SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in
Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

A Novel Approach to Microwave Heating Control System: Crow Search Algorithm-Based PID Controllers

Dhidik Prastiyanto[1,*], Esa Apriaskar[1], Ilya Amelia[1], Dimas Alfarizky Ilham[1], Viyola Lokahita Bilqis[1]

[1] Department of Electrical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, 50229, Indonesia

ARTICLE INFO

Article history:
Received 2 October 2024
Received in revised form 3 November 2024
Accepted 9 November 2024
Available online 30 November 2024

Keywords:
Microwave heating system; crow search algorithm; tuning; ARX model; MATLAB simulation

ABSTRACT

Microwave heating technology has been implemented in various fields of life due to its superior advantages over conventional heaters. These advantages have sparked significant interest among researchers to further develop this technology, particularly from control system point of view. One crucial aspect of control system microwave heating development is finding an optimal controller tuning method to control the temperature properly. However, the research on control system tuning for this topic is still in its early stages. The main aim of this article is to utilize a novel approach with the potential to effectively enhance the performance of microwave heating control systems, namely Crow Search Algorithm (CSA). Autoregressive with Exogenous Variables (ARX) is used to simulate the proposed controller and assess its performance. The proposed controller is evaluated through simulations using MATLAB. Based on the fitness value tests, the optimized CSA solution tracks heating patterns well and predominantly produces a relatively small standard deviation of fitness values in the testing of the microwave heating control system. Overall, CSA effectively optimized controller parameters and achieved efficient control for the microwave heating system.

1. Introduction

Leveraging microwave technology has extended across various sectors, encompassing both industrial and household domains [1], for thermal energy needs such as rice cooking [2], thermal sterilization [3], pasteurization, and food drying [4]. Microwave energy can be absorbed by materials and converted into heat, leading to microwave heating [4]. One distinctive advantage of microwave heating over other heating technologies is its ability to heat objects selectively or uniformly in their distribution [5].

Research on microwave heating control systems generally focuses on achieving the desired system response with a specific setpoint for the measured temperature [6]. This involves developing new control methods or modifying existing controllers to improve their performance. Additionally, advancements in microwave heating modeling and control methods indirectly enhance the quality

---

[*] *Corresponding author.*
E-mail address: dhidik.prastiyanto@mail.unnes.ac.id

https://doi.org/10.37934/aram.127.1.110

of products processed using this technology [7]. Consequently, this research primarily centers around managing temperatures within microwave heating setups.

Several researchers have evaluated control methods to determine the most optimal approach. Yuan *et al.*, [1] described various methods for adjusting the power coefficient in a microwave generator employing two distinct types of controllers, namely the Sliding Mode Controller and the Proportional Integral Derivative (PID) Controller. They were compared to determine the best control method to achieve the desired temperature. Another study by Huang and Sites [8] demonstrated that a microwave heating process using a PID controller integrated with optimization algorithms is suitable for food pasteurization at the desired temperature. However, implementing the PID controller in microwave heating is not the only aspect that needs to be considered. Tuning the PID controller's parameters to optimize system performance is a challenging task [9]. Various performance requirements, including high accuracy, energy efficiency, and low cost, make controller parameter tuning crucial for achieving the desired level of satisfaction [10]. In many cases, the use of artificial intelligence particularly metaheuristic algorithms have demonstrated effectiveness in finding optimal parameters for a controller in studies [10-16].

One application metaheuristic algorithm employed as an optimization method is the Genetic Algorithm (GA). Research conducted by Apriaskar *et al.*, [17] showed that GA can be used in microwave heating to detect the most optimal PID parameters, enabling the preservation of specific heating patterns. However, the tuning process of microwave heating systems has not been thoroughly explored using algorithms that are more optimal than GA. Despite the achievement of GA in attaining optimal parameters in prior research, it is important to acknowledge that GA requires meticulous tuning of numerous parameters [18[. The utilization of these numerous parameters can increase the sensitivity of its performance to small variations in parameter values, thereby complicating the process of identifying the optimal optimizer architecture. However, this concern can be addressed by using algorithms with fewer parameters, such as the alternative solution known as CSA introduced by Askarzadeh A [19]. From that article, CSA outperformed Particle Swarm Optimization, GA, and Harmony Search in control applications. CSA is considered to be a promising tuning method that can produce satisfactory results [20]. A study integrating CSA and PID controller was conducted to enhance the DC motor control system in terms of performance [21]. The results showed that adaptive PID tuning with CSA significantly improved DC motor control system in terms of performance. The result is that the system exhibited faster, more stable, and more accurate responses while reducing system errors. CSA has gained significant interest worldwide due to its advantages, such as its simple implementation, few parameters, and flexibility, according to research by Hussien *et al.*, [22]. Based on these advantages, this study used CSA as the optimization method for the PID in the microwave heating control system.

