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Reduction of Large Scale Linear Dynamic MIMO Systems Using ACO-PID Controller

Reducción de sistemas MIMO dinámicos lineales a gran escala mediante el controlador ACO-PID

Jafaar M. Daif-Alkhasraji[1], Salam W. Shneen[2], and Mohammed Q. Sulttan[3]

ABSTRACT

The MIMO technique is an essential element in the standards of communication systems (IEEE 802.11n, IEEE 802.11ac, WiMAX, and LTE) because it helps to increase their capacity. This paper employs a model order reduction (MOR) technique with a PID controller, an ACO algorithm, and the ITAE fitness function to reduce the large-scale linearity of the MIMO technique. The numerator and denominator parameters are set by minimizing the ITAE fitness function between the transient responses of the original and the reduced model. The objectives are achieved with the PID controller and the ACO algorithm for the unit step input. The simulation results show a good system performance. The controller performance is presented with regard to the dynamic response in terms of rising time, settling time, and overshoot/undershoot. Moreover, the results of the proposed method are compared with four literature reports for validation purposes. Evaluating the parameters within the time frame and the error values with and without the PID controller and ACO algorithm allowed validating the functioning of the proposed method. Furthermore, the simulation results revealed that the proposed scheme exhibited sufficient robustness and demonstrated a reduction in the time-domain response and error values.

Keywords: LS-MIMO, model order reduction (MOR), PID controller, ant colony optimization

RESUMEN

La técnica MIMO es un elemento esencial en los estándares de sistemas de comunicación (IEEE 802.11n, IEEE 802.11ac, WiMAX y LTE) porque ayuda a aumentar la capacidad del sistema. En este trabajo se utiliza una técnica de reducción del orden del modelo (MOR) con un controlador PID, un algoritmo ACO y la función fitness de ITAE para reducir la linealidad de gran escala de la técnica MIMO. Los parámetros del numerador y denominador se establecen minimizando la función de aptitud de ITAE entre las respuestas transitorias del modelo original y el modelo reducido. Se alcanzan los objetivos con el controlador PID y el algoritmo ACO para la entrada de paso unitario. Los resultados de la simulación muestran un buen rendimiento del sistema. El rendimiento del controlador se presenta con base en la respuesta dinámica en términos de tiempo de subida, tiempo de asentamiento y sobreimpulso y subimpulso. Además, los resultados del método propuesto se comparan con cuatro reportes de la literatura para su validación. La evaluación de los parámetros en el marco temporal y de los valores de error con y sin el controlador PID y el algoritmo ACO permitió comprobar el funcionamiento del método propuesto. Asimismo, los resultados de la simulación revelaron que el esquema propuesto presentaba suficiente robustez y demostraba una reducción de la respuesta en el dominio temporal y de los valores de error.

Palabras clave: LS-MIMO, reducción del orden del modelo (MOR), controlador PID, optimización por colonias de hormigas

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Introduction

Enhancing spectral efficiency is essential, especially in 5G wireless communication systems. In this regard, large-scale systems with multiple inputs and multiple outputs (LS-MIMO) are a promising technology that supports a broad notch of the data for multiple concurrent users, along with the ability to increase spectral efficiency. Furthermore, high-order MIMO can considerably improve the dependability and security of communication systems, obtaining extraordinary locative multiplexing gains, unlike restricted range systems (Ouyang & Yang, 2018; Sulttan, 2019; Han et al., 2020; X. Yang et al., 2020; Dang et al., 2021). Moreover, by increasing the physical antenna size, many intrinsic advantages can be exploited, *e.g.*, channel hardening and increased cell coverage, area, and throughput. This is allowed by high-order MIMO in integration with massive infrastructures such as airport roofs, the walls of theaters and stadiums, and large indoor shopping centers, also providing an extremely reliable technology for 6G systems (Khudhair et al., 2016; Sulttan, 2016). Despite the benefits of LS-MIMO, these advantages come at the price of increasing the complexity of the hardware, which is most notable in signal processing operation for transceivers. Therefore, there is still a need to seek an additional pragmatic, low-complexity reducing algorithm for large-scale systems (Rusek et al., 2012). It is noteworthy that, for point-to-point configurations, the receiver aspect has additional complexity when compared to the transmitter side. For example, the more antennas are employed for the transmitter aspect, the higher the system complexity, which rises exponentially with a huge number of antennas.

[1]Electrical engineer, University of Technology (UOT), Iraq. PhD in Optical Wireless Communication Engineering, Newcastle University, United Kingdom. Affiliation: Lecturer, University of Technology, Electromechanical Engineering Department, Baghdad, Iraq. E-mail: jaafar.m.dhaif@uotechnology.edu.iq
[2]Electrical engineer, University of Technology (UOT), Iraq. PhD in Power Electronics, Huazhong University of Science and Technology (HUST), China. Affiliation: Energy and Renewable Energies Technology Center, University of Technology, Baghdad, Iraq. E-mail: salam.w.shneen@uotechnology.edu.iq
[3]Electrical engineer, University of Technology (UOT), Iraq. PhD in Information and Communications Engineering, Huazhong University of Science and Technology (HUST), China. Affiliation: Assistant professor, University of Technology, Electromechanical Engineering Department, Baghdad, Iraq. E-mail: mohammed.q.mohammed@uotechnoloy.edu.iq

