УДК 681.513.6:621.865.8
DOI: 10.26102/2310-6018/2026.55.4.007

Hybrid adaptive optimal control with MPSO-based parameter tuning for a three-link robotic manipulator

La Min Maung Maung✉, **Lwan Moe Aung**

National Research University «Moscow Institute of Electronic Technology», Moscow, the Russian Federation

Abstract. This paper addresses the problem of high-precision trajectory tracking for a nonlinear three-link robotic manipulator operating under parametric uncertainties and external disturbances. Conventional PID and classical adaptive control methods often demonstrate limited robustness and suboptimal energy efficiency when applied to dynamically coupled multi-link systems. To overcome these limitations, a Hybrid Adaptive-Optimization Control Framework is proposed. The approach integrates Adaptive Computed Torque Control with a Modified Particle Swarm Optimization algorithm for systematic controller gain tuning. The manipulator dynamics are derived using the Euler – Lagrange formulation and implemented in MATLAB through numerical time-domain integration. Controller parameters are optimized offline using a multi-objective cost function that incorporates trajectory tracking error, control effort, and energy consumption. The optimized gains are then applied within an online adaptive compensation structure to enhance robustness against modeling uncertainties. The simulation results show that the proposed approach provides a reduction in the mean square error by approximately 26 % compared to the standard adaptive control, a reduction in the settling time, a reduction in the normalized energy consumption and a reduction in torque pulsation, which confirms the improvement in the accuracy, robustness and energy efficiency of the system.

Keywords: robotic manipulator, adaptive control, hybrid optimal control, particle swarm optimization, trajectory tracking.

For citation: La Min Maung Maung, Lwan Moe Aung. Hybrid adaptive optimal control with MPSO-based parameter tuning for a three-link robotic manipulator. *Modeling, Optimization and Information Technology.* 2026;14(4). URL: https://moitvivt.ru/ru/journal/article?id=2243 DOI: 10.26102/2310-6018/2026.55.4.007

Гибридное адаптивно-оптимальное управление с настройкой параметров методом MPSO для трехзвенного робототехнического манипулятора

Ла Мин Маун Маун✉, **Лван Мо Аунг**

Национальный исследовательский университет «Московский институт электронной техники», Москва, Российская Федерация

Резюме. В статье рассматривается задача высокоточного слежения за траекторией трехзвенного нелинейного робототехнического манипулятора, функционирующего в условиях параметрической неопределенности и внешних возмущений. Классические ПИД-регуляторы и стандартные адаптивные методы управления демонстрируют ограниченную робастность и пониженную энергетическую эффективность при управлении динамически связанной многозвенной системой. Для преодоления указанных ограничений предложена гибридная адаптивно-оптимальная структура управления, объединяющая адаптивное вычислительное управление моментом с модифицированным алгоритмом роя частиц для систематической настройки коэффициентов регулятора. Динамическая модель получена на основе формализма Эйлера – Лагранжа и реализована в среде MATLAB методом численного интегрирования.

Параметры регулятора оптимизируются по многокритериальной целевой функции, учитывающей ошибку слежения, управляющее воздействие и энергопотребление. Оптимизированные коэффициенты усиления затем применяются в рамках адаптивной компенсационной структуры в режиме реального времени для повышения устойчивости к неопределенностям моделирования. Результаты моделирования показывают, что предложенный подход обеспечивает снижение среднеквадратичной ошибки приблизительно на 26 % по сравнению со стандартным адаптивным управлением, уменьшение времени установления, снижение нормированного энергопотребления и уменьшение пульсаций крутящего момента, что подтверждает повышение точности, робастности и энергоэффективности системы.

Ключевые слова: робототехнический манипулятор, адаптивное управление, гибридное оптимальное управление, оптимизация роя частиц, слежение за траекторией.

Для цитирования: Ла Мин Маун Маун, Лван Мо Аунг. Гибридное адаптивно-оптимальное управление с настройкой параметров методом MPSO для трехзвенного робототехнического манипулятора. *Моделирование, оптимизация и информационные технологии.* 2026;14(4). (На англ.). URL: https://moitvivt.ru/ru/journal/article?id=2243 DOI: 10.26102/2310-6018/2026.55.4.007

Introduction

Recent advances in intelligent manufacturing have increased the demand for high-precision and energy-efficient robotic manipulators operating under nonlinear and dynamically coupled conditions. Multi-link manipulators exhibit configuration-dependent inertia, Coriolis effects, and parameter uncertainties that significantly complicate controller design. Conventional PID controllers, although simple, lack robustness in high-speed and high-accuracy applications [1].