2. Methodology

2.1 Model Microwave Heating Control System

In this article, a microwave heating control system was designed using a model that takes microwave power as input and temperature measurement or probe as output, as depicted in Figure 1. In addition, Yuan *et al.*, [1] mathematical model used the black box approach to create an ARX model of the system's characteristics. Since the system operates in a continuous time frame with input time delay, the equation of the microwave heating model can be formulated as Eq. (1).

$$y(t) = a_1(t-1) + \cdots a_n y(t-n) = b_1 u(t-1) + \cdots + b_m u(t-m) \tag{1}$$

The output signal of the system is represented by $y(t)$, and the input signal is represented by $u(t)$. The Laplace transform of Eq. (1) is given by Eq. (2). The Laplace transform of $A(s)$ and $B(s)$ are provided in detail in Eq. (3) and Eq. (4), respectively.

$$G(s)\frac{B(s)}{A(s)} \tag{2}$$

$$A(s) = 1 + a_1 s + \cdots + a_n s^n \tag{3}$$

$$B(s) = b_1 s + \cdots + b_m s^m \tag{4}$$

The dynamic system in the parameter models can depict the microwave heating control system $a_1(i = 1, \ldots, n)$ and $b_j(j = 1, \ldots, m)$, where both parameters are based on the ARX model. The parameters in Eq. (5) can be obtained from the continuous system form. The details of A(z) and B(z) are provided in Eq. (6) and Eq. (7).

$$A(z)y(t) = B(z)u(t) + e(t) \tag{5}$$

$$A(z) = 1 - 0.3149_{z}^{-1} - 0.3164_{z}^{-2} - 0.1912_{z}^{-3} - 0.1773_{z}^{-4} \tag{6}$$

$$B(z) = 3.97 \times 10^{-5}{}_{z}^{-1} - 1.492 \times 10^{-5}{}_{z}^{-2} + 5.33 \times 10^{-5}{}_{z}^{-3} + 8.983 \times 10^{-5}{}_{z}^{-4} \tag{7}$$

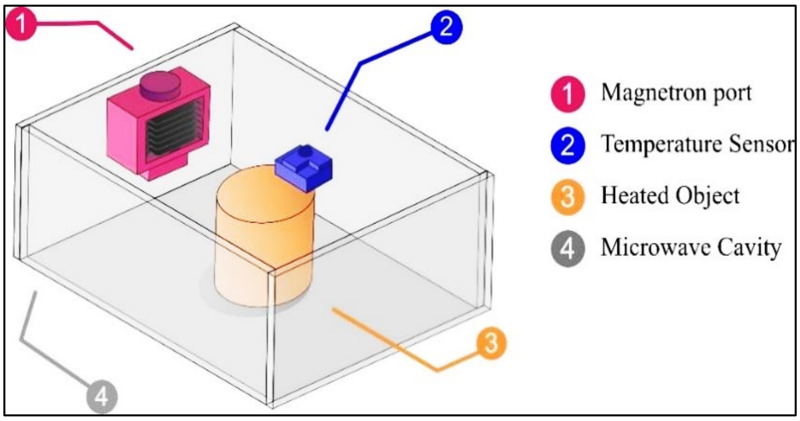

Fig. 1. Microwave heating control system design

2.2 PID Controller

PID control is a versatile and popular control method with effective control in a wide range of systems [23]. This is because of its ease of operation in adjusting the PID control parameters to achieve optimal performance [24]. PID operates by utilizing the feedback output to calculate the system error value, which then serves as an adjuster for the actuator to provide the system output. In the case of this microwave heating control system, the actuator is the magnetron, and PID plays a role in adjusting the magnetron's output with microwave power form. The PID controller has a general equation as shown in Eq. (8), a transfer function equation as shown in Eq. (9), and a discrete form resulting from the Z-transform in Eq. (10).