On the other hand, extra attention is paid to the receiver aspect of the MIMO model, as the transmitted data must be provided to several users (Jaldén & Ottersten, 2005; Larsson, 2009). In terms of applications, MIMO has been considered to be one of the crucial technologies in third, fourth, and fifth-generation (3G, 4G, and 5G) wireless communication systems since it offers considerable increases in link range and data rate without additional bandwidth or transmit power increases. Such technologies play an essential role in many applications in communication systems, such as GSM, Bluetooth, WiMAX, WLAN, wireless sensors, portable devices, handheld gadgets, automobiles, smartphones, and many more (Sharma et al., 2022; Bizaki, 2011). Furthermore, in order to provide an acceptable service, the number of antennae must be increased for multi-user scenarios. In this vein, large arrays come with a crucial challenge regarding reliability and computationally effective detection (Lyu et al., 2019). As for analysis or controller design, complicated expressions to simulate physical techniques, which imply complex handling of high-order differential formulas, have inevitably led to low-order designs. Such mathematical formulas could be adopted to provide a sufficient performance. Hence, comprehensive knowledge is required, along with decreasing complexity with simple system designs (Vasu et al., 2012). A considerable amount of literature on designing PID controllers for SISO and MIMO prototypes has been published (Lengare et al., 2012; Labibi et al., 2009; Rajinikanth & Latha, 2012; Hu et al., 2010). One of the critical missions of LS-MIMO technology is to reduce the complexity of dynamic designs. Given that dynamic systems contain many variables, notably many mathematical models, it is hard to adopt a complex mathematical form, since the system works in real time. Additionally, memory capacity requirements must be fulfilled, and quick and reliable results must be obtained based on system design (Juneja & Nagar, 2015; Al-doraiee & Al-Qaraawi, 2013; Muhsen & Raafat, 2021). Therefore, over the past few years, heuristic techniques have been widely employed in the literature to achieve optimal performance regarding the obstacles posed by MIMO controller configurations (Hassanzadeh & Mobayen, 2011; Lones, 2014). The difficulty of controlling the MIMO scheme arises from the disruption occurring in one branch, which entails changes in the other branches. Compared to the traditional methods, such as the Zeigler and Nichols and Cohen and Coon tuning techniques, the heuristic process is free of any mathematical calculations. Much of the current literature on MIMO proposes several heuristic approaches to obtain an optimum performance via tuning approaches, *e.g.*, Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), the Firefly Algorithm (FA), and Ant-Colony Optimization (ACO) (Saroja et al., 2017; Sivakumar et al., 2015; X.-S. Yang, 2009; Daraji & Hale, 2014; AL-Suhail & Miry, 2015; Aziz et al., 2022). It is common knowledge that organizing and executing a controller-based centralized method is a complicated issue when compared to the decentralized method. It is worth adding that, according to the criteria for designing MIMO systems, several methods must be adopted, *i.e.*, the centralized method (Vu et al., 2007), the decentralized method (Lengare et al., 2012; Lones, 2014; Labibi et al., 2009), and optimal controllers with decouplers (Dhanraj & Nanjundappan, 2014; X.-S. Yang, 2009; Liu et al., 2003; Sivakumar et al., 2015).

Suman and Kumar (2020) suggested an approach to reducing the order of large-scale linear dynamical systems based on the Balanced Singular Perturbation Approximation method. This method relies on retaining the dominant system modes and comparatively eliminating the less significant eigenvalues. Furthermore, through the proposed approach, the time and frequency response of the system has shown an excellent match when compared to that of other approaches in the literature. Kumari and Vishwakarma (2019) proposed an algorithm that employs the renovated pole clustering technique and numerator coefficients computed by factor division in order to reduce the order of large-scale linear dynamic MIMO systems. This method is also applicable to linear MIMO systems. Abdullah (2016) proposed a new modified PSO technique to reduce the order of large-scale linear SISO and MIMO systems based on the linear descending inertia weight strategy. The suggested modification of the PSO algorithm provided better characteristics in terms of global search capabilities and fast convergence speed, thus making it effective and efficient. Abu-Al-Nadi et al. (2013) proposed a model order reduction using an invasive weed optimization technique in a linear multivariable system. This technique was applied with the combined advantages of retaining the dominant poles and error minimization. The proposed algorithm showed good results, reducing the 10th order of the MIMO linear model in a practical power system to the 3rd order. Vishwakarma and Prasad (2009) suggested a new mixed method to reduce the order of large-scale linear dynamic MIMO systems. This method uses modified pole clustering to synthesize the common denominator polynomial of the reduced-order transfer function matrix while a GA computes the coefficients of the numerator elements by reducing the integral square error between the time responses and the system elements. The proposed algorithm was illustrated and compared against other reduction techniques, showing good stability when the original high-order system is stable.

In this manuscript, the MIMO PID control is optimized while adopting the ACO algorithm, and it is integrated with ITAE as a fitness function. Two scenarios are analyzed, *i.e.*, open and closed loops with and without the PID controller, aiming to achieve system robustness and reduce the order of the large-scale MIMO system.

