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Fractional-Order PID Controller Based on Immune Feedback Mechanism for Time-Delay Systems

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Abstract: The control of processes with time delays is crucial in process industries such as petrochemical, hydraulic, and manufacturing. It is a challenging task for automation engineers, as it may affect both phase and gain margins. In this case, a robust control system is preferred. This article presents a novel controller structure combining computational intelligence (CI) and fractional-order control. A fractional-order PID (FOPID) controller based on a bio-inspired immune feedback mechanism (IFM) is developed for controlling processes described as first-order plus time-delay systems (FOPTD). A genetic algorithm (GA) is used to optimize the controller parameters. Fractional-order control has been used to give extra flexibilities and an immune feedback mechanism for its self-adaptability. Numerical simulations are presented to validate the proposed control strategy in terms of reference tracking and disturbance rejection. Comparative simulation results with an immune integer-order PID controller are also included to demonstrate the efficiency of the proposed fractional-order method.

Keywords: fractional-order PID; immune feedback mechanism; genetic algorithm; time-delay system

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1. Introduction

The control of time-delay systems is a key aspect in industrial applications, such as remote control, high-speed network communications, distillation units, and so on. Regarding process control technology, time delay is used to reflect systems with aftereffects, time lags, or to approximate higher-order systems. Quite frequently, FOPTD models are used to approximate the dynamics of nonlinear and complex systems. Due to unmodeled dynamics, the control of such systems can be challenging and robustness is usually sought.

The most widely used controller in the process industry, including those that exhibit FOPDT dynamics, is the classical PID controller. To determine the parameters of the controller, simple approaches such as the Ziegler–Nichols or Cohen–Coon tuning rules are used [1,2]. The PID controller is the staple industrial controller due to its well-known characteristics such as simplicity in the design, giving the possibility to adjust the dynamics of the control system, the availability of numerous model-based tuning techniques, and easy implementation. Overall, these controllers provide an excellent cost/benefit ratio, which makes the PID the first choice for automation engineers in the industry. Nevertheless, the performance of a PID is limited, especially when modeling errors occur. To ensure the robustness of the control algorithm, various techniques can be used.

In this paper, a novel approach is considered that combines fractional calculus and immune feedback systems. Fractional calculus has gained a lot of attention and became a powerful mathematical tool in science and engineering, since many dynamic systems are properly described by fractional-order (FO) dynamics [3–5]. Fractional calculus is a generalization of the classical integer-order calculus and consists of integro-differential operators of non-integer orders [6]. Researchers have proven that FO controllers can replace their integer-order counterparts [7,8]. This has led to a significant number of studies regarding the design and analysis of these controllers [9]. The only disadvantage of such controllers consists in the need to approximate their dynamics for implementation purposes. In control practice, the fractional-order controllers are approximated to integer-order transfer functions of high orders. Various techniques can then be used to lessen the order of the approximation [10].

Several studies presented in the literature attempted to find an optimum setting for the fractional controller parameters that meet the design requirements [11–16]. Modern optimization search techniques called "evolutionary algorithms", including the genetic algorithm (GA) and the particle swarm optimization (PSO), have been extensively applied to enhance the performance of fractional-order controllers [17,18]. Numerous tools have also been proposed for fractional-order system analysis, modeling, and controller synthesis. Several tools have been developed to enable the design and analysis of fractional-order control systems, mainly in MATLAB, such as the Ninteger toolbox [19] and Fomcon toolbox [20], to name just a few. However, the hardware realization of FOPID controllers is more challenging.

The improved performance and increased robustness of fractional-order controllers is enhanced in this paper through the use of artificial immune systems, which represent a nature-inspired mechanism. Due to their adaptive and self-organized features, artificial immune systems are considered to be powerful techniques for controlling a wide range of systems, including non-linear or time-delayed ones [21–23]. This artificial intelligence control is a promising technique that can be associated with other control laws such as fractional-order control.

In the literature, researchers proposed different techniques to control time-delay systems [24–26], including those using fractional-order controllers (FOC) [27–31]. A lot of tuning methods have been developed for FOC for time-delay systems, some of them based on the classical closed loop system, which require a process model, such as Ziegler–Nichols-based methods [32], Hermite–Biehler and Pontryagin theorems in [33], using linear programming formulation [34], techniques based on a frequency-domain approach [35,36], and others based on optimizing a certain performance index such as Integral of Square Error (ISE) and Integral of Time Absolute Error (ITAE) [37,38]. Another type of tuning of FOC for time-delay systems is based on Internal Model Control (IMC) approach [39,40] and Smith Predictor control [41–44]. Several control algorithms that combine fractional calculus and advanced control strategies [45–48] have been also developed.