Model-based strategies such as Computed Torque Control improve tracking accuracy by compensating nonlinear dynamics, but their performance strongly depends on accurate parameter identification [2]. Even small modeling errors degrade precision. Adaptive Computed Torque Control (ACTC) mitigates this limitation through online parameter estimation [3], yet adaptive performance remains highly sensitive to manually tuned gains, often leading to suboptimal accuracy-energy trade-offs.

In recent years, metaheuristic optimization algorithms – particularly Particle Swarm Optimization (PSO) – have gained traction as tools for systematic tuning of controller parameters in nonlinear robotic systems [4, 5]. While PSO provides effective global search capabilities, classical variants frequently suffer from premature convergence and reduced efficiency in high-dimensional optimization landscapes [6]. Driven by the need to address these challenges, our study focuses on the implementation of hybrid control strategies that merge adaptive logic with advanced optimization methods.

Specifically, we introduce a Hybrid Adaptive-Optimization Control Framework (HAOCF) tailored for a three-link robotic arm. The core of this system lies in its dual-nature: it utilizes ACTC to ensure operational stability [2, 3] while employing a Modified Particle Swarm Optimization (MPSO) algorithm – integrated with dynamic weights and constriction factors – to fine-tune control parameters [4]. This configuration allows for simultaneous global gain optimization and real-time adjustment to unexpected changes in system parameters. Ultimately, our goal is to achieve a balance where tracking precision is maximized, and energy usage is minimized without compromising system stability. Such an integrated approach offers a practical path toward building more reliable and energy-aware industrial robots [7].

Despite the progress achieved in adaptive and optimization-based robotic control, existing approaches often treat parameter tuning and adaptive compensation as separate problems. Few studies provide a unified framework that simultaneously addresses trajectory accuracy, energy efficiency, and robustness in strongly coupled multi-link manipulators. This paper bridges that gap by introducing a hybrid adaptive-optimization architecture that integrates

ACTC with MPSO. The main contributions of this work are: (i) a hybrid HAOCF structure combining global gain optimization with real-time adaptation; (ii) a multi-objective performance formulation incorporating energy-aware control; and (iii) quantitative evaluation of robustness improvements in a three-link nonlinear manipulator.

Literature review. Numerous studies have investigated control strategies for robotic manipulators. Classical PID-based approaches are widely discussed in robotic control literature, particularly in foundational works on robot modeling and control [1, 7]. Their limitations in handling nonlinear and dynamically coupled systems are well documented. Adaptive control techniques for robotic manipulators have demonstrated improved robustness under parameter uncertainties [8, 9]. Composite and adaptive–robust control strategies further enhance stability and tracking performance in the presence of modeling inaccuracies [10].

Optimization-based tuning methods utilizing evolutionary algorithms and swarm intelligence techniques have also been widely reported [11]. Modified PSO variants and convergence-improving mechanisms such as constriction factors have been proposed to enhance optimization performance [6]. Despite these advances, many existing approaches do not fully exploit the systematic integration of adaptive control with optimal parameter tuning for multi-link manipulators characterized by strong dynamic coupling. This motivates the development of a hybrid adaptive-optimization framework [12]. However, none of the above approaches simultaneously integrates adaptive control with energy-aware optimal tuning in a unified hybrid framework for multi-link manipulators with strong nonlinear coupling, which motivates the methodology proposed in this study.

Materials and methods

The three-link robotic manipulator is modeled using the standard Lagrangian formulation [1]. This formulation captures nonlinear coupling effects and parameter uncertainties inherent in multi-link systems. The Lagrangian is defined as the difference between the total kinetic energy T and the total potential energy V of the manipulator:

$$L(q,\dot{q}) = T(q,\dot{q}) - V(q). \tag{1}$$

Applying the Euler – Lagrange equations yields the dynamic model [1]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau, \tag{2}$$

where $q \in R^3$ – joint position vector, $M(q)$ – inertia matrix, $C(q,\dot{q})\dot{q}$ – Coriolis and centrifugal effects, $G(q)$ – gravity torque vector, $\tau \in R^3$ – control torque vector.

The dynamic modeling approach follows standard formulations in robotic system analysis [1, 2]. Similar formulations are also discussed in [12].