PID controller

The most straightforward and attractive solution in industrial control design implementation corresponds to Proportional-Integral-Derivative (PID) controllers, which do not have a complicated configuration and are very efficient. This, in addition to their competitive pricing and low maintenance expenses. Furthermore, through adequate parameter tuning, the dynamic response of a system can be improved by reducing the overshoot while reducing and/or eliminating the steady-state error, consequently enhancing the system's stability (Hanifah et al., 2013; Nagaraj & Murugananth, 2010; Xu, 2010).

The purpose of tuning a PID controller is to ensure that its proportional, integral, and derivative factors are appropriate to the design, aiming to guarantee a closed-loop scheme implementation and a strong arrangement of the control loop over a broad spectrum of functions (Xu, 2010). It is worth mentioning that it is hard to adjust the PID controller without expertise. A manual optimum adjustment could be easy for experts because of the long times needed to obtain ideal operation results. In this regard, every factor in the PID controller could yield different outcomes. For instance, when adjusting to obtain a more satisfactory transient design response, the model response might be delayed under disruption circumstances (Hanifah et al., 2013; Nagaraj & Murugananth, 2010). Such a controller for SISO (Figure 1a) can be expressed mathematically in the time domain as in Prainetr et al. (2019); Oudah et al. (2021).

$$u(t) = k_p\, e(t) + k_i \int_0^t (t)dt + k_d \frac{d}{dt} e(t), \quad (1)$$

where k_p, k_i, and k_d represent the proportion gain factor, the integral gain factor, and the derivative gain, respectively, while e stands for the error and t denotes simultaneous time.

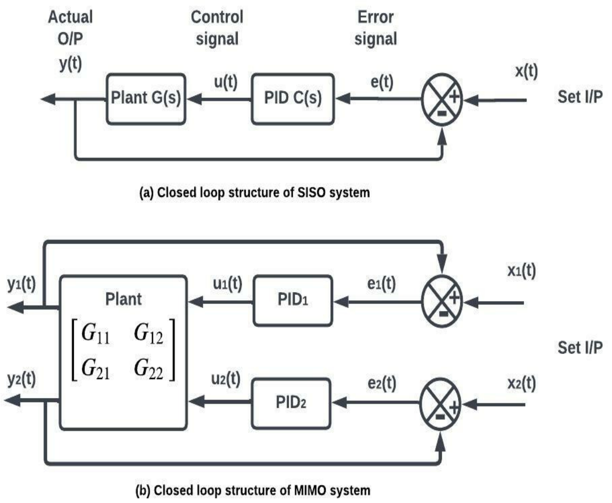

Figure 1. Block diagram of SISO and MIMO controllers
Source: (Prainetr et al., 2019; Oudah et al., 2021)

In the s-domain, the transfer function of Equation (1) takes the form of Equation (2) (Saad et al., 2012).

$$C(s) = \frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s, \quad (2)$$

where $E(s)$, $U(s)$ represent the error and control signals applied to the plant model, respectively. For convenience, it is said that using two SISO schemes to construct a MIMO system is more applicable. Hence, this research adopts a heuristic strategy integrated with PID controller design and the ACO method for considering MIMO approaches. Figure 1b shows a schematic diagram configuration that includes the pair of controllers PID_1 and PID_2. Such a scheme yields the following expressions (Suresh et al., 2017):

$$\text{PID}_1 = k_{p_1} + \frac{k_{i_1}}{s} + k_{d_1} s, \quad \text{(3a)}$$

$$\text{PID}_2 = k_{p_2} + \frac{k_{i_2}}{s} + k_{d_2} s, \quad \text{(3b)}$$

Ant Colony Optimization (ACO)

Scientists have studied the social behavior of insects and animals and simulated them using algorithms. One such technique in the swarm intelligence family is Ant Colony Optimization (ACO) (Hanifah et al., 2013; Nagaraj & Murugananth, 2010; Xu, 2010). This approach has different applications, notably in industrial systems. It was developed by (1991, 1996; ?) and inspired by an empirical implementation conducted by Goss et al. (1989) to characterize ant behavior when it comes to using the shortest trajectories to travel over a binary bridge, which was designed so that one path was longer than the other. The insects were allowed to randomly select the path, with identical ant numbers in each branch. In his experiment, as time went by, it was found that the number of ants using the shortest trajectory was greater than those using the long lane. The reason for this is that, in order to return to the nest earlier, the ants must follow the short route. This, in turn, leads to an extra focus of the pheromone on the fastest time track (Goss et al., 1989).

Figure 2 (Hanifah et al., 2013) depicts the proposed PID controller with ACO. It is noteworthy that all the quantities of each factor were allocated to three different vectors. Moreover, it was assumed that the ants used all vectors as trajectories between the nests by selecting a lane between the terminations (Start-End).