In this paper, a significant contribution that has not yet been reported in the literature is presented that also combines advanced control algorithms with fractional calculus. A new controller structure is designed and the sensitivity analysis is performed. The new controller consists of a fractional-order PID (FOPID) based on an immune feedback system (IFM). This approach is novel to the state of the art. Both the FOPID and the IFM parameters are tuned by the genetic algorithms (GA). To demonstrate the performance of our proposed control technique, we applied it to control the FOPTD system.

This paper consists of six sections. Following the Introduction, Section 2 describes the fundamentals of FO controllers and briefly discusses their implementation. Section 3 presents the bio-inspired immune feedback controller. Section 4 focuses on the design of a new controller structure: the FOPID controller based on IFM. The simulation results are shown in Section 5, demonstrating the effectiveness of the proposed methodology. A comparative evaluation with other techniques is executed and presented there as well. Finally, in Section 6, the main conclusions of the paper are summarized, as well as further research ideas on the topic.

2. Fractional-Order PID Controller

2.1. Fractional-Order PID Control

The fractional-order PID (FOPID) controller is a generalization of the standard PID controller. The transfer function of a FOPID controller can be described in Laplace domain as [6]:

$$C_{FOPID} = \frac{U(s)}{E(s)} = K_p + K_i s^{-\lambda} + K_d s^{\mu}; (\lambda, \mu > 0) \tag{1}$$

The result in (1) can be used to determine the time-domain representation of the control signal of a FOPID:

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \tag{2}$$

where K_p, K_i, and K_d are the proportional, integral, and derivative gains, while λ and μ are the fractional orders of integration and differentiation, usually $\lambda, \mu \in (0, 2)$. Using (2), the block diagram of the FOPID can be derived as indicated in Figure 1. Because of the two supplementary tuning parameters, λ and μ, the FOPIDs have increased flexibility in the design and can be tuned to be more robust compared to their integer-order counterparts.

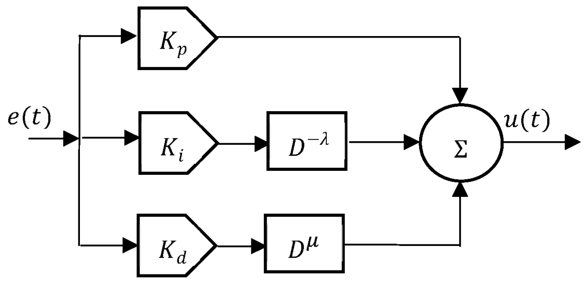

Figure 1. Block diagram of a fractional-order PID (FOPID) controller.

2.2. Integer-Order Approximations

The most common approach to implement fractional-order systems is to approximate them with usual (integer-order) transfer functions, possibly of high orders. Several approximation methods exist, among which the Oustaloup filter approximation for FO operator is the most popular [49]. The integer-order approximation takes the form of a ratio of two polynomials with subsequent poles and zeros. The approximation is accurate enough in a certain frequency range, which is selected a priori. Although popular among researchers, several other approximation methods have emerged, such as the Modified Oustaloup Filter method [50]. Continued Fraction Expansion (CFE) is also an available option for continuous-time approximations of the fractional-order operator. However, the user cannot specify the desired frequency range. The method provides accurate low frequencies approximation [51]. A similar method to the CFE is Matsuda's method. This is based on manipulating the approximated frequency points using logarithmically spaced set points [52]. Carlson's method uses Newton's iterative solution within a fixed frequency range, but other methods have been developed to allow the selection of the frequency range [53]. Some recent good review papers on the approximation of fractional-order PIDs are available [54,55].

2.3. Oustaloup's Recursive Approximation

In this manuscript, the Oustaloup recursive approximation method is used. The Oustaloup recursive approximation is a filter that produces good fitting of the fractional-order differentiator within a frequency range (w_b,w_h). It can be described mathematically using the following equation [56]:

$$G_f = K \prod_{k=-N}^{N} \frac{s + w_k'}{s + w_k} \tag{3}$$

where the poles, zeros, and gain of the filter can be evaluated from:

$$w_k^{'} = w_b \left(\frac{w_h}{w_b}\right)^{\frac{k+N+\frac{1}{2}(1-\gamma)}{2N+1}}, \ w_k = w_b \left(\frac{w_h}{w_b}\right)^{\frac{k+N+\frac{1}{2}(1-\gamma)}{2N+1}}, \ K = w_h^{\gamma} \tag{4}$$

where γ is the order of the differentiation of the differentiation, $2N + 1$ is the order of the filter, and the frequency fitting range is given by (w_b, w_h).

To implement the fractional-order PIDs designed in this paper, a frequency range of $\omega \in \{10^{-2}, 10^2\}$ rad/s was selected, with 4th order.

3. Immune Feedback Mechanism

Humans survive against illness and hostile environments thanks to natural IFM in the human system. However, the dynamic equilibrium of the immune system can be disrupted by an antigen. The fundamental cells that are concerned in the process of immunology are antigen Ag, antibodies Ab, B-cells B, helper T cells (T_h), and suppressor T cells (T_s).

