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Optimized PI-PD Control for Varying Time Delay Systems Based on Modified Smith Predictor

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Abstract: Time delay is a challenging problem that is frequently encountered in many fields of engineering systems. In this paper, an optimal proportional integral minus proportional derivative (PI-PD) controller with a modified smith predictor (MSP) for varying time delay systems is proposed. The optimal value of the tuning parameter sets of the PI-PD controller for step reference tracking and disturbance rejection is obtained based on two swarm intelligence techniques named flower pollination algorithm (FPA) and heap-based optimization (HBO). Three-time delay processes are used for evaluation. To evaluate the performance of each control structure, a compromised cost function between minimizing the control effort and improving the time response of the system is used. The simulation results based on MATLAB show the PI-PD controller with MSP tuned by HBO exhibits better performance than other controller structures.

Keywords: Varying time delay system, Modified smith predictor, PI-PD controller, Swarm optimization, Flower pollination algorithm, Heap-based optimization.

1. Introduction

Time delay is frequently encountered in many fields of engineering systems such as networked systems [1], injection mould systems [2], telerobotic systems [3] and power systems [4]. It is considered an important issue due to its direct impact on the system's performance [5]. Various control strategies such as a proportional-integral-derivative (PID) controller and smith predictor (SP) have been proposed to ensure the stability of the system and achieve the desired performance. In terms of PID controller, Hägglund and Åström [6] and Hang et al. [7] showed that using conventional methods (i.e. Ziegler & Nichols) to tune the PID controller for TDS may not provide satisfactory closed-loop responses. They modified the Ziegler-Nichols tuning formula by including a constant weighting factor on the set-point [6] and normalized process gain with normalized dead-time [7]. Fong-Chwee and Sirisena [8] proposed three self-tuning pole assignment PID controllers for fractional dead time, known and constant dead time, and constant time plus time varying dead time. Another control scheme to deal with delay is the Smith predictor. The main advantage of the smith predictor approach is that the time delay is eliminated from the characteristic equation of the closed-loop system [9]. However, the Smith predictor exhibits poor performance when the system has uncertainties and/or is subjected to disturbances [10, 11]. In this direction, different modifications of the Smith predictor have been proposed. Matausek and Micic [12] presented a modification of the Smith predictor for controlling TDS with integral action. The structure of the controller consists of three tuning parameters: the dead time, the proportional gain, and the desired time constant of the first-order closed loop. Kaya and Atherton [13] showed that by using the PI-PD controller with the smith predictor, the set-point tracking and the disturbance rejection performance are improved. Another modification of the smith predictor is proposed by Liu et al. [14]. The new modification scheme is based on a proportional controller to stabilize the set-point response, and then an H_2 optimal controller for set-point tracking under disturbance. Hassan et al [1] and Tan et al. [15] proposed a set-point weighting strategy combined with PID controller. The simulation results show that the proposed controller provides

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good set-point tracking and fast recovery from the effect of disturbance with minimal overshoot. A nonlinear PID controller was designed for TDS by Jin et al. [16]. As compared to conventional PID control, a nonlinear gain is incorporated in cascade with the integral action in the proposed nonlinear PID. In comparison with these classical tuning approaches, the genetic algorithm (GA) was used in this work to final the optimal parameters of the controller. Recently, Liu et al. [17] proposed an event-triggered adaptive fuzzy control (AFC) approach for stochastic nonlinear time-delay systems.

Each of the previous studies brought some improvements in the performance of the time delay system to some extent but searching for better performance has been an ongoing research. In the same direction with exploring the performance of combining the design of controller strategies with new swarm optimization techniques, this paper presents a comparative study between two control strategies (standalone proportional integral minus proportional derivative (PI-PD) and PI-PD with MSP) for TDS. The optimal value of the tuning parameter sets of the PI-PD controller for step reference tracking and disturbance rejection is obtained based on two swarm intelligence optimization techniques named flower pollination algorithm (FPA) and heap-based optimization (HBO). The cost function of the optimization is designed based on two objectives. The two objectives are reducing control effort and improving the response performance of the system.

The remainder of this paper is organized as follows: Section 2 describes time delay systems. The development of the proposed controller is given in section 3. Section 4 explains the two swam optimization techniques that are employed to tune the adjustable parameters of the PI-PD controller. The simulation results are discussed in section 5. Finally, the conclusion is summarized in section 6.

2. Time delay system

Engineering applications, such as network control systems, power systems, hydraulic systems, industrial production systems, and robotic systems, are inherent with delays in their dynamics [18]. Delays in the system are a challenging problem in control systems. Compared to systems without delay, the presence of delay is considered the main cause of oscillations, instability, and poor control performances [9, 19]. They can be in the forward (i.e. controller to actuator delay) or/and in the feedback (i.e. sensor to controller delay) of the

