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RESEARCH ARTICLE

Design of I-PD Controller Based Modified Smith Predictor for Processes With Inverse Response and Time Delay Using Equilibrium Optimizer

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ABSTRACT In the process control industry, it is arduous to control some integrating or unstable processes since they involve time delays and have an inverse response. Conventional controllers such as PID cannot provide sufficient control performance alone in the control of these systems. This article proposes a control algorithm based on an I-PD-based Smith predictor for the control of time-delayed integrating or unstable inverse processes. The controller parameters are tuned by using the Equilibrium optimizer (EO) algorithm, which is presented in the literature in 2020, in the proposed control approach. The EO algorithm aims to determine the optimal controller parameters by minimizing the error and control signal using a multi-objective function based on ITAE performance criterion. Thus, the controller parameters that will provide the set-point tracking and disturbance rejection control most properly can be determined. Simulation studies are conducted based on different process structures to evaluate the performance of the proposed method. The proposed method is compared with studies from the literature in terms of set-point tracking, parameter uncertainties, control signals, and disturbance rejection. It is seen that the transient responses and disturbance rejection of the time-delayed and inverse response integrating or unstable processes are improved with the proposed method.

INDEX TERMS Equilibrium optimizer algorithm, I-PD controller design, inverse response, non-minimum phase system, smith predictor, time delay systems.

I. INTRODUCTION

Process control methods have made remarkable advances in industry over the last few decades. The control of unstable, and integrating processes is significantly more challenging than that of stable processes because the presence of unstable poles can lead to excessive overshoot and long settling times in some cases, and may result in the loss of a balance between inputs and outputs when a load disturbance occurs [1]. The system defined as non-minimum phase or inverse response if at least one zero of the transfer function lies in the right half plane on the complex plane [2]. The presence of time delay and the inverse response in these processes makes their control much harder.

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Some investigations have been published in the literature on these systems, which have zero in the right half of the s-plane. Gu et al. [3] suggested an auto-tuning method to control time delay and inverse response integrating processes using a Proportional Integral (PI) and Proportional Integral Derivative (PID) controller. A study on tuning PI and PID parameters in time-delayed and non-minimum phase integrating systems is suggested in [4]. To tune PI/PID controllers based on model-based analysis, the researchers use direct synthesis (DS) methods to reject disturbances. After that, the gold section search technique is used to find the optimum tuning parameter based on the model. An approach based on the Smith predictor is presented by Jeng and Lin [5] to control integrating processes with non-minimum phase and time delay by using the PID controller. For stable non-minimum-phase systems with time delay, disturbance rejection control is explored in another study [6]. Uma and Rao [7] presented a modified Smith predictor-based control scheme for some processes in which one of the two controllers performs disturbance rejection and the other performs set point tracking. In their method using internal model control (IMC)-based and direct synthesis approach, they realized the control of second-order unstable processes with dead-time and non-minimum phase or minimum phase. Another study includes an IMC-based control with an optimal H_2 minimization framework for the design of controllers at some integrating process that involve time delay and inverse response [8]. In their proposed control scheme, they used a PID controller and a pre-filter and reported that the suggested controller provides significantly improved performance compared to the approaches in the literature, especially for perturbations. Using the polynomial approximation to obtain controller parameters, Kumar and Manimozhi [9] realized the control of processes with time delays and inverse response integration systems. In his study, Kaya presented a controller design method for non-minimum phase integrating systems [10]. The design method using integral performance indices is designed in Smith predictor structure. Another study on the control of integrating processes with inverse response is conducted by Ozyetkin et al. [11]. Stability boundary locus is obtained and controller parameters are determined according to the weighted geometrical center method. Irshad and Ali [12] investigated the control of inverse response systems by determining PI/PID controller parameters using the PSO algorithm based on integral performance criteria. A research based on IMC and PID controller control of second-order time delay and inverse response processes is presented in [13]. Kaya's method gives optimum analytical tuning rules for Integral-Proportional Derivative (I-PD) controllers in integrating processes [14]. A significant feature of Kaya's study that the suggested I-PD controller produces acceptable output responses even when both nominal and perturbed conditions are applied. A filtered PID controller is proposed by Siddiqui et al. [15] to control time-delayed and inverse processes, and the controller parameters are calculated using direct synthesis method. Raja and Ali [16] proposed a tuning method based on the PI-PD controller structure for integrating and unstable processes with dead time and inverse response. In [17], a novel PID control tuning method for processes with time delay and inverse response is presented. Although very good output responses are obtained with this method, the large number of parameters to be determined can be considered as a disadvantage. Another research focuses on the design of a PID controller for a second-order plus time delay non-minimum phase system that is unstable [18].

In the industry, the PID controller is one of the most commonly used controllers due to its simple structure and high performance [19]. It is noteworthy, however, that the PID controller may not be sufficient for the control of unstable, integrating, and oscillating systems, especially if there is a time delay [20]. Contrary to PID controllers, Proportional Integral-Proportional Derivative (PI-PD) controllers provide more effective control for unstable, integrating, and oscillatory processes. In the PI-PD controller structure, the PI control is located in the forward path, while the PD controller is in the feedback. With an internal PD feedback loop, it is possible to change an open-loop unstable system to an open-loop stable system, and to ensure the poles of the stable process are positioned in the appropriate location for resonant or integrating processes [21]. By updating the location of the roots in the s-plane, the desired output response can be obtained by providing much more effective control with the PI controller positioned on the forward path. In some studies [22], [23], [24], improve system output responses are obtained by using only I controller instead of PI controller in the forward path. In this way, the number of parameters to be determined is reduced from four parameters to three parameters.

Apart from conventional control structures such as PID, different control structures are also used in process control and one of these structures is Smith predictor. The Smith predictor structure introduced to the literature by O. J. M Smith [25] is accepted as one of the most frequently used controller structures in the control of time-delayed processes. The Smith predictor structures proposed in the following years are shown that they can be used in the control of integrating processes involving time delays [26]. A control scheme using a combination of Smith predictor and PI-PD controller structures is presented in Kaya's study [27]. Thus, a control scheme that will provide an advantage in the control of time-delayed integrating and unstable processes is proposed. Figure 1 shows a basic Smith predictor structure, which includes a time-delayed plant, a time-delayed model, and a controller. The controller to be used here is generally in the form of a PID controller.

