Comprehensive Analysis and Applications of Fuzzy PID Control

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Abstract. With the advancement of artificial intelligence and enhanced computing power, the integration and application of fuzzy control and other algorithms have garnered significant attention. This paper reviews the innovations and challenges of fuzzy control systems, focusing on the fundamental principles, development history, optimization algorithms, and future development prospects and challenges of fuzzy PID control. Through a comprehensive literature review and case analysis, the advantages and limitations of fuzzy PID control in practical applications are examined, and the impact of various optimization algorithms on its performance is evaluated. The research findings demonstrate that fuzzy PID control holds substantial application potential in managing complex nonlinear systems, particularly when integrated with intelligent algorithms. However, challenges remain, including the complexity of the design and debugging process and the lack of standardized protocols. The study concludes that future research should emphasize algorithm optimization, system integration, and intelligent development to enhance the applicability and efficacy of fuzzy PID control across a broader range of scenarios.

Keywords: Fuzzy pid control, optimization, control system, intelligent control.

1. Introduction

Over the past few decades, fuzzy control systems have garnered significant interest due to their versatility and capacity to manage nonlinearity, uncertainty, and complexity across various applications. Among the diverse forms of fuzzy control systems, fuzzy PID (Proportional-Integral-Derivative) control is a prominent method that combines the benefits of fuzzy logic with traditional PID control. This work aims to provide an in-depth examination of the developments, background, and challenges associated with fuzzy PID control systems.

The early applications of fuzzy logic in control systems are closely linked to the development of fuzzy PID control [1]. Fuzzy logic, which can accommodate imprecise information and simulate human reasoning, offers a practical solution to dynamically adjusting PID parameters using fuzzy sets and rules. Fuzzy PID control integrates the core principles of PID controllers with fuzzy logic to enhance performance in systems where traditional PID controllers may falter. Various optimization algorithms, such as genetic algorithms, particle swarm optimization, and neural networks, have been developed to augment this approach [2, 3]. These hybrid strategies have shown promising results in enhancing control robustness and accuracy.

Despite these advancements, fuzzy PID control systems still face several challenges. One of the main issues is the design and tuning of fuzzy rules and membership functions, typically derived from expert knowledge, making the process time-consuming. Additionally, in real-time applications, the computational complexity associated with fuzzy logic operations poses a significant challenge. When integrating fuzzy PID controllers with emerging technologies such as cyber-physical systems and the Internet of Things (IoT), scalability and interoperability become critical concerns [4].

This review paper delves into the fundamental concepts of fuzzy PID control, tracing its historical evolution and exploring the various optimization strategies employed to enhance its efficiency. It also addresses the potential benefits and challenges that fuzzy PID control systems may encounter in the future, providing recommendations for future research directions and practical applications.

2. Basic Principles of Fuzzy PID Control

2.1. Definition and Functionality of PID Controllers

PID control is a feedback mechanism in the control system, which stands for proportional integral control. Specific control actions on the system are achieved by adjusting the control parameters - proportional parameter K_p, integral parameter K_i, and derivative parameter value K_d. PID controller is the most used controller in industrial control systems and is often used in speed control, temperature control, pressure control and other fields. The structure of conventional control system with PID controller is shown in Fig.1.

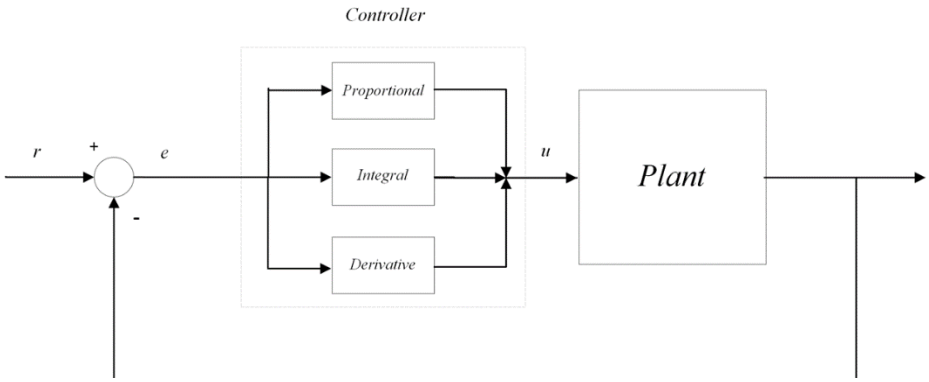


Figure 1. The PID controller's control system architecture (Photo credit: Original)