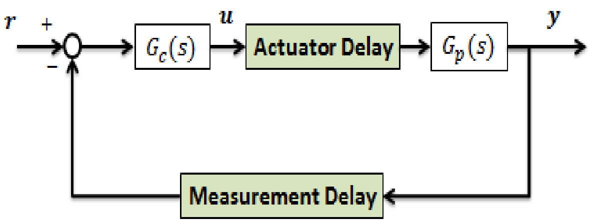

Figure. 1 Time delay system

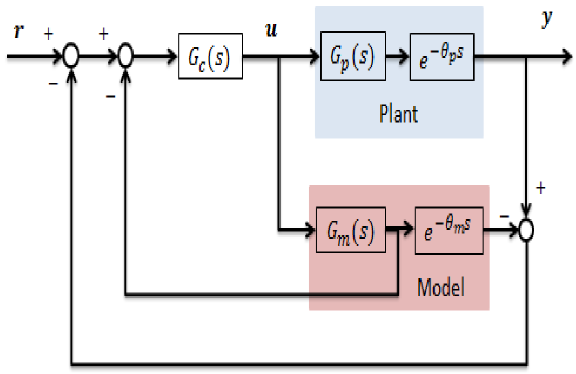

Figure. 2 Classical smith predictor

system as shown in Fig. 1 [1, 11]. The linear time-invariant (LTI) time-delay (TD) single-input single-output (SISO) systems subject to input disturbances can be described by [20]:

$$y(s) = G_P(s)e^{-hs}[u(s) + w(s)] \tag{1}$$

where $y(s)$ is the plant output, $G_P(s)$ is the free delay transfer function of the process, $u(s)$ is the control input, $w(s)$ is the input disturbance, h is the time delay.

In this paper, three systems with a time delay are considered. These systems represent a wide range of industrial applications. These systems are second, third, and fourth-order as given [1]:

$$G_1(s) = \frac{e^{-4s}}{s^2+2s+1} \tag{2}$$

$$G_2(s) = \frac{e^{-5s}}{(s+1)^3} \tag{3}$$

$$G_3(s) = \frac{e^{-5s}}{(s+1)(0.25s+1)(0.125s+1)} \tag{4}$$

3. Controller design

Various control strategies have been proposed to deal with TDS. Among them, the smith predictor (SP) is considered the most popular control scheme to deal with TDS [10]. The original form of SP has been modified to a different structure. In this paper, the modified SP (MSP) that is proposed in [21] is adopted with two proportional controllers. Besides, the PI-PD controller is used as the main controller of the overall control system. The following two subsections explain the two controllers.

3.1 Modified smith predictor

The classical Smith predictor shown in Fig. 2 is a well-known compensator approach for TDS [13]. The close loop transfers function of the system in Fig. 1 is given by:

$$G(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-\theta_p s}}{1+G_c(s)\left(G_m(s)+G_p(s)e^{-\theta_p s}-G_m(s)e^{-\theta_m s}\right)} \quad (5)$$

where:

$G(s)$	Close loop transfer function of the system
$Y(s)$	Output of the system
$R(s)$	Input to the system
$G_p(s)e^{-\theta_p s}$	Plant transfer function
$G_m(s)e^{-\theta_m s}$	Model of the plant
$G_c(s)$	Controller

Based on the assumption that the model of the system $G_m(s)e^{-\theta_m s}$ is matched with the actual system $G_p(s)e^{-\theta_p s}$, the close loop transfer function that is given by Eq. (5) becomes:

$$G(s) = \frac{G_c(s)G_p(s)e^{-\theta_p s}}{1+G_c(s)G_m(s)} \quad (6)$$

It can be notice from Eq. (6) that the main advantage of the Smith predictor approach is that the time delay is eliminated from the characteristic equation of the closed loop system. Therefore, the design of the controller $G_c(s)$ can be based on the model of the plant without the time delay [9]. However, it is often difficult to have an accurate model of the industrial process. This leads to a mismatch between the model of the system and the actual system. Besides, the system is often subject to disturbance. For these circumstances, the Smith predictor exhibits poor performance [11, 15]. To overcome these limitations of the classical Smith predictor, Majhi and Atherton [21] introduced a modified smith predictor (MSP) which has two more controllers ($G_{c1}(s)$ and $G_{c2}(s)$) associated with the main controller $G_c(s)$ of the system as shown in Fig. 3.

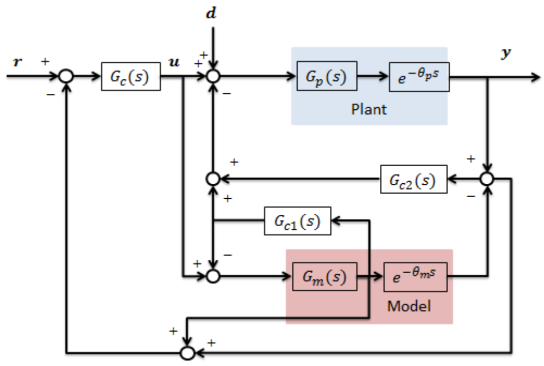

Figure. 3 Modified smith predictor

The $G_{c1}(s)$ controller modifies the pole's location of the transfer function, whereas the controller $G_{c2}(s)$ is used for tracking a set point. If the two controllers are set to zero ($G_{c1}(s)$=$G_{c2}(s)$=0), the control structure is returned to the classical smith predictor.

It can be noticed that the MSP has a complicated structure. For this reason, the two controllers ($G_{c1}(s)$and $G_{c2}(s)$) in this paper are selected to be proportional controllers. Besides, the main controller $G_c(s)$of the control system is selected to be the PI-PD controller and it will be explained in the next subsection.

