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2DOF PID Controller Design for a Class of FOPTD Models – An Analysis with Heuristic Algorithms

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Abstract

In recent years, a number of controller design procedures are developed and implemented in process industries to enhance the performance of closed loop processes. In this paper, heuristic algorithm based Two Degrees Of Freedom (2DOF) PID controller design is proposed for a class of First Order Plus Time Delay (FOPTD) systems existing in the literature. Minimization of the weighted sum of multiple objective functions is considered to monitor the heuristic search towards the optimal controller parameters. A detailed comparative analysis between well known heuristic methods, such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), Cuckoo Search (CS) and Firefly Algorithm (FA) are presented. The popular 2DOF PID structures, such as Feed Back Structure (FBS) and Feed Forward Structure (FFS) are considered in this work to enhance the performance of FOPTD systems. From the results, it is noted that, proposed controller provides enhanced results for the reference tracking and disturbance rejection operations.

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Keywords: FOPTD; 2DOF PID controller; heuristic algorithm; reference tracking; disturbance rejection.

1. Introduction

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In process industries, despite the major progress in superior process control methodologies, PID controllers are widely used because of its structural simplicity, reputation, easy in performance, acceptance simplicity and adaptability [1, 6]. In the literature, several articles are available to study the tuning procedures and implementation of a single Degree Of Freedom (1DOF) PID controller for stable, unstable and nonlinear systems [1,7,9]. The recent studies on fine tuning the 1DOF PID have provided insight for better understanding of the controller performance for a class of process models. For most of the systems, 1DOF PID offers a feasible outcome either for reference tracking operation or disturbance rejection operation.

Nomenclatures

K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
α, β	Tuning parameters
M_p	Overshoot
t_s	Settling time
D	Dimension of search
J_{min}	Objective function to be minimized

Abbreviations

PID	Proportional + Integral + Derivative
DOF	Degree Of Freedom
ITAE	Integral Time Absolute Error
ITSE	Integral Time Square Error

In recent years, various forms of Two Degrees Of Freedom (2DOF) PID controllers are widely discussed by the researchers [6,9,]. A detailed study on various 2DOF structures existing in the literature can be found in the article by Araki and Taguchi [2].

Most of the conventional controller tuning methods existing in the literature is purely model dependent. The tuning methodology employed for one particular reduced process model may not offer a suitable response for other process models. Hence, in recent years, heuristic algorithm based model free controller design procedure is widely adopted by the researchers [6,8-10].

In the proposed work, popular 2DOF PID structures, such as Feed Back Structure (FBS) and Feed Forward Structure (FFS) are considered to stabilize First Order Plus Time Delay (FOPTD) models existing in the literature using heuristic algorithms, such as PSO, BFO, CS and FA. The performances of the considered algorithms are analyzed based on the time domain parameters (M_p, t_s), error values (*ITSE*, *ITAE*) and the search time taken by the algorithms.

2. 2DOF PID

In general, 2DOF PID structure improves the overall closed loop performance of the process. A detailed study on various 2DOF structures are clearly presented by Araki and Taguchi [2]. In this work, the 2DOF PID structures considered by Latha and Rajinikanth [6] is adopted to stabilize the FOPTD process models.

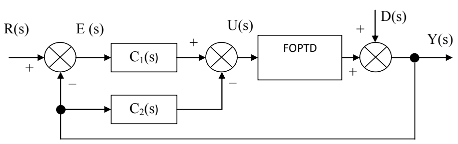

Fig 1. Feedback structure

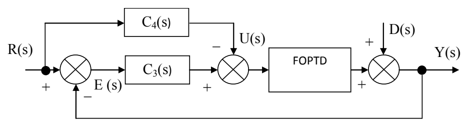

Fig 2. Feed forward structure

$$C_1(s) = K_p(1-\alpha) + K_i + (1-\beta)K_d D_f(s) \quad (1)$$

$$C_2(s) = K_p\left(\alpha + \beta \tau_d D_f(s)\right) = K_p\,\alpha + \beta K_d D_f(s) \tag{2}$$