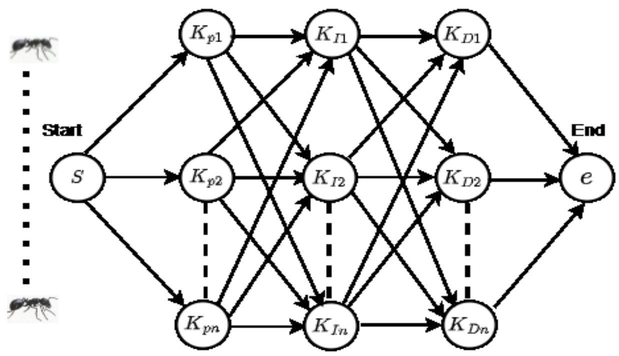

Figure 2. Pictorial description of PID tuning employing ACO for a three-parameter controller
Source: (Hanifah et al., 2013)

When using the ant algorithm, the pheromone is regularly updated at the start of each trajectory between the three nests, aiming to achieve the fastest round with the lowest expense. This work adopted ACO as the tuning approach for the PID controller. In this context, an arbitrary initial value is set as a pheromone for each junction point. The ants then arbitrarily decide the route they want to follow. Additionally, a number of ants are positioned at the start node and at every single iteration in order to determine their solution to the problem, which is known as a *trip*. Using pseudo-random proportional action choice rules, the probability P_{ij} in Equation (4) is computed as the estimated value between two nodes i, j according to two parameters: heuristic and metaheuristic (Prainetr et al., 2019).

$$P_{ij}^k = \frac{\tau_{ij}^{\alpha}(t).\, \eta_{ij}^{\beta}}{\sum\limits_{I \in \mathscr{R}_i^k} \tau_i^{\alpha}(I).\, \eta_{iI}^{\beta}}, \quad (4)$$

where τ_{ij} stands for the pheromone initial value and is updated regularly according to two parameters: α and β; and η represents the reciprocal of the span between the two nodes. The value ($\eta_{ij} = 1/d_{ij}$) directs the allocation of ants to the nodes, preventing them from being excessively far away. The impact of pheromone density on a certain route refers to the direction that the ant adopts, denoted by α, which is a positive value in Equation (4). It is noteworthy that, if $\alpha = 0$, the closest node will be selected every time, whereas, if $\beta = 0$, only the chemical factor (pheromone) tracks recreate on the selection (Prainetr et al., 2019; Chebli et al., 2018).

ITAE

ITAE stands for integrating the multiplication of time by an absolute error. The main feature of this approach is that it has acceptable damped oscillation with a fairly low overshoot value. The expression (5) defines such a method, while Figure 3 exhibits its block diagram.

$$\text{ITAE} = \int_0^\infty t\,|e(t)|\,dt, \tag{5}$$

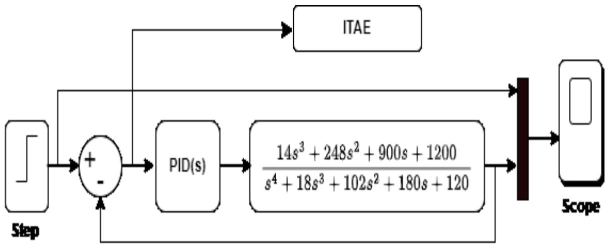

Figure 3. Simulation model showing ITAE with a PID controller
Source: (Prainetr et al., 2019; Chebli et al., 2018)

Methodology

In this section, the procedures of the ACO algorithm are presented in some detail with the aid of the flowchart shown in Figure 4 (Prainetr et al., 2019; Chebli et al., 2018).

According to this Figure, the first step is to assign the initial values of the number of ants, chemical factors, and control parameter constants, such as K_p, K_i, and K_d, using a random variable uniformly distributed over [0, 1]. Then, several ants are positioned at the node, and the values related to the multi-goals is calculated. Afterwards, the consecutive node is selected, and its probability is estimated via Equation (6).

$$P_{(rob)}{}_{ij}^{q}(t) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t).\,\eta_{ij}^{\beta}}{\sum_{I\in\mathscr{R}_i^q}\tau_i^{\alpha}(I).\,\eta_{iI}^{\beta}}, & \text{if } i \in \mathscr{R}^q \\ 0, & \text{if } i \notin \mathscr{R}^q \end{cases} \tag{6}$$

where $j = [p,\ i,\ d]$ is investigatory, and $\mathscr{R}^q$ denotes path impacts of ant q within a specific interval. In the next step, the value of chemical factor $\Delta\tau_{ij}^{q}(t)$ for any iteration t on each route is determined via Equation (7).

$$\Delta\tau_{ij}^{q}(t) = \begin{cases} \frac{L^{min}}{L^q(t)}, & \text{if } i, j \in \mathscr{R}^q \\ 0, & \text{else}, \end{cases} \tag{7}$$

where $L^q(t)$ signifies the total length traveled by the ant q, and L^{min} represents the optimization obtained by a group of ants up to the current iteration.

Note that a high value of α might lead the formula to quickly converge to the sub-optimal route by increasing the