3.2 PI-PD controller

The proportional plus integral plus derivative (PID) controller is the most common control scheme that is used in a control system due to its simplicity and robustness [22, 23]. A proportional integral minus proportional derivative (PI-PD) controller is a modified structure of the PID controller. The block diagram of the PI-PD controller is shown in Fig. 4 [24, 25]. The first part of the controller is the PI. The proportional term of the PI part of the controller changes the control signal proportionally to the error. The integral term of the PI part of the controller changes the control signal proportionally to the integration of the error. On the other hand, the second part of the controller is the PD. The proportional term of the PD part of the controller changes the control signal proportionally to the output. In the same way, the derivative term of the PD part of the controller changes the control signal proportionally to the derivative of the output. The control law u of the PI-PD controller is given by [26]:

$$u = K_{p1}e + K_i \int e - K_{P2}\, y - K_d \frac{dy}{dt} \quad (7)$$

where:

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e	Error
K_{p1}, K_{P2}	Proportional gains
K_i	Integral gain
K_d	Derivative gain

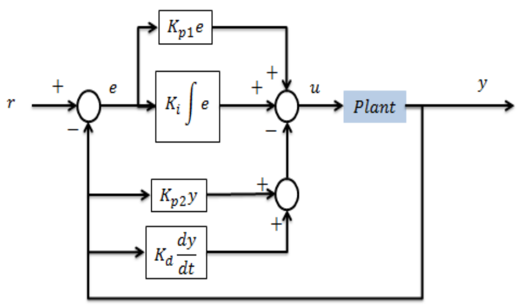

Figure. 4 Block diagram of the PI-PD controller

4. Swarm optimization technique

Several methods have been adopted in the literature to tune the design variables of various structures of the PID controller, among them, the PI-PD controller. The most popular adopted methods are the swarm optimization techniques. These algorithms are population-based methods. Besides, these methods are well known for their simplicity of implementation, handling of multi-dimensional problems, and robustness [27, 28]. In this paper, two swarm optimization techniques named flower pollination algorithm (FPA) and heap-based optimization (HBO) are proposed to find the optimal value of the adjustable gains of the PI-PD controller. In the next two subsections, the explanation of the two methods is given.

4.1 Flower pollination algorithm

The flower pollination algorithm (FPA) is a swarm-based optimization algorithm introduced by [29] inspired by the pollination phenomena in the flower [29]. The basic concept of pollination is the transformation of the pollen from the male into the female. This process can occur in two ways which are biotic and abiotic. The pollinator in the biotic process could be performed by the animal and/or the insect. On the other hand, the pollinator in the abiotic process could happen based on the wind and/or the water [30, 31]. Yang [29] simulates this behavior of the pollination as a search algorithm to find the optimal solution of an optimization problem. The pseudo-code of the FPA is shown in Fig. 5. As most of the swarm optimization, the FPA starts by initializing a population of n of nests as candidate solutions within the search range of the problem as given in Eq. (8).

1. Input

- ✓ Objective function, Population size (N), Switch probability (p_a), Number of iteration (T_{max})

2. Initialization

- ✓ Initialize population N flowers based on Eq. (8)
- ✓ Evaluate objective function
- ✓ Assign x_g

3. Loop:

- ✓ For t = 1:T
- ✓ For i = 1:N
- ✓ Select a random value r
- ✓ If $r < p_a$
  - ➢ Generate a step size (σ)
  - ➢ Generate a new solution based on Eq. (9) (global pollination)
- ✓ Else
  - ➢ Choose two solutions randomly among all solutions
  - ➢ Generate a new solution based on Eq. (10) (local pollination)
- ✓ Perform greedy selection and update x_g
- ✓ If $t < T_{max}$ go to Loop

4. Print the Optimal Solution

Figure. 5 Pseudo-code of the FPA

$$x_i = x_{lb} + rand * (x_{ub} - x_{lb}), i = 1,2, \dots, N \quad (8)$$

where:

i	Index of the population
N	Number of population
x_i	Individual solution
x_{lb}	The lower bound of the search space
x_{ub}	The upper bound of the search space
rand	Random value between [0,1]

The FPA algorithms have two ways of searching: local search and global search. In the global search, the algorithm exploits the area around the global best solution as given in Eq. (9). On the other hand, in the local search, the algorithm explores a new area randomly as given in Eq. (10). In order to achieve a balance between these two ways of searching, the FPA has a switching operator p_a.

In the algorithm, a random value r between 0 and 1 is generated. If $r < p_a$, the algorithm executes a global search as given in Eq. (9), whereas if $r \geq p_a$, the algorithm executes a local search as given in

Eq. (10).

$$x_i(K+1) = x_i(k) + \sigma\left(x_g - x_i(k)\right), k = 1,2,\ldots, T_{max} \quad (9)$$

$$x_i(k+1) = x_i(k) + \varepsilon\left(x_j - x_q\right), k = 1,2,\ldots, T_{max} \quad (10)$$

where

K	Index of the iteration
T_{max}	Maximum number of iteration
$x_i(k)$	Current solution
$x_i(K+1)$	New solution
σ	Step size
x_g	The best position found by the population
ε	Random value between [0,1]
x_j, x_q	The position of two solutions selected randomly from the population

4.2 Heap-based optimization

Based on principle of the corporate rank hierarchy that used to organize a group of people to meet certain goals, Askari et al. [32] developed the Heap-based optimization. The algorithm is consisted of three ways of learning. The first way is based on the sharing of information between the subordinates and their immediate boss. The second way is based on the information that is shared within colleagues. The third way is based on the self-learning of the individual person [32]. The pseudo-code of the HBO is shown in Fig. 6.

