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Analysis of multivariable objective functions for the PID controller tuned by a radial movement optimization

Radyal hareket optimizasyonu ile ayarlanmış OİT denetleyicisi için çok değişkenli amaç fonksiyonlarının analizi

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Abstract

In this study, a second order plus dead time (SOPDT) test system was designed in MATLAB/Simulink platform to analyze the performance of multivariable objective functions (MOFs). These functions consisted of classical error-based objective functions (CEBOFs): integral of time-weighted absolute error, integral of squared error, integral of absolute error, integral of time-weighted squared error, and transient state parameters: maximum percentage overshoot and settling time which has w_1 and w_2 coefficients, respectively. A proportional integral derivative (PID) controller was employed to control the SOPDT system. In the optimization process, the radial movement optimization (RMO) algorithm was used to tune PID controller parameters. To demonstrate the performance of MOFs, numerical and graphical results were presented in the study, where settling time, maximum percentage overshoot, rise time, peak time and steady state error were given. The obtained results clearly showed that MOFs had a better performance than all CEBOFs in settling time and overshoot value. RMO algorithm also had a robust convergence rate and speed, proving the best optimal solution for all MOFs in the first seven iterations.

Keywords: PID controller, RMO algorithm, Multivariable objective functions, Error-based objective functions.

Öz

Bu çalışmada, çok değişkenli amaç fonksiyonlarının (ÇDAF) performans analizi için MATLAB/Simulink ortamında ikinci dereceden zaman gecikmeli bir test sistemi oluşturulmuştur. Analiz edilen amaç fonksiyonları, zaman ağırlıklı mutlak hatanın integrali, hatanın karesinin integrali, mutlak hatanın integrali ve zaman ağırlıklı hatanın karesinin integrali gibi klasik hata tabanlı amaç fonksiyonlarının (KHTAF), geçici durum parametreleri yüzde aşma ve yerleşme zamanı ile toplamından elde edilmiştir. Fonksiyonlarda yüzde aşma ve yerleşme zamanı sırasıyla w_1 ve w_2 katsayıları ile ağırlıklandırılmıştır. Sistemin kontrolü oransal integral türev (OİT) denetleyici ile yapılmıştır. OİT denetleyicinin parametreleri radyal hareket optimizasyonu (RHO) kullanılarak ayarlanmıştır. Çalışmada ÇDAF'lerin performansını göstermek için yerleşme süresi, maksimum yüzde aşma, yükselme süresi, tepe süresi ve kalıcı durum hatası bilgileri sayısal ve görsel olarak sunulmuştur. Elde edilen sonuçlar ÇDAF'lerin yerleşme süresi ve aşma değeri bakımından KHTAF'lere göre daha iyi performansa sahip olduğunu açıkça göstermektedir. Aynı zamanda RHO algoritması ilk yedi yinelemede optimal çözüme ulaşarak sağlam yakınsama oranı ve hızına sahip olduğunu kanıtlamıştır.

Anahtar kelimeler: OİT denetleyici, RHO algoritması, Çok değişkenli amaç fonksiyonları, Hata tabanlı amaç fonksiyonları.

1 Introduction

Today, there are many control methods such as fuzzy logic control [1]-[3], sliding mode control [4], and predictive control [5]-[7] in the literature. Among them, proportional integral derivative (PID) controller and its combinations (P, I, PI, and PD) are widely used in control applications due to its advantages such as structural simplicity, robust performance, and ease of implementation [8]-[10]. It has three actions: proportional, integral, and derivative, and its gains are K_P, K_I, and K_D, respectively. The performance of the controller is highly dependent on these gain factors. Therefore, they must be optimally tuned to obtain an acceptable closed loop system response. Conventional tuning methods such as Ziegler-Nichols [11],[12], Yuwana-Seborg [13], and Cohen-Coon [14] have already been used by most of the researchers for many years. However, they have some drawbacks, such as requiring numerical computations and more time to carry out trial and error procedures while finding the optimized PID parameters [15].