The commonly used equation of PID controller:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

In this formula $u(t)$ can be recognized as the control output and $e(t)$ shows the error of the system.

2.2. Foundations of Fuzzy Logic Control

Fuzzy logic control is a new control method that is used to handle the logic system which is uncertain and hard to predict. The fuzzy logic originated from the vagueness in the process of human thinking and decision -making. Or uncertainty caused by environmental changes. Fuzzy logic can be used to represent and handle fuzzy concepts, fuzzy relationships and vague judgments, to realize the intelligence and autonomy of the artificial intelligence system. It is also a method of modeling logical reasoning, in which a statement's truth is a degree of truth that goes from zero, which is false, to one, which is true, instead of being binary, with only two options of true or false, as is the case in classical logic. A fuzzy inference system is a function that, rather of employing more abstract mathematical formulas, maps a set of inputs to outputs using rules that are understandable by humans. Fuzzy logic makes this possible. In order to better understand fuzzy logic, first introduce several basic concepts.

Fuzzy Sets: Fuzzy set is a concept that adds uncertainty and imprecision to traditional mathematical sets. It can be utilized to quantify the extent to which an entity possesses a specific attribute. A fuzzy set usually consists of a region called the "core" and a region called the "expansion". The core region represents an entity that fully belongs to the fuzzy set, and the expansion region represents an entity that partially belongs to the fuzzy set.

Fuzzy Relationship: A fuzzy relation is a relationship established between fuzzy sets, which is used to describe the degree of relationship between two fuzzy sets. A "relationship matrix" is a type of mathematical model that can be used to express it. The matrix associated with it is a two-dimensional matrix in which each element represents the relationship between two fuzzy sets.

Fuzzy Rule: Fuzzy rule is used in fuzzy logic and control systems to describe the relationship between an input and another output. Typically, a fuzzy rule has two parts: a condition component

and a result part. The input scenario is described in the condition component, while the output result is described in the result part.

2.3. Mechanisms of Fuzzy PID Controllers

Fuzzy control theory is a bridge between fuzzy logic and control theory. It combines these two parts to deal with control problems of uncertainty and fuzziness. The core concepts of fuzzy control theory include fuzzy system model, fuzzy control strategy and fuzzy system stability. The Fuzzy PID controller is the most important part. A fuzzy controller is a controller used in fuzzy logic and control systems to generate an output signal based on an input signal and fuzzy rules. A fuzzy controller usually includes a data structure called "fuzzy rule base" that keeps track of all fuzzy rules, and an algorithm called a "fuzzy inference engine". The fuzzy rule base stores all fuzzy rules, by using the input signal and the fuzzy rule base, the fuzzy inference engine produces an output signal. Now it comes to the operation process of fuzzy controller. Output signal analysis: For a fuzzy controller, the output signal usually needs to be analyzed into a digital value, a process called "analysis". As shown in Fig 2.

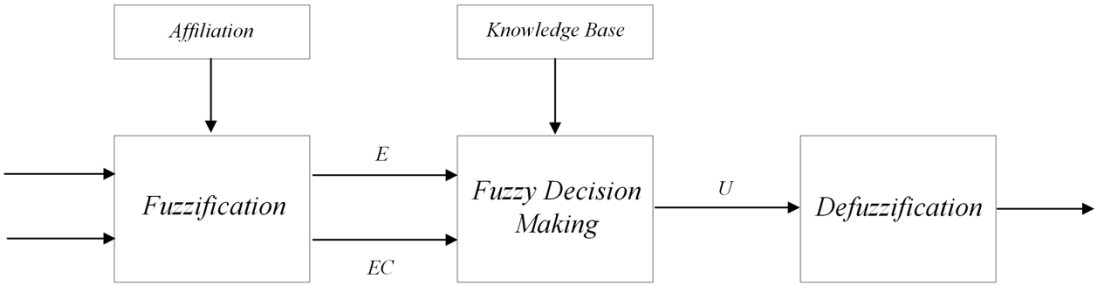


Figure 2. Simplified flow chart of Fuzzy PID Controller (Photo credit: Original)