Like FPA, HBO starts by initializing a population of n of workers as candidate solutions within the search range of the problem as given in Eq. (8). To simulate the first sharing of information between the subordinates and their immediate boss, each subordinates x_i in the k^{th} iteration is updated its position based on the position of the boss x_g as given in Eq. (11) [32, 33].

$$x_i(k+1) = x_g + \gamma\lambda|x_g - x_i(k)| \quad (11)$$

The parameter λ is computed as:

$$\lambda = 2r - 1 \quad (12)$$

where r is a random value between [0, 1].
The parameter γ is computed as:

$$\gamma = 2 - \frac{k}{T_{max}} \quad (13)$$

In terms of the cooperation between the subordinates,

1. Input

- ✓ Objective function, Population size (N), Number of iteration (T_{max})

2. Initialization

- ✓ Initialize population N workers based on Eq. (8)
- ✓ Evaluate objective function
- ✓ Assign x_g

3. Loop:

- ✓ For t = 1:T
- ✓ For i = 1:N
- ✓ Compute γ and λ based on Eq. (12) and Eq. (13) respectively
- ✓ Compute p_1, p_2 and p_3 based on Eq. (16), Eq. (17) and Eq. (18) respectively
- ✓ Generate a random value p between [0, 1]
- ✓ If $p \le p_1$
  - ➢ Generate a new solution based on Eq. (15) (self-learning)
- ✓ If $p > p_1$ and $p \le p_2$
  - ➢ Generate a new solution based on Eq. (11) (subordinates and boss learning)
- ✓ If $p > p_1$ and $p \le p_2$
  - ➢ Generate a new solution based on Eq. (14) (subordinates among them learning)
- ✓ Perform greedy selection and update x_g
- ✓ If $t < T_{max}$ go to Loop

4. Print the Optimal Solution

Figure. 6 Pseudo-code of the HBO

each subordinate x_i in the k^{th} iteration is updated its position based on the position of other subordinate x_j as given in Eq. (14) [31, 32].

$$x_i(k+1) = \begin{cases} x_i + \gamma\lambda\left|x_i - x_j\right|, \text{if: } f_{x_i} < f_{x_j} \\ x_j + \gamma\lambda\left|x_j - x_i\right|, \text{if: } f_{x_j} \le f_{x_i} \end{cases} \quad (14)$$

In terms of self-learning, as illustrated in Eq. (15), this phase is accomplished by maintaining the employee's prior position in the subsequent generation [32, 33].

$$x_i(k+1) = x_i(k) \quad (15)$$

To achieve a balance in the exploitation and exploration capabilities of the HBO, it is required to ensure the best trade-off between choosing the way of updating the position of each agent in the population. To achieve the best trade-off between them, the concept of the roulette wheel with three proportions: the parameters p_1, p_2 and p_3 are used. In the algorithm, a random value p between [0, 1] is generated. Based on the value of p, if $p \leq p_1$, the agent of the algorithm update its position based on Eq. (15), if $p > p_1$ and $p \leq p_2$, the agent of the algorithm update its position based on Eq. (11) and if $p > p_2$ and $p \leq p_3$, the agent of the algorithm update its position based on Eq. (14). The parameters p_1, p_2 and p_3 are computed using the formulas in Eqs. (16), (17), and (18), respectively.

$$p_1 = 1 - \frac{k}{T_m} \tag{16}$$

$$p_2 = p_1 + \frac{1-p_1}{2} \tag{17}$$

$$p_3 = p_2 + \frac{1-p_1}{2} = 1 \tag{18}$$

5. Results and discussions

In this section, the simulations of controlling the TSD using the two control structures, standalone PI-PD controller and PI-PD controller with MSP, are presented. MATLAB software is used to conduct simulations and evaluate the performance. The objective of the controller is to make the system follow a unit step input. In addition, to evaluate the proposed controller in terms of disturbance rejection, it is assumed that the system is subjected to a small step input disturbance. Moreover, to ensure the robustness of the proposed controller, the variation of the time delay is also considered.

The performance of the PI-PD controller is optimized by tuning the adjusted parameters K_{p1}, K_i, K_d and K_{p2} of the control law that is given in Eq. (7) using two swarm optimizations (FPA and HBO). The cost function of the optimization is built based on the two objectives. The first objective F_1 is to reduce the error between the desired output and the actual output. The integral of absolute errors (IAE) as given in Eq. (19) [34] is used for the first objective.

$$F_1 = IAE = \int_{t=0}^{t_{sim}} |e(t)|dt \tag{19}$$

where t_{sim} is the simulation time and $e(t)$ refers to the error between the desired output and the actual output. The second objective F_2 is to reduce the control signal effort as given in Eq. (20)

$$F_2 = \int_{t=0}^{t_{sim}} |u(t)|dt \tag{20}$$

Table 1. Algorithm parameters of CSO and ICSO

Parameters	Values	
	FPA	HBO
Population Size (N)	25	25
Number of Iterations (T_{max})	30	30
Probability (β)	0.25	-
Step size (σ)	1	-

Table 2. Set of controller's parameters for the PI-PD controller based on FPA and HBO for the second-order system

PI-PD Parameters	FPA	HBO
K_{p1}	5.3	6.4
K_i	0.43	0.8
K_d	12.8	18.86
K_{p2}	1.3	0.9

where $u(t)$ refers to the control signal. As a result, the cost function F is given by:

$$F = \omega_1 F_1 + \omega_2 F_2 \tag{21}$$

where ω_1 and ω_2 are used as a weight to justify between the two objectives. The parameters of the FPA and HBO are listed in Table 1. In the next subsections, the simulation results of each process are illustrated.