Metaheuristic optimization algorithms have been widely used in the controller design process because of their success in finding the optimal solution. Some of these algorithms are particle swarm optimization (PSO) [16]-[19], cuckoo search algorithm (CSA) [20],[21], genetic algorithm (GA) [22],[23] ant colony optimization (ACO) [24], and radial movement optimization (RMO) [25],[26]. They use predefined objective functions to optimize the controller parameters. Among the optimization methods, RMO, developed by Rahmani and Yusof in 2014, is an efficient algorithm for global optimization of multivariable systems. Compared to the other algorithms, its superiority in accuracy, consistency, and convergence speed has been indicated in different studies [26]-[28].

The objective function should be well-defined during the optimization process to obtain the desired system response. Commonly, classical steady-state error-based objective

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functions (CEBOFs) such as integral of time-weighted error (ITAE), integral of squared error (ISE), integral of absolute error (IAE), and integral of time-weighted squared error (ITSE) have been preferred in the literature [29]-[31]. In addition, objective functions are also obtained by combining parameters such as maximum overshoot, settling time, the amplitude of control signal, and CEBOFs. Performance analysis of error-based and user-defined objective functions has been presented in [32], where the PSO algorithm was used to tune PID parameters. Naidu et al. [33] proposed multiobjective optimization using the weighted sum approach to optimize the PID-controlled load frequency control system. In [34], the authors considered a three-parameter-based objective function, consisting of ISE, overshoot, and settling time. There is also lots of research based on weighted-sum-based objective functions in the control applications [35]-[38].

When the control literature is examined, it is seen that there is a lack of study in the field in terms of analyzing the performance of multivariable objective functions (MOFs) for all classical error-based functions (CEBOFs). In this paper, a second order plus dead time (SOPDT) system was designed in MATLAB/Simulink platform, and the performance analysis of MOFs was investigated. To the best of our knowledge, RMO has been used for the first time in this study to optimize PID parameters with MOFs. Moreover, a comparison of RMO and PSO was also made to show their performance on different transfer functions. Numerical and graphical results are presented to show the effect of MOFs on transient and steady-state characteristics.

The rest of this paper is organized as follows: Section 2 introduces theoretical information about RMO and PID controller under the title of Materials and Method. In Section 3, the optimization and simulation process parameters are given, and the SOPDT system is introduced. Numerical and graphical results are presented in Section 4, which also includes the effects of w_1 and w_2 coefficient pairs on MOFs. Finally, conclusions and recommendations are given in Section 5.

2 Material and method

2.1 Radial movement optimization

Radial movement optimization is a swarm-based random (stochastic) optimization method. Although many aspects are like other swarm-based optimization algorithms, the most obvious difference is the movement of particles in the swarm. They move radially around a center point, and this point is updated every iteration. In this method, the best solution for the current iteration is R_{best}, and the best solution obtained for all iterations is called G_{best}which gives the solution to the problem when conditions are met, such as the maximum iteration number, the best fitness value (FV), or the lowest FV change. The flowchart of the RMO is given in Figure 1.

Particle locations are kept in the X_{ij} matrix. The first variable (i) is the particle index, and the second variable (j) is the dimension index. After the particle number and size are determined, the particles are randomly distributed to the search space according to Eq. 1.

$$X_{ij} = X_{\min(j)} + rand(0,1)[X_{\max(j)} - X_{\min(j)}] \quad (1)$$

The velocities of all particles in each iteration are kept in the V_{ij} matrix. Particle velocities are determined randomly with each iteration as given in Eq. 2 and Eq. 3.

$$V_{ij} = rand(0,1)V_{\max(j)} \quad (2)$$

$$V_{\max(j)} = \frac{X_{\max(j)} - X_{\min(j)}}{N} \quad (3)$$

After the particle velocities are determined, the positions of the particles are calculated by Eq. 4.

$$X_{ij} = V_{ij} + C_{P(j)} \quad (4)$$

where C_P is the central point around which all particles move.