Figure 2 shows the principle of the feedback mechanism. Once the antigen enters the body, it is identified by antigen-presenting cells (APC) then the information is transmitted to the T cells. In the wake of receiving the message, B cells are stimulated by T cells and promptly produce antibodies to wipe out the antigen. Once the number of antigens increases, the quantity of T_h cells will also increase and the human body can make more B cells to safeguard itself. Alongside the decrease in antigens, the number of T_s cells in the body increases and the number of B cells consequently reduces. After a while, the immune system tends to equilibrium.

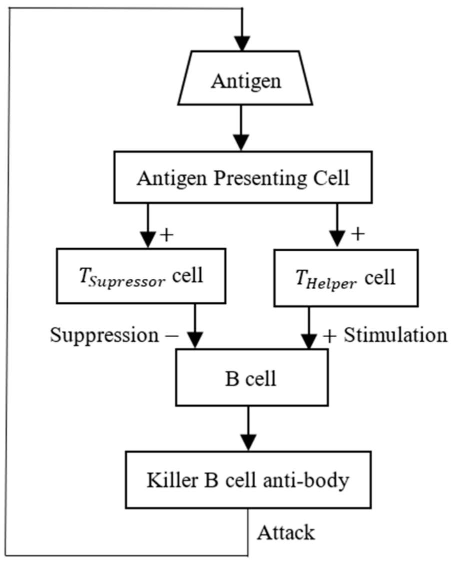

Figure 2. Immune-regulating system.

The immune feedback theory can be described by the following equations [21]:

$$B(k) = T_h(k) - T_s(k) \tag{5}$$

$$T_h(k) = k_1 \varepsilon(k) \tag{6}$$

$$T_s(k) = k_2\{f[\Delta B(k-d]\}\varepsilon(k) \tag{7}$$

where $\varepsilon(k)$ is the consistency of the antigen at the kth generation, k_1 is the stimulation factor, k_2 is the suppression factor, $\Delta B(k-d)$ is the change of B cells consistency, and d is the delay time of the immune response.

From (6) and (7), the relational expression for the consistency of B cells and the antigen is as follows:

$$
\begin{aligned}
B(k) &= k_1\varepsilon(k) - k_2\{f[\Delta B(k-d]\}\varepsilon(k) \\
&= k\{1-\eta f[\Delta B(k-d)]\}\varepsilon(k)
\end{aligned}
\tag{8}
$$

The control of the response speed is ensured by $k = k_1$ and the stabilization effect is controlled by $\eta = k_2/k_1$. Thus, the performance of the immune feedback methods rely heavily on how these factors are chosen.

A bio-inspired feedback mechanism controller of the immune system is developed in this paper. Table 1 shows the comparison between an immune system and the general control system.

Table 1. Immune system vs. control system.

Immune System	Control System
The k generation reproduction of antigens and antibodies.	The k sampling time of discrete system.
$Ag(k)$ is the antigen concentration of k generation.	$e(k)$ is the difference between setpoint value and output value at the k sampling time.
$B(k)$ is the B cell concentration of the k generation.	$\mu(k)$ is the output value of controller at the k sampling instant.

Equation (8) can be assumed as a discrete-time feedback control law. When this analogy is applied directly to design a feedback controller, the resulting immune feedback looks like a proportional controller with the gain adjusted using its own output. Therefore, the proportional IFM control method is as follows:

$$
\mu(k) = k\{1-nf[\Delta\mu(k-d)]\}e(k) = k_{pI}e(k) \tag{9}
$$

where $k_{pI} = k\{1-nf[\Delta\mu(k-d)]\}$ is the nonlinear proportional gain of the immune controller.

We assume that the change of T cells consistency based on the antigen entering to the body is described by the following nonlinear function [57]:

$$
f(x) = 1 - \frac{2}{1+\exp(-cx)} \tag{10}
$$

where $-1 < f(x) < 1$ and the value of parameter c determines the zone of action of variable x.

The immune feedback controller can be described as follows:

$$
u(k) = k\left[1 - n\left(1 - \frac{2}{1+\exp(-cx)}\right)\right]e(k) \tag{11}
$$

A list of the all symbols used in this section to ddetail the immune feedback mechanism is given in Table 2.

Table 2. Interpretation of immune system symbols.

Symbol	Interpretation in the Immune System
$\varepsilon(k)$	Amount of antigens at the kth generation
$T_h(k)$	Output from T_h stimulated by the antigens
$T_s(k)$	Effect of T_s on B cells
$B(k)$	Total stimulation of B cells
k_1	Stimulation factor
k_2	Suppression factor
$\eta = k_2/k_1$	Stabilization factor
$f(x)$	The effect of the reaction of B cells and the antigens

4. Design of Fractional-Order PID Controller Based on Immune Feedback Mechanism

4.1. Principle

As shown in (11), it is clear that the immune feedback controller is a nonlinear proportional controller. Since it cannot correct errors due to noise and nonlinear interference, it is not used alone. On the other hand, FOPID can comprehensively consider past, present, and future deviation information, having more degrees of freedom for the integral and derivative actions. Thus, it is possible to improve the performance of the control system by connecting the immune feedback controller with FOPID controller.