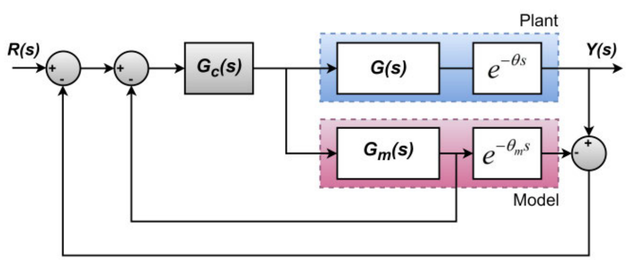

FIGURE 1. Basic smith predictor block diagram.

The determination of controller parameters has been investigated by scientists and researchers for many years and interest in this topic has been increasing in recent years [28]. The adventure of tuning methods, which started with Ziegler- Nichols tuning methods, has attracted attention today thanks to the variety of optimization techniques. Besides Ziegler-Nichols tuning methods, Åström-Hägglund, Kappa-Tau, Cohen-Coon, methods based on frequency and time response, methods of pole placement, methods based on gain-phase margin are the major examples of classical PID tuning methods [29]. Tuning methods based on parameter optimization against classical tuning methods are attractive with their superior performance. Some of the meta-heuristic optimization algorithms used to determine the control parameters are as follows: Genetic Algorithm (GA) [30], Particle Swarm Optimization (PSO) [31], Ant Colony Optimization (ACO) [32], Tabu Search (TS) [33], Harmony Search (HS) [34], Artificial Bee Colony (ABC) [35], Firefly Algorithm (FA) [36], Cuckoo Search (CS) [37], Bat Algorithm (BA) [38], Flower Pollination Algorithm (FPA) [39], and Grey Wolf Optimizer (GWO) [40].

The main research goal of this study is to improve the control performance of inverse response processes, which are frequently used in the process control industry. It is noteworthy that the number of parameters to be determined in the methods proposed in the studies examining the control of time-delayed inverse response processes is high. By optimizing fewer parameters, better set-point tracking and disturbance rejection control can be achieved, which is the motivation for the study. The aim and main contributions of this study are summarized below.

- In this study, a tuning procedure for a Smith predictor based on I-PD controller is presented for the control of some processes with time delay and inverse response.
- The EO algorithm, which was introduced to the literature in 2020, is used for the first time in the control of time-delayed and inverse response processes, and the controller parameters are determined.
- A multi-objective function is proposed that utilizes the error in the control system and the control signal together.
- The control of both set-point tracking and disturbance rejection are improved for integrating or unstable inverse response processes with time delay.

The remainder of the paper is organized as follows. In the second section, EO is introduced. The third section contains the proposed method. In this section, the proposed control algorithm and the determination of the controller parameters are explained. The fourth section includes the simulation study. In this section, simulation studies are realized for four dead-time and inverse response processes and compared with some studies from the literature. The last section is the conclusions.

II. EQUILIBRIUM OPTIMIZER ALGORITHM

The equilibrium optimization algorithm proposed by Faramarzi et al. [41] in 2020 is inspired by the volume mass balance control models used to predict both dynamic and equilibrium states. In the study of Faramarzi et al., the EO algorithm is compared with some effective optimization algorithms (such as PSO, GWO, GA, and Gravity Search Algorithm-GSA) in the literature and its advantages are demonstrated.

A physics-based meta-heuristic algorithm known as the EO aims to simulate the behavior of equilibrium on a known control volume in order to study how equilibrium will behave. Therefore, it attempts to find the state of equilibrium of the volume based on a chunk mass equation over a period of time by measuring how much chunk steps out, takes in, and generates in the volume. The first-order ordinary differential equation expressing the general time-dependent mass-balance equation [42] is defined as in Equation 1.

$$V\frac{dC}{dt} = QC_{eq} - QC + G \tag{1}$$

The VdC/dt in the equation gives the rate of change of mass in the control volume, Q the volumetric flow rate, C_{eq} the concentration at equilibrium, C the concentration in the control volume (V), and G the rate of change of mass in the control volume.

Equation 1 is rearranged to solve for *dC/dt*, which is a function of Q/V. Lambda (λ) is written instead of Q/V in the equation and represents the inverse of the settling time or the rotational rate. As a result, Equation 1 is reconstructed as follows.

$$\frac{dC}{\lambda C_{eq} - \lambda C + G/V} = dt \tag{2}$$

Equation 3 is obtained by integrating both sides of Equation 2.

$$\int_{C_0}^{C} \frac{dC}{\lambda C_{eq} - \lambda C + G/V} = \int_{t_0}^{t} dt \tag{3}$$

As a result, Equation 3 is arranged as follows:

$$C = C_{eq} + (C_0 - C_{eq})F + \frac{G}{\lambda V}(1 - F) \tag{4}$$

F in Equation 4 is calculated as in Equation 5.

$$F = \exp[-\lambda(t - t_0)] \tag{5}$$

In Equation 4, C_0 represents the concentration (density) values, and in Equation 5, t_0 represents the initial time. Equation 4 is the basic equation of the EO algorithm and shows the updating rule of particles as in the PSO algorithm. In Equation 4, each particle operates according to three independent states to update the concentration. The first step is the balance of concentration and represents one of the best solutions randomly selected in the pool. The second step shows the difference in concentration (density) between the present particle and the equilibrium state, which directly affects the search mechanism. The third step is related to the derivation rate and plays a role in improving the search. It makes a significant contribution to the search process, especially when moving in small steps or ratios.

The optimization process is started with the initial population. The initial concentration is determined using a random distribution, taking into account the number of particles. Equation 6 represents the initial population.

$$C_i^{initial} = C_{\min} + rand_i(C_{\max} - C_{\min}) \quad i = 1, 2, 3, \ldots n \tag{6}$$

n is the number of particles in the population, $C_i^{initial}$ is the initial concentration vector for each particle, C_{max} and C_{min} represent the maximum and minimum values of the particles. It is also a random vector derived from $rand_i[0\ 1]$.