Input signal processing: For a fuzzy controller, the input signal usually needs to be mapped into a fuzzy set, a process called "quantization".

Fuzzy reasoning: For a fuzzy controller, fuzzy reasoning is the process of mapping input signals to output signals.

3. Development History of Fuzzy PID Control

3.1. Timeline of major milestones and breakthroughs

Lotfi Zadeh published the concept of fuzzy sets in 1965 [5]. In order to overcome the drawbacks of conventional binary logic and address ambiguous and uncertain issues more skillfully, the study defined the fundamental operations of fuzzy logic and fuzzy sets, such as union, intersection, and complement. The widespread use of this theory in control systems, artificial intelligence, and other domains was made possible by the foundation it established.

E.H. Mamdani developed the first fuzzy logic controller in 1975 by utilizing fuzzy set theory as the foundation which greatly promoted industrial production. He confirmed the efficiency of fuzzy logic control and began to use fuzzy logic controllers to regulate the operation of complex systems [6].

In 1981, Zade mentioned in his article that when the input information is uncertain, fuzzy logic control has greater advantages than traditional control, and proposed a better solution to the fuzzy problem [7]. He presented the ideas of fuzzy reasoning and fuzzy variables [8]. Based on this method and the development of computer science, fuzzy logic has been applied to the field of artificial intelligence, which can better handle more complex and dynamic problems.

In 1993, the International Fuzzy Systems Association (IFSA) was formally established, marking the maturity of fuzzy logic control technology and promoting the rapid application and development of fuzzy control technology in other fields.

Between 2000 and 2020, fuzzy control has been applied in intelligent transportation systems, big data and the Internet of Things. Fuzzy logic control can handle complex systems more efficiently, greatly facilitating people's lives. As shown in Table 1.

Table 1. Timeline and Milestone of Fuzzy Control

Time	Milestone and Contribution	
	Milestone	Contribution
1965	Lotfi Zadeh proposed the concept of fuzzy sets.	Defined the fundamental operations of fuzzy logic and fuzzy sets, laying the theoretical foundation.
1975	E.H. Mamdani first applied fuzzy control theory to industrial production and created the first fuzzy logic controller in 1975.	Confirmed the efficiency of fuzzy logic control and applied to complex systems.
1981	Zade improved fuzzy control theory and proposed new concepts.	Applying fuzzy control to the field of artificial intelligence.
1993	IFSA was established.	Promoting the application and development of fuzzy control technology.
2000-2020	Application in the field of intelligence.	Handle complex systems more efficiently.

3.2. Evolution of technology and methodologies

Like other technologies, fuzzy control theory has been continuously innovated over time. Based on the “Fuzzy set” theory, Zadeh enhanced fuzzy logic's capacity to handle ambiguity and fuzzy data in 1981 by introducing the ideas of fuzzy variables and fuzzy reasoning. Made algorithm innovation Including a variety of fuzzy reasoning methods like Mamdani method and Sugeno method to meet different application needs.

During the period of 1990-2000, based on the fuzzy control theory, Scientists have proposed two new methods: Adaptive Fuzzy Control and Fuzzy Neural Network. By introducing an adaptive mechanism, adaptive fuzzy control improves the system's resilience and adaptability by allowing the fuzzy controller to automatically modify parameters in response to changes in the environment. As for Fuzzy Neural Network, it combines neural networks and fuzzy logic to improve the performance of fuzzy systems using the learning capabilities of neural networks [9].