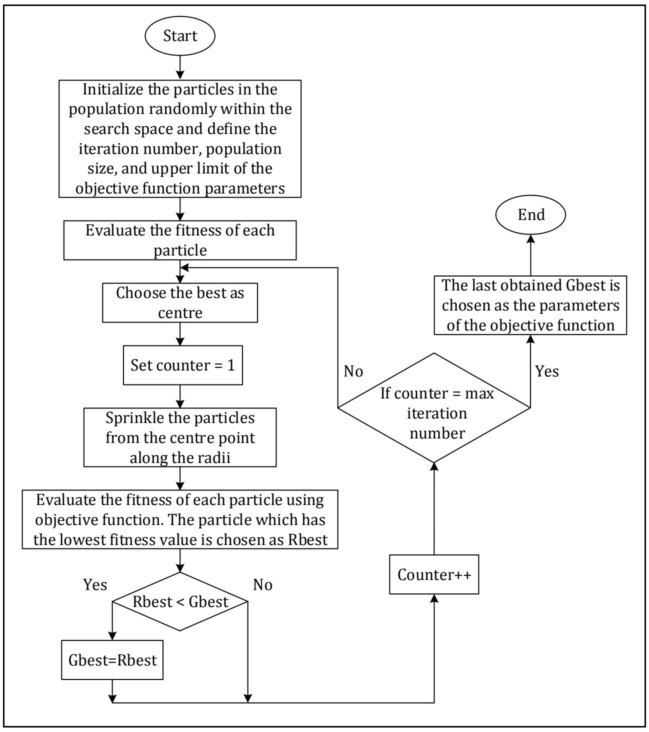


Figure 1. Flowchart of RMO.

FVs are obtained according to the newly calculated positions of the particles. Then R_{best} and G_{best} variables are updated according to these FVs. Then the C_P is calculated using Eq. 5 and Eq. 6.

$$C_P^{k+1} = C_P^k + U_P \quad (5)$$

$$U_P = C_1(G_{best} - C_P^k) + C_2(R_{best} - C_P^k) \quad (6)$$

where C_1 and C_2 are weighting constants. They determine the weight of finding a new center point using the current iteration and the best solutions in previous iterations. They are generally chosen in the range of 0.4 to 0.9, and it is recommended to take C_2 constant bigger than C_1 .

2.2 PID controller

PID controller has been frequently used in industrial applications due to its simple structure, easy applicability, and high performance. It consists of the sum of three essential components: proportional, integral, and derivative action. They contribute to the control signal according to the amplitude, area, and slope of error. The effect of the controller depends on the weights of these components. The general structure of the PID controller is shown in Figure 2.

In frequency-domain, the transfer function of a parallel form of the PID controller is given in Eq. 7.

$$G_C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + sK_D \quad (7)$$

where $U(s)$ is the control signal and $E(s)$ is the error signal, which is the difference between reference and output signal, K_P, K_I, and K_D, are proportional, integral, and derivative gains, respectively.

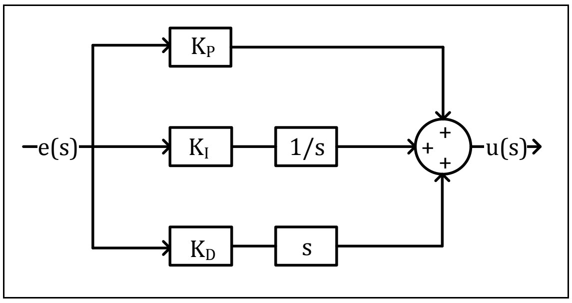


Figure 2. General structure of the PID controller.

3 Optimization

In the optimization process, the RMO algorithm was employed to optimize the PID controller parameters K_P, K_I, and K_D. The objective functions used in the process were selected as multivariable. They consisted of classical error-based metrics, i.e., ITAE, ISE, IAE, and ITSE, and transient state parameters, i.e., maximum percentage overshoot (M_O) and settling time (T_S).

The mathematical expression of classical and multivariable objective functions is given in Eq. 8–Eq. 12.

$$ITAE = \int_0^t t|e(t)|d(t) \quad (8)$$

$$ISE = \int_0^t e(t)^2 d(t) \quad (9)$$

$$IAE = \int_0^t |e(t)|d(t) \quad (10)$$

$$ITSE = \int_0^t te(t)^2 d(t) \quad (11)$$

$$MOFs = \begin{bmatrix} ITAE \\ ISE \\ IAE \\ ITSE \end{bmatrix} + w_1 * M_O + w_2 * T_S \quad (12)$$

where $e(t)$ is the error signal in time domain, t is the simulation time, w_1 and w_2 are coefficients of M_O and T_S, respectively.

Schematic diagram of the optimization process is shown in Figure 3.