In the "equilibrium pool and candidates" step, which is called the global optimal point in the algorithm, four candidate solutions are determined around the best solution. $C_{eq,pool}$, which is called the equilibrium pool in the algorithm and shown in Equation 7, consists of five elements.

$$\vec{C}_{eq,pool} = \left\{ \vec{C}_{eq(1)}, \vec{C}_{eq(2)}, \vec{C}_{eq(3)}, \vec{C}_{eq(4)}, \vec{C}_{eq(ave)} \right\} \tag{7}$$

At the end of the optimization, all particles are updated with the same number of updates relative to all candidate solutions.

In the exponential step, the main concentration values are updated. λ represents a random vector between [0,1] as follows.

$$\vec{F} = e^{-\vec{\lambda}(t-t_0)} \tag{8}$$

In Equation 8, t represents time and decreases with the number of iterations. It is calculated with the following equation.

$$t = \left(1 - {iter}/{\max\_iter}\right)^{\left(a2\frac{iter}{\max\_iter}\right)} \tag{9}$$

Equation 11 is considered to ensure that the algorithm reaches the optimal point.

$$\vec{t}_0 = \frac{1}{\vec{\lambda}} \ln(-a_1 \mathrm{sign}(\vec{r} - 0.5)[1 - e^{-\vec{\lambda}t}]) + t \tag{10}$$

Equation 11 is obtained by substituting t_0 in Equation 8.

$$\vec{F} = a_1 \mathrm{sign}(\vec{r} - 0.5)[e^{-\vec{\lambda}t} - 1]) \tag{11}$$

The generation rate is the next step in finding the optimal solution by improving the algorithm's ability to work or use it. The first-order exponential decay model is defined as Equation 12.

$$\vec{G} = \vec{G}_0 e^{-\vec{k}(t-t_0)} \tag{12}$$

Here, k is the reduction coefficient and G_0 is the initial value. The equation of the generation rate is given as Equation 13.

$$\vec{G} = \vec{G}_0 e^{-\vec{\lambda}(t-t_0)} = \vec{G}_0 \vec{F} \tag{13}$$

In Equation 13, G_0 is calculated as given in Equations 14 and 15.

$$\vec{G}_0 = \overrightarrow{GCP}(\vec{C}_{eq} - \vec{\lambda}\vec{C}) \tag{14}$$

$$\overrightarrow{GCP} = \begin{cases} 0.5 r_1 & r_2 \geq GP \\ 0 & r_2 < GP \end{cases} \tag{15}$$

The GCP generation rate in the equation represents the control parameter, while the r_1 and r_2 values are random values in the [0, 1] range. The updating rules of the EO algorithm are given as in Equation 16.

$$\vec{C} = \vec{C}_{eq} + (\vec{C} - \vec{C}_{eq})\vec{F} + \frac{\vec{G}}{\vec{\lambda}V}(1 - \vec{F}) \tag{16}$$

Algorithm 1 Pseudo-Code of EO Algorithm

Initialize the parameters a_1, a_2, V, GP, max_t, N, Dim;
Initialize the concentration in control volume $\vec{C}_i$;
Initialize the equilibrium pool $\overrightarrow{C_{eq,pool}}$;
While ($t \leq max\_t$)
  Check the boundary and calculate the fitness $FitC$;
  Update the equilibrium pool $\overrightarrow{C_{eq,pool}}$;
  Update $\vec{C}$ and $FitC$ with greedy strategy;
  For each search agents
    Update random variables $\vec{\lambda}, \vec{r_n}, r_1, r_2$;
    Randomly select the $\vec{C}_{eq}$ in the $\overrightarrow{C_{eq,pool}}$;
    Calculate the $\vec{F}$ and $\vec{G}$ by Equations 11 and 13;
    Update concentrations $\vec{C}$ by Equation 16
  End For
  t=t+1;
End While
Return $\vec{C}_{eq,1}$ and its fitness;

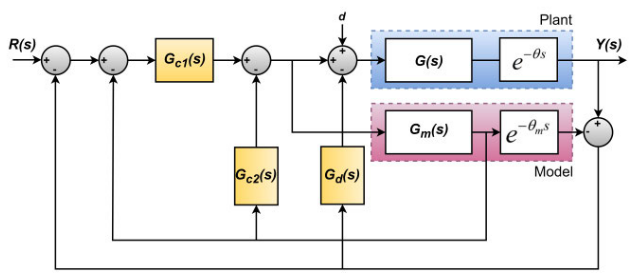

FIGURE 2. Modified smith predictor block diagram.

The algorithm continues with steps such as particle's memory saving, exploration ability of EO, and computational complexity analysis. The Pseudo-code of the EO algorithm is given in Algorithm 1 [43].

III. PROPOSED TUNING METHOD

In this section, the proposed control scheme would be given and integral performance criteria and multi-objective function would be introduced.

A. PROPOSED CONTROL SCHEME

In the literature, modified Smith predictor structures are encountered in different structures [44], [45]. Figure 2 shows the modified Smith predictor scheme proposed by Kaya [27]. In the diagram, Kaya [27] considers G_{c1} controller as the PI controller, G_{c2} and G_d controllers as the PD controller. In the proposed modified Smith predictor structure, unlike Kaya's work, the G_{c1} controller is considered as an I controller, so the number of parameters to be determined decreased to five parameters instead of six parameters. Ultimately, the reduction in the number of controller parameters can be considered as an advantage.

In this diagram, G_{c1} and G_{c2} controllers are in I-PD controller structure and are used for control of set-point

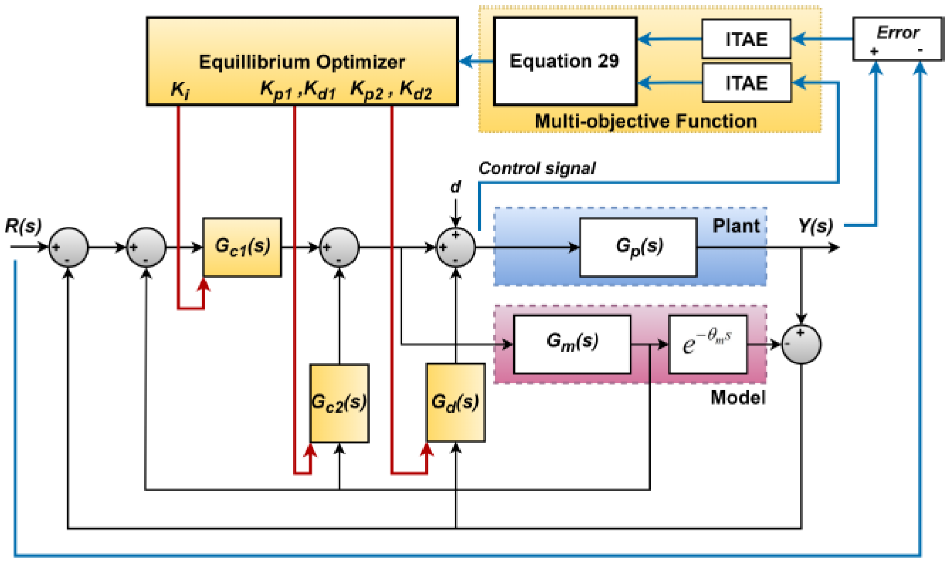

FIGURE 3. Block diagram of proposed method with EO.