$$C_3(s) = K_p\left(1 + \frac{1}{\tau_i s} + \tau_d D_f(s)\right) = K_p + K_i + K_d D_f(s) \tag{3}$$

$$C_4(s) = K_p\left(\alpha + \beta \tau_d D_f(s)\right) = K_p\,\alpha + \beta K_d D_f(s) \tag{4}$$

where α *and* β are controller weighting parameters ranging from 0 to 1 and $D_f(s)$ is the derivative filter term given by $s/(1+N_f s)$. In this work, N_f is chosen as 20.

Fig 1. depicts the feedback 2DOF structure with a PD controller in the inner loop and a PID in the outer loop. In this structure, the PID responds on error signal *e(t)* and the PD works on the process output *y(t).* Fig 2. shows the feed forward 2DOF structure with a PD in the feed forward loop and a in the closed loop. The PID controller responds on error signal *e(t)* and the PD controller works on the reference input *r(t)*. The major advantage of the 2DOF structure is, it is free from the proportional and derivative kick effect and supports smooth reference tracking response.

3. Heuristic Algorithms in this Study

In recent years, a considerable number of heuristic algorithms are proposed by the researchers to find optimal solutions for a class of engineering optimization problems. The details of the existing heuristic algorithms can be found in the recent article by Fister et al. [4]. In this paper, the following heuristic algorithms are considered to offer optimal 2DOF PID controller parameters.

3.1 Particle swarm optimization

PSO is an evolutionary optimization technique, developed due to the inspiration of the social activities in flock of birds and school of fish [5]. It has two basic equations namely the velocity update and position update as given below:

$$V_i^{(t+1)} = W^t . V_i^t + C_1 R_1 (P_i^t - S_i^t) + C_2 R_2 (G_i^t - S_i^t) \tag{5}$$

$$X_i^{(t+1)} = X_i^t + V_i^{(t+1)} \tag{6}$$

where W^t = inertia weight coefficient (typically 0.75), V_i^t = current velocity of particle, $V_i^{(t+1)}$ = updated velocity of particle, C_1 = 2.1, and C_2 = 1.8 [9].

3.2 Bacterial foraging optimization

BFO is developed by mimicking the foraging behavior of *E. coli* bacteria [8]. In this work, the enhanced BFO algorithm discussed by Rajinikanth and Latha is adopted [9,10]. The initial algorithm parameters are assigned as follows:

Number of *E.Coli* bacteria = N

$$N_c = \frac{N}{2};\ N_s = N_{re} \approx \frac{N}{3};\ N_{ed} \approx \frac{N}{4};\ N_r = \frac{N}{2} \quad \text{Ped} = \left(\frac{N_{ed}}{N + N_r}\right);$$

$$d_{attractant} = W_{attractant} = \frac{N_s}{N}; \quad \text{and} \quad h_{repellant} = W_{repellent} = \frac{N_c}{N}. \tag{7}$$

3.3 Cuckoo search

CS was initially proposed by Yang and Deb in 2009 [14]. This algorithm is based on the breeding tricks of parasitic cuckoos. In CS, the new solution ($X_i^{(t+1)}$) mainly depends on the old solution ($X_i^{(t)}$) and the search guiding procedure. In this work, Lévy Flight (LF) based search is considered as presented below:

$$X_i^{(t+1)} = X_i^{(t)} + \alpha' \oplus LF \quad (8)$$

3.4 Firefly algorithm

FA is a nature inspired metaheuristic algorithm proposed by Yang [15,16]. This algorithm is developed by imitating the flashing illumination patterns produced by invertebrates such as glowworm and firefly [17]. A detailed analysis on FA can be found in [17]. In this work, LF based firefly discussed is literature is adopted and the following update equation is considered:

$$X_i^{t+1} = X_i^t + \beta_0 e^{-\gamma d_{ij}^2} (X_j^t - X_i^t) + \alpha . sign(rand - ½) \oplus Lévy \quad (9)$$

3.5 Implementation

Fig 3 shows the proposed controller tuning procedure. The heuristic algorithm is employed to find the best possible values of 2 DOF PID parameters , such as K_p, K_i, K_d, α, and β. In this work, the dimension of the search is chosen as five.