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \frac{d}{dt} e(t) \tag{8}$$

$$C(s) = k_p + \frac{k_i}{s} + k_d s \tag{9}$$

$$C(s) = k_p + \frac{k_i T_s}{z-1} + \frac{k_d(z-1)}{T_s Z} \tag{10}$$

The PID controller is made up of three main parts: proportional (P), integral (I), and derivative (D), which work together to control the system as shown in Figure 2. Each part has its advantages and disadvantages [25]. The proportional part can speed up the system response but may lead to a high overshoot. The integral part has a similar effect as the proportional part in terms of how it affects rise time and overshoot, but it also eliminates the steady-state error. The derivative part can help to improve stability, especially in systems that are prone to oscillations. The PID controller parameters kp, ki, and kd must be adjusted to match specific environmental conditions in order to achieve accurate control [26]. Therefore, tuning methods for these parameters can greatly assist in optimizing the controller's response, as tested in this article using CSA.

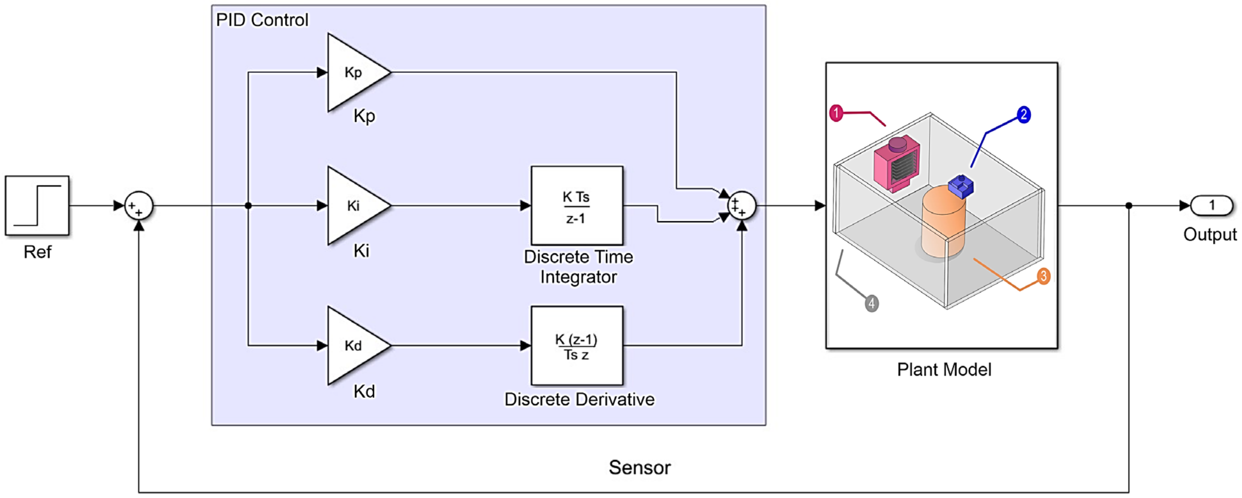

Fig. 2. MATLAB Simulink block diagram of discrete PID controller

2.3 Crow Search Algorithm

CSA is one of the metaheuristic optimization algorithms that adapt to the behaviour of crows. Crows are known for their intelligence in social interactions within their flock when searching, deceiving, and hiding food locations. This ability can be described as exploration in seeking optimal solutions and exploitation of previously discovered solutions [27]. The algorithm's solutions are likened to food hiding locations, where these locations contain parameters to be optimized, enabling CSA to improve the performance of a controller. In this case, CSA is used to tune the PID controller parameters Kp, Ki, and Kd, which will affect the microwave heating control system operation. Figure 3 illustrates the stages of CSA applied to the PID controller.

Some PID implementations emphasize the importance of setting limits for the parameters Kp, Ki, and Kd. This is because setting parameters beyond a wide range can cause the control signal to be unimplementable on electronic devices [28]. This article will adopt the same parameter range, with Kp ranging from 0 to 1000, while Ki and Kd will have a range of 0 to 80. After adjusting the parameters, the determination of CSA parameters, such as flock size, iterations flight length (fl), and awareness probability (AP), is crucial. The scope of the solutions is determined by fl, where larger values widen the scope to be more general, while smaller values narrow it to local areas. Hence, selecting a smaller fl value is essential to obtain the best solution. Similarly, choosing a smaller AP will trigger more new crow positions, providing more new solutions and improving the percentage of better solutions.