Between 2000 and 2020, Multi-objective optimization algorithm had been developed. Complex Multi-objective issues are solved with it. Related methods such as Genetic Algorithms or Particle swarm optimization, etc.

3.3. Impact on the field of control systems

Fuzzy control has a significant impact on the development of control systems. Before the birth of fuzzy control systems, it was often very difficult to control nonlinear systems, and traditional linear control theory could not solve nonlinear problems well. Therefore, fuzzy control systems provide a good method for dealing with this type of problem.

It is the beginning of machines imitating human thinking and behavior. The most important part of fuzzy logic control is the “Fuzzy set”. This means that it no longer needs to set an exact value at the input but use fuzzy sets instead which greatly reduces the input constraints. At the same time, it also laid the foundation for the later proposal of the neural network algorithm.

Fuzzy control provides the possibility for the realization of multi-model systems. In order to adapt to various operating states while the system is operating, it can model the system into numerous fuzzy subsystems and transition between these subsystems based on the system state. By using this multi-model control approach, the control system's flexibility and adaptability can be increased, making it more capable of handling shifting operational situations and work settings.

In the area of human-computer interaction, fuzzy control is also very useful since it helps robots mimic human thought and decision-making processes more accurately, leading to a more intelligent and natural interface between humans and computers.

4. Common Optimization Algorithms and Application Areas

4.1. Optimization Techniques

Over time, fuzzy control has evolved into advanced optimization algorithms. The most widely used ones are Particle Swarm Optimization and Genetic Algorithm. These two algorithms are still very important today.

Particle Swarm Optimization (PSO): PSO is first proposed by Kennedy and Eberhart in 1955 [10]. It is a type of evolutionary algorithm which starting from a random solution, find the optimal solution through iteration. This algorithm has the advantages of fast convergence and high accuracy. The example of bird population is used to explain the principle of PSO in the article of Kennedy and Eberhart. Fig. 3 shows a simplified flowchart to briefly explain the PSO principle.

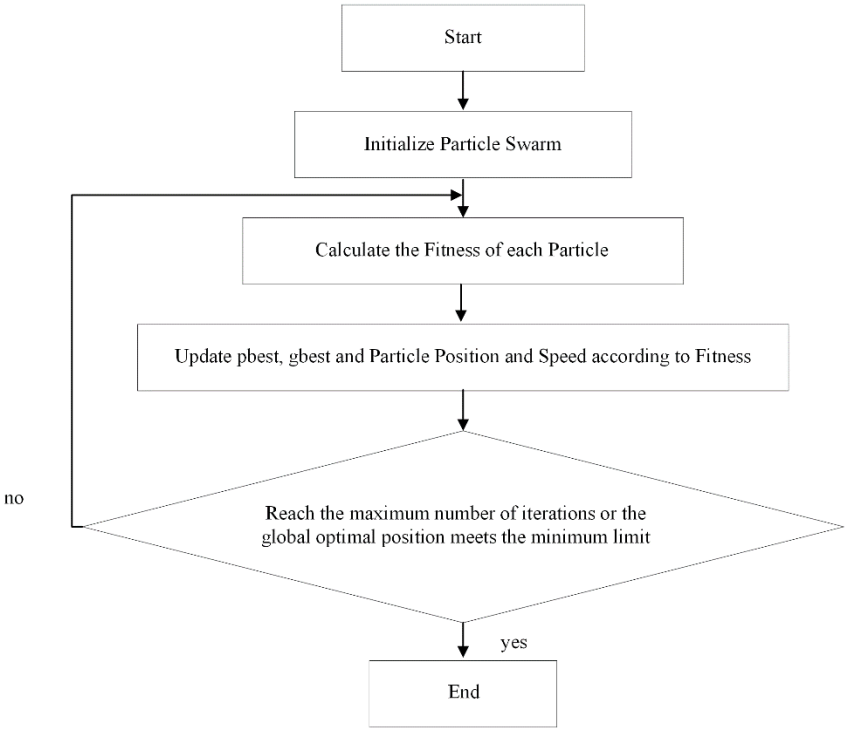


Figure 3. Simplified Flowchart of PSO (Photo credit: Original)

PSO has two basic formulas: Speed update formula and Location update formula.

$$v_i^t = wv_i^{t-1} + c_1 r_1 (pbest_i^{t-1} - x_i^{t-1}) + c_2 r_2 (gbest_i^{t-1} - x_i^{t-1}) \quad (2)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (3)$$

In the formula, v represents the speed, x is the location and w is the inertia factor, c_1 and c_2 stands for learning factor. $pbest$ is the individual optimal position, $gbest$ is the global optimal position.