tracking. In addition, the G_d controller is in the structure of a PD controller and is used for disturbance rejection control.

G_{c1} and G_{c2} controllers are given in Equations 17 and 18, respectively.

$$G_{c1}(s) = \frac{K_i}{s} \tag{17}$$

$$G_{c2}(s) = K_{p1} + K_{d1}s \tag{18}$$

The disturbance rejection controller, G_d, is given in Equation 19.

$$G_d(s) = K_{p2} + K_{d2}s \tag{19}$$

The transfer functions of integrating, double integrating, and unstable time-delayed non-minimum phase processes to be controlled are in the structure of Equations 20, 21, and 22. The model used in the Smith predictor structure is chosen as the perfect model.

$$G_p(s) = \frac{K(-T_0s+1)}{s(Ts+1)}e^{-\theta s} \tag{20}$$

$$G_p(s) = \frac{K(-T_0s+1)}{s^2(Ts+1)}e^{-\theta s} \tag{21}$$

$$G_p(s) = \frac{K(-T_0s+1)}{s(Ts-1)}e^{-\theta s} \tag{22}$$

It is known that the Smith predictor performs a successful control in time-delayed processes. Furthermore, the PI-PD controller structure also provides effective control in integrating and unstable processes. By using an integral controller instead of the PI controller, the number of parameters is reduced, and the Smith predictor and I-PD controller structures are combined. Thus, the control of processes that are known to be difficult to control can be carried out effectively with the proposed control algorithm.

B. DETERMINATION OF CONTROLLER PARAMETERS

Optimal controller parameters can be determined by minimizing the error or control signal by using integral performance criteria in the controller tuning procedure. Integral performance criteria are defined as objective or cost functions in optimization algorithms and provide minimization. First, in 1953, Graham and Lathrop used the integral of the square of the error (ISE) and the integral of the absolute value of the error (IAE) performance criteria [46]. Then, the integral of the square of the time-weighted error (ITSE) and the absolute value of the time-weighted error (ITAE) was developed [47]. The mathematical expressions of some of the performance criteria reported in the literature are given in Equations 23-28 [28].

- Integral of Error (IE) defined as,

$$IE = \int_0^t e(t)dt \tag{23}$$

- Mean Square Error (MSE) given as

$$MSE = \frac{\int_0^t e^2(t)dt}{t} \tag{24}$$

- Integral Squared Error (ISE) given as

$$ISE = \int_0^t e^2(t)dt \tag{25}$$

- Integral Absolute Error (IAE) given as

$$IAE = \int_0^t |e(t)|\, dt \tag{26}$$

- Integral of the Square of the Time-Weighted Error (*ITSE*) given as

$$ITSE = \int_0^t te^2(t)dt \tag{27}$$

- Integral of the Absolute of the Time-Weighted Error (*ITAE*) given as

$$ITAE = \int_0^t t\,|e(t)|\,dt \tag{28}$$

The block scheme of the proposed optimization algorithm is given in Figure 3.

In the diagram in the figure, the multi-objective function is defined as in Equation 29 by taking the error of the system and the control signal. The multi-objective function is produced by applying the ITAE performance criterion to both the error and control signal.

$$J_{proposed} = w_1.\int_0^t t\,|e(t)|\,dt + w_2.\int_0^t t\,|u(t)|\,dt \tag{29}$$

In Equation 29, w_1 and w_2 are the weighting coefficients and are chosen by trial and error.

The optimization algorithm is run by adapting the multi-objective function to the EO algorithm and making various initial settings as lower and upper bound of controller parameters, maximum iteration number and particle number. In this study, the particle number is taken as 30 and the maximum iteration number is taken as 100. The lower and upper bounds of the controller parameters are chosen at different values for each sample. The error and control signal generated by the control system against the reference input form the inputs of the multi-objective function. Then the error and control signal is updated according to the new controller parameters and the objective function continues to decrease. Thus, the loop continues until the stopping criterion is met. Optimal controller parameters are obtained when the stopping criterion is met.

IV. ILLUSTRATIVE EXAMPLES

This section presents simulation studies for various examples in the literature, such as inverse response integrating or unstable systems with time delay. The proposed method is compared with the considerable studies in the literature, which Begum et al. [8], Kaya [10], [14], Divakar and Kumar [17], Ozyetkin et al. [11], and Kumar and Manimozhi [9]. Various metrics are used to assess the closed-loop responses: IAE, ISE, TV, settling time (t_s), and overshoot percentage (OS %).

To evaluate the manipulated input usage we have a tendency to work out the total variation (TV) of the input $u(t)$, that is add of all its moves up and down [48]. TV is hard to outline compactly for a non-stop signal, however if we discretize the input signal as a sequence, $[u_1, u_2, \ldots, u_i \ldots]$,

$$TV = \sum_{i=1}^{\infty} |u_{i+1} - u_i| \tag{30}$$

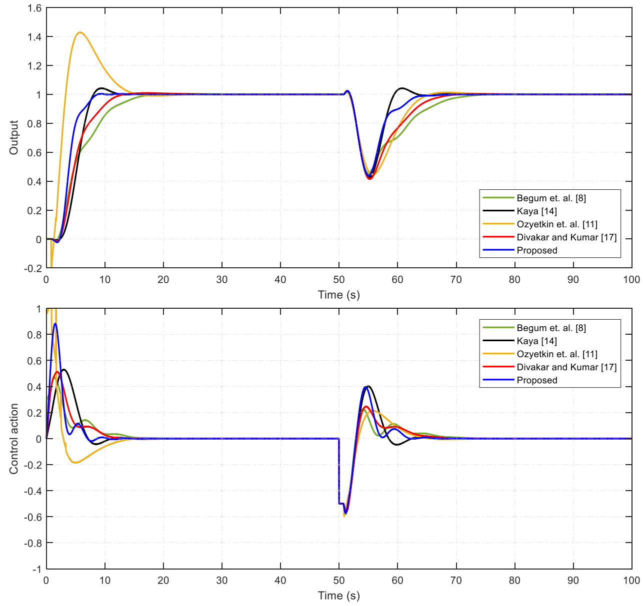

FIGURE 4. System responses for Example 1 (Top: Output response, Bottom: Control signal).

then which need to be as small as possible. The total variation is a good indicator of a signal's smoothness.