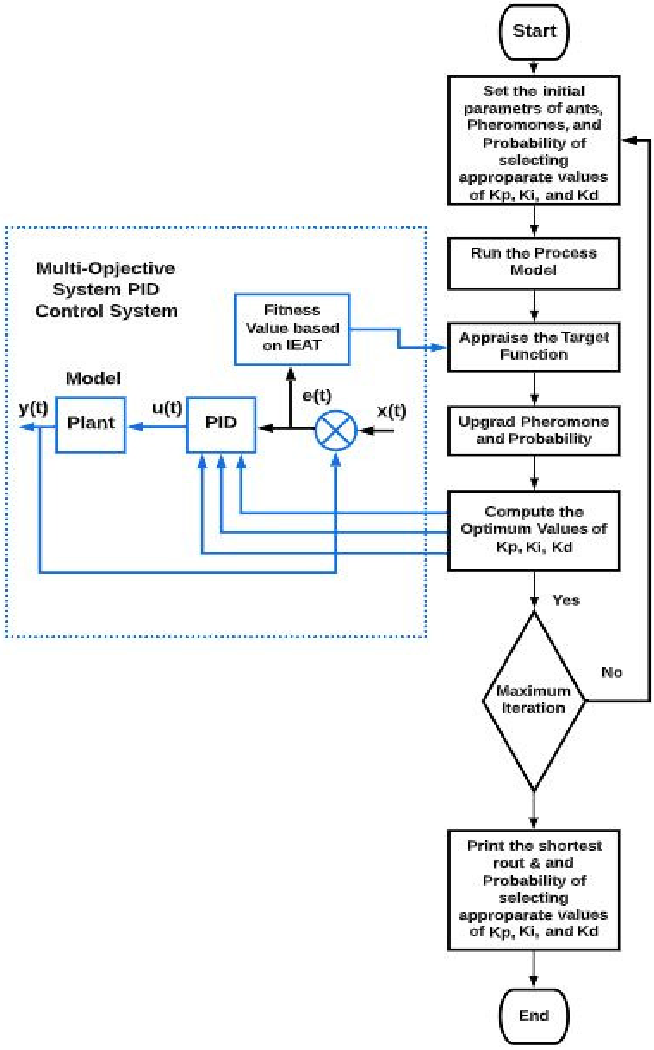

Figure 4. Flowchart for tuning the PID algorithm via ACO for SISO as a single branch of a MIMO scheme
Source: Authors

chemical factor, particularly regarding the initial arbitrary value. For the sake of convenience, the chemical factor concentration was allowed to evaporate in order to prevent early convergence. This, in order to avoid an unlimited increment in chemical factor trails. In other words, a reasonable trade-off between these two factors is required. Thus, the chemical factor is given by Equation (8).

$$\tau_{ij}(t) = \rho\tau_{ij}(t-1) + \sum_{k=1}^{m}\Delta\tau_{ij}^{k}(t), \tag{8}$$

where m denotes the amount of ants, t denotes the iteration, and ρ indicates the rate of chemical factor vaporization in the range of $0 < \rho \leq 1$. Afterwards, as soon as the steady-state zone of the PID controller is solved, the optimal quantities must be explored over a limited zone according to the multi-parameters.

It is well known that closed-loop schemes are commonly evaluated in terms of resilience, preciseness, reliability, and steady-state transition response, to name a few. In this vein, modern technologies demand additional advanced performance criteria, so the time at which errors occur must be considered. This issue has been widely explained in the literature.

Concerning the system's dynamic, this work considers a remarkable performance criterion known as the *Integrated Time Absolute Error standard* (ITAE). This index is widely used since it has higher selectivity when compared to other methods. It is less concentrated on the initial error and prioritizes the system error.

It is worth mentioning that this work was conducted using a Simulink model (MATLAB 2018b). This model entrusted with the the transfer function (TF), the ACO algorithm, and the remarkable performance criterion (ITAE) using codes of the M-file type. The PID controller was also implemented using the Simulink model.

Simulation results and discussions

This section presents and discusses the simulation results. This is done in two directions. The first one is to offer and discuss the results of the open-loop system, comparing them against to those of a closed-loop system with and without control (PID controller and ACO-PID controller). Figure 5 shows the step response of the system in an open loop and in a closed loop.

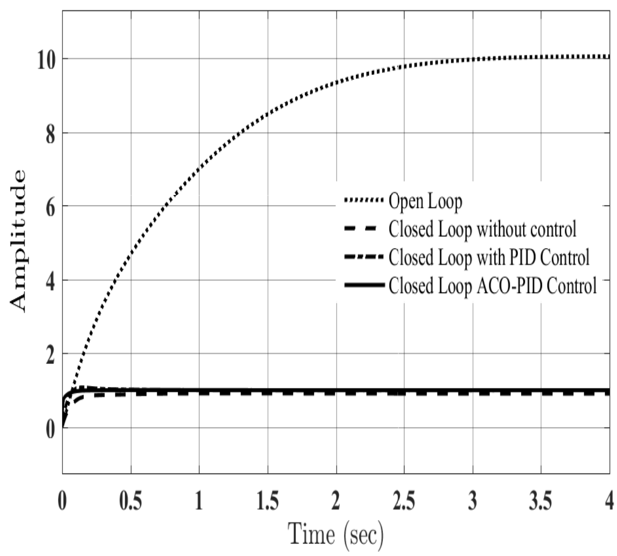

Figure 5. Step response of the system in open and closed loops (with and without control)
Source: Authors

The second direction concerns the results obtained for the system in a closed loop without control and in a closed loop with control (PID controller and ACO-PID controller) Figure 6 shows the step response of the system in a closed loop (with and without control). Of course, all types of the system referred to earlier include the cost function ITAE actions which help to reduce the large scale of a MIMO system.

According to the results shown in Figure 5, there is a large performance gap between the open- and closed-loop systems, as there is no optimization in the former, which is also less reliable. On the contrary, the closed-loop system is optimized and more reliable.