5.1 Second order

In this subsection, the simulation results regarding to the second-order system that is given in Eq. (2) are presented. The values of the designed gains K_{p1}, K_i, K_d and K_{p2} of the PI-PD controller based on FPA and HBO tuning methods are given in Table 2. The convergence of HBO and FPA is shown in Fig. 7. Fig. 8 shows the output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on FPA. Fig. 9 shows the output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on HBO. Fig. 10 shows the output response and control signal for the MSP-PI-PD controller based on HBO and FPA.

In terms of controller structure, it can be seen from Figs. 8 and 9 that if the standalone PI-PD controller is used, the output response has an oscillation and overshoot. When the MSP is added, the output response improves and becomes smooth.

In terms of the tuning method, Fig. 7 shows that HBO has better convergence towards the minimum

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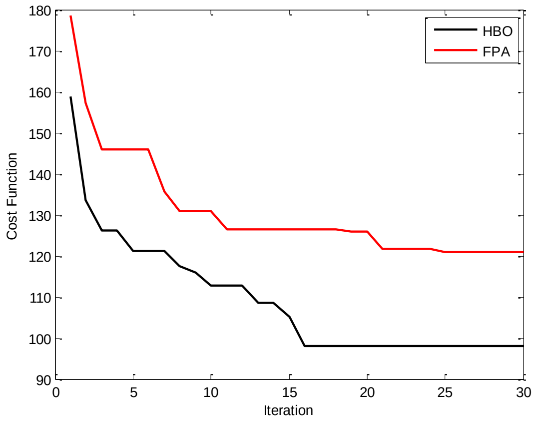

Figure. 7 Convergence of HBO and FPA for the second order system

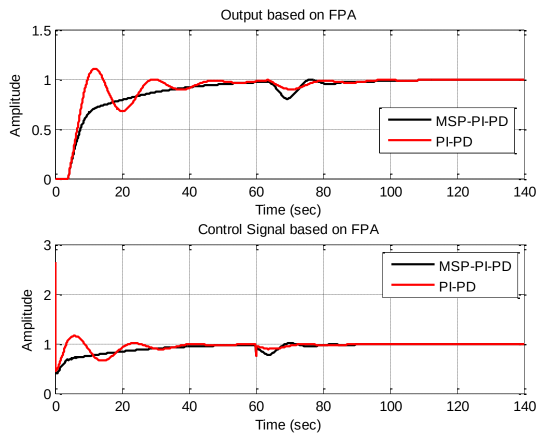

Figure. 8 Output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on FPA for the second-order system

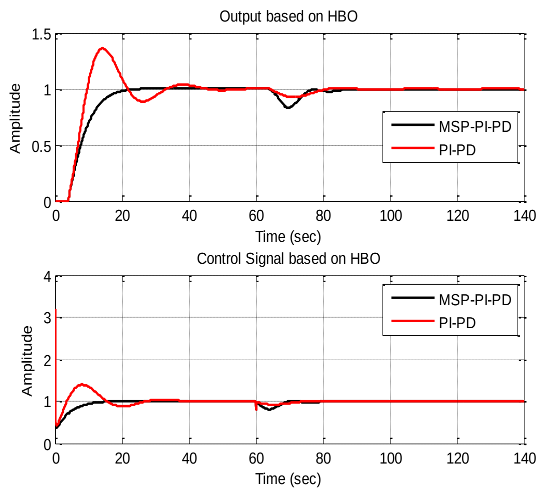

Figure. 9 Output response and the control signal for the MSP-PI-PD and the standalone PI-PD controllers based on HBO for the second-order system

cost function than FPA. This improvement can also be seen in Fig. 10. Fig. 10 shows that the output

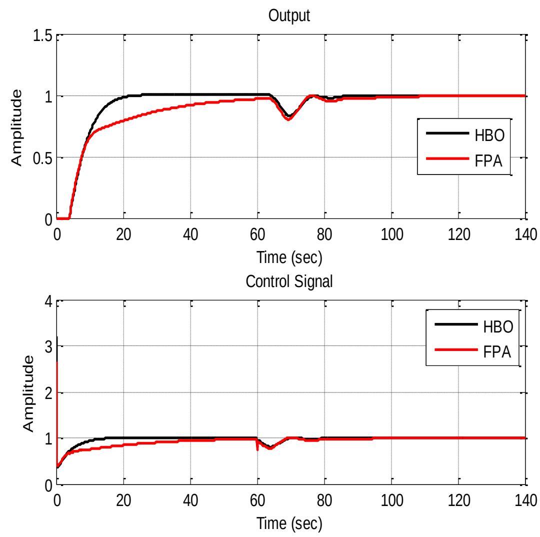

Figure. 10 Output response and the control signal for the MSP-PI-PD controller based on HBO and FPA for the second-order system

Table 3. Performance index comparison for the second-order system

Index	FPA		HBO	
	PI-PD	PI-PD +MSP	PI-PD	PI-PD +MSP
F	124.426	120.81	122.423	98.113

response of the PI-PD controller tuned by the HBO with MSP has better response than the output response of the PI-PD controller tuned by the FPA with MSP. Moreover, Table 3 shows the cost function for both objectives (control signal and output response) for the PI-PD tuned by HBO with MSP has less value than others.