Table 1 contains the TV, ISE, and IAE performance values for nominal and perturbed systems for all examples. The systems are evaluated under both servo and disturbance input.

Example 1: Let's consider a fourth-order time delay and inverse response system. The example was studied by Begum et al. [8], Kaya [14], Ozyetkin et al. [11], and Divakar and Kumar [17].

$$G(s) = \frac{0.5(1-0.5s)}{s(0.1s+1)(0.4s+1)(0.5s+1)}e^{-0.7s} \tag{31}$$

Controller parameters for method of Begum et al. [8] are given by k_c = 09947, t_i = 8.3061, and t_d = 1.238. In addition, the pre-filter used is given as $F_R = (1.984s+1)/(8.3863s^2+8.0915s+1)$. In Kaya's method [15], I-PD controller parameters are determined as $k_c = 1.151$, $t_i = 5.156$, and $t_d = 0.782$. In the method of Ozyetkin et al. [12], the PID controller parameters obtained according to the weighted geometrical center method are $k_p = 0.9445$, $k_i = 0.1429$, and $k_d = 1$. Finally, in the Divakar and Kumar methods [18], the parameters of the set-point filter, PID controller, and PID filter are obtained as follows. Set-point filter is $F_R = (2s+1)/ (0.0954s^4+1.5121s^3+8.4489s^2+7.375s+1)$. PID controller parameters are $k_p = 0.964$, $k_i = 0.134$, and $k_d = 0.938$. Additionally, the PID controller filter is $F_{PID} = (0.013s^2+0.202s+1)^2/[(0.004s^2+0.086s+1)(0.095s^2+0.2857s+1)]$.

In the optimization algorithm for Example 1, the upper and lower bounds of the controller parameters are defined as [0 0 0 0 0], and [2.5 2.5 2.5 2.5 2.5], respectively. Thus, the controller parameters obtained by the proposed method are 0.6590, 2.3115, 1.4932, 0.8053, and 1.1051 for I-PD and PD controllers, respectively. The unit step responses of the

TABLE 1. Performance specifications under nominal and perturbed condition.

	Nominal system (Servo + Regulatory)			Perturbed system (+ %) (Servo + Regulatory)			Perturbed system (- %) (Servo + Regulatory)		
Methods	*TV*	*ISE*	*IAE*	*TV*	*ISE*	*IAE*	*TV*	*ISE*	*IAE*
Example 1									
Begum [8]	4.276	5.684	10.39	4.425	5.71	10.33	4.489	5.737	10.6
Kaya [14]	4.841	5.522	7.882	6.386	5.774	8.842	4.989	5.47	8.343
Ozyetkin [11]	5051	4.278	8.512	5052	4.796	8.563	5051	3.966	8.738
Divakar and Kumar [17]	4.47	5.6	9.33	4.389	5.665	9.175	4.75	5.626	9.722
Proposed	4.385	4.465	6.868	5.591	4.671	7.02	4.765	4.426	7.289
Example 2									
Begum [8]	2.717	0.1417	1.267	3.004	0.1424	1.195	2.901	0.1503	1.349
Kaya [10]	44.6	1.782	2.925	44.31	1.749	2.754	44.97	1.831	3.139
Divakar and Kumar [17]	2.83	0.1196	1.031	2.95	0.1179	0.9833	3.201	0.13	1.103
Proposed	3.237	1.833	2.536	3.118	1.808	2.546	3.585	1.871	2.681
Example 3									
Begum [8]	0.7004	4.034	10.68	0.8701	4.227	10.81	0.6094	3.902	10.6
Kaya [14]	0.8506	10.92	15.97	1.081	11.2	16.65	0.7231	10.73	15.95
Proposed	0.8404	8.932	13.57	1.151	9.111	13.87	0.7036	8.828	13.5
Example 4									
Begum [8]	0.4161	0.02651	0.8463	0.6468	0.02706	0.8515	0.404	0.02663	0.8473
Divakar and Kumar [17]	0.3903	0.01166	0.4699	0.5327	0.01197	0.4737	0.3745	0.01174	0.4714
Kumar and Manimozhi [9]	0.3882	0.1226	0.9734	0.4316	0.1217	0.9807	0.3774	0.1231	0.9728
Proposed	0.4561	0.08388	0.7428	0.6736	0.08382	0.7745	0.4431	0.08455	0.7446

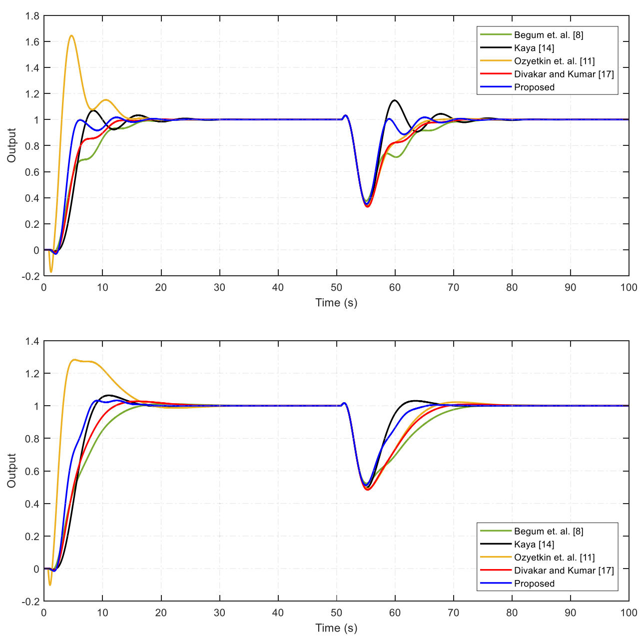

FIGURE 5. Perturbed system responses for Example 1 (Top: Change in parameters +10%, Bottom: Change in parameters −10%).