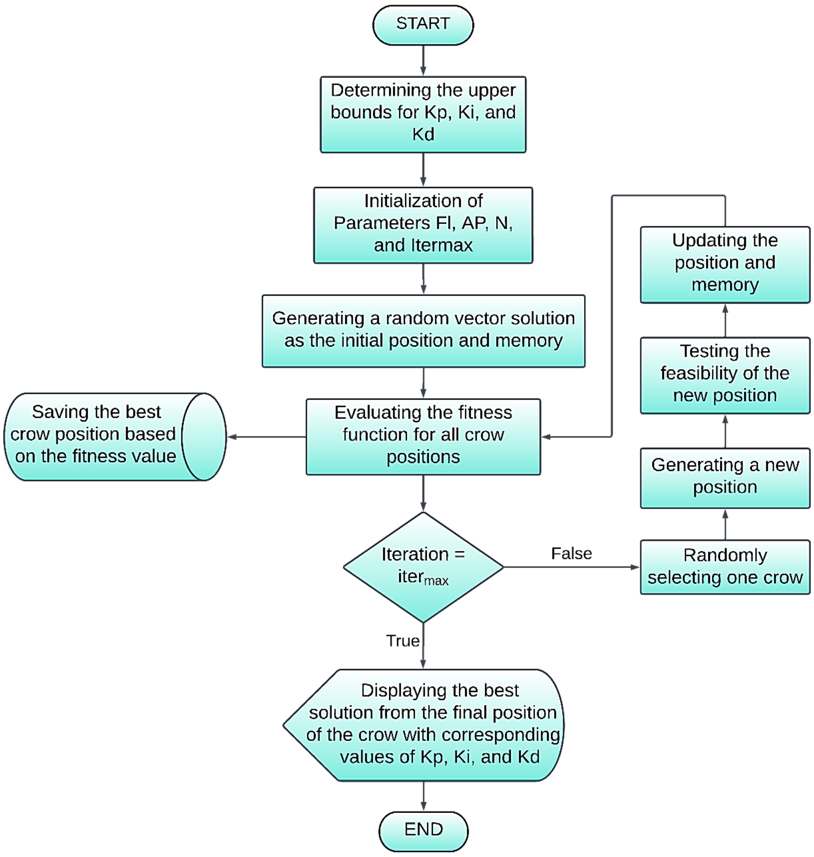

Fig. 3. CSA tuning flowchart for PID controller

In the CSA with the PID Controller, the first step is to determine the upper bounds of Kp, Ki, and Kd. Subsequently, CSA parameters such as fl, AP, N (number of crows in the population), and Itermax (maximum number of iterations) are initialized. Next, the initial positions and memories of the crows are randomly generated as solution vectors. These positions represent combinations of Kp, Ki and Kd values that are being evaluated during the optimization process step. Following this, the fitness function is evaluated for each crow position, measuring the solution quality based on predetermined performance criteria. The crow position with the best fitness value is stored for use in the subsequent iteration.

The iteration loop continues until the number of iterations reaches the specified maximum. In each iteration, the steps involve randomly selecting one crow from the population (j) and generating a new position based on the determined displacement. If a randomly selected crow becomes aware of its followers (r), it creates a new position randomly; otherwise, it creates a new position using Eq. (11).

$$x^{i,iter+1} = \begin{cases} x^{i,iter} + r_i \times fl^{i,iter} \times \left(m^{j,iter} - x^{i,iter}\right) & r_j \geq \ AP^{i,iter} \\ \text{a random position otherwise} & \end{cases} \tag{11}$$

The crows test new positions for their suitability by calculating their fitness value. If a new position has a higher fitness value than the crow's current position, the crow updates its position and memory with the new position. The iteration process will keep running until it reaches the maximum iteration limit or other stopping criteria. The final result of the CSA with the PID controller is the best solution found after all the iterations, which is represented by the final position of the crow and the corresponding values of Kp, Ki, and Kd.

3. Results

3.1 CSA Parameters

The initial step in evaluating the performance of CSA can begin with observing its fitness values. The optimization results of the CSA parameters can be considered better if they primarily show an improvement in fitness values that fluctuate from the previous iterations. Besides ensuring the proper functioning of CSA, determining the minimum range of iteration bounds for testing is also crucial to minimize excessive testing. In this article, three random tests were conducted, each with 100 iterations. From Figure 4, it can be observed that all three tests fitness values work well and reach stability around the 70th iteration. Therefore, setting the iteration at 70 as the minimum iteration bound can be considered sufficient to represent the optimum results of the CSA testing.