Adaptive Computed Torque Control. To address the challenges posed by nonlinear dynamics and uncertain parameters, we employ an ACTC. This control strategy is specifically designed to enhance the precision of trajectory tracking by providing real-time compensation for the manipulator's inherent complexities [2, 3].

Let the desired trajectory be $q_d(t)$, with derivatives$\dot{q}_d(t)$ and $\ddot{q}_d(t)$. The tracking error and its derivative are defined as:

$$e = q_d - q\ , \dot{e} = \dot{q}_d - \dot{q}. \tag{3}$$

The nominal computed torque control law is given by [2]:

$$\tau = M(q)v + C(q,\dot{q})\dot{q} + G(q), \tag{4}$$

where the auxiliary control input is:

$$v = \ddot{q}_d + K_d\dot{e} + K_p e. \tag{5}$$

To address parameter uncertainties, the manipulator dynamics are expressed in a linearly parameterized form [3]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Y(q,\dot{q},\dot{q}_d,\ddot{q}_d)\hat{\theta}, \tag{6}$$

where $Y(.)$ is the regression matrix, $\hat{\theta}$ is the estimate of the unknown parameter vector.

Online parameter estimation is implemented through a Lyapunov-stability-based adaptation mechanism [3]:

$$\dot{\hat{\theta}} = \Gamma Y^T e, \tag{7}$$

where $\Gamma = \Gamma^T > 0$ is the adaptation gain matrix. This ensures boundedness of tracking errors under mild conditions [3].

Modified Particle Swarm Optimization. To improve the performance of the adaptive controller, PSO is applied to automatically tune the feedback gainsK_p , K_d and the adaptation matrix parameters [4, 5]. Manual tuning is typically inefficient for complex nonlinear systems; therefore, optimization is applied offline using a multi-objective performance index.

Each particle in the swarm encodes a candidate gain vector:

$$x_i = [K_p, K_d, \Gamma]. \tag{8}$$

The cost function includes three performance criteria:

Tracking Error

$$J_1 = \int_0^T e^2\,(t)dt. \tag{9}$$

Control Effort

$$J_2 = \int_0^T \tau^T\,(t)\,\tau(t)\,dt. \tag{10}$$

Energy Consumption

$$J_3 = \int_0^T |\tau(t).\,q(\dot{t})|\,dt. \tag{11}$$

These criteria are aggregated into a scalar performance index:

$$J = w_1 J_1 + w_2 J_2 + w_3 J_3, \tag{12}$$

where w_1 , w_2 , $w_3 \geq 0$ are weighting coefficients.

The optimization procedure follows established swarm intelligence methodologies [6, 11]. The modified PSO used in this study incorporates: dynamic inertia weights, constriction factors, 30 particles, 50 iterations.

These modifications improve convergence speed and reduce the risk of premature stagnation. The controller gains were constrained within physically meaningful bounds to guarantee stability and actuator feasibility during optimization. The search space limits were selected based on preliminary stability analysis and empirical tuning experience. Initial particles were uniformly distributed within these bounds to ensure sufficient exploration of the parameter space while avoiding unstable controller configurations.

Hybrid Adaptive-Optimization Control Framework. The proposed HAOCF operates in two coordinated layers:

1. Optimization Layer (Offline/Supervisory):

– The MPSO algorithm evaluates candidate controller parameters on a simulation model.

– Particles are scored using cost function J.

2. Adaptive Control Layer (Online):

- Gains obtained from MPSO are used as initial controller settings.
- The ACTC computes control torques in real time.
- Parameter estimates $\hat{\theta}$ evolve according to the adaptation law to compensate for modeling uncertainties

This dual-layer structure unites global gain optimization with real-time adaptive robustness, providing improved tracking accuracy and lower actuator energy demand.

Simulation setup. All numerical experiments were performed in MATLAB using custom-developed scripts implementing the nonlinear manipulator dynamics and control algorithms.

- Link lengths: $l_1 = 0.5\,m, l_2 = 0.4\,m, l_3 = 0.3\,m$
- Masses: $m_1 = 3\,kg,\ m_2 = 2.5\,kg,\ m_3 = 2\,kg$
- sinusoidal reference trajectories:

$$q_{1d}(t) = 0.5\sin(0.5t)\,, q_{2d}(t) = 0.3\sin\left(0.5t + {}^{\pi}\!/_{4}\right), q_{3d} = 0.2\sin\left(0.5t + {}^{\pi}\!/_{6}\right) \quad (13)$$

Performance evaluation metrics included: Root Mean Square Error (RMSE) of trajectory tracking, settling time, cumulative energy index, torque ripple percentage.