closed-loop systems obtained according to all design methods are shown in Figure 4. A step response with an amplitude of 0.5 at $t = 50$s is applied to evaluate the disturbance rejection performance of all design methods. Figure 4 also shows the control signals for Example 1. The proposed method stands out among the others as the one with no overshoot and the shortest settling time. In terms of disturbance rejection, we observe a response that has no overshoot, and settling time faster than the others, as expected. In particular, the design method of Ozyetkin et al. [11] has an overshoot of about 40% and provides inverse response with a greater amplitude than other methods. Analyzing the control signal of the proposed method reveals that it is within quite reasonable limits.

It was assumed that three parameters of the model transfer function (K, T_0, θ) would change by $\pm 10\%$ in order to analyze the robustness of all design methods. The closed-loop unit step responses of the perturbed systems obtained by increasing these three parameters by 10% are shown in Figure 5. The figure (bottom) shows the closed-loop unit step responses for perturbed systems with parameters decreased by 10%. It is noteworthy that in both set point tracking and disturbance rejection in both perturbed systems, the proposed method gives a fast response compared to other methods.

Example 2: A well-known example of an industrial process, whose process model is given below, is the regulation of the level of a boiler steam drum by adjusting the boiler feed water to the drum. This industrial process model is investigated by Begum et al. [8], Kaya [10], and Divakar and Kumar [17], and the proposed method and these presented methods are compared.

$$G(s) = \frac{0.547(-0.418s + 1)}{s(1.06s + 1)} e^{-0.1s} \tag{32}$$

Begum et al. [8] determined the PID controller parameters as follows: $k_c = 3.2306$, $t_i = 3.5055$, and $t_d = 0.7981$. The pre-filter is $F_R = (0.85s + 1)/(2.5018s^2 + 3.4186s + 1)$. For this process, Kaya [10] determined the controllers in the control structure as follows: $G_{c1} = 1.69(1+1/11.5s)$, $G_{c2} = 0.22+0.74s$, and $G_d = 1.636(1+1.06s)$. In the method of Divakar and Kumar [17], PID controller parameters are $k_p = 3.779$, $k_i = 1.4319$, and $k_d = 2.4609$. The filter of PID controller and set-point filter are $F_{PID} = (0.0002s^2+0.025s+1)^2/[(0.00002s^2+0.004s + 1)(0.0021s^2+0.0399s + 1)]$, $F_R = (0.2s + 1)/(0.0004s^4+0.043s^3+1.784s^2+2.664s + 1)$, respectively.

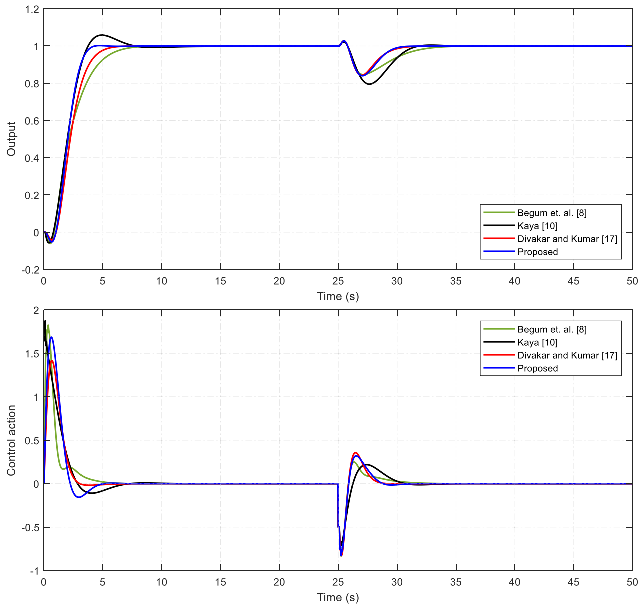

FIGURE 6. System responses for Example 2 (Top: Output response, Bottom: Control signal).

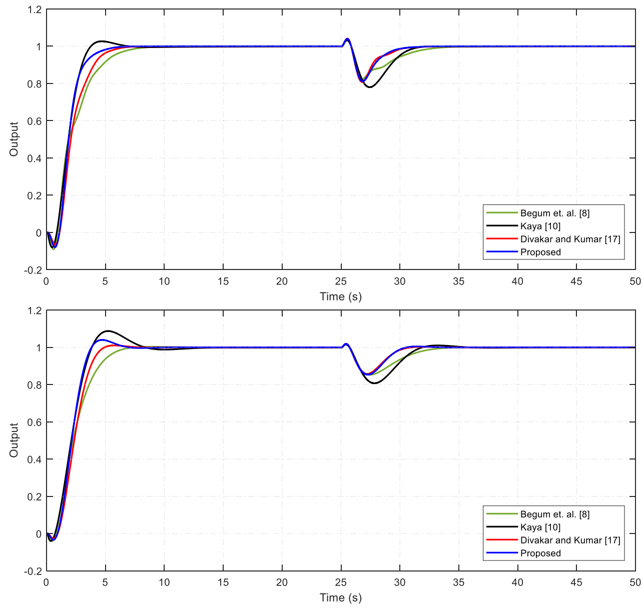

FIGURE 7. Perturbed system responses for Example 2 (Top: Change in parameters +10%, Bottom: Change in parameters −10%).

In the proposed optimization algorithm, the search area of the controller parameters is scanned in the range of [0 5]. Thus, in the proposed control structure, I-PD parameters are 2.4315, 4.9999, 2.8003, and PD controller parameters are 3.0533, 2.5258. In Figure 6, the unit step responses are shown for all closed-loop systems. The disturbance rejection performance of all design methods is evaluated using a step response with an amplitude of 0.5 at $t = 25$s. It can be seen from the figure that Kaya's method [10] is higher in the overshoot value of set-point tracking and disturbance rejection. This method also has a long settling time. The method of Begum et al. [8] has a long settling time, although a response without overshoot is obtained in both set-point tracking and disturbance rejection. Although Divakar and Kumar [17] obtained better responses than the other two methods, a faster response is obtained with the proposed method than Divakar and Kumar's method [17]. Although similar performance is obtained in disturbance rejection, set-point tracking is a shorter settling time compared to Divakar and Kumar method [17]. In Figure 6, control signals of all methods are also shown.