Genetic Algorithm (GA): GA is an optimization method founded in genetics and natural selection.

Combining GA with fuzzy controllers can globally optimize fuzzy control rules and get rid of the limitations of fuzzy control rules from human experience. GA was proposed by J.H.

Holland in 1992. GA usually go through several parts: encoding, initialization, genetic operation, and decoding to select the optimal solution [11]. The most important genetic operations include crossover, mutation, and inversion. Fig. 4 illustrates the main process of GA.

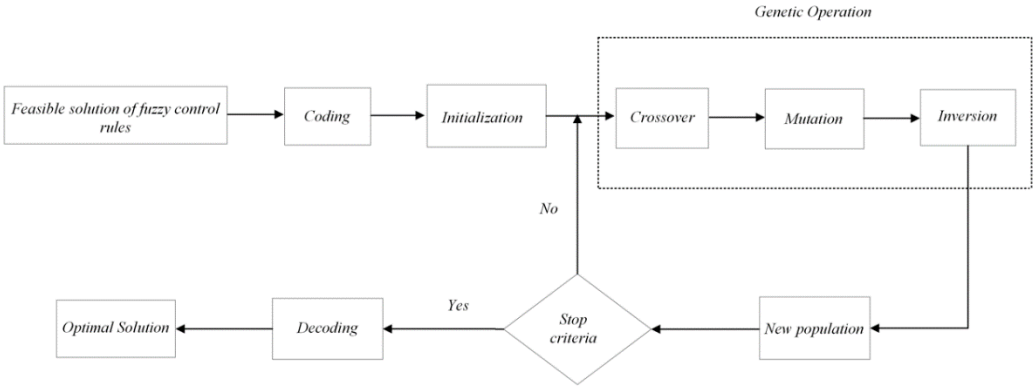


Figure 4. GA Flowchart (Photo credit: Original)

The crossover operation is used to generate new offspring. Common crossover methods consist of both two-point and single-point. In addition, different crossover algorithms are derived for specific situations such as heuristics crossover and simulated binary crossover (SBX) and heuristic normal distribution crossover operator [12]. This paper focus on the basic theory. Therefore, the formula for single point crossover is as follows:

$$Offspring_1 = (Parent_1[0:k], Parent_2[k:n]) \tag{4}$$

$$Offspring_2 = (Parent_2[0:k], Parent_1[k:n]) \tag{5}$$

Where k is the intersection and n is the chromosome length.

Mutation operations are used to maintain the diversity of the population. Common methods include bit flip mutation, etc. The formula for bit flip mutation is as follows:

$$Gene_i = \begin{cases} 1, & if\ Gene_i = 0 \\ 0, & if\ Gene_i = 1 \end{cases} \tag{6}$$

4.2. Application in Temperature Control

In many environments, maintaining a stable temperature is critical for comfort, energy efficiency and safety. Traditional PID control system has several disadvantages, for example there are a lot of strict limitations like not effective for nonlinear, time-varying, uncertain systems and requires extensive debugging when handle complex systems. Conventional temperature control systems, such as switching thermostats or PID controllers, can sometimes lead to oscillations, overshoots or slow response times.

Fuzzy PID control can provide perfect solution for this problem. It has strong adaptability which means that maintain relatively stable performance in the face of changes in system parameters or changes in the environment. Then better robustness and high activity is also the strength in temperature control. Fuzzy Logic Controllers (FLCs) can provide a smoother, more adaptive response, especially in environments with complex and non-linear thermal dynamics. Fig. 5 is the basic working process of fuzzy PID control working in temperature control systems.