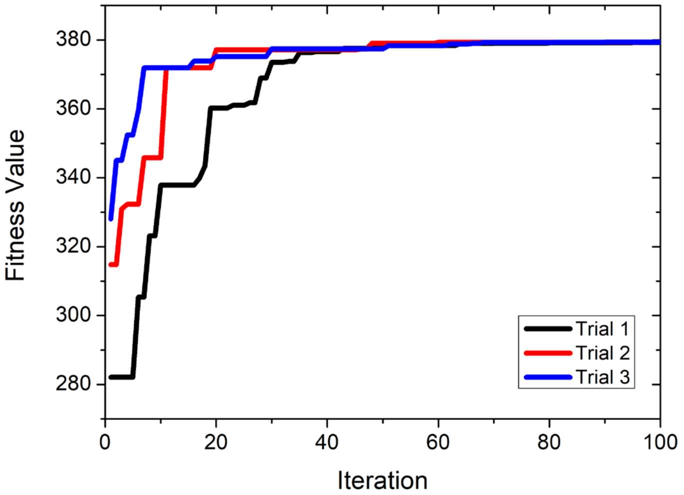

Fig. 4. Fitness value of crow search algorithm

The minimum iteration bound can be used to conduct testing for the most suitable flock size. The testing is carried out by selecting the best flock size from several candidate sizes, namely 10, 20, 30, 40, and 50 based on the fitness values obtained. Table 1 presents all flock size test results conducted during five initial experiments. The researchers disregarded flock sizes 10 and 20 due to their low fitness results, which could hinder the controller from reaching its best performance. The fitness values of 30, 40, and 50 were nearly optimal, but flock size 40 predominantly produces the highest fitness value, so the researchers chose this value for the CSA parameter. Table 2 provides details about the CSA testing parameters applied to the microwave heating control system.

Table 1
Fitness value of flock size test

Test	Flock size				
	10	20	30	40	50
1	378,9960	378,8084	378,5376	379,1404	378,3409
2	374,2528	337,4492	378,5148	379,1852	378,5635
3	378,3421	378,0144	378,6646	378,1755	378,7915
4	378,5004	378,8084	378,7072	379,0427	378,7915
5	372,0444	378,8084	378,3668	378,2422	378,8968

Table 2
CSA parameters

CSA parameter	Value
Flock size	40
Iteration	70
Flight length	2
Awareness probability	0.1

3.2 Best Solutions from Parameter Optimization

After applying the specified minimum bound, twenty tests were conducted for each CSA. The number of tests was directly related to the number of solutions generated. From the twenty tests conducted, the fitness values showed an average difference of approximately 0.41 between each test. The same trend was observed for parameters Kp and Ki with relatively small standard deviation values. However, the parameter Kd exhibited a different behaviour, characterized by a wide variation of values, resulting in a standard deviation of 13.41. Based on this analysis, selecting the best solution, also known as the best individual, can be achieved by considering the highest fitness value. It is expected that the best solution will deliver optimal controller performance in the system. Table 3 provides detailed results of the twenty tuning tests, and Figure 5 displays the graphical representation of the best solutions obtained.

Table 3
Performance of 20 tuned running tests

Specifications parameter	PID parameters			Fitness value
	Kp	Ki	Kd	
Best value	999.73	80.00	62.91	379.19
Standard deviation	1.09	0.21	13.41	0.41
Mean	999.13	79.81	55.33	378.69

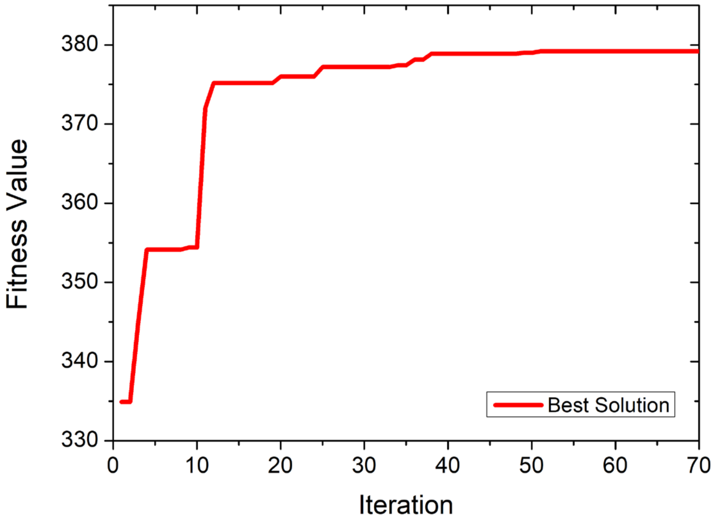

Fig. 5. Best fitness value each iteration

3.3 Performance Evaluation

The previously obtained best solutions also yielded the most optimal PID control parameters. The performance of these parameters in the microwave heating control system must be evaluated to validate them. The system is set with a heating pattern as the setpoint. The pattern starts at 19 degrees Celsius and steadily increases to 45 degrees Celsius for over 250 seconds. The temperature then remains constant at 45 degrees Celsius for a while before increasing again to 75 degrees Celsius until the conclusion of the simulation. Figure 6 demonstrates that the microwave system accurately tracks the desired heating pattern when parameters are optimized using CSA.