The algorithm is as follows:

$$U(k) \; = k_{pI}(k) \cdot C_{FOPID}(k) \cdot e(k) \tag{12}$$

where $k_{pI}(k)$ is the immune controller and C_{FOPID} is the transfer function of the FOPID, which can be expressed as indicated in (1).

FOPID based on IFM using GA is presented in Figure 3.

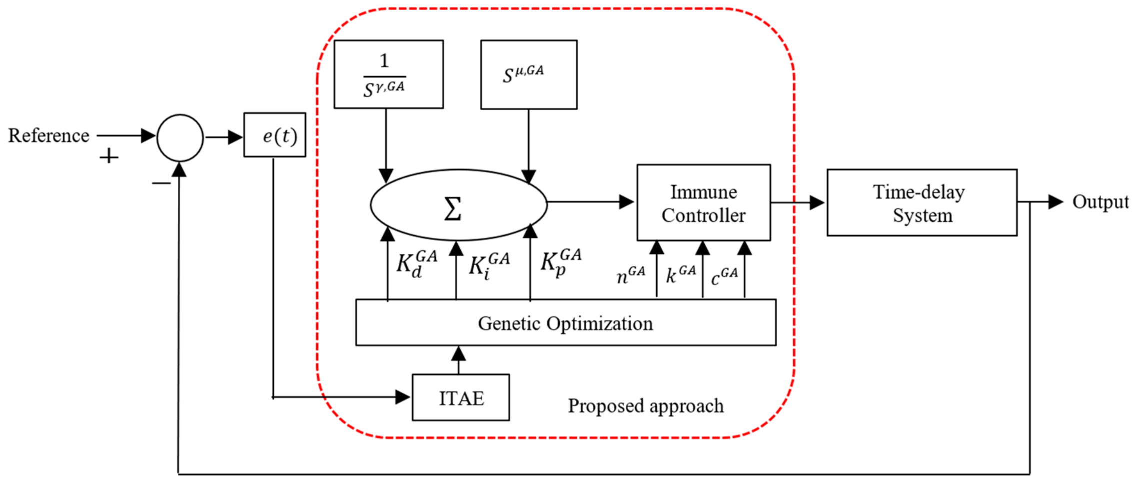

Figure 3. FOPID control based on immune feedback mechanism (IFM).

4.2. Tuning

The tuning of the parameters is a requirement for intelligent controllers, therefore FOPID based on IFM is tuned using GA.

GA is a method based on the evolution of chromosomes. High efficiency can be achieved by searching for the global optimal solution in the problem space. It does not suffer from the old optimization drawbacks, such as getting stuck in local minima.

First, the appropriate set of values for the FOPID and immune parameters is considered as the parent. Then, a crossover operation is performed between two appropriate values to obtain a new set of parameters. This is how first-generation offspring are formed. The total population will increase and selection operations will be performed on the population. Good chromosomes are preserved, while the worst chromosomes are excluded. Next, the chromosomes are evaluated using the Integral Time Absolute Error (ITAE) performance index. If the ITAE value is not satisfactory, a chromosomal crossover will be performed again between the best ones. The mutation process continues to achieve more optimal results until the ITAE value falls within the threshold. Optimal values are achieved by following the steps above for each GA cycle applied.

5. Simulation Results

The proposed control structure is validated on FOPTD processes. Many industrial systems can be approximated to such models. To demonstrate the efficiency of the proposed method, a comparison with an immune PID control algorithm is performed. Time-delay variations are challenging for control systems, since without a properly designed controller, the closed loop system can become unstable. Then, to evaluate the robustness of the proposed method, modeling uncertainties regarding time-delay variations are considered. Robustness is also tested considering time constant variations.

The transfer function of the process is given by:

$$P(s) = \frac{1}{2.5s + 1} e^{-1.8s} \tag{13}$$

To find a search space of the genetic algorithm and initialize the FOPID parameters, the classical Ziegler–Nichols (ZN) tuning method is applied, yielding the controller gains listed in Table 3.

Table 3. Initial PID parameters computed according to the ZN tuning rules.

K_p	K_i	K_d
1.7152	0.5848	1.2576

GA is then used for fine optimization, with ITAE used as the fitness function. The search space for the FOPID parameters is set between [0, 500] for the controller gains and [0, 1] for the fractional orders. The resulting FOPID controller is approximated using the Oustaloup recursive approximation method with $N = 4$ within $[10^{-2}, 10^2]$ rad/s. For the immune feedback mechanism, the parameters are as indicated next: the range of n (Steady gene) and c (Coefficient) is [0, 50], while the k (Immune gain) is [0, 200].