The results of the system without control (Figure 6) show the following: rising time = 0,147 s, overshoot = 0,446%, and undershoot = 1,98%. The parameters of the system with a closed-loop PID controller have K_p = 2, K_i = 12, and K_d =

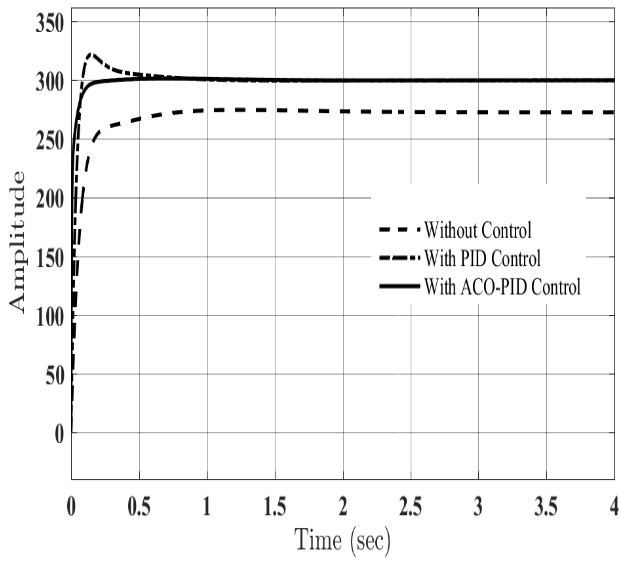

Figure 6. Step response of the closed-loop system with and without control (PID controller and ACO-PID controller)
Source: Authors

0,001. Thus, the results are as follows: rising time = 0,0572 s, settling time = 0,418 s, overshoot = 7,27%, and undershoot = -0,003%. Furthermore, the results obtained for the closed-loop system with the ACO-PID controller, which works with K_p = 4,8, K_i = 9,5, and K_d = 0,11, are as follows: rising time = 0,0441 s, settling time = 0,115 s, and overshoot = 0,132%.

In light of the above, the closed-loop system with the ACO-PID controller responds quickly and is relatively stable (*i.e.*, there is a reduction in the large scale of the MIMO system) in comparison with the system with the PID controller and that without control.

Table 1 compares the response parameters of the proposed method based on step input regarding rising time (s), settling time (s), and overshoot (%) in four ways that have already been described in the literature (Goyal et al., 2019; Saraswat et al., 2015; Parmar et al., 2007; Prasad & Pal, 1991). It can be seen that the combination of ITAE and the ACO-PID controller reduces the response time, effectively reducing the large scale of MIMO techniques.

Conclusion

This work proposes a control method based on the combination of ITAE as a fitness function and ACO as an optimization algorithm with a PID controller. Using MATLAB 2018b, the m.file was dedicated to the transfer function (TF), the ACO algorithm, and the ITAE. Simulink was used to concstruct the PID controller. The desired response model was obtained by changing the three PID parameters (K_p, K_i, and K_d values). The method was validated by measuring time domain parameters such as rising time, settling time, and overshoot/undershoot. According to the simulation results for two scenarios (with and without control), it was concluded that improvements of about 30 and 29,5% can be achieved for response speed and relative stability, respectively. By comparing the results with those in the literature, it can be observed that our proposed approach can provide a remarkable and superior dynamic response. Therefore, it is inferred that this enhanced ratio can reduce the time response of large-scale MIMO systems.

Table 1. Comparison between the proposed method and four techniques introduced in the literature based on step input response parameters

Models	Rising time (s)	Settling time (s)	Overshoot (%)
4^{th} order (proposed method)	0,044 1	0,115	0,132
4^{th} order by Goyal *et al.*	2,26	3,93	0
2^{nd} order by Saraswat *et al.*	2,34	4,09	0
2^{nd} order by Parmar *et al.*	2,19	3,22	1,3
2^{nd} order by Prasad *et al.*	15,4	27,4	0

Source: Authors

CRediT author statement

All of the authors have significantly contributed to the research. Jafaar M. Daif-Alkhasraji was involved in the background research, method development, simulation results, drafting of the paper, and results discussion. Salam W. Shneen contributed to the method proposal, the simulation results, and the data collection and tabulation. Mohammed Q. Sulttan provided guidance during the entire research and the writing process. He supervised the research and provided critical feedback.

References

Abdullah, H. N. (2016). Reduction of large scale linear dynamic siso and mimo systems using modified particle swarm optimization algorithm. In *2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA)* (pp. 166–171).

Abu-Al-Nadi, D. I., Alsmadi, O. M., Abo-Hammour, Z. S., Hawa, M. F., & Rahhal, J. S. (2013). Invasive weed optimization for model order reduction of linear mimo systems. *Applied Mathematical Modelling*, *37*(6), 4570–4577.

Al-doraiee, F., & Al-Qaraawi, H. M. S. H. J., Salih. (2013). Design and implementation of adaptive wavelet network pid controller for aqm in the tcp network. *Iraqi Journal of Computers, Communications, Control and Systems Engineering*, *13*(1), 9–17. https://ijccce.uotechnology.edu.iq/article_78386.html.

AL-Suhail, G. A., & Miry, M. H. (2015). Combining genetic algorithm and direction of arrival for mimo wireless communication system. *Iraqi Journal of Computers, Communications, Control and Systems Engineering*, *15*(2. https://ijccce.uotechnology.edu.iq/article_106699.html).