If we observe the control signal generated, Figure 7 shows that the controller produces varied control signals. The graph shows that the maximum power output of a microwave heating control system was less than 2000 W, which is the maximum power output of a common magnetron used in microwave heating control systems. This signal indication suggests that the device can be protected from excessive disturbances, ensuring the overall system's protection.

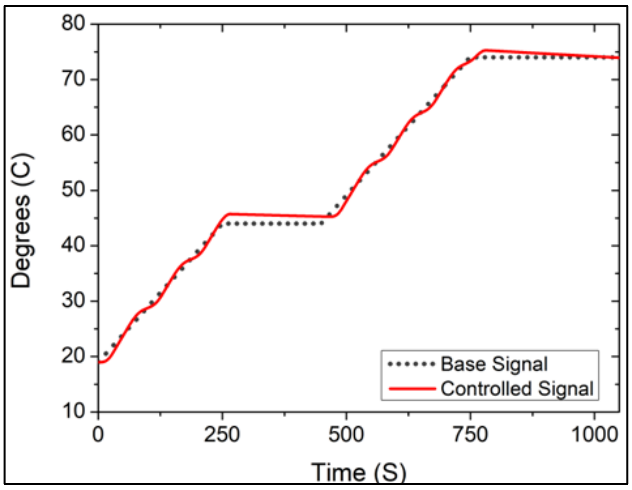

Fig. 6. The output control system response

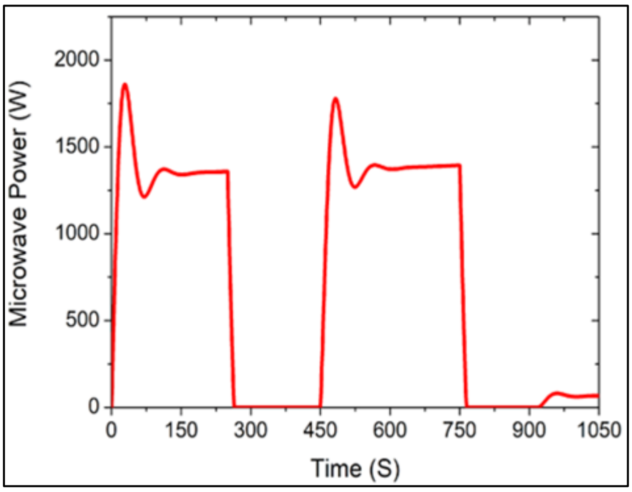

Fig. 7. The control signal generated by CSA

To ensure that the control system performs consistently and produces the desired results, there are several steps for further research. One way to address the limitation of the microwave heating control system is to use the anti-windup method. This method could be implemented in hardware, making it a viable option for practical applications. Considering the relatively high standard deviation of the Kd parameter produced by CSA, algorithm development is another potential recommendation. Some possible developments include optimizing the algorithm, adjusting CSA parameters, and fine-tuning the fitness function.

4. Conclusions

In conclusion, this work presents the utilization of CSA as an optimization algorithm for the PID controller in the microwave heating control system. Before tuning the control parameters, testing, such as iteration bounds and flock size, is necessary to maximize the CSA's solutions. In these tests, using fitness value as an evaluation criterion is crucial both before and during the tuning process. Based on the fitness value testing results, the best solution obtained from CSA optimization works well in the microwave heating control system, with PID control parameter values of 999.73, 80, and 62.91 for Kp, Ki, and Kd, respectively. The research can be further developed from various perspectives, such as controlling formula limitations to prevent the control signal from exceeding the actuator's designated value. Considering optimization approaches, the development of CSA parameter selection, improving the fitness function, or exploring other optimization methods for non-linear control systems could be viable options for future development.

Acknowledgement

The authors are grateful to the Faculty of Engineering UNNES for their financial support of this research project.