A SOPDT test system was developed in the MATLAB/Simulink environment to measure the performance of RMO on the specified objective function. The transfer function of the SOPDT test system is given in Eq. 13.

$$G_1(s) = \frac{0.6105}{s^2 + 1.02s + 0.561} e^{-0.23s} \quad (13)$$

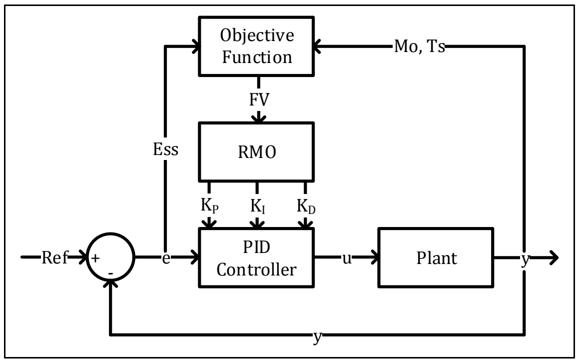


Figure 3. Block diagram of the optimization process.

Both optimization and simulation parameters are presented in Table 1, where C_1 and C_2 coefficients, population size, maximum iteration number, upper and lower limit of K_P K_I K_D, independent trials number, reference value, simulation time, and sampling time information are given, respectively. For the consistent simulation results, the independent trials number was chosen 10 as in [32].

Table 1. Optimization and simulation parameters.

Parameter	Value
C_1	2
C_2	2
Population size	50
Maximum iteration	50
K_P	[0 15]
K_I	[0 2]
K_D	[0 8]
Independent trials	10
Reference	1
Simulation time (t)	10s
Sampling time (dt)	0.01s

4 Results and discussion

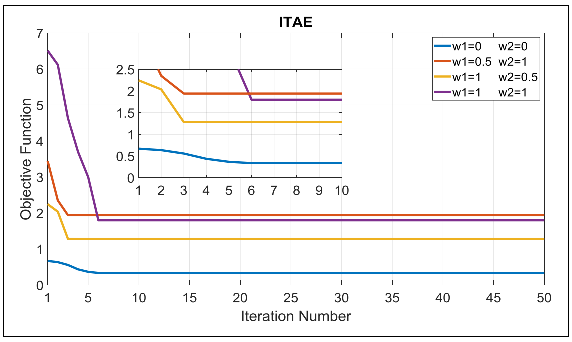
In the study, w_1 and w_2 weighting coefficient pairs were set to $(0, 0)$ which correspond to CEBOFs, $(0.5, 1)$, $(1, 0.5)$, and $(1, 1)$ for each MOF. Optimization results are presented in Table 2, where w_1 and w_2 weighting coefficients, iteration, FV, and optimized PID parameters (K_P, K_I, and K_D) are given, respectively. Bold signifies the best result.

Table 2. Optimization results.

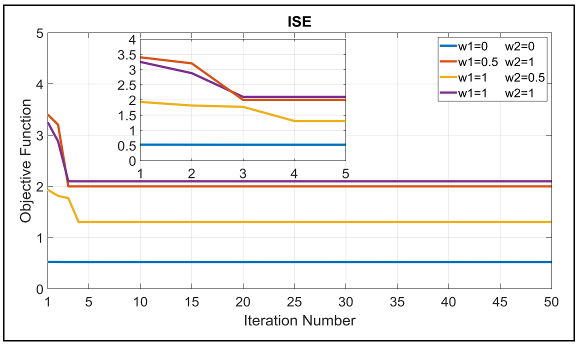
OF	w_1	w_2	*Iter.*	*FV*	K_P	K_I	K_D
ITAE	0	0	6	**0.3355**	10.118	1.3303	5.3719
	0.5	1	3	1.9405	7.0076	1.1500	4.1657
	1	0.5	3	1.2817	6.5285	1.1006	3.9667
	1	1	6	1.7984	7.2347	1.1378	4.2638
ISE	0	0	3	**0.5241**	14.985	1.8625	7.3906
	0.5	1	3	2.0012	7.4431	1.0747	4.3345
	1	0.5	4	1.3057	7.6190	1.1302	4.4389
	1	1	3	2.1004	7.0510	1.0416	4.1392
IAE	0	0	5	**0.7210**	11.198	1.3599	5.9446
	0.5	1	5	2.1777	7.6417	1.1759	4.4383
	1	0.5	2	1.5419	7.2257	1.0952	4.2718
	1	1	6	2.1621	7.5368	1.1377	4.4011
ITSE	0	0	2	**0.1577**	13.045	1.5191	6.5003
	0.5	1	3	1.5845	7.4431	1.0747	4.3345
	1	0.5	2	0.8978	7.4897	1.0870	4.3544
	1	1	6	1.5728	7.5368	1.1377	4.4011

