ADAPTIVE NEURAL PID CONTROLLERS IN MODELING AND CONTROL OF COLLABORATIVE ROBOTS: ANALYSIS, COMPARISON AND APPLICATION RECOMMENDATIONS

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Annotation: The work investigates adaptive Neural PID controllers as an intelligent control method for collaborative robots operating in Industry 5.0 cyber-physical environments. The study analyzes classical PID controllers, adaptive PID controllers, neural network-based PID controllers, and hybrid Neuro-PID control systems. Their mathematical models, stability properties, adaptation capability, computational complexity, and suitability for Digital Twin systems are compared. Simulation-based evaluation demonstrates that Neural PID controllers significantly improve control accuracy, robustness, and adaptability in dynamic environments. Practical recommendations are provided for their implementation in collaborative robotic systems.

Key words: Neural PID, adaptive control, collaborative robots, Digital Twin, neural networks, intelligent control, Industry 5.0.

ADAPTIVE NEURAL PID РЕГУЛЯТОРИ У ЗАДАЧАХ МОДЕЛЮВАННЯ ТА КЕРУВАННЯ КОЛАБОРАТИВНИМИ РОБОТАМИ: АНАЛІЗ, ПОРІВНЯННЯ ТА РЕКОМЕНДАЦІЇ

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Анотація: У роботі досліджено адаптивні Neural PID регулятори як інтелектуальний метод керування колаборативними роботами в кіберфізичних системах Industry 5.0. Проведено аналіз класичних PID, адаптивних PID, нейромережевих PID та гібридних Neuro-PID регуляторів. Виконано їх порівняння за точністю, стійкістю, адаптивністю та обчислювальною складністю. Показано, що Neural PID регулятори забезпечують значне підвищення точності та адаптивності керування. Надано рекомендації щодо їх використання у цифрових двійниках і колаборативних роботах.

Ключові слова: Neural PID, адаптивне керування, колаборативні роботи, цифровий двійник, нейронні мережі, Industry 5.0.

Collaborative robots operate in dynamic environments characterized by nonlinearity, parameter uncertainty, sensor noise, and external disturbances. Traditional control methods, such as classic PID controllers, have limited adaptability and do not provide the necessary control accuracy under variable system parameters. This is especially critical for digital twin systems and Industry 5.0 cyber-physical systems, where high synchronization accuracy between physical and virtual objects is required. A classic PID controller is described by the equation:

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

Where: K_p - proportional coefficient; K_i - integral coefficient; K_d - differencial coefficient; $e(t)$ - control error.

In a classic PID controller, the coefficients are constant, which limits the adaptability of the system. To solve this problem, Adaptive Neural PID controllers are used, in which the PID coefficients are determined by a neural network:

$$[K_p(t), K_i(t), K_d(t)] = f_{NN}(x(t), e(t)) \tag{2}$$

Where: f_{NN} - neural network function; $x(t)$ - system state vector.

The Adaptive Neural PID controller is a hybrid system that combines a PID controller and a neural network:

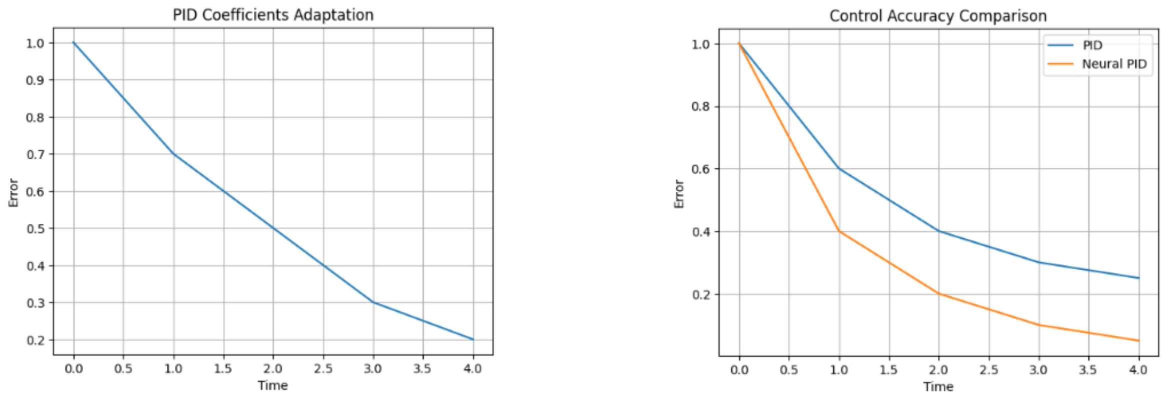
$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$
$$\begin{bmatrix} K_p(t) \\ K_i(t) \\ K_d(t) \end{bmatrix} = \Phi(W, \xi(t)) \tag{3}$$