The performance index reduces form 124.426 in the case of PI-PD tuned by FPA, 122.423 in the case of PI-PD tuned by HBO, 120.81 in the case of MSP-PI-PD tuned by FPA to 98.113 in the case of MSP-PI-PD tuned by HBO.

These results reveal that the PI-PD controller tuned by the HBO with MSP can achieve better performance for second-order varying time delay systems subject to disturbance.

5.2 Third order

In this subsection, the simulation results regarding to the third-order system that is given in Eq. 3 are presented. The values of the designed gains K_{p1}, K_i, K_d and K_{p2} of the PI-PD based on FPA and HBO tuning methods are given in Table 4. The convergence of HBO and FPA is shown in Fig. 11.

Fig. 12 shows the output response and control

Table 4. Set of controller's parameters for PI-PD controller based on FPA and HBO for the third-order system

PI-PD Parameters	FPA	HBO
K_{p1}	5.2	6.8
K_i	0.3	0.54
K_d	14.7	19.4
K_{p2}	0.8	1.2

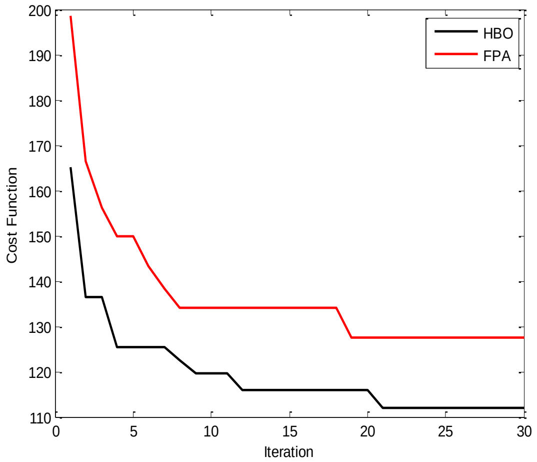

Figure. 11 Convergence of HBO and FPA for third order system

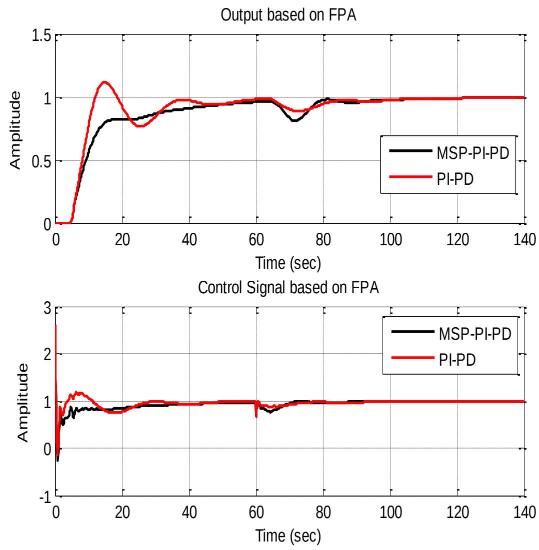

Figure. 12 Output response and control signal for MSP-PI-PD and PI-PD controllers based on FPA for third order system

signal for the MSP-PI-PD and the standalone PI-PD controllers based on FPA. Fig. 13 shows the output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on HBO. Fig. 14 shows the output response and control signal for the MSP-PI-PD controller based on HBO and FPA.

In terms of controller structure, similar to the second order, it can be seen from Figs. (12) and (13) that if the standalone PI-PD controller is used, the output response has an oscillation and overshoot. When the MSP is added, the output response is improved and becomes smooth. In terms of the tuning method, it can be seen from Fig. (11) that HBO has better convergence towards the minimum cost function than FPA. This improvement can also be seen in Fig. (14). Fig. (14) shows that the output response of the PI-PD controller tuned by the HBO with MSP has a better response than the output response of the PI-PD controller tuned by the FPA with MSP. Moreover, Table (5) shows the cost function for both objectives (control signal and output response) of the PI-PD controller tuned by the HBO with MSP has less value than others.