The optimal parameters obtained from GA are listed in Table 4 for the FOPID and Table 5 for the IFM. These were obtained after 10,660 function evaluations and 55 generations, resulting in the best function value of 14.13. A maximum number of 800 iterations was chosen for the GA.

Table 4. Optimal parameters of the FOPID for the first numerical example.

K_p	K_i	K_d	λ	μ
401.5	65.1	0.016	0.48	0.06

Table 5. Optimal parameters of the IFM for the first numerical example.

k	n	c
9.77×10^{-5}	0.0001	20.47

Figure 4 presents the results of the genetic algorithm. The upper plot shows the best and mean score of the fitness function at every generation. The lower plot shows the percentage of stop criteria that are met.

To evaluate the closed loop performance, a unit step reference signal is supplied at the input of the control system. The numerical simulation results obtained using the optimal FOPID with IFM are given in Figure 5. An immune PID controller was also designed and the closed loop results are also indicated in Figure 5. The comparative simulation results show that the proposed algorithm ensures a good settling time without overshoot and a zero steady state error. The FOPID with IFM achieves similar performance to the immune PID controller, with the latter achieving a faster settling time, but also exhibiting some small oscillatory dynamics. However, as indicated in Figure 6, the proposed algorithm requires less control effort compared to the immune PID controller, an important advantage of the FOPID. Comparisons of various time domain specifications obtained using the immune PID controller and the proposed control algorithm are given in Table 6.

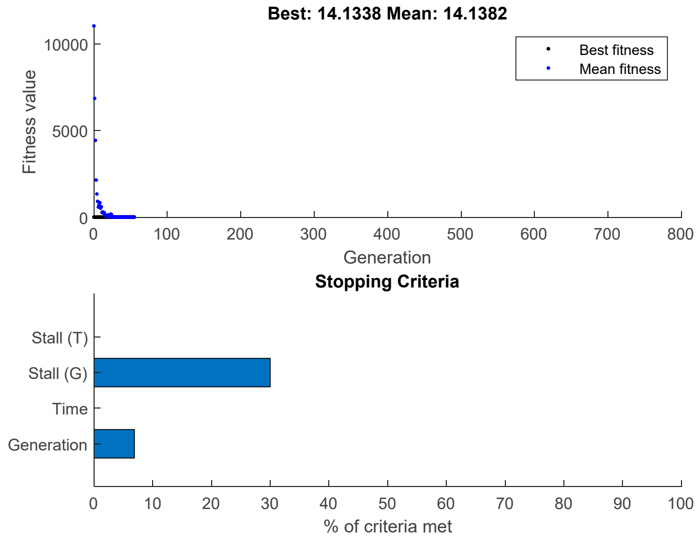

Figure 4. Results of the genetic algorithm for the first numerical example.

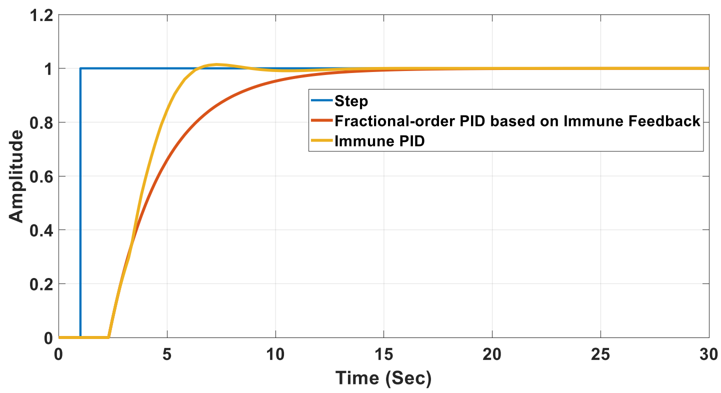

Figure 5. Step response of FOPID based on IFM vs. immune PID for the first numerical example.

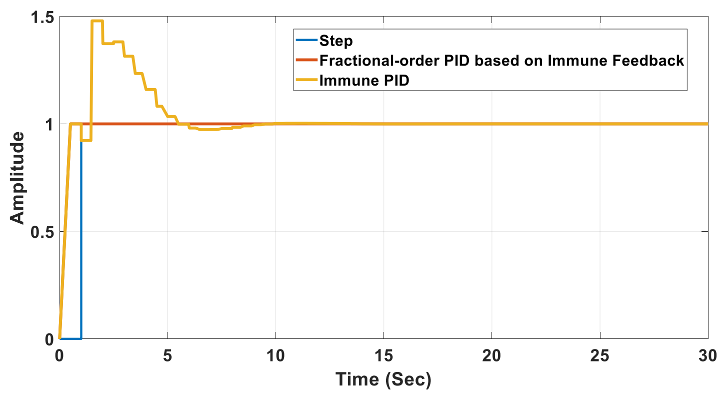

Figure 6. Control signal of FOPID based on IFM vs. immune PID for the first numerical example.