References

[1] Yuan, Yupeng, Shan Liang, Qingyu Xiong, Jiaqi Zhong, and Zhihui Wang. "Thermodynamics model based temperature tracking control in microwave heating." *Journal of Thermal Science and Technology* 11, no. 1 (2016): JTST0004-JTST0004. https://doi.org/10.1299/jtst.2016jtst0004

[2] Lakshmi, S., A. Chakkaravarthi, R. Subramanian, and Vasudeva Singh. "Energy consumption in microwave cooking of rice and its comparison with other domestic appliances." *Journal of Food Engineering* 78, no. 2 (2007): 715-722. https://doi.org/10.1016/j.jfoodeng.2005.11.011

[3] Novotny, Miloslav, Jan Skramlik, Karel Suhajda, and Vladimir Tichomirov. "Sterilization of biotic pests by microwave radiation." *Procedia Engineering* 57 (2013): 1094-1099. https://doi.org/10.1016/j.proeng.2013.04.138

[4] Chandrasekaran, S., S. Ramanathan, and Tanmay Basak. "Microwave food processing—A review." *Food Research International* 52, no. 1 (2013): 243-261. https://doi.org/10.1016/j.foodres.2013.02.033

[5] Fulo, Harvey F., Morgan A. Vincent, Albert E. Stiegman, and Gregory B. Dudley. "Cooperative application of conventional and microwave heating." *Asian Journal of Organic Chemistry* 9, no. 6 (2020): 961-966. https://doi.org/10.1002/ajoc.202000157

[6] Li, Jianshuo, Qingyu Xiong, Kai Wang, Xin Shi, Shan Liang, and Min Gao. "Temperature control during microwave heating process by sliding mode neural network." *Drying Technology* 34, no. 2 (2016): 215-226. https://doi.org/10.1080/07373937.2015.1037889

[7] Menéndez, J. A., A. Arenillas, Beatriz Fidalgo, Yolanda Fernández, Leire Zubizarreta, Esther G. Calvo, and José Miguel Bermúdez. "Microwave heating processes involving carbon materials." *Fuel Processing Technology* 91, no. 1 (2010): 1-8. https://doi.org/10.1016/j.fuproc.2009.08.021

[8] Huang, Lihan, and Joseph Sites. "Automatic control of a microwave heating process for in-package pasteurization of beef frankfurters." *Journal of Food Engineering* 80, no. 1 (2007): 226-233. https://doi.org/10.1016/j.jfoodeng.2006.05.019

[9] dos Santos Coelho, Leandro. "Tuning of PID controller for an automatic regulator voltage system using chaotic optimization approach." *Chaos, Solitons & Fractals* 39, no. 4 (2009): 1504-1514. https://doi.org/10.1016/j.chaos.2007.06.018

[10] Joseph, Stephen Bassi, Emmanuel Gbenga Dada, Afeez Abidemi, David Opeoluwa Oyewola, and Ban Mohammed Khammas. "Metaheuristic algorithms for PID controller parameters tuning: Review, approaches and open problems." *Heliyon* 8, no. 5 (2022). https://doi.org/10.1016/j.heliyon.2022.e09399

[11] Triwiyatno, Aris, Sumardi Sumardi, and Esa Apriaskar. "Robust fuzzy control design using genetic algorithm optimization approach: case study of spark ignition engine torque control." *Iranian Journal of Fuzzy Systems* 14, no. 3 (2017): 1-13. https://doi.org/10.22111/ijfs.2017.3238

[12] Oladipo, Stephen, Yanxia Sun, and Zenghui Wang. "Optimization of PID controller with metaheuristic algorithms for DC motor drives." *International Review of Electrical Engineering* 15, no. 5 (2020): 352-381. https://doi.org/10.15866/iree.v15i5.18688

[13] Raza, Yarooq, Syed Faiz Ahmed, Athar Ali, M. Kamran Joyo, and Kushsairy A. Kadir. "Optimization of PID using PSO for upper limb rehabilitation robot." In *2018 IEEE 5th International Conference on Engineering Technologies and Applied Sciences (ICETAS)*, pp. 1-4. IEEE, 2018. https://doi.org/10.1109/ICETAS.2018.8629100

[14] Rajamand, Sahbasadat. "Effective control of voltage and frequency in microgrid using adjustment of PID coefficients by metaheuristic algorithms." *IETE Journal of Research* 68, no. 5 (2022): 3526-3539. https://doi.org/10.1080/03772063.2020.1769509

[15] Acharya, Bishwa Babu, Sandeep Dhakal, Aayush Bhattarai, and Nawraj Bhattarai. "PID speed control of DC motor using meta-heuristic algorithms." *International Journal of Power Electronics and Drive Systems* 12, no. 2 (2021): 822. https://doi.org/10.11591/ijpeds.v12.i2.pp822-831

[16] Vanchinathan, K., and K. R. Valluvan. "A metaheuristic optimization approach for tuning of fractional-order PID controller for speed control of sensorless BLDC motor." *Journal of Circuits, Systems and Computers* 27, no. 08 (2018): 1850123.https://doi.org/10.1142/S0218126618501232.