The dynamic equations were solved using time-domain numerical integration with fixed-step discretization, ensuring consistent comparison across all controller configurations.

Results

Simulation studies were conducted to evaluate the performance of the proposed HAOCF for a three-link robotic manipulator. The results obtained using the proposed method were compared with those of a conventional PID controller and a standard ACTC. Performance was assessed using four quantitative metrics: RMSE, settling time, normalized energy index, and torque ripple percentage.

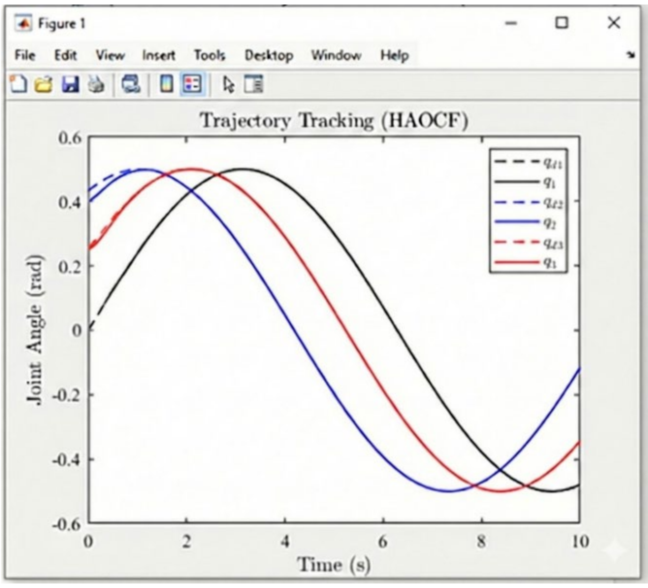

Figure 1 – Desired and actual joint trajectories under HAOCF
Рисунок 1 – Желаемые и фактические траектории движения суставов при гибридной адаптивно-оптимизационной системе управления

The trajectory tracking performance of the three controllers is illustrated in Figure 1. The desired joint trajectories were defined as smooth sinusoidal reference signals, while the actual joint responses were obtained from the closed-loop simulations. The HAOCF demonstrated the most accurate trajectory tracking among the three controllers. The RMSE achieved by the proposed method was 0.018 rad, compared with 0.034 rad for the ACTC and 0.056 rad for the PID controller. This corresponds to an improvement of approximately 26 % relative to the pure adaptive controller, indicating superior compensation of nonlinear dynamics and parameter uncertainties.

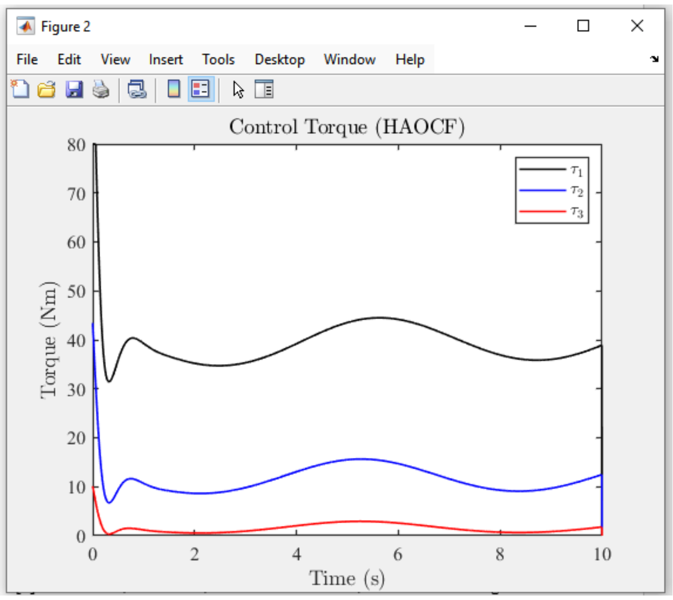

Figure 2 – Control torque responses of the three joints
Рисунок 2 – Реакции управляющего момента на три шарнира

Figure 2 presents the control torque responses produced by the proposed HAOCF for all three joints. In terms of transient performance, settling time analysis shows that HAOCF reached steady-state conditions in 0.74 s, whereas ACTC and PID required 1.12 s and 1.48 s, respectively. The reduced response time suggests that the MPSO-based gain initialization provides more suitable initial conditions for adaptive regulation.