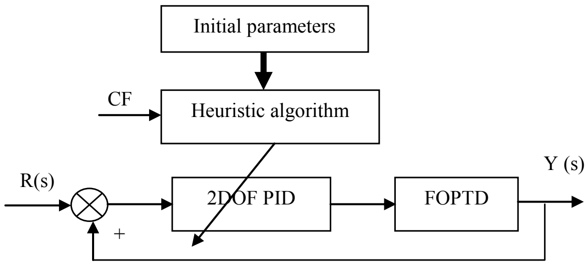

Fig 3. Block diagram of proposed controller design procedure

In heuristic algorithm based search procedure, the optimization accuracy mainly relies on the cost function assigned to guide the search. In this paper, a weighted sum of cost function shown below is considered:

$$J_{min} = w_1 * M_p + w_2 * t_s + w_3 * ITSE + w_4 * ITAE \quad (10)$$

where the weights are chosen as $w_1 = w_2 = 2$ and $w_3 = w_4 = 0.5$

A bounded search is considered for the controller parameter values (ie. Each parameter is bounded between a minimum and a maximum value). The heuristic search explores the five dimensional search space in order to identify the optimal solutions.

4. Results and Discussions

In the proposed work, the initial algorithm parameters are assigned as follows: number of agents is chosen as twenty, dimension of search is five, cost function is chosen as J_{min}, maximum iteration number is chosen as 500. For each algorithm, the heuristic search is repeated ten times and the average value is chosen as the optimized value. All the simulation work is carried using Matlab software. The proposed work is tested on the following three FOPTD models. In this work, for all the considered process models, a disturbance signal of 0.5 (50% of setpoint value) is considered to analyze the regulatory response of the designed 2DOF PID.

Process 1: The first-order stable process model is considered [12,13]:

$$G(s) = \frac{1}{s+1} e^{-0.5s} \quad (11)$$

Heuristic algorithm based based controller design is initially proposed for the above process using the feedback 2DOF structure with the following bounded values 0% < K_p < 50%, 0% < K_i < 20%, 0% < K_d < 50%, 0% < α < 100% and 0% < β < 100%. During the search, the heuristic algorithm explores the search space based on the controller range. Ten independent runs are performed with each heuristic algorithm and the average value of the search is considered as optimal value. In this process, the controller values and the corresponding performance values are presented in Table 1 and the corresponding response is presented in Fig 4. For this process, the BFO tuned 2DOF PID offers better response compared with other methods. Similar response is obtained with the feed forward 2DOF structure.