Aziz, G. A., Jaber, M. H., Sulttan, M. Q., & Shneen, S. W. (2022). Simulation model of enhancing performance of tcp/aqm networks by using matlab. *Journal of Engineering and Technological Sciences*, *54*(4. https://doi.org/10.5614/j.eng.technol.sci.2022.54.4.4).

Bizaki, H. K. (2011). *Mimo systems: Theory and applications*. BoD–Books on Demand. https://doi.org/10.5772/610.

Chebli, S., Elakkary, A., & Sefiani, N. (2018). Ant colony optimization based on pareto optimality: application to a congested router controlled by pid regulation. *Systems Science and Control Engineering*, *6*(1), 360–369. https://doi.org/10.1080/21642583.2018.1509395.

Dang, H. N., Nguyen, H. T., & Nguyen, T. V. (2021). Joint detection and decoding of mixed-adc large-scale mimo communication systems with protograph ldpc codes. *IEEE Access*, *9*, 101013–101029. https://doi.org/10.1109/ACCESS.2021.3097444.

Daraji, A., & Hale, J. (2014). Reduction of structural weight, costs and complexity of a control system in the active vibration reduction of flexible structures. *Smart Materials and Structures*, *23*(9), 095013. https://doi.org/10.1088/0964-1726/23/9/095013.

Dhanraj, A. V., & Nanjundappan, D. (2014). Design of optimized pi controller with ideal decoupler for a non linear multivariable system using particle swarm optimization technique. *International Journal of Innovative Computing, Information and Control*, *10*(1), 341–355. https://api.semanticscholar.org/CorpusID:16599826/.

Dorigo, M., Maniezzo, V., & Colorni, A. (1991). Positive feedback as a search strategy.

Dorigo, M., Maniezzo, V., & Colorni, A. (1996). Ant system: optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, *26*(1), 29–41.

Goss, S., Aron, S., Deneubourg, J., & Pasteels, J. (1989). Self-organized shortcuts in the argentine ant. *Naturwissenschaften*, *76*(12), 579–581. https://doi.org/10.1007/BF00462870.

Goyal, R., Parmar, G., & Sikander, A. (2019). A new approach for simplification and control of linear time invariant systems. *Microsystem Technologies*, *25*, 599–607. https://doi.org/10.1007/s00542-018-4004-1.

Han, Y., Jin, S., Wen, C.-K., & Ma, X. (2020). Channel estimation for extremely large-scale massive mimo systems. *IEEE Wireless Communications Letters*, *9*(5), 633–637. https://doi.org/10.1109/LWC.2019.2963877.

Hanifah, R., Toha, S., & Ahmad, S. (2013). Pid-ant colony optimization (aco) control for electric power assist steering system for electric vehicle. In *2013 IEEE International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)* (pp. 1–5. https://doi.org/10.1109/ICSIMA.2013.6717979).

Hassanzadeh, I., & Mobayen, S. (2011). Controller design for rotary inverted pendulum system using evolutionary algorithms. *Mathematical Problems in Engineering*, *2011*, 1-17. https://doi.org/10.1155/2011/572424.

Hu, W., Cai, W.-J., & Xiao, G. (2010). Decentralized control system design for mimo processes with integrators/differentiators. *Industrial and Engineering Chemistry Research*, *49*(24), 12521–12528.

Jaldén, J., & Ottersten, B. (2005). On the complexity of sphere decoding in digital communications. *IEEE Transactions on Signal Processing*, *53*(4), 1474–1484.

Juneja, M., & Nagar, S. (2015). Comparative study of model order reduction using combination of pso with conventional reduction techniques. In *2015 International Conference on Industrial Instrumentation and Control (ICIC)* (pp. 406–411).

Khudhair, A. A., Jabbar, S. Q., Sulttan, M. Q., & Wang, D. (2016). Wireless indoor localization systems and techniques: survey and comparative study. *Indonesian Journal of Electrical Engineering and Computer Science*, *3*(2), 392–409.

Kumari, A., & Vishwakarma, C. (2019). Order reduction of dynamic systems by using renovated pole clustering technique. In *2019 2nd International Conference on Power Energy, Environment and Intelligent Control (PEEIC)* (pp. 532–537).

Labibi, B., Marquez, H. J., & Chen, T. (2009). Decentralized robust pi controller design for an industrial boiler. *Journal of Process Control*, *19*(2), 216–230.

Larsson, E. G. (2009). Mimo detection methods: How they work [lecture notes]. *IEEE Signal Processing Magazine*, *26*(3), 91–95.

Lengare, M., Chile, R., & Waghmare, L. M. (2012). Design of decentralized controllers for mimo processes. *Computers and Electrical Engineering*, *38*(1), 140–147.

Liu, G., Yang, J., & Whidborne, J. (2003). Multiobjective optimization and control. *Baldock, Hertfordshire,, England: Research Studies Press Limited*, *15*(2), 77–78.

Lones, M. A. (2014). Metaheuristics in nature-inspired algorithms. In *Proceedings of the Companion Publication of the 2014 Annual Conference on Genetic and Evolutionary Computation* (pp. 1419–1422).