For Example 2 in the model in Equation 20, as in Example 1, by changing the K, T_0, θ parameters +10% and −10%, Figure 7 is obtained. Thus, the robustness analysis of the designed controllers can be realized and the proposed approach can be compared with others in terms of robustness testing. It is clear from Figure 7 that the presented approach provides both a rapid response in set-point tracking and an appropriate response in disturbance rejection control.

Example 3: A process in the structure in Equation 21 is given below. The plant was studied by Kaya [14].

$$G(s) = \frac{(-0.7s + 1)}{s^2(s + 1)} e^{-0.2s} \tag{33}$$

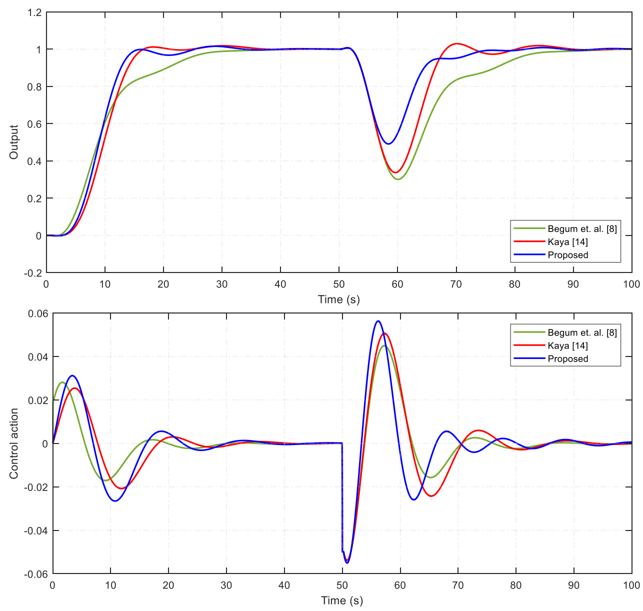

FIGURE 8. System responses for Example 3 (Top: Output response, Bottom: Control signal).

I-PD controller parameters are determined by Kaya's proposed method (IST^3E) for this process as follows: $k_c = 0.088$, $t_i = 9.70$, and $t_d = 4.676$ [14]. In addition, Kaya presented the controller parameters that he determined by using the method of Begum et al. [8] in order to make comparisons in his study. The controller parameters in the study of the Kaya's are taken exactly and the results are compared.

In this study, the lower bounds of the controller parameters are chosen as [0 0 0 0 0] and the upper bounds of [1 1 1 1 1] and the results are obtained as follows: $K_i = 0.0125$, $K_{p1} = 0.1120$ $K_{d1} = 0.4474$, $K_{p2} = 0.1109$, and $K_{d2} = 0.5335$.

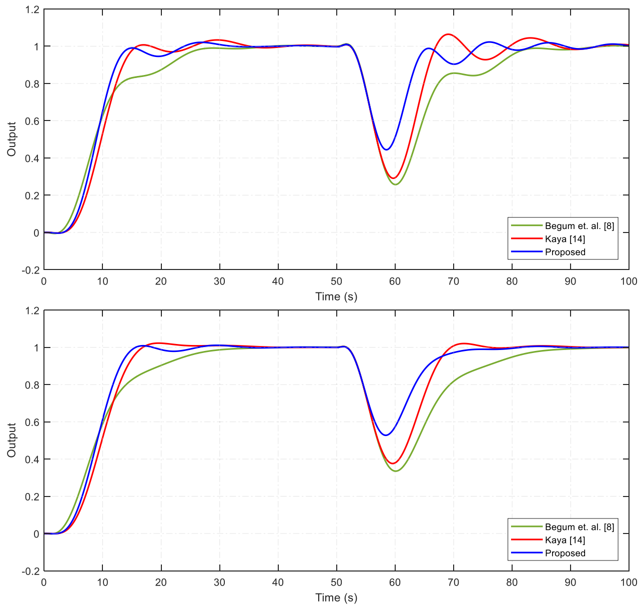

FIGURE 9. **Perturbed system responses for Example 3 (Top: Change in parameters +20%, Bottom: Change in parameters −20%).**

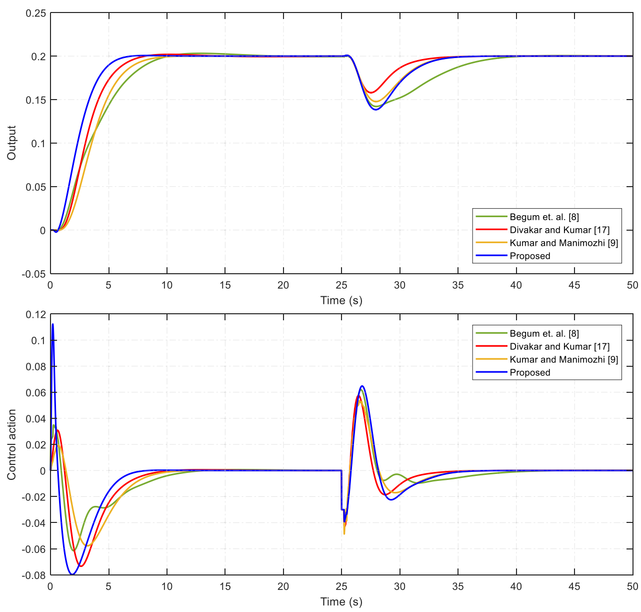

FIGURE 10. **System responses for Example 4 (Top: Output response, Bottom: Control signal).**

By substituting the determined controller parameters, the unit step output responses of the system are obtained as in Figure 8. Also, the control signal of the system is given in Figure 8. Using a disturbance input with an amplitude of −0.05 at $t = 50$s, the performance of the control system against the disturbance input is evaluated. It can be said that with the proposed method, faster set-point tracking is provided than Kaya's method and especially the disturbance control is much superior. It can be seen from Figure 8 that the control signals are of very small amplitude in both methods.