[17] Apriaskar, E., D. Prastiyanto, M. A. Malik, A. E. Ramadhan, R. Destanto, H. Abdullah, and M. K. Osman. "Microwave heating control system using genetic algorithm-based PID controller." In *IOP Conference Series: Earth and Environmental Science*, 969, no. 1, p. 012060. IOP Publishing, 2022. https://doi.org/10.1088/1755-1315/969/1/012060

[18] Alhijawi, Bushra, and Arafat Awajan. "Genetic algorithms: Theory, genetic operators, solutions, and applications." *Evolutionary Intelligence* 17, no. 3 (2024): 1245-1256. https://doi.org/10.1007/s12065-023-00822-6

[19] Askarzadeh, Alireza. "A novel metaheuristic method for solving constrained engineering optimization problems: crow search algorithm." *Computers & structures* 169 (2016): 1-12. https://doi.org/10.1016/j.compstruc.2016.03.001

[20] Spea, Shaimaa R. "Solving practical economic load dispatch problem using crow search algorithm." *International Journal of Electrical & Computer Engineering (2088-8708)* 10, no. 4 (2020). https://doi.org/10.11591/IJECE.V10I4.PP3431-3440

[21] Alkrwy, Amer, Arkan Ahmed Hussein, Thamir H. Atyia, and Muntadher Khamees. "Adaptive tuning of PID controller using crow Search algorithm for DC motor." In *IOP Conference Series: Materials Science and Engineering*, vol. 1076, no. 1, p. 012001. IOP Publishing, 2021. https://doi.org/10.1088/1757-899x/1076/1/012001

[22] Hussien, Abdelazim G., Mohamed Amin, Mingjing Wang, Guoxi Liang, Ahmed Alsanad, Abdu Gumaei, and Huiling Chen. "Crow search algorithm: theory, recent advances, and applications." *IEEE Access* 8 (2020): 173548-173565. https://doi.org/10.1109/ACCESS.2020.3024108

[23] Abdolrasol, Maher GM, M. A. Hannan, SM Suhail Hussain, and Taha Selim Ustun. "Optimal PI controller based PSO optimization for PV inverter using SPWM techniques." *Energy Reports* 8 (2022): 1003-1011. https://doi.org/10.1016/j.egyr.2021.11.180

[24] Cekdin, Cekmas, Choirul Rizal, Fadilah Husna, and Siti Sailah. "PID Control and Overshoot Elimination: Oscillation Curve Simulation." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 40, no. 1 (2024): 154-163. https://doi.org/10.37934/araset.40.1.154163

[25] Xu, Xian, and Qingling Wang. "Speed control of hydraulic elevator by using PID controller and self-tuning fuzzy PID controller." In *2017 32nd Youth Academic Annual Conference of Chinese Association of Automation (YAC)*, pp. 812-817. IEEE, 2017. https://doi.org/10.1109/YAC.2017.7967521

[26] Dedania, Radhit, and Sang-Woo Jun. "Very low power high-frequency floating point fpga pid controller." In *Proceedings of the 12th International Symposium on Highly-Efficient Accelerators and Reconfigurable Technologies*, pp. 102-107. 2022. https://doi.org/10.1145/3535044.3535060

[27] Wijayaningrum, Vivi Nur, and Novi Nur Putriwijaya. "An improved crow search algorithm for data clustering." *EMITTER International Journal of Engineering Technology* 8, no. 1 (2020): 86-101. https://doi.org/10.24003/emitter.v8i1.498

[28] Jin, Maolin, Jun Young Lee, Pyung-Hun Chang, Min-Gyu Kim, and Sang Hoon Kang. "Automatic gain tuning for robust PID control using time-delay control." *IFAC-PapersOnLine* 50, no. 1 (2017): 4318-4323. https://doi.org/10.1016/j.ifacol.2017.08.856