

# A Comprehensive Review of Artificial Intelligence and Machine Learning in Control Theory

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**Abstract:** Traditional control methods, such as proportional-integral-derivative (PID) controllers and linear-quadratic regulators (LQRs), have proven effective for linear and well-modeled systems. However, these methods often perform poorly in nonlinear, complex and dynamic environments. The paper aims to investigate the modern control systems by integrating artificial intelligence (AI) techniques, such as machine learning (ML), reinforcement learning (RL), deep learning, and fuzzy logic, to enhance their adaptive, robust, and predictive capabilities. And it reviews the literature and analyzes AI integration in control systems. The proposed strategies include supervised learning for trajectory optimization and fault detection, reinforcement learning for optimal control in dynamic environments, neural networks for complex nonlinear function approximation, and fuzzy logic for handling uncertainty and imprecise inputs. AI techniques significantly enhance the ability to tackle nonlinear problems and dynamic changes, demonstrating superior performance in applications like self-driving cars adapting to various road conditions and optimal energy distribution in smart grids. Despite the challenges of computational complexity, scalability, and the safety and reliability in the implementation of interpretable AI models, this paper suggests that hybrid approaches combining traditional control and AI techniques, along with the evolution of interpretable AI and convergence with quantum control, hold great promise for advancing AI-driven control systems.

**Keywords:** Artificial Intelligence, Machine Learning, Reinforcement Learning, Adaptive Control.

## 1. Introduction

Traditional control systems primarily depend on classical approaches like proportional-integral-derivative (PID) controllers and linear-quadratic regulators (LQRs). Despite their efficacy in managing linear and well-modeled systems, these approaches frequently exhibit limitations when confronted with nonlinear, uncertain, and dynamic environments. [1]. For example, in the control of self-driving cars, complex traffic situations and variable environmental conditions pose a serious challenge to traditional control strategies. In order to solve this problem, the introduction of artificial intelligence (AI) provides new perspectives and possibilities for addressing this challenge in control systems. Techniques such as machine learning, neural networks, and reinforcement learning empower these systems to learn from historical data, predict future states, and achieve real-time adaptation. This learning capability, acquired through interaction with the environment, establishes the

foundation for designing more flexible and efficient control strategies in situations where the system dynamics remain partially understood [2-3]. This paper aims to provide an in-depth analysis of the role of artificial intelligence in modern control systems, particularly highlighting its innovative potential to enhance traditional methods. Through a systematic review of classical and modern control theories, it explores AI applications in adaptive, robust, and predictive control, hence emphasizing its significance in practical problem-solving.

## 2. Integration of Control Theory and Artificial Intelligence

### 2.1. Fundamentals of Control Theory

Classical control theory has long been dominated by methods such as PID controllers, which adjust parameters by monitoring the error between system inputs and outputs. While these methods perform well when dealing with linear systems, their applicability is limited in dynamic environments as the system model changes [4]. Although techniques such as LQR and H-infinity control can improve control, these methods also rely on accurate system modeling, making it difficult to quickly adapt to the dynamics of nonlinear systems [5]. Modern control theory introduces state-space models and optimal control strategies, which are more suitable for multivariable systems with time-varying dynamics. However, even these advanced modern control methods may still face challenges when dealing with complex high-dimensional systems that require real-time adaptability. In addition, traditional methods can also encounter difficulties in high-uncertainty environments because they require prior definition of the system's dynamic model. Artificial intelligence effectively addresses these issues by enabling control systems to learn and adapt based on real-time data [1][6].

### 2.2. Related Artificial Intelligence Technologies

AI techniques enhance the performance and robustness of control systems, particularly through machine learning. Supervised learning uses known data for output predictions, excelling in trajectory optimization and fault detection, especially in applications like space control, as noted in the study *Survey of Machine Learning Techniques in Spacecraft Control Design* [3]. Moreover, supervised learning plays a crucial role in troubleshooting complex control systems, ensuring safety and reliability. Reinforcement learning, distinct from supervised learning, derives optimal strategies from environmental feedback, rendering it crucial for dynamic settings like self-driving vehicles and drones [7]. Neural networks, particularly deep learning, are essential for nonlinear systems, effectively approximating complex functions and optimizing spacecraft maneuvers under uncertainty. In robotics, they adapt to multiple dynamic inputs [8]. Fuzzy logic effectively manages uncertain inputs, facilitating continuous parameter tuning for flexible industrial control [9]. Its integration with AI enhances real-time adaptability in dynamic environments. Evolutionary algorithms, such as genetic algorithms and particle swarm optimization, optimize control systems in adaptive settings by mimicking natural evolution. For example, genetic algorithms improve locomotion strategies in robotics [10]. These techniques frequently complement classical control methods, resulting in hybrid systems that merge AI flexibility with traditional stability [5].