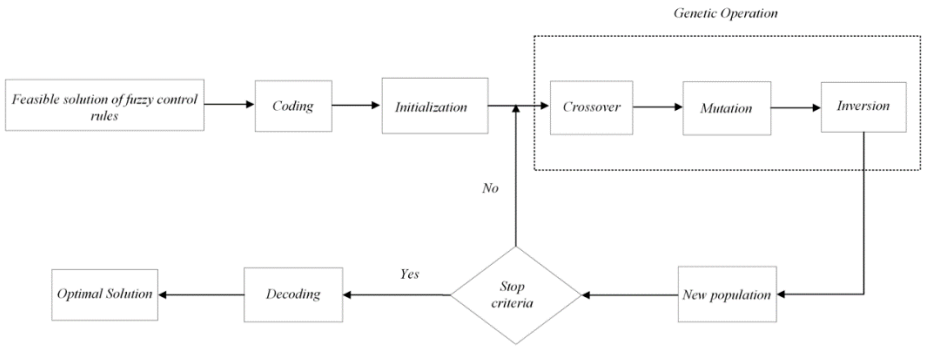


Figure 5. Temperature Control System using Fuzzy PID Control (Photo credit: Original)

Nowadays, fuzzy control has improved in the temperature control system. For example, Wei Jiang and Xuchu Jiang come up with the new fuzzy self-tuning PID algorithm in order to control temperature which improves the efficiency of temperature control and can be used in complex temperature transformation situation [13].

4.3. Robotics and Automation

In the realm of automation and robotics, there is an often-utilized application. For robotics, fuzzy logic is widely used to plan a route and avoid obstacles. The fuzzy controller can deal with the uncertainty of the sensor data and ensure that the robot navigates independently in a complex environment. Traditional mobile robots usually need two fuzzy controllers, but Masmoudi proposed that under the condition that it does not reduce the accuracy, only one fuzzy controller can achieve the function of robot navigation and obstacles [14].

Similarly, the application of fuzzy control and automation is gradually mature. Fuzzy control in industrial automation is mainly reflected in process control, motor control and intelligent manufacturing. For motor control, in 1996 Guillemin introduced a method that fuzzy logic in the standard microcontroller, the motor speed is adjusted by the implementation of the motor current to adjust the motor current. After continuous innovation, the technology of fuzzy control motor control has gradually matured. For intelligent manufacturing, adaptive control and production process optimization are accomplished using fuzzy control. The system is capable of dynamically adjusting production parameters to enhance both production efficiency and product quality through the integration of sensor data and fuzzy logic algorithms.

5. Future Prospects and Challenges

Fuzzy control technology has made great progress since the 1990s and has derived efficient algorithms such as particle swarm optimization and genetic algorithm. Fuzzy control technology has become mature, but the design and debugging process of fuzzy control systems is still too complicated, especially when using fuzzy control to process multivariable and nonlinear systems. In practical applications, although the IFSA organization has been established, there is still no unified standard and tool in actual industrial production, which leads to compatibility issues. In particular, the compatibility issues between traditional control systems and fuzzy control systems. In addition, people's pursuit of high performance has also increased the cost and technical requirements of fuzzy control implementation.

Although there are still many challenges, fuzzy control technology has a promising development in the future:

Integrate artificial intelligence and machine learning technologies to improve the accuracy and efficiency of fuzzy control in complex dynamic environments [15].

Fuzzy control technology can be applied on the Internet of Things and a new round of industrial innovation in the future [16]. For example, it can be applied in the fields of intelligent manufacturing, intelligent transportation, etc. This is because fuzzy control technology has the ability to process a large amount of sensor data while maintaining high accuracy and good performance.

Develop adaptive fuzzy control technology to enable fuzzy controllers to maintain good performance in dynamic and complex environments.