As shown in Table 2, ITAE, ISE, IAE, and ITSE provided the minimum FV when $w_1 = 0$ and $w_2 = 0$. Another significant result was that the second-best FV for all MOFs was obtained when $w_1 = 1$ and $w_2 = 0.5$.

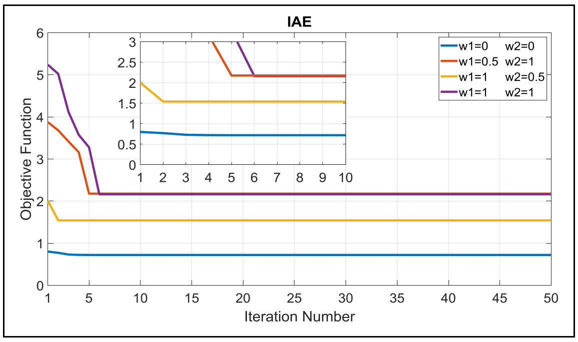
The convergence of each investigated objective function, which provided the best optimal solution for different weighting factors (w_1 and w_2), is given in Figure 4. Although MOFs had three independent performance criteria, the convergence rate and speed of RMO showed consistent results proving the minimum FV in the first seven iterations.



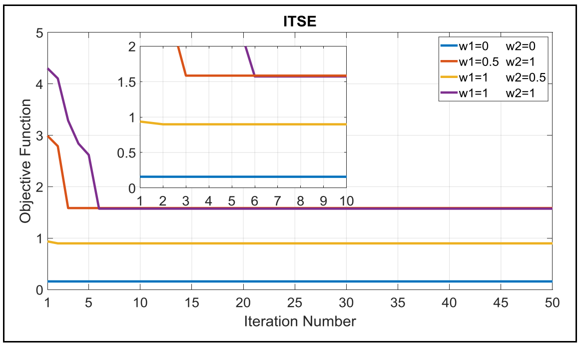
(a)



(b)



(c)



(d)

Figure 4. The best FVs obtained with different $w_1$and w_2 values in 10 trials for ITAE. (a): ISE, (b): IAE, (c): and ITSE, (d).

Numerical results of the transient and steady-state characteristics are presented in Table 3, where w_1 and w_2 weighting coefficients, maximum percentage overshoot (M_O), settling time (T_S), rise time (T_R), peak time (T_P), and steady-state error (E_{SS}) are given, respectively. Bold and bold underlined signify the best and general best value, respectively.

Table 3. Transient and steady-state characteristics with optimized PID controller parameters.

OF	w_1	w_2	M_O(%)	T_S	T_R	T_P	E_{SS}
ITAE	0	0	4.089	2.162	**0.526**	**1.23**	**<u>1.358e</u>$^{-5}$**
	0.5	1	0.164	**1.424**	0.748	3.39	7.365e^{-4}
	1	0.5	0.085	1.518	0.799	3.65	4.148e^{-5}
	1	1	**0.024**	1.393	0.727	3.31	4.772e^{-5}
ISE	0	0	13.75	4.556	**<u>0.376</u>**	**<u>0.99</u>**	4.816e^{-3}
	0.5	1	**<u>0</u>**	1.362	0.708	10.0	2.508e^{-3}
	1	0.5	**<u>0</u>**	**1.344**	0.696	0.99	**9.391e^{-4}**
	1	1	0.037	1.410	0.741	1.66	3.005e^{-3}
IAE	0	0	4.345	2.455	**0.485**	**1.15**	**6.675e^{-5}**
	0.5	1	0.111	**<u>1.328</u>**	0.691	3.13	2.423e^{-4}
	1	0.5	**<u>0</u>**	1.412	0.732	10.0	1.236e^{-3}
	1	1	**<u>0</u>**	1.353	0.702	10.0	5.836e^{-4}
ITSE	0	0	10.31	3.039	**0.420**	**1.07**	8.366e^{-4}
	0.5	1	**<u>0</u>**	1.362	0.708	10.0	2.508e^{-3}
	1	0.5	**<u>0</u>**	**1.353**	0.704	10.0	2.195e^{-3}
	1	1	**<u>0</u>**	1.3533	0.702	10.0	**5.836e^{-4}**