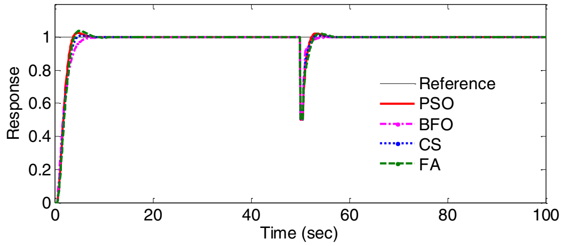

Fig. 4. Reference tracking and disturbance rejection performance for Process 1

Table 1. Optimized controller parameters and the performance measure values

	Method	Iteration	K_p	K_i	K_d	α	β	M_p	t_s
Process1	PSO	193	0.9842	1.0248	0.0722	0.9011	0.9201	0.096	5.895
	BFO	276	1.3105	0.9832	0.1103	0.8004	0.9037	0.000	8.361
	CS	174	1.0738	0.9937	0.0994	0.9377	0.9261	0.074	6.773
	FA	158	0.8475	0.9118	0.1006	0.9468	0.9022	0.098	8.427
Process 2	PSO	227	3.0664	0.0833	1.4673	0.8394	0.8831	0.241	274.6
	BFO	284	4.8244	0.1033	1.1433	0.8611	0.8902	0.255	256.8
	CS	141	4.1038	0.0799	1.0132	0.9028	0.9117	0.000	137.4
	FA	138	3.7994	0.1122	1.1741	0.9261	0.9336	0.248	198.3
Process 3	PSO	188	−0.5506	−0.0593	−0.1948	0.8931	0.8855	0.093	32.83
	BFO	231	−0.6103	−0.0472	−0.1084	0.8927	0.8794	0.000	26.38
	CS	179	−0.5811	−0.0394	−0.1002	0.9038	0.9163	0.000	25.91
	FA	163	−0.6091	−0.0663	−0.1337	0.9112	0.9088	0.036	29.17

Process 2: The FOPTD model of the spherical tank system is given below [10,11]:

$$G(s) = \frac{3.6215}{330.46s+1} e^{-11.7s} \tag{12}$$

The heuristic algorithm based search is proposed for this system, as discussed in process 1. The optimal controller parameters and the corresponding performance measurre values are presented in Table 1. Fig 5 depicts the servo and regulatory operation with a disturbance signal of 0.5. The CS based method offers satisfactory response compared with the alternatives.

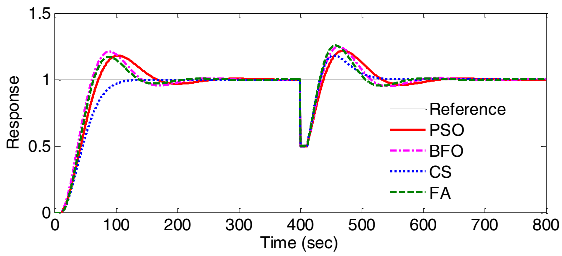

Fig. 5. Reference tracking and disturbance rejection for spherical tank system

Process 3: The first-order unstable process with the following transfer function model is considered [3,7]:

$$G(s) = \frac{-5.8644}{5.89s+1} e^{-0.1s} \tag{13}$$

Designing a suitable controller for unstable system is quite defficult compared with stable system. In this work, the controller bouundaries are assigned as $-60\% < K_p < 0\%$, $-25\% < K_i < 0\%$, $-25\% < K_d < 0\%$, $0\% < \alpha < 100\%$ and $0\% < \beta < 100\%$. The optimal controller parameters and the corresponding iteration number, M_p, and t_s are presented in Table 1. From Fig 6, it is noted that, the FA tuned 2DOFPID offers better result compared with PSO, BFO and CS,

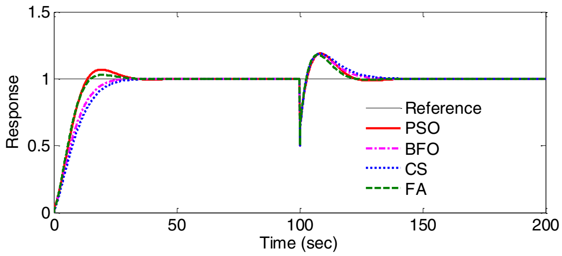

Fig. 6. Reference tracking and disturbance rejection for unstable bioreactor model

5. Conclusions

In this paper, design of 2DOF PID controller design is proposed using PSO, BFO, CS and FA. The proposed method is tested on two stable FOPTD models and one unstable FOPTD model. The proposed controller design procedure is validated using traditional measures, such as M_p and t_s. The results show that, number of iteration taken by the LF driven CS and FA is comparatively smaller than PSO and BFO. The simulation result also confirms that, even though there is a structural difference, the feedback and feed forward 2DOF PID offers similar process response for the servo and regulatory operations.

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