6. Conclusion

This study provides a comprehensive review of fuzzy PID control systems, highlighting key advancements and insights. Fuzzy PID controllers blend fuzzy logic with traditional PID principles, enhancing the performance of nonlinear and uncertain system management. Integrating optimization techniques such as neural networks, genetic algorithms, and particle swarm optimization significantly boosts controller efficiency and regulation. These hybrid systems prove invaluable in various

industrial applications due to their exceptional control accuracy and robustness. The review underscores the importance of fuzzy PID control systems in modern control engineering. These systems offer a more adaptable and flexible approach, especially in complex and uncertain environments, improving the functionality of current control systems and unlocking new industrial possibilities in robotics, autonomous vehicles, and smart manufacturing.

Fuzzy PID control systems are poised for significant growth and innovation. With ongoing research, they hold great promise for integrating artificial intelligence, the Internet of Things, and industrial innovation in intelligent manufacturing. In summary, fuzzy PID control systems are a dynamic and evolving field with substantial potential to address contemporary control challenges. By combining fuzzy logic with PID principles, these systems provide robust solutions for various applications. Continued research and innovation are essential to overcoming current limitations and fully realizing the potential of fuzzy PID control in the future.

References

[1] Zadeh LA. Fuzzy sets. Information and Control. 1965; 8 (3): 338-53.

[2] Mamdani EH, Assilian S. An experiment in linguistic synthesis with a fuzzy logic controller. International Journal of Man-Machine Studies. 1975; 7 (1): 1-13.

[3] Zadeh LA. Fuzzy sets as a basis for a theory of possibility. Fuzzy Sets and Systems. 1978; 1 (1): 3-28.

[4] Zadeh LA. Outline of a new approach to the analysis of complex systems and decision processes. IEEE Transactions on Systems, Man, and Cybernetics. 1973; (1): 28-44.

[5] Abou Omar MS, Khedr TY, Abou Zalam BA. Particle swarm optimization of fuzzy supervisory controller for nonlinear position control system. In: 2013 8th International Conference on Computer Engineering & Systems (ICCES). IEEE; 2013. p. 138-45.

[6] Kennedy J, Eberhart R. Particle swarm optimization. In: Proceedings of ICNN'95-International Conference on Neural Networks. Vol. 4. IEEE; 1995. p. 1942-8.

[7] Katoch S, Chauhan SS, Kumar V. A review on genetic algorithm: past, present, and future. Multimedia Tools and Applications. 2021; 80: 8091-26.

[8] Wright AH. Genetic algorithms for real parameter optimization. In: Foundations of Genetic Algorithms. Vol. 1. Elsevier; 1991. p. 205-18.

[9] Eshelman LJ, Caruana RA, Schaffer JD. Biases in the crossover landscape. In: Proceedings of the Third International Conference on Genetic Algorithms. 1989. p. 10-19.

[10] Zhu, X., Xu, H., Zhao, Z.. An Environmental Intrusion Detection Technology Based on WiFi. Wireless Personal Communications, 2021, 119 (2), 1425-1436.

[11] Jiang W, Jiang X. Design of an intelligent temperature control system based on the fuzzy self-tuning PID. Procedia Engineering. 2012; 43: 307-11.

[12] Omrane H, Masmoudi MS, Masmoudi M. Fuzzy logic based control for autonomous mobile robot navigation. Computational Intelligence and Neuroscience. 2016; 2016 (1): 9548482.

[13] Guillemin P. Fuzzy logic applied to motor control. IEEE Transactions on Industry Applications. 1996; 32 (1): 51-6.

[14] Radanliev P. Artificial intelligence and quantum cryptography. Journal of Analytical Science and Technology. 2024; 15 (1): 4.

[15] Zhu, X., Guo, C., Feng, H., Huang, Y., Feng, Y., Wang, X., & Wang, R. A Review of Key Technologies for Emotion Analysis Using Multimodal Information. 2024, Cognitive Computation, 1-27.

[16] Rawat DB, Brecher C, Song H, Jeschke S. Industrial Internet of Things: Cybermanufacturing Systems. Cham, Switzerland: Springer; 2017.