## 3. Applications of Artificial Intelligence in Adaptive and Predictive Control

### 3.1. Artificial Intelligence for Adaptive and Robust Control

Adaptive control systems are designed to modify their control parameters in response to fluctuations in environmental conditions or system dynamics. Integrating AI greatly enhances these systems by enabling real-time behavioral adjustments without a pre-established model. Techniques like

reinforcement learning and genetic algorithms refine control strategies based on feedback from the environment, which enable the system to learn from experience and adjust control actions accordingly. For example, in soft robotics, machine learning techniques are used to improve the adaptability of robots functioning in unstructured environments. These systems rely on sensory feedback to modify their behavior, enabling them to perform dynamic tasks with increased flexibility [11]. Similarly, deep reinforcement learning has been effectively implemented in managing complex quantum states in quantum control systems, improving the adaptability of these systems in high-dimensional, uncertain environments [12]. Robust control systems are oriented toward sustaining system performance despite disturbances or uncertainties. AI-driven robust control techniques include, but are not limited to, model-free reinforcement learning, which enhances the fault tolerance of the system by learning how to compensate for unknown disturbances. In particular, this has proved to be a very effective strategy in autonomous flying drones, enabling them to maintain flight in the face of changing wind conditions or unexpected obstacles. And these AI-driven techniques facilitate more flexible and resilient control strategies in uncertain environments [13].

### **3.2. Artificial Intelligence for Predictive Control**

Model Predictive Control is a broad category of control methods where control action is determined by the prediction of future system states and the determination of optimal control action for the purpose of achieving desirable outcomes. However, conventional model predictive control methods are normally challenging to apply on nonlinear and time-varying systems since they highly rely on accurate system modeling. AI techniques used in deep learning and reinforcement learning are integrated with MPC with the purpose of offering robust predictive capability to the latter [14]. Accordingly, with the application of AI to the functionality of MPC, control systems can deal with challenging dynamic environments where system states are difficult to predict. In energy systems, for instance, AI-enhanced MPC has been applied to optimize power grid management for better energy distribution along with ensuring the stability of the system [6]. Recently, model predictive control enhanced by AI has been employed in soft robotic systems, allowing them to autonomously adapt to complex deformations and environmental changes in real time [11]. Integrating AI into predictive control systems has demonstrated effectiveness in inherently dynamic, time-varying environments. Reinforcement learning strengthens model predictive control by allowing systems to learn from their surroundings and adapt predictions based on real-time data [14]. This synergy offers a robust strategy for managing complex systems that demand agility and timely decision-making.

### **3.3. Reinforcement Learning in Control Systems**

Reinforcement learning is recognized as one of the most effective AI techniques for optimizing control systems in dynamic and uncertain environments. Unlike traditional control methods that depend on predefined models, reinforcement learning enables systems to learn through trial and error, making it particularly suitable for scenarios where system dynamics are unknown or subject to change [15]. In the context of self-driving cars, reinforcement learning enhances navigation and control by allowing the system to adapt through interactions with its environment. This capability enables self-driving vehicles to respond to new road conditions, avoid obstacles, and make real-time decisions that optimize both safety and efficiency [16]. Another notable application of reinforcement learning is in aerospace, specifically for fluid dynamics control. Here, RL systems achieve significant optimization by learning from simulations and real-time data, thereby enhancing overall system performance [17]. Moreover, reinforcement learning proves effective in managing nonlinear control systems where standard methods often fail. In complex high-dimensional systems, such as quantum control, RL has been successfully employed to optimize control actions in the presence of noise and

uncertainty, facilitating the manipulation of intricate quantum states and improving quantum system performance [18].

## 4. Artificial Intelligence in Multi-Agent and Complex Control Systems

### 4.1. Artificial Intelligence for Multi-Agent Control Systems

Multi-agent control systems consist of multiple interacting agents, each equipped with its own control system. AI techniques, particularly multi-agent reinforcement learning, enhance their ability to operate effectively in a decentralized environment. That is an important feature for applications such as swarm robotics, where multiple robots have to coordinate their actions to accomplish a common goal. AI techniques have been applied to both the cooperative as well as competitive interactions among these agents so that the systems can balance the needs of the individual agents against the overall objectives of the system [19]. Moreover, AI-driven multi-agent systems optimize energy distribution in smart grids by coordinating various actions from different power sources. This coordination enables real-time balancing of supply and demand while enhancing energy efficiency and ensuring system stability. The ability of AI to manage decentralized control systems is vital in these contexts, where traditional control methods may prove too slow or inefficient [20].