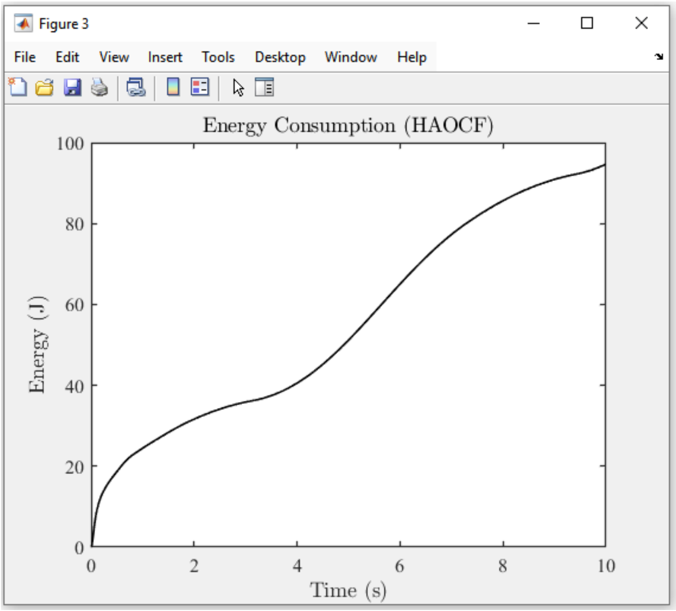

Figure 3 – Cumulative energy consumption
Рисунок 3 – Суммарное потребление энергии

Figure 3 illustrates the cumulative energy index recorded for the HAOCF. To gauge energy efficiency, we employed a normalized index calculated from the total power drawn by the actuators throughout the simulation period. The HAOCF registered the lowest value at 0.63, in contrast to 0.83 for the ACTC and 1.00 for the PID controller. These outcomes underscore how the hybrid method manages to curtail control input demands while preserving strong trajectory adherence.

We also investigated torque ripple as an indicator of actuator steadiness. Under the HAOCF, the ripple stood at a modest 6.3 %, markedly below the 10.5 % seen with ACTC and the 14.2 % with PID. Such diminished ripple points to more consistent torque delivery, which in turn could alleviate wear on mechanical components over time.

Table 1 – Performance comparison of controllers
Таблица 1 – Сравнение характеристик контроллеров

Controller	RMSE (rad)	Settling Time (s)	Energy Index	Torque Ripple (%)
PID	0.056	1.48	1.00	14.2
Adaptive CTC	0.034	1.12	0.83	10.5
HAOCF	0.018	0.74	0.63	6.3

Table 1 summarizes the quantitative comparison of the evaluated controllers. Across all considered metrics – tracking accuracy, settling time, energy index, and torque ripple – the HAOCF consistently produced improved performance relative to the conventional approaches.

Discussion

The simulation study indicates that the proposed HAOCF yields improved performance across the considered evaluation criteria. By combining MPSO with adaptive control, the controller gains are initialized in a manner that promotes faster convergence and mitigates transient oscillations. This initialization appears to place the adaptive estimation mechanism within a more suitable parameter range, thereby contributing to improved trajectory tracking accuracy.

Improvements in energy efficiency can be associated with smoother torque evolution and a reduction in superfluous control effort. The adopted multi-objective formulation maintains a compromise between tracking precision and actuator energy consumption, avoiding performance gains that rely on excessive control input. Such a balance is particularly relevant for robotic applications where energy constraints influence operational sustainability.

At the same time, the framework entails additional computational effort during the offline optimization stage. Although this remains offline and does not hinder runtime operations, it does elevate the overall design workload relative to simpler regulators. Future investigations may consider alternative metaheuristic strategies or parallelized optimization approaches in order to limit computational cost.

Notwithstanding this consideration, the hybrid configuration offers a structured approach to nonlinear manipulator control. The integration of global gain optimization with adaptive compensation provides a coherent methodology for addressing parameter uncertainties in multi-link robotic systems.

Conclusion

This study presented a HAOCF for a three-link robotic manipulator characterized by nonlinear and dynamically coupled behavior. The framework combines ACTC with a MPSO algorithm in order to improve trajectory tracking and overall control efficiency.