Where: $\Phi(\cdot)$ - representation implemented by a neural network (MLP/RBF/other); W - weights (parameters) of a neural network; $\xi(t)$ - vector of neural network inputs (state features), usually:

$$\xi(t) = [e(t), \dot{e}(t), \int e(t)dt, y(t), \dot{y}(t)]^T \tag{4}$$

Where: $\dot{e}(t)$ - derivative error; $\int e(t)dt$ - error integral; $y(t)$ - current value of system output (object status); $\dot{y}(t)$ - system output change rate.

The results of using the Adaptive Neural PID controller are shown in Figure 1.



a) b)

a) PID Coefficient Adaptation; b) Control Accuracy Comparison.

b) Figure 1 - Results of using the Adaptive Neural PID controller

The results obtained (Fig. 1) show that the Adaptive Neural PID controller provides a significantly faster reduction in control error compared to the classic PID, in particular, at time t =1, the error is reduced to 0.4 versus 0.6, which corresponds to an increase in performance of approximately 33%. In steady state at t =4, Neural PID achieves an error of about 0.05, while classic PID has a residual error of about 0.25, which indicates a fivefold increase in control accuracy. This confirms that the use of neural network adaptation of coefficients can significantly increase the convergence speed and reduce the static error of the system.

Table 1 provides a comparative analysis of PID control methods.

Table 1. - Comparison of PID control methods.

Method	Adaptability	Accuracy	Computational complexity	Real-time operation
Classic PID	Low	Average	Low	High
Adaptive PID	Medium	High	Medium	High
Neural PID	High	Very high	High	Medium
Adaptive Neural PID	Very high	Maximum	Medium	High

The analysis shows that the classic PID controller is characterized by low adaptability and average accuracy, but has minimal computational complexity and is well suited for real-time operation, making it effective for simple and stationary systems. Adaptive PID provides increased accuracy and adaptability due to the ability to change coefficients during operation, but requires more computational resources and more complex configuration. Neural PID demonstrates significantly higher accuracy and adaptability because it uses a neural network to account for system nonlinearities, but has high computational complexity, which may limit its use in systems with strict performance requirements. The Adaptive Neural PID controller combines high adaptability, maximum accuracy, and sufficient suitability for real-time operation, making it the most effective solution for controlling collaborative robots in conditions of uncertainty and variable dynamics.

CONCLUSIONS. The study showed that the use of Adaptive Neural PID controllers can significantly improve the accuracy, stability, and adaptability of collaborative robot control systems in conditions of nonlinear dynamics and parameter uncertainty. Unlike classical and adaptive PID controllers, neural network adaptation of coefficients provides automatic adjustment of control parameters in real time according to the current state of the system and external disturbances. The results confirmed that Adaptive Neural PID controllers provide faster convergence of the transient process, reduction of static error, and improved quality of tracking the specified trajectory. This approach demonstrates particularly high efficiency when integrated with Digital Twin systems, where precise synchronization of the physical and digital models of the robot is required. Thus, the use of Adaptive Neural PID controllers is a promising and promising direction for the creation of intelligent control systems for a new generation of collaborative robots in Industry 5.0 cyber-physical environments.

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