Table 6. Comparison of various time domain specifications.

Controller Used	Peak (%)	Settling Time (s)	Rise Time (s)	Steady State Error (%)
Immune PID	1.4	5.7	2.76	1
FOPID based on IFM	No overshoot	9.8	5.44	0

To test the robustness of the proposed control algorithm time constant variations of $\pm 20\%$ are considered and the results regarding setpoint tracking are indicated in Figure 7, while the corresponding control signals are given in Figure 8. The results demonstrate the efficiency of the proposed algorithm. The required control effort is significantly smaller compared to the immune PID controller. At the same time, there is no overshoot in the case of the proposed FOPID with IFM, in contrast to the immune PID. The drawback of the FOPID is its smaller settling time.

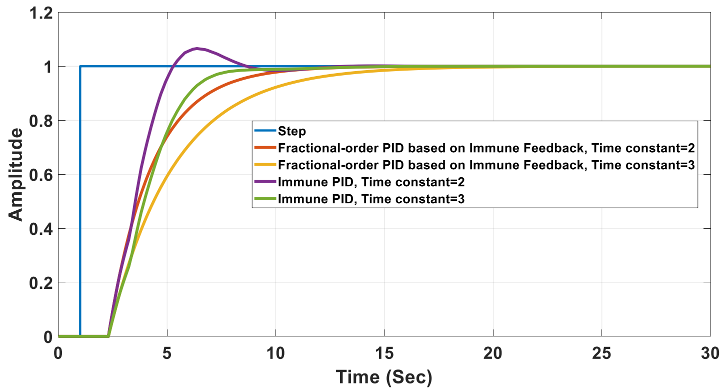

Figure 7. Reference tracking results for ±20% time constant variations for the first numerical example.

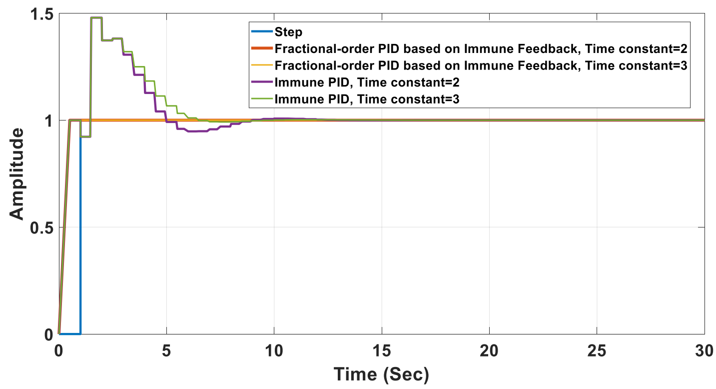

Figure 8. Control signal for ±20% time constant variations for the first numerical example.

Figure 9 shows the reference tracking results when considering −44%, as well as +122% time-delay variations. For −44% time-delay variations (time delay = 1 s), both control algorithms achieve zero overshoot and a similar settling time. In the case of the +122% variation, corresponding to a time delay of 4 s, the proposed FOPID with IFM ensures a faster settling time without any overshoot compared to the immune PID controller, where an overshoot of 17% is obtained. The corresponding control signals are indicated in Figure 10, with a smaller control effort required by the FOPID with IFM in comparison to the immune PID.

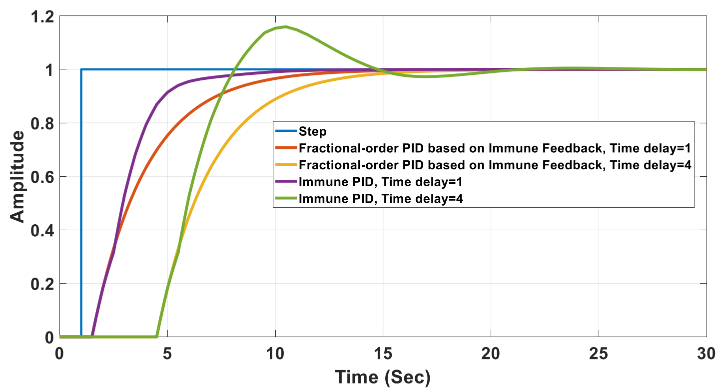

Figure 9. Reference tracking results for significant time-delay variations for the first numerical example.

