biosynthesis. In this operation, the biomass/microbes consume nutrients from the substrate (feed) to cultivate and to produce more cells and important products. During this operation the bioreactor is kept under a controlled environment with constant pH, temperature, agitation rate and dissolved oxygen level to attain better growth of microbes [20].

A number of studies are available in the literature for model based control of bioreactor. The following mathematical equations considered in this research work, can describe a variety of industrial bioreactors [4,18];

Cell balance : $$\frac{dX}{dt} = (\mu - D)X \quad (2)$$

Substrate balance : $$\frac{dS}{dt} = D(S_f - S) - \frac{\mu X}{Y} \quad (3)$$

Product balance : $$\frac{dP}{dt} = -D\,P + (\alpha\,\mu + \beta)\,X \quad (4)$$

Monod kinetics : $$\mu = \frac{\mu_{max}\,S}{K_m + S} \quad (5)$$

where, 'μ' is the specific growth rate, 'X' the biomass concentration, 'S' the substrate concentration and 'α' and 'β' are yield parameters for the product. At steady state, the variables will be; $X = X_s$, $S = S_s$, and $P = P_s$.The nominal parameter and constant values considered in the mathematical equations are presented in Table 1.

Table 1 Parameters of benchmark bioreactor [4]

Parameter		Values
$X1(s)$	Biomass Concentration	0; g / L – lag phase 0.9951; g / L – growth phase 1.5302; g / L – stationary phase
$X2(s)$	Substrate Concentration	4.0; g / L – lag phase 1.5122; g / L – growth phase 0.1746; g / L - stationary phase
D	Dilution rate	0.3 ; hr^{-1}
X_{fs}	Feed substrate concentration	4.0 g / L
μ_{max}	Maximum specific growth rate	0.53; hr^{-1}
K_m	Substrate saturation constant	0.12; g / L
Y	Cell mass yield	0.4
K_1	Substrate inhibition constant	0.4545; L / g

In this work, the growth phase and the stationary non-linear models are considered to analyse the controller performance. The PID controller is designed and its performance verified separately for the growth phase and the stationary phase.

2.(b) Magnetic Levitation System

MLS is an electro-mechanical system and the construction detail is depicted in Fig 2. In this system, a controller is used to regulate the electric current (i) until the electromagnetic force (f) equals to the weight of the steel ball (m*g). When the above condition is reached, the ball will levitate in an equilibrium state [21].

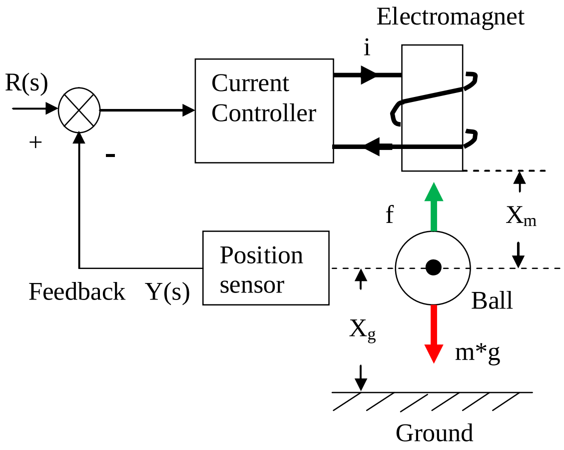

Fig. 2Construction of Magnetic Levitation System

The mathematical model of the MLS is described below;

Voltage applied to the coil : $V(t) = R\, i(t) + L \frac{d\, i(t)}{dt}$ (6)

Force by the electromagnet is : $f(x,i) = c\left(\frac{i}{x}\right)^2$; and $c = \frac{L_0 X_0}{2}$ (7)

Mechanical force on the ball : $m\frac{d^2x}{dt^2} = (m*g) - c\,(\frac{i}{x})^2$ (8)

Where x = X_m is the distance between ball and magnet, i = current through coil, L = inductance of the coil, R= internal resistance of the coil, m= mass of the ball, g = acceleration due to gravity, L_0 is the additional inductance of the magnetic coil due to the ball placed at the equilibrium position x_0.