The comparison results show that ITAE, IAE, and ITSE provided the minimum E_{ss} value when $w_1 = 0$ and $w_2 = 0$, where ITAE was the best according to the overall table. However, unlike the others, ISE had the lowest E_{ss} value when $w_1 = 1$ and $w_2 = 0.5$. It can also be concluded that the best T_R and T_P values were obtained for all ITAE, ISE, IAE, and ITSE when $w_1 = 0$ and $w_2 = 0$ where ISE was the best among them.

According to the results about the M_O parameter, it can be concluded that the best improvement was in the ITSE objective function, which guaranteed that M_O value was 0% for (0.5, 1), (1, 0.5), and (1, 1) coefficient pairs. ISE with (0.5, 1), (1, 0.5), and IAE with (1, 0.5), (1, 1) also provided the minimum M_O values. The minimum T_S value was 1.328 and obtained with IAE objective function when $w_1 = 0.5$ and $w_2 = 1$. Also, T_S values of the other MOFs (ITAE, ISE and ITSE) were better than CEBOFs ($w_1 = 0$ and $w_2 = 0$). System responses of ITAE, ISE, IAE, and ITSE objective functions for different w_1 and w_2 pairs are given in Figure 5-Figure 8, respectively. They were obtained using the best K_P, K_I, and K_D parameters given in Table 2. ISE and ITSE had the worst M_O and T_S values when $w_1 = 0$ and $w_2 = 0$ as seen in Figure 6 and Figure 8. However, M_O values of ISE and ITSE with (1, 0.5) were reduced from 13% and 10% to zero, respectively, which means being without oscillation in system response. Also, T_S values of these objective functions (ISE and ITSE) were reduced by 70% and 55% compared to the (0,0) coefficient pair.

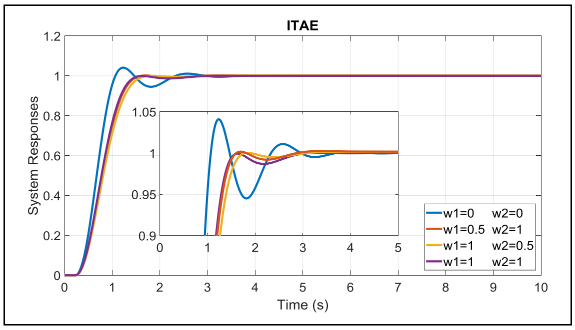


Figure 5. System responses for ITAE objective functions.

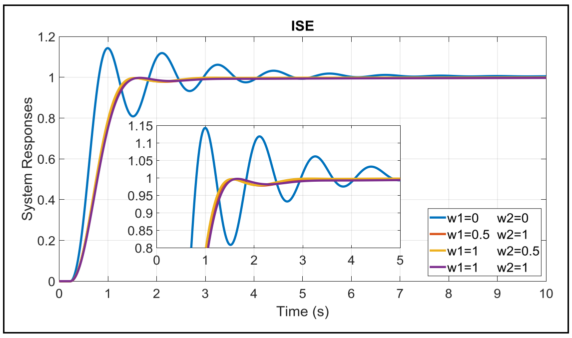


Figure 6. System responses for ISE objective functions.

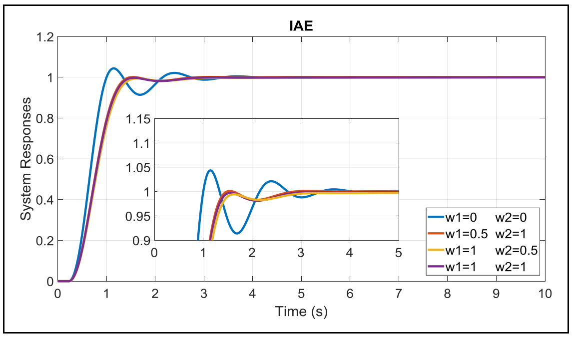


Figure 7. System responses for IAE objective functions.