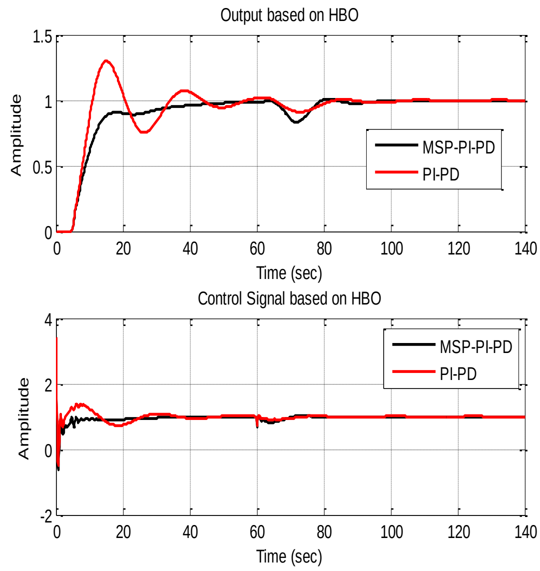

Figure. 13 Output response and control signal for MSP-PI-PD and PI-PD controllers based on HBO for third order system

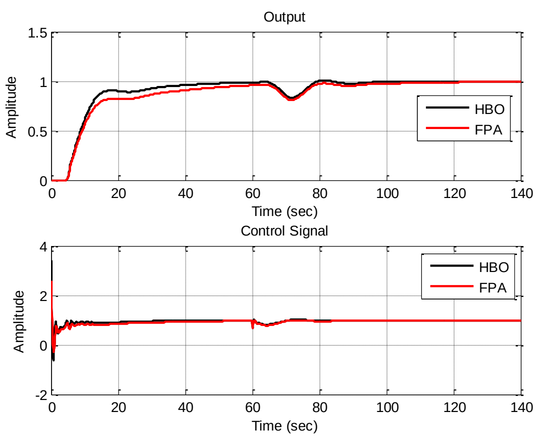

Figure. 14 Output response and control signal for MSP-PI-PD controller based on HBO and FPA for third order system

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Table 5. Performance index comparison for the third order system

Index	FPA		HBO	
	PI-PD	MSP-PI-PD	PI-PD	MSP-PI-PD
F	134	127.54	132.777	112.089

The performance index reduces form 134 in the case of PI-PD tuned by FPA, 132.777 in the case of PI-PD tuned by HBO, 127.54 in the case of PI-PD +MSP tuned by FPA to 112.089 in the case of PI-PD +MSP tuned by HBO.

These results reveal that the PI-PD tuned by the HBO with MSP can achieve better performance for third order varying time delay system subject to disturbance.

5.3 Fourth order

In this subsection, the simulation results regarding to the fourth order system that is given in Eq. (4) are presented. The values of the designed gains K_{p1}, K_i, K_d and K_{p2} of the PI-PD controller based on FPA and HBO tuning methods are given in Table 6. The convergence of HBO and FPA is shown in Fig. 15.

Table 6. Set of controller's parameters for PI-PD controller based on FPA and HBO for the fourth order system

PI-PD Parameters	FPA	HBO
K_{p1}	2.8	1.3
K_i	0.25	0.33
K_d	4.7	3.5
K_{p2}	0.3	0.1

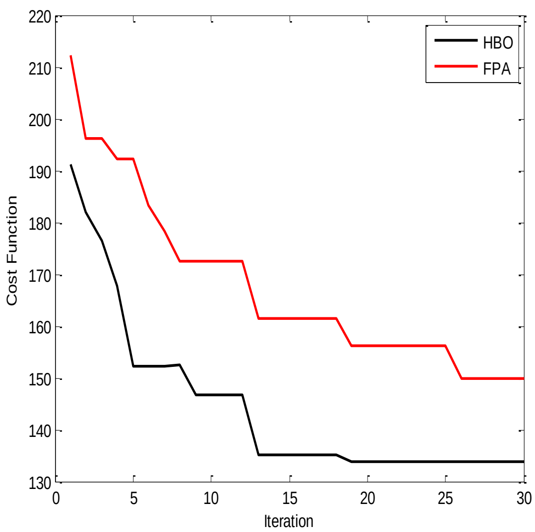

Figure. 15 Convergence of HBO and FPA for fourth order system

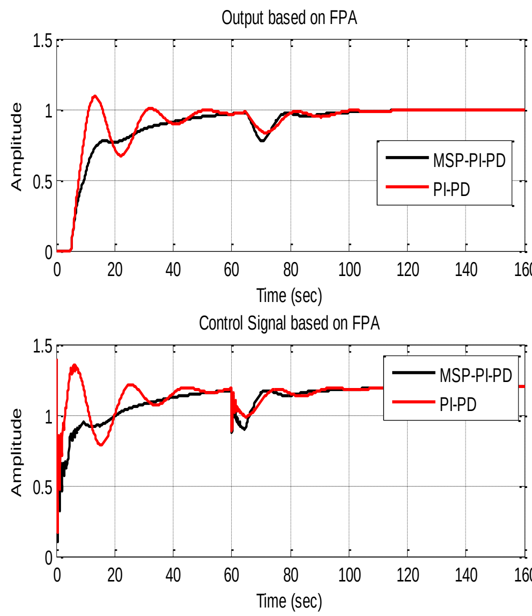

Figure. 16 Output response and control signal for MSP-PI-PD and PI-PD controllers based on FPA for fourth order system

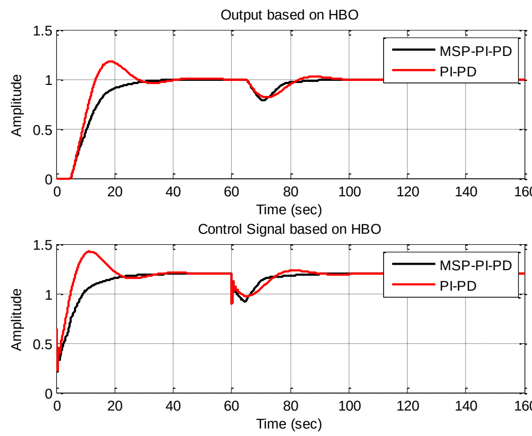

Figure. 17 Output response and control signal for MSP-PI-PD and PI-PD controllers based on HBO for fourth order system

Fig. 16 shows the output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on FPA. Fig. 17 shows the output response and control signal for the MSP-PI-PD and the standalone PI-PD controllers based on HBO. Fig. 18 shows the output response and control signal for the MSP-PI-PD controller based on HBO and FPA.