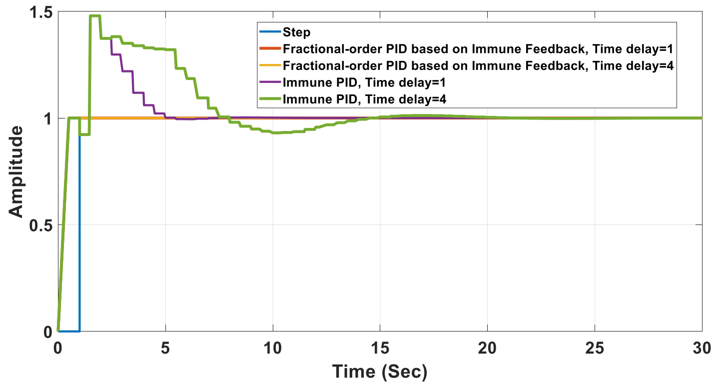

Figure 10. Control signal for significant time-delay variations for the first numerical example.

The immune PID controller exhibits increased oscillations and overshoot when increasing the time constant and time delay, whereas the FOPID based on the IFM controller reaches the desired setpoint with excellent results in terms of overshoot and rise time. The comparison of the control signals shows that the FOPID based on IFM has less effort in all cases than the immune PID controller. Consequently, overall, the FOPID based on IFM is more robust and exhibits superior performance.

To evaluate load disturbance rejection, an input disturbance of a random number with variance = 1 was applied at the process input. Figure 11 shows that the fractional-order based on IFM ensures a fast setting time when rejecting a random disturbance compared with the immune PID controller.

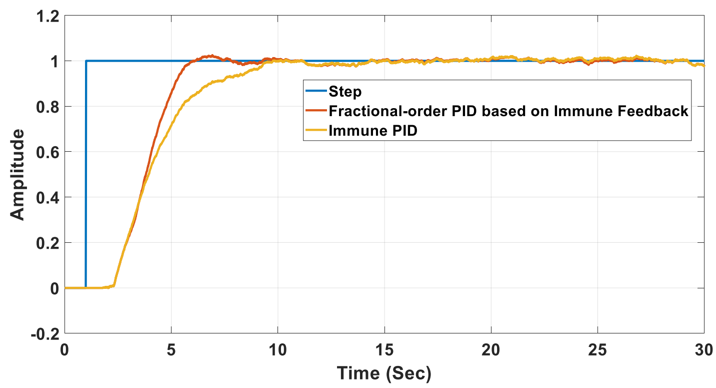

Figure 11. Load disturbance rejection using a random number for the first numerical example.

To study the strength of the new approach, a delay-dominant process was also considered, where the time delay is taken to be twice as much as the process time constant.

The transfer function of the process is given by:

$$P(s) = \frac{1}{2s+1}e^{-4s} \tag{14}$$

The optimal parameters obtained from GA are as listed in Table 7 for the FOPID and Table 8 for the IFM. These were obtained after 21,300 function evaluations and 111 generations, resulting in the best function value of 19.3689. A maximum number of 800 iterations was chosen for the GA.

Table 7. Optimal parameters of the FOPID for the second numerical example.

K_p	K_i	K_d	λ	μ
1.8257	0.0079346	3.1803	0.066297	0.99368

Table 8. Optimal parameters of the IFM for the second numerical example.

k	n	c
0.257	4.427	0.093956

Figure 12 shows the reference tracking results. The corresponding control signals are indicated in Figure 13. The proposed FOPID with IFM ensures similar closed loop performance compared to the immune PID. However, much like in the previous case, the FOPID with IFM requires less control effort in comparison to the immune PID. Comparisons of various time domain specifications obtained using the immune PID controller and the proposed control algorithm are given in Table 9.

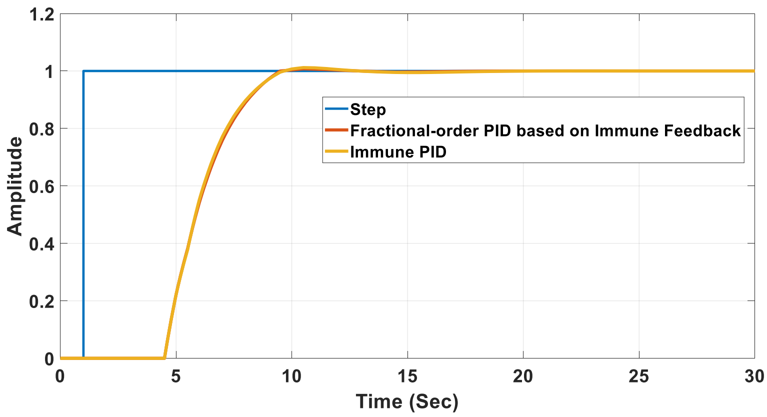

Figure 12. Step response of FOPID based on IFM vs. immune PID for the second numerical example.