### 4.2. Artificial Intelligence in Nonlinear and Complex Control Systems

The main challenges for nonlinear dynamics lie in the fact that traditional control methods are mostly based on linear approximations of system behavior. In this case, they have bad performance in setting proper control in systems with complicated, nonlinear behaviors. Some AI techniques, especially neural networks and deep reinforcement learning, are effective in nonlinear system management by learning control policies that adapt to changing dynamics [21]. In the applications of AI in aerospace, it is being applied to control fluid dynamics in turbulent environments. The reinforcement learning will optimize the system's behavior by learning from simulations and real-time data in adapting to the nonlinearities and complexities of the fluid system [22]. AI methods have been applied in quantum control to control the inherent nonlinearity and noise of high-dimensional quantum systems for better and more efficient control [18]. In areas outside of robotics and energy systems, for example, AI can work out nonlinear systems. This is important in modeling complex dynamics using AI since it allows control systems to make better predictions of system behavior and make more informed decisions. It thus makes AI quite useful when applied to the control of systems that show unpredictable or chaotic behavior.

### 4.3. Industrial and Practical Applications of Artificial Intelligence for Control

At present, the practical applications of AI-based control systems include autonomous vehicles, drones, and robotics. In such systems, AI facilitates real-time decision-making, thereby enabling the controller to adapt to varying ambient conditions for the purpose of optimizing performance. To illustrate, in the context of autonomous drones, AI methodologies are employed to ensure stability in the face of changing environmental conditions, such as fluctuations in wind speed and the presence of obstacles. Consequently, this offers a potential solution for navigating complex environments with minimal human involvement [23]. AI has been used to enhance the adaptability and control of robots that interact with an unpredictable environment. The application of machine learning for the processing of sensory feedback enables soft robots to make real-time adaptations in their behaviour, facilitating their proficiency in the performance of dynamic tasks such as medical procedures or industrial automation [11]. AI-driven control systems have also been applied in energy systems, where they are used to optimize power grid management. AI-based predictive control technology can

balance supply and demand on the fly for a power grid by maintaining stability and improving energy efficiency in situations when renewable sources of energy start to dominate. This is due to the fact that this will dynamically impact the adjustments that are going to happen within the power grid [20]. Application fields in health care include robotic surgery and prosthetics. Applications of this nature obviously require the finest degree of accuracy and flexibility that is realistically achievable in a manufactured device. The incorporation of AI into these devices enables them to react in real time to changes in the condition of the patient, thereby optimizing surgical results and prosthetic performance [24].

## 5. Limitations and Future Prospects

### 5.1. Limitations and Challenges

Integrating AI into control systems poses significant challenges. A major concern is the computational complexity of many AI algorithms, requiring extensive resources for training and real-time operation, which can limit processing power for immediate decision-making [5]. Scalability is another challenge, as AI systems must handle increased complexity in larger control environments. Additionally, the lack of transparency in AI models, particularly those using deep learning, renders their decision-making processes opaque. This lack of clarity can be particularly problematic in critical systems, such as aerospace and healthcare, where failures may have serious consequences. Thus, developing explainable AI is crucial for building trustworthy control systems [25]. Moreover, ensuring safety and reliability remains a significant issue. Despite the potential of AI to boost control performance, it is crucial to ensure safety and robustness in critical applications. Rigorous testing and validation are necessary to confirm an AI system's ability to manage unexpected scenarios and operate safely under various conditions.

### 5.2. Future Directions and Research Opportunities

AI in control systems is a fast-growing area, and more exciting advances are foreseen. Such work could be the integration of AI with conventional control techniques like fuzzy logic and MPC toward obtaining hybrid control systems with the advantages of each approach. These hybrid systems may further increase performance and scalability in complex control environments that are more flexible or adaptable than with the conventional methods alone [9]. Key research areas include explainable AI, which aims to develop interpretable and transparent models. This is crucial in safety-critical application, where understanding AI decision-making is essential. Enhancing transparency can increase researchers' confidence in AI-driven control systems, ensuring compliance with safety and reliability standards in critical application [8]. Despite harnessing AI methods to manage quantum state complexity and optimize control in high-dimensional systems, this emerging field presents several intriguing avenues for further investigation. Also, AI can enhance the efficiency and performance of quantum control systems, potentially leading to significant breakthroughs in the field [12].

## 6. Conclusion

The results show that artificial intelligence provides innovative solutions for system adaptation, robustness and model predictive control in dynamic environments, profoundly changing the traditional face of control theory. Techniques such as machine learning, reinforcement learning and deep learning play an important role in optimizing control system performance in real-time and coping with complex nonlinear dynamics. The wide range of applications of these techniques from self-driving cars to quantum control systems demonstrates their strong potential in different fields,

showing the versatility and effectiveness of AI. Despite the many advances, research still faces a number of challenges, including issues of computational complexity, scalability, and interpretability. For example, in high-dimensional systems, the demand for computational resources may lead to decreased efficiency, while the lack of interpretability may affect user trust and system security. Thus, while AI-driven control systems show good promise, these obstacles must be addressed. Future research could focus on developing hybrid models that combine traditional control methods with AI techniques to achieve greater flexibility and adaptability.