From Eqn. 9, coil inductance (L) is a nonlinear function and it is a function of ball position x.

The approximate inductance is $L(x) = L + \frac{L_0 x_0}{x}$ (9)

Linear form of Eqn.3 can be written as ;

$$m\frac{dx^2}{dt} = -c\left(\frac{i_0}{x_0}\right)^2\left\{1 + 2\left[\frac{i(t)}{i_0} - \frac{x(t)}{x_0}\right]\right\} + mg \qquad (10)$$

When $c\left(\frac{i_0}{x_0}\right)^2 = m*g$, Eqn.10 can be written as:

$$m\frac{dx^2}{dt} = -\frac{2i_0c}{x_0^2}i(t) + \frac{2i_0^2c}{x_0^3}x(t) \qquad (11)$$

In Eqn.11, x(t) and i(t) are the incremental displacement and incremental magnet current around their nominal values x_0 and i_0. The linearized state model of the system around the point $x_1 = x_{01}$ is presented below;
The state vector for the system is $X_0 = [x_{01}\ \ x_{02}\ \ x_{03}]^T$ (12)

At equilibrium, $x_{02} = 0$ and $x_{03} = x_{01}\sqrt{\frac{mg}{c}}$. (13)

The linearized state model of the system is;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{Cx_{03}^2}{Mx_{01}^3} & 0 & -2\frac{Cx_{03}}{Mx_{01}^2} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^2} & -\frac{R}{L} \end{bmatrix};\ B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix};\ C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \qquad (14)$$

The MLS parameters are assigned as m = 0.05kg, g = 9.81 m/s2, L = 0.01H, R = 1Ω, C = 0.0001, x01 = 0.012 M, x02 = 0 M/s, and x03 = 0.84A [21].

The mathematical model of the considered MLS is represented in Eqn, 10 and this model is considered during the controller design procedure.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1633.33 & 0 & -23.33 \\ 0 & 116.66 & -100 \end{bmatrix} ;\ B = \begin{bmatrix} 0 \\ 0 \\ 100 \end{bmatrix} ;\ C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (15)$$

III. HEURISTIC ALGORITHMS

In the proposed work the recent heuristic algorithms discussed below are considered.

3. (a) Cuckoo Search

CS is one of the successful algorithms, proposed by Yang [11]. This algorithm is based on the breeding tricks of parasitic cuckoos.
The mathematical expression of the CS considered in this study is given below [15,16]:

$$X_i^{(t+1)} = X_i^{(t)} + \alpha \oplus Levy(\lambda) \quad (16)$$

where $X_i^{(t)}$ is the initial position, $X_i^{(t+1)}$ is the updated position, α is chosen as 1.2 and $\oplus$ is the symbol for entry wise multiplication.
In this work, Levy Flight (LF) based search methodology is considered to update the position of the agents. LF is a random walk in which the search steps can be drawn using the following Levy distribution[13].

$$Levy \sim u = t^{-\lambda} \quad for \quad (1 < \lambda \le 3) \quad (17)$$

3.(b) Firefly algorithm

The classical FA was initially discussed by Yang [12]. It is a nature-inspired meta-heuristic algorithm, in which flashing illumination patterns generated by invertebrates, such as glowworms and fireflies, were at the essence of its creation.The traditional FA is developed by considering the following conditions. Recently, FA based approach is implemented for the gray scale and RGBimage segmentation by the researchers.
The movement of the attracted firefly *i* towards a brighter firefly *j* can be determined by the following position update equation:

$$X_i^{t+1} = X_i^t + \beta_0 e^{-\gamma d_{ij}^2} (X_j^t - X_i^t) + \alpha_1 . sign(rand - 1/2) \oplus Levy(\lambda) \quad (18)$$

where X_i^{t+1} is theupdated position of firefly, X_i^t is theinitial position of firefly,and $\beta_0 e^{-\gamma d_{ij}^2} (X_j^t - X_i^t)$ may be considered as the attractive force between fireflies [11,13,14].