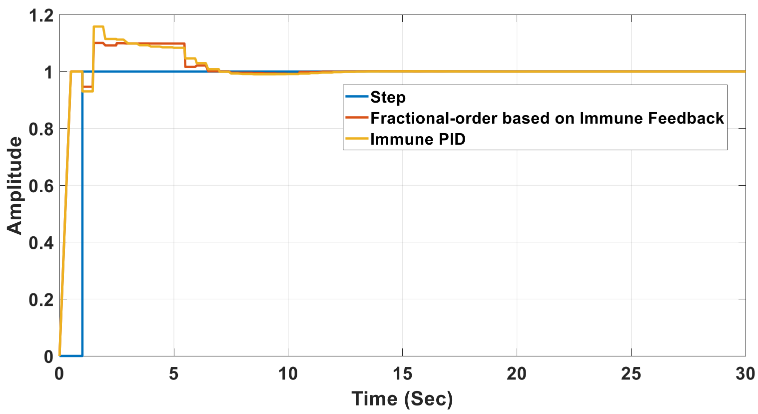

Figure 13. Control signal of FOPID based on IFM vs. immune PID for the second numerical example.

Table 9. Comparing various time domain specifications.

Controller Used	Peak (%)	Settling Time (s)	Rise Time (s)	Steady State Error (%)
Immune PID	No overshoot	8.6	8.0	0
FOPID based on IFM	No overshoot	8.6	8.0	0

The robustness to time-delay variations is tested in Figure 14, with corresponding control signals given in Figure 15. A ±50% time-delay variation was considered. The closed loop results show that similar performance is obtained with the proposed method compared to a traditional immune PID controller. Nonetheless, the required control effort is slightly smaller for the proposed FOPID with IFM in comparison to the immune PID, as indicated in Figure 15.

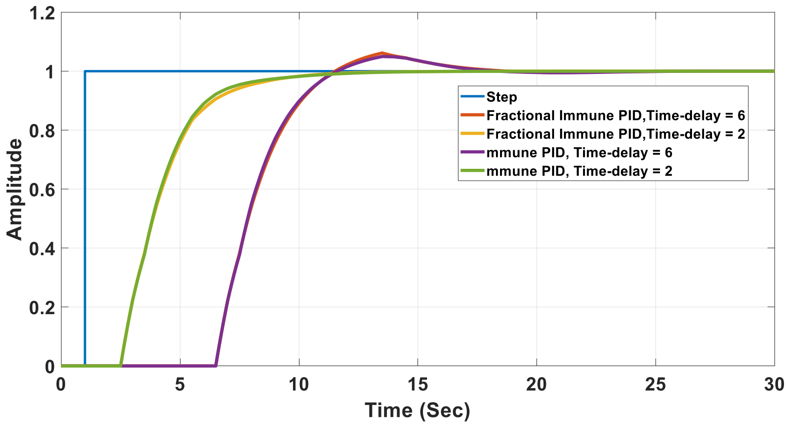

Figure 14. Reference tracking results for significant time-delay variations for the second numerical example.

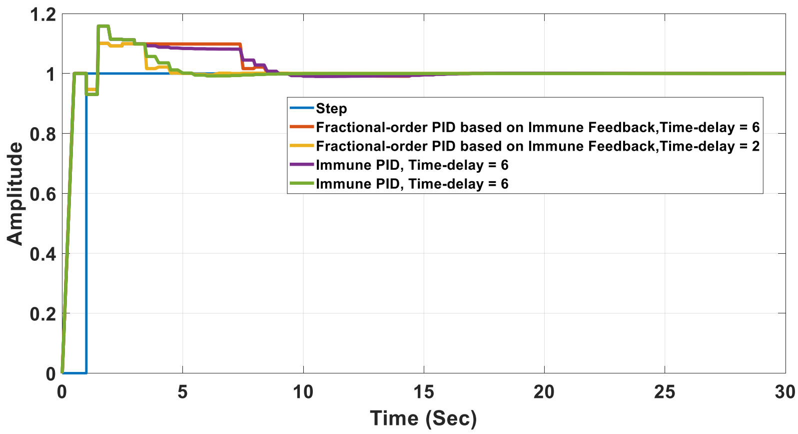

Figure 15. Control signal for significant time-delay variations for the second numerical example.

6. Conclusions

In this paper, a new control structure based on a FOPID controller and an IFM is developed. The proposed controller is validated on FOPDT processes, both lag- and delay-dominant ones, but could be easily extended to other types of processes. Numerical simulations have been presented to demonstrate the efficiency of the proposed controller. The robustness to delay variations was especially considered to showcase the advantages of the proposed algorithm. Comparative simulation results with an immune PID controller demonstrate the effectiveness of the proposed control algorithm, especially for lag-dominant processes. In this case, the proposed FOPID with IFM manages to achieve better robustness despite delay variations. In both situations, the required control effort is smaller compared to that of the immune PID controller, which also represents an advantage of the proposed method.

Several other delay- and lag-dominant processes have been tested and similar results as indicated in this manuscript have been obtained. Further research includes testing the proposed control algorithm on various other types of processes. At the same time, the tuning of the FOPID with IFM could be modified to use particle swarm optimization (PSO) and Cuckoo Search. An online adaptation rule is also considered as a further research possibility. Further research includes the experimental validation of the proposed algorithm.

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