In terms of controller structure, it can be seen from Figs. 16 and 17 that if the standalone PI-PD controller is used, the output response has an oscillation and overshoot. When the MSP is added, the output response becomes smooth.

In terms of the tuning method, Fig. 5 shows that HBO has better convergence towards the minimum cost function than FPA. This improvement can be

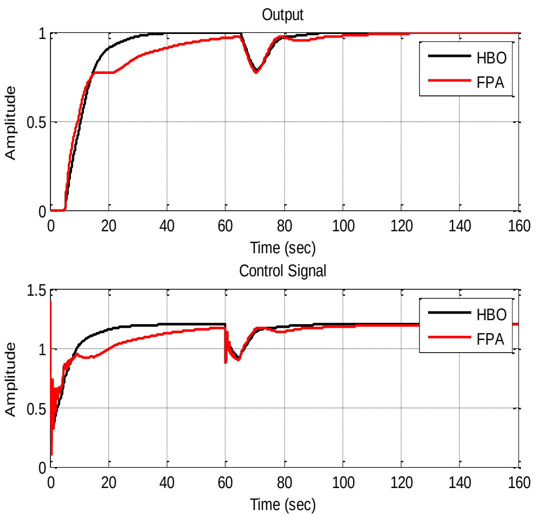

Figure. 18 Output response and control signal for MSP-PI-PD controller based on HBO and FPA for fourth order system

Table 7. Performance index comparison for the fourth order system

Index	FPA		HBO	
	PI-PD	PI-PD +MSP	PI-PD	PI-PD +MSP
F	158.962	150	154.669	133.805

seen in Fig. 18. Fig. 18 shows that the output response of the PI-PD controller tuned by the HBO with MSP has a better response than the output response of the PI-PD controller tuned by the FPA with MSP. Moreover, Table 7 shows the cost function for both objectives (control signal and output response) of the PI-PD controller tuned by the HBO with MSP has less value than others.

The performance index reduces form 158.962 in the case of PI-PD tuned by FPA, 154.669 in the case of PI-PD tuned by HBO, 150 in the case of PI-PD +MSP tuned by FPA to 133.805 in the case of PI-PD +MSP tuned by HBO for the fourth order system.

These results reveal that the PI-PD tuned by the HBO with MSP can achieve better performance for fourth order varying time delay system subject to disturbance.

6. Conclusion

In this paper, the problem of designing an intelligence controller for varying time delay systems is addressed. Two controller structures, standalone PI-PD controller and MSP+PI-PD controller, are proposed. The objective of the controller is to make the system follows a unit step input and disturbance rejection. The optimal value of the tuning parameter sets of the PI-PD controller is formulated as an optimization problem. The cost function of the optimization is constructed by taking into account two objectives. The first objective is to improve the output response of the system and the second is to reduce the control effort. Three-time delay processes are used to evaluate the proposed controller. In terms of controller structure, the simulation results reveal that the PI-PD controller with MSP approach improves the performance response by eliminating the oscillation of the system compared to the standalone PI-PD controller. In terms of tuning process, both swarm intelligence optimization techniques are found to be effective in finding the parameters of the PI-PD controller. However, the HBO shows better capability in comparison with the FPA for tuning the adjustable parameters of the PI-PD controller in terms of improving time response performance and reducing the cost function.

It was found that for second order process, the performance index reduces form 124.426 in the case of PI-PD tuned by FPA, 122.423 in the case of PI-PD tuned by HBO, 120.81 in the case of MSP-PI-PD tuned by FPA to 98.113 in the case of MSP-PI-PD tuned by HBO.

In terms of third order, the performance index reduces form 134 in the case of PI-PD tuned by FPA, 132.777 in the case of PI-PD tuned by HBO, 127.54 in the case of MSP-PI-PD tuned by FPA to 112.089 in the case of MSP-PI-PD tuned by HBO.

Lastly, the performance index reduces form 158.962 in the case of PI-PD tuned by FPA, 154.669 in the case of PI-PD tuned by HBO, 150 in the case of MSP-PI-PD tuned by FPA to 133.805 in the case of MSP-PI-PD tuned by HBO for the fourth order process.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Author contributions

Conceptualization: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; methodology: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; software: Attarid k. Ahmed; validation: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; formal analysis: Attarid k. Ahmed; investigation: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; resources: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; data curation: Attarid k. Ahmed; writing-original draft preparation Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; writing-review and editing: Attarid k. Ahmed, Huthaifa Al-Khazraji and Safanah M. Raafat; visualization: Attarid k. Ahmed; supervision: Huthaifa Al-Khazraji and Safanah M. Raafat; project administration: Huthaifa Al-Khazraji and Safanah M. Raafat and Attarid k. Ahmed.

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