## References

- [1] Quade, M., Isele, T.M. and Abel, M. (2020) *Machine learning control—explainable and analyzable methods*. *Physica D: Nonlinear Phenomena*, 412, 132582.
- [2] Cherubini, G., et al. (2020) *Guest Editorial Introduction to the Special Issue of the IEEE L-CSS on Learning and Control*. *IEEE Control Systems Letters*, 4(3): 710-712.
- [3] Shirobokov, M., Trofimov, S., and Ovchinnikov, M. (2021). *Survey of machine learning techniques in spacecraft control design*. *Acta Astronautica*, 186, 87-97.
- [4] Moe, S., Rustad, A.M. and Hanssen, K.G. (2018). *Machine Learning in Control Systems: An Overview of the State of the Art*. *SGAI Conferences*.
- [5] Duriez, T., Brunton, S.L., & Noack, B.R. (2017). *Machine Learning Control (MLC)*.
- [6] Weinan, E., Han, J., & Long, J. (2022). *Empowering Optimal Control with Machine Learning: A Perspective from Model Predictive Control*. *IFAC-PapersOnLine*.
- [7] Tsiamis, A., et al. (2022) *Statistical Learning Theory for Control: A Finite-Sample Perspective*. *IEEE Control Systems*, 43: 67-97.
- [8] Vaupel, Y., et al. (2020) *Accelerating nonlinear model predictive control through machine learning*. *Journal of Process Control*, 92, 261-270.
- [9] Vachkov, G. and Nikolov, M. (1995) *Successive fuzzy rule based tuning of industrial control systems*. *Proceedings of 1995 IEEE International Conference on Fuzzy Systems, Japan*, 1995.
- [10] Bensoussan, A., et al. (2022) *Machine learning and control theory*. *Handbook of numerical analysis*.
- [11] Chin, K., Hellebrekers, T. and Majidi, C. (2020) *Machine Learning for Soft Robotic Sensing and Control*. *Advanced Intelligent Systems*, 2.
- [12] Perrier, E., Tao, D. and Ferrie, C. (2020). *Quantum geometric machine learning for quantum circuits and control*. *New Journal of Physics*, 22.
- [13] Zaitceva, I. and Andrievsky, B. (2022) *Methods of Intelligent Control in Mechatronics and Robotic Engineering: A Survey*. *Electronics* 11, 15: 2443.
- [14] Diveev, A.I., et al. (2021) *Machine learning control based on approximation of optimal trajectories*. *Mathematics*.
- [15] Tsiamis, A., et al. (2022) *Statistical learning theory for control: A finite-sample perspective*. *IEEE Control Systems*, 43: 67-97.
- [16] Kondratenko, Y., et al. (2022). *Machine Learning Techniques for Increasing Efficiency of the Robot's Sensor and Control Information Processing*. *Sensors (Basel, Switzerland)*, 22.
- [17] Pino, F., et al. (2022) *Comparative analysis of machine learning methods for active flow control*. *Journal of Fluid Mechanics*, 958.
- [18] Niu, M.Y., et al. (2018) *Universal quantum control through deep reinforcement learning*. *Quantum Information*, 5.
- [19] Dong, W. and Zhou, M. (2017). *A supervised learning and control method to improve particle swarm optimization algorithms*. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 47, 1135-1148.
- [20] Zhang, L., et al. (2023) *Challenges and opportunities of machine learning control in building operations*. *Building Simulation*, 16: 831-852.
- [21] Leephakpreeda, T., Limpichotipong, S. and Netramai, C. (2004) *Genetic Reinforcement Learning with Updating Table of Q-value Function : Obstacle Avoidance Robot*.
- [22] Pino, F., et al. (2022) *Comparative analysis of machine learning methods for active flow control*. *Journal of Fluid Mechanics*, 958.
- [23] Zaitceva, I., and Andrievsky, B.R. (2022). *Methods of Intelligent Control in Mechatronics and Robotic Engineering: A Survey*. *Electronics*.
- [24] Israilov, S., et sl. (2023) *Reinforcement learning approach to control an inverted pendulum: A general framework for educational purposes*. *PLOS ONE*, 18.
- [25] Qiu, P. and Xie, X. (2021) *Transparent Sequential Learning for Statistical Process Control of Serially Correlated Data*. *Technometrics*, 64: 487-501.