Lyu, S., Wen, J., Weng, J., & Ling, C. (2019). On low-complexity lattice reduction algorithms for large-scale mimo detection: The blessing of sequential reduction. *IEEE Transactions on Signal Processing*, *68*, 257–269.

Muhsen, A. N., & Raafat, S. M. (2021). Optimized pid control of quadrotor system using extremum seeking algorithm. *Engineering and Technology Journal*, *39*(6), 996–1010.

Nagaraj, B., & Murugananth, N. (2010). A comparative study of pid controller tuning using ga, ep, pso and aco. In *2010 international conference on communication control and computing technologies* (pp. 305–313).

Oudah, M. K., Sulttan, M. Q., & Shneen, S. W. (2021). Fuzzy type 1 pid controllers design for tcp/aqm wireless networks. *Indonesian Journal of Electrical Engineering and Computer Science*, *21*(1), 118–127.

Ouyang, C., & Yang, H. (2018). *Massive MIMO antenna selection: Asymptotic upper capacity bound and partial CSI.* https://doi.org/10.48550/arXiv.1812.06595.

Parmar, G., Prasad, R., & Mukherjee, S. (2007). Order reduction of linear dynamic systems using stability equation method and ga. *International Journal of Electrical and Computer Engineering*, *1*(2), 244–250.

Prainetr, S., Phurahong, T., Janprom, K., & Prainetr, N. (2019). Design tuning pid controller for temperature control using ant colony optimization. In *2019 ieee 2nd international conference on power and energy applications (icpea)* (pp. 124–127).

Prasad, R., & Pal, J. (1991). Stable reduction of linear systems by continued fractions. *Journal-Institution of Engineers India, Part El, Electrical Engineering Division*, *72*, 113–113.

Rajinikanth, V., & Latha, K. (2012). Setpoint weighted pid controller tuning for unstable system using heuristic algorithm. *Archives of Control Sciences*, *22*(4), 481–505.

Rusek, F., Persson, D., Lau, B. K., Larsson, E. G., Marzetta, T. L., Edfors, O., & Tufvesson, F. (2012). Scaling up mimo: Opportunities and challenges with very large arrays. *IEEE Signal Processing Magazine*, *30*(1), 40–60.

Saad, M. S., Jamaluddin, H., & Darus, I. Z. (2012). Pid controller tuning using evolutionary algorithms. *Wseas Transactions on Systems and Control*, *7*(4), 139–149.

Saraswat, P., Parmar, G., & Bhatt, R. (2015). Application of differential evolution in order reduction of large scale systems. In *4th international conference,icatetr-2015, bkit kota* (pp. 124–127).

Saroja, K., Stefka Sharon, R., Meena, S., & Chitra, K. (2017). Multi-loop pid controller design for distillation column using firefly algorithm. *International Journal of Engineering and Technology (IJET)*, *9*(2), 1404–1410.

Sharma, P., Tiwari, R. N., Singh, P., Kumar, P., & Kanaujia, B. K. (2022). Mimo antennas: Design approaches, techniques and applications. *Sensors*, *22*(20), 7813.

Sivakumar, R., Rajinikanth, V., & Sankaran, D. (2015). Multi-loop pi controller design for tito system: An analysis with ba fa pso and bfo. *Australian Journal of Basic and Applied Sciences*, *9*(16), 249–254.

Sulttan, M. Q. (2016). A new approach of detection algorithm for reducing computation complexity of mimo systems. *Indonesian Journal of Electrical Engineering and Computer Science*, *1*(1), 159–167.

Sulttan, M. Q. (2019). Enhancement of k-best sphere detection algorithm performance in mimo systems. In *IOP Conference Series: Materials Science and Engineering* (Vol. 518, p. 052007).

Suman, S. K., & Kumar, A. (2020). Reduction of large-scale dynamical systems by extended balanced singular perturbation approximation. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 939.

Suresh, A., Meena, S., & Chitra, K. (2017). Controller design for mimo process using optimization algorithm. *International Journal of Pure and Applied Mathematics*, *117*, 163–170.

Vasu, G., Santosh, K., & Sandeep, G. (2012). Reduction of large scale linear dynamic siso and mimo systems using differential evolution optimization algorithm. In *2012 IEEE Students' Conference on Electrical, Electronics and Computer Science* (pp. 1–6).

Vishwakarma, C., & Prasad, R. (2009). Mimo system reduction using modified pole clustering and genetic algorithm. *Modelling and Simulation in Engineering*, *2009*, 1–5.

Vu, T. N. L., Lee, J.-T., & Lee, M.-Y. (2007). Design of multi-loop pid controllers based on the generalized imc-pid method with mp criterion. *International Journal of Control, Automation, and Systems*, *5*(2), 212–217.

Xu, Z. (2010). A novel robust pid controller design method. In *2010 international conference on computer application and system modeling (iccasm 2010)* (Vol. 6, pp. V6–332).

Yang, X., Cao, F., Matthaiou, M., & Jin, S. (2020). On the uplink transmission of extra-large scale massive mimo systems. *IEEE Transactions on Vehicular Technology*, *69*(12), 15229–15243.

Yang, X.-S. (2009). Firefly algorithms for multimodal optimization. In *International Symposium on Stochastic Algorithms* (pp. 169–178).