3. (c) PID controller

Industrial PID controllers typically accessible as a packaged form and to perform well with the industrial process problems, the PID controller requires optimal tuning. In this research work, a non-interacting form of PID controller structure is considered. A low pass filter is used with the derivative term to reduce the effect of measurement noise. The PID structure is defined below [3]:

$$G_c(s) = K_p \left[1 + \frac{1}{T_i\, s} + \frac{T_d\, s}{\frac{T_d\, s}{N} + 1} \right] \quad (19)$$

where $K_p / T_i = K_i$, $K_p * T_d = K_d$, N = filter constant = 10.

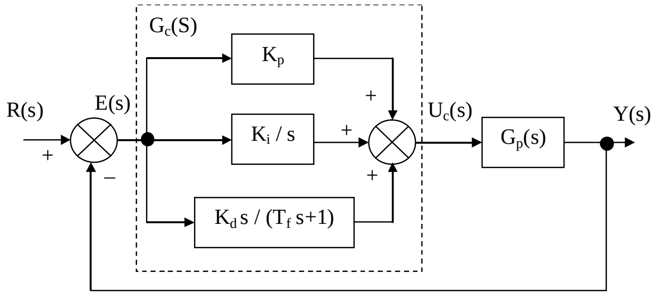

Fig. 3 Parallel PID structure

Cost function considered in this study is presented below:

$$J_{max}(K_p, K_i, K_d) = w_1 . ISE + w_2 . M_p + w3. ISE + + w4. IAE \qquad (20)$$

Where $ISE = \int_0^T e^2(t)\,dt$; $IAE = \int_0^T |e(t)|\,dt$; e – the error between the setpoint and process response, M_p – the overshoot, t_s- the settling time, w_1=w_2 = 2 and w_3=w_4=1.

IV. RESULTS AND DISCUSSIONS

This section presents the results of the simulation study obtained using the Matlab 2010a software. During the simulation study, the following algorithm parameters are assigned: number of agents (N) is chosen as 20, number of iteration is chosen as 1000, the dimension of search (D) is assigned as 3 and the algorithm is allowed to search the controller parameters till the $J_{max}$is reached. This controller design procedure is repeated 10 times and the average value is recorded as the optimal controller parameter.

Initially, the controller design procedure is implemented on the non-linear bioreactor model discussed in [4,18] using the CS algorithm. Firstly, the PID design is implemented for the growth phase model by assigning the process parameters as discussed in Table 1. Secondly, the same procedure is repeated with the stationary phase model. The average of the controller parameters and its corresponding ISE and IAE values are depicted in Table 2. Similar procedure is repeated with the FA algorithm and the corresponding values are also in Table 2. Later, this procedure is implemented for the unstable MLS system. From Table 2, it can be noted that, even though CS and FA offers different K_p, K_i and K_d values, the ISE and IAE values are approximately similar.

Table 2. Controller parameters and its corresponding error values

Process			K_p	K_i	K_d	ISE	IAE
Bioreactor	Growth phase model	CS	-0.4892	-0.0521	- 0.1615	1.3322	2.4235
		FA	-0.5193	-0.0484	- 0.1714	1.3695	2.3042
	Stationary phase model	CS	-0.6215	-0.0475	- 0.3846	0.7124	1.5883
		FA	-0.7927	-0.0674	- 0.5190	0.6952	1.5936
MLS	PID	CS	-80.8465	-4.4194	-4.2217	50.3422	15.8904
		FA	-80.9166	-4.2937	-4.6253	51.4836	16.3601
	I-PD	CS	-80.8465	-4.4194	-4.2217	1.9395	4.0417
		FA	-80.9166	-4.2937	-4.6253	2.0118	4.1762

The superiority of the proposed approach is confirmed with a simulation study using Matlab software. Fig.4 and Fig.5 depicts the servo response for the growth phase of the nonlinear bioreactor model. Fig.6 and Fig.7 shows the servo response for the stationary phase. From these figures, it can be confirmed that, the PID controlled designed with the CS and FA offers approximately similar result.