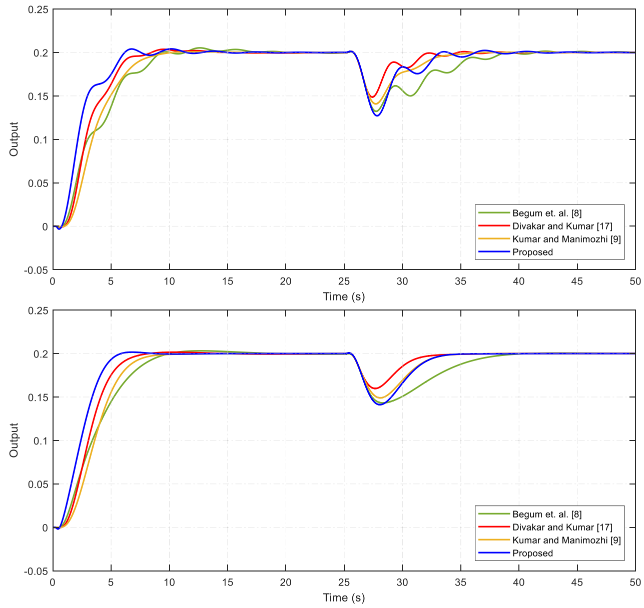

FIGURE 11. **Perturbed system responses for Example 4 (Top: Change in parameters +10%, Bottom: Change in parameters −10%).**

Different from the other two examples for the perturbed system responses, two parameters, T_0 *and* θ, are changed to +20% and −20%, and the results in Figure 9 are presented. When the responses of perturbed systems are examined, it is seen that all methods are robust and the proposed method is superior to Kaya's method [14] for both cases. As a result, Kaya stated that his method in his study is faster than the method of Begum et al. [8]. Considering that the proposed method is faster in both servo and regulatory responses compared to Kaya's method [14], the proposed method is also superior to the method of Begum et al. [8].

Example 4: An inverse response unstable and integrating process with a time delay in the structure in Equation 22 is given below. The process was studied by Begum et al. [8], Divakar and Kumar [17], and Kumar and Manimozhi [9].

$$G(s) = \frac{(-0.2s+1)}{s(s-1)}e^{-0.2s} \tag{34}$$

Begum et al. [8] determined the PID controller parameters and set-point filter for this process as follows: $k_c = 0.4451$, $t_i = 5.218$, and $t_d = 4.33$ and $F_R = (1.3s + 1)/(21.9s^2+5.0833s + 1)$. Divakar and Kumar determined the PID controller parameters, PID filter parameters, and set-point filter as follows: $k_p = 0.7513$, $k_i = 0.2162$, $k_d = 1.952$, $F_{PID} = (0.0008s^2+0.05s + 1)^2/[(0.0001s^2+0.0065s + 1)(0.0054s^2+0.037s + 1)]$, $F_R = (0.1s + 1)/ (0.0075s^4+0.4542s^3+9.195s^2+3.358s + 1)$, respectively. Kumar and Manimozhi [9] determined the PID controller parameters, PID filter parameters, and set-point filter as follows: $k_p = 0.5635$, $k_i = 0.1467$, $k_d = 1.8559$, $F_{PID} = (0.0225s^2+0.3s+1) / [(0.0097s^2+0.2485s+1)$, $F_R = 1/(12.65s^2+3.84s + 1)$, respectively.

The lower bounds of the controller parameters in Example 4 are set at [0 0 0 0 0] and the upper bounds at [4 4 4 4 4], and the results are as follows: $K_i = 1.4748$, $K_{p1} = 3.4663$ $K_{d1} = 3.9861$, $K_{p2} = 0.3348$, and $K_{d2} = 1.7737$. The output responses obtained against 0.2 reference input by applying the parameters determined by the proposed method and the parameters determined by other methods to the process in Equation 34 are shown in Figure 10. A disturbance input with an amplitude of 0.03 is also applied to the system at $t = 25$s. As can be seen from Figure 10, the proposed method has a fast rise time, no overshoot and a superior output response compared to the answers of other methods. It is seen that the amplitude of the proposed method is very slightly large in the disturbance rejection control, and the settling times are almost the same as the other responses. Control signal outputs of the systems are also given in Figure 10. Although the initial performance of the control signal in the proposed method is higher than other methods, it is noteworthy that it has a very small amplitude value.

The output responses obtained by changing the two parameters T_0 and θ +10% and −10% for the robustness analysis are illustrated in Figure 11. It can be said that the present technique almost does not deteriorate the output response at −10% parameter change, and it provides a good output response even though there is slight oscillation at +10% parameter change. In terms of perturbed systems, when the proposed technique is compared with other techniques, it can be said that the proposed technique is superior in set-point tracking, and the settling times are equal, although it exceeds the disturbance rejection control.

V. CONCLUSION

In this study, a new Smith predictor-based control algorithm is proposed for the control of some integrating or unstable inverse response processes with time delay. With the proposed control algorithm, it is aimed to improve the set-point tracking of time-delayed inverse response processes, to improve the disturbance rejection performance, and to design a system that is robust to parameter uncertainty. The EO algorithm, which was introduced to the literature in 2020, has been adapted for use in determining the controller parameters. An algorithm with superior performance is designed by integrating the multi-criteria objective function designed according to the error and control signal into the optimization algorithm.

In the four examples presented, the proposed control technique is compared with some studies published in the literature. The results of the proposed method are listed below.

- For all examples, the proposed method provides a fast, non-overshoot response and superior set-point tracking over other methods.
- Superior performance is provided in the disturbance rejection control, especially in Examples 2 and 3, whereas almost similar performances are observed in Examples 1 and 4.
- Robustness analysis is investigated by changing two or three parameters of the processes by +10%, −10%, or +20%, −20%. The analysis shows that the designed controllers are robust to parameter uncertainties in the control of processes.
- Although control signals with slightly larger amplitudes are observed in some examples compared to other methods, acceptable control signals are observed in the proposed method.

As a result, I-PD controller-based Smith predictor is combined with the EO algorithm and a control method for control of inverse response systems with time delay is presented to the literature. Finally, by the proposed method in future studies, servo and regulatory responses of non-minimum phase processes can be developed by using fractional order controllers.

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