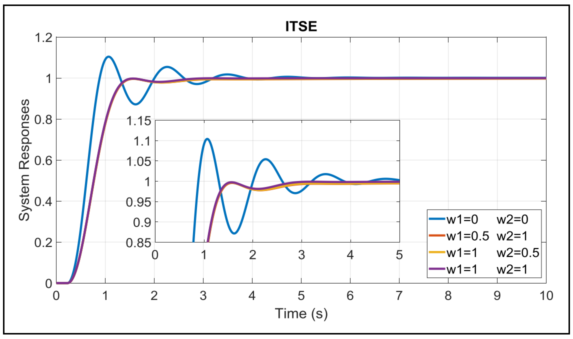


Figure 8. System responses for ITSE objective functions.

In the last part of the study, the PSO algorithm, which is widely preferred in the literature, was compared with the RMO algorithm. The comparison was performed using the SOPDT test system $G_1(s)$ and the process model $P_8(s)$, which was presented as the process model by Hagglund and Aström in [39]. When $\alpha = 0.2$, the transfer function of $P_8(s)$ was obtained as in Eq. 14.

$$P_8(s) = \frac{1 - 0.2s}{s^3 + 3s^2 + 3s + 1} \tag{14}$$

The ITAE fitness function was used for the comparison because it had a minimum steady-state error value. Numerical results of the comparison are presented in Table 4, where TF is the transfer function, and OA is the optimization algorithm.

The comparison results show that RMO algorithm reached the optimal FVs much faster than PSO for all objective functions obtained from both transfer functions. RMO also had the best FVs for all MOFs. However, PSO had better FVs than RMO when $w_1 = 0$ and $w_2 = 0$.

Taken together, proposed MOFs can be used in applications where M_O is undesirable, or a fast system response is required. However, a disadvantage is that MOFs have a higher E_{SS} value than CEBOFs, which causes a bigger FV. On the other hand, RMO has provided a very effective solution for the use of MOFs with the fastest convergence rate for all CEBOFs and MOFs in different transfer functions.

Table 4. Comparison of RMO and PSO algorithm.

TF	w_1	w_2	*OA*	*ITAE*	
				Iter.	*FV*
$G_1(s)$	0	0	RMO	**6**	0.3355
			PSO	45	**0.3344**
	0.5	1	RMO	**3**	**1.9405**
			PSO	23	2.5912
	1	0.5	RMO	**3**	**1.2817**
			PSO	47	1.5155
	1	1	RMO	**6**	**1.7984**
			PSO	30	2.6094
$P_8(s)$	0	0	RMO	**3**	1.8365
			PSO	40	**1.7348**
	0.5	1	RMO	**2**	**5.6615**
			PSO	29	6.6658
	1	0.5	RMO	**4**	**4.5847**
			PSO	38	4.6822
	1	1	RMO	**3**	**5.7191**
			PSO	38	6.8293

5 Conclusion

In this study, a detailed analysis of MOFs was performed. For this purpose, a SOPDT test system was designed in MATLAB/Simulink platform, and the RMO algorithm was employed to tune PID controller parameters (K_P, K_I, and K_D). The obtained results show that all MOFs met the design criteria based on transient and steady-state response characteristics. Among MOFs, ISE with (1, 0.5) seemed to be the best choice for PID controller with the minimum overshoot, steady-state error, and second-best T_R value as well as the second-best FVs. On the other hand, the best FV was obtained with ITSE objective function when $w_1 = 0$ and $w_2 = 0$ for this system.

In terms of directions for future research, the optimization process can be performed using different types of objective functions and input signals. Additionally, the maximum iteration number can be reduced considering the convergence rate of the RMO. Simulation and convergence time can be included in the comparison of optimization algorithms. Also, another optimization algorithm, such as ACO, GA, and CSA, etc., may be used to compare the obtained results. Finally, control signals generated using K_P, K_I, and K_D obtained from optimization algorithms can be compared in further studies.

6 Author contribution statements

In the scope of this study, Doğan Can SAMUK contributed to the formation of the idea, literature review, obtained the simulation results, data analysis and writing the paper. Oğuzhan ÇAKIR contributed to analyses of results, writing and revision of the article.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain an ethics committee approval for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

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