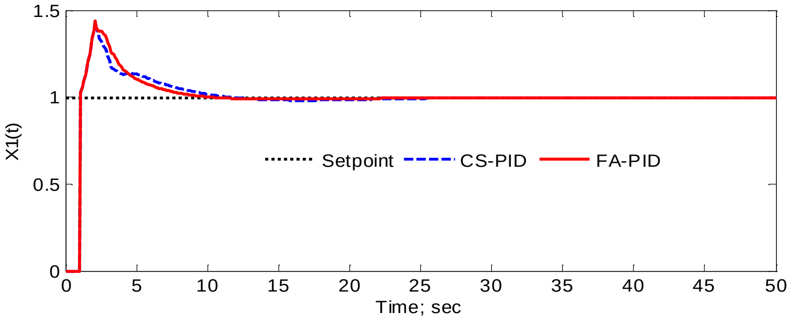

Fig.4Biomass value for grown phase

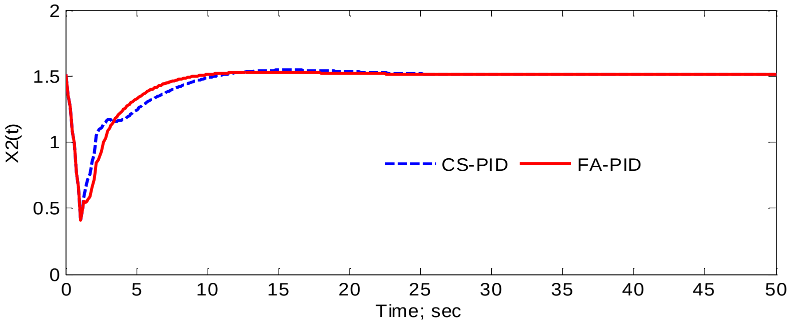

Fig.5Substrate value for grown phase

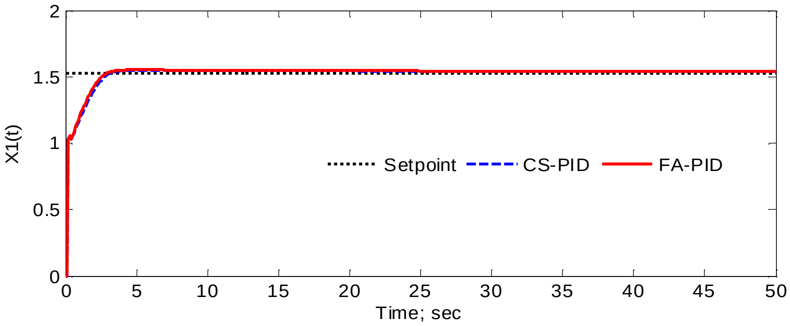

Fig.6 Biomass value for stationary phase

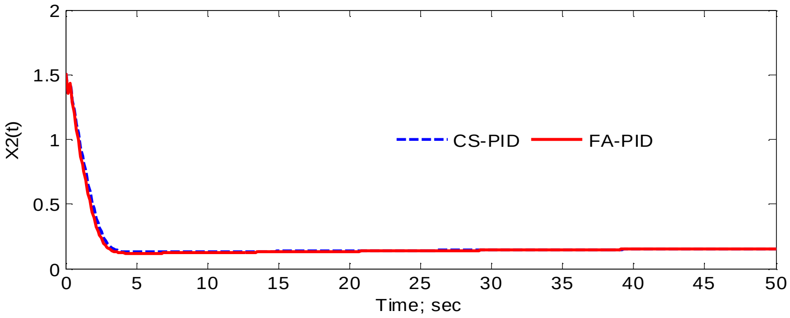

Fig.7Substrate value for stationary phase

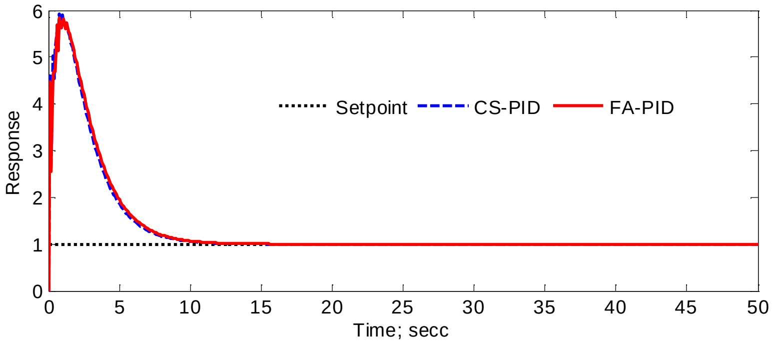

Fig. 8 Servo response of MLS with PID controller

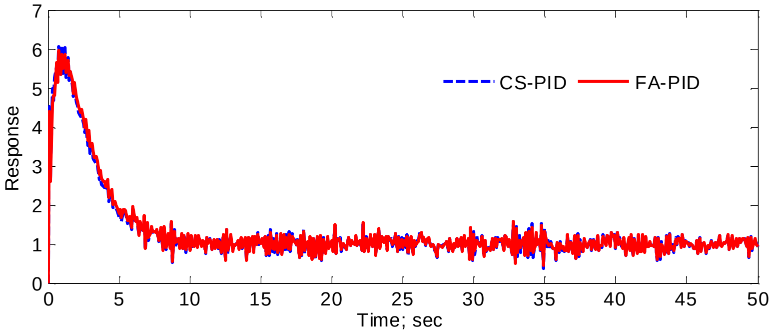

Fig.9Servo response of MLS in the presence of measurement noise

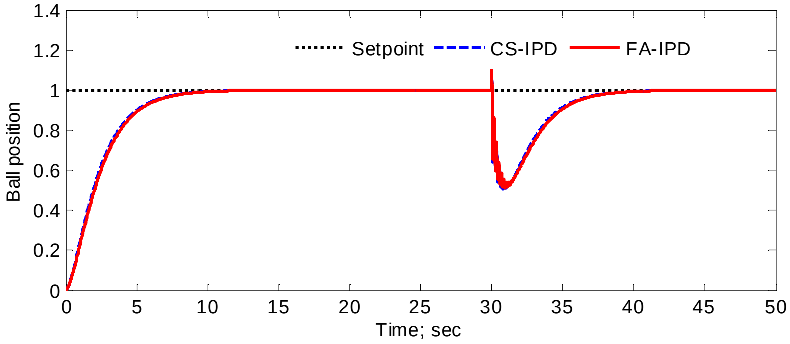

Fig.10Regulatory response of MLS system with IPD controller

Proposed controller design procedure is then implemented on the MLS system. Fig. 8 shows the servo response of the MLS model. In order to test the robustness of this PID controller is validated by introducing a measurement noise (white noise with zero mean) is the feedback loop. Fig. 9 confirms the robustness of the CS and FA designed PID. The above figures shows a larger overshoot, which can be minimized using an I-PD controller [22]. From Fig.10 it is noted that, the I-PD controller offers better reference tracking and disturbance rejection for the MLS system.

V. CONCLUSIONS

In this work, design of PID controller is proposed for bioreactor and Magnetic Levitation System using Lévy flight based Cuckoo Search (CS) algorithm and Firefly Algorithm (FA). In the proposed work, a weighted sum of objective function is considered and maximization of this objection function is chosen as the terminating criteria for heuristic search. Proposed simulation work is implemented using the Matlab software and the performance of servo operationis verified. The result confirms that, the controller designed with the CS and FA offers similar result.

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