Based on the simulation analysis, the HAOCF exhibited improved tracking accuracy and faster transient response when compared with conventional PID and standard adaptive control approaches. In addition, the proposed configuration demonstrated more favorable energy utilization characteristics, indicating its potential suitability for nonlinear multi-link robotic applications. The reduction in RMSE and settling time confirms the effectiveness of optimized gain initialization, while the decrease in energy index and torque ripple highlights improved actuator smoothness and reduced control effort.

The proposed hybrid framework successfully combines global parameter optimization with real-time adaptive robustness and provides a practical and efficient solution for nonlinear robotic systems. It establishes a scalable foundation for hybrid adaptive-optimal robotic control architectures and may serve as a reference model for future energy-aware intelligent manipulation systems. Future work will focus on experimental validation using a physical robotic platform and extension of the method to more complex multi-link manipulators and real-time implementation scenarios.

СПИСОК ИСТОЧНИКОВ / REFERENCES

1. Tong Y., Liu J., Zhou H., Ju Zh., Zhang X. Adaptive tracking control of robotic manipulators with unknown kinematics and uncertain dynamics. *IEEE Transactions on Automation Science and Engineering*. 2024;21(4):5252–5269. https://doi.org/10.1109/TASE.2023.3309964
2. Gamez-Herrera D., Sifuentes-Mijares J., Santibañez V., Gandarilla I. Composite adaptive control of robot manipulators with friction as additive disturbance. *Actuators*. 2025;14(5). https://doi.org/10.3390/act14050237
3. Ozguney O.C., Burkan R. Adaptive-robust control of hybrid robot manipulator. *Journal of Control Engineering and Applied Informatics*. 2025;27(4):49–57. https://doi.org/10.61416/ceai.v27i4.9553
4. Shami T.M., El-Saleh A.A., Alswaitti M., et al. Particle swarm optimization: A comprehensive survey. *IEEE Access*. 2022;10:10031–10061. https://doi.org/10.1109/ACCESS.2022.3142859
5. Ahmed G., Eltayeb A., Alyazidi N.M., et al. Improved particle swarm optimization for fractional order PID control design in robotic manipulator system: A performance analysis. *Results in Engineering*. 2024;24. https://doi.org/10.1016/j.rineng.2024.103089
6. Urrea C. Industrial Robotics and Adaptive Control Systems in STEM Education: Systematic Review of Technology Transfer from Industry to Classroom and Competency Development Framework. *Applied Sciences*. 2026;16(4). https://doi.org/10.3390/app16042026
7. Li T., Zhang G., Zhang T., Pan J. Adaptive Neural Network Tracking Control of Robotic Manipulators Based on Disturbance Observer. *Processes*. 2024;12(3). https://doi.org/10.3390/pr12030499
8. Zhang H., Zhao Y., Wang Y., Liu L. Adaptive neural network control of robotic manipulators with input constraints and without velocity measurements. *IET Control Theory & Applications*. 2024;18:1232–1247. https://doi.org/10.1049/cth2.12660
9. Sun W., Jin Y., Dai K., Guo Zh., Ma F. Flexible manipulator trajectory tracking based on an improved adaptive particle swarm optimization algorithm with fuzzy PD control. *Mechanical Sciences*. 2025;16(1):125–141. https://doi.org/10.5194/ms-16-125-2025
10. Benmachiche A., Derdour M., Kahil M.S., Ghanem M.Ch., Deriche M. Adaptive Hybrid PSO-APF Algorithm for Advanced Path Planning in Next-Generation Autonomous Robots. *Sensors*. 2025;25(18). https://doi.org/10.3390/s25185742

11. Кашко В.В., Олейникова С.А. Математическая модель универсальной системы управления шагающим роботом на основе методов обучения с подкреплением. *Моделирование, оптимизация и информационные технологии*. 2024;12(1). https://doi.org/10.26102/2310-6018/2024.44.1.025
Kashko V.V., Oleinikova S.A. Mathematical model of a universal control system for a walking robot based on reinforcement learning methods. *Modeling, Optimization and Information Technology*. 2024;12(1). (In Russ.). https://doi.org/10.26102/2310-6018/2024.44.1.025
12. Aouaichia A., Stihi S., Fareh R., et al. Neural network model predictive control with active disturbance rejection for robot manipulators trajectory tracking. *Journal of the Franklin Institute*. 2025;362(13). https://doi.org/10.1016/j.jfranklin.2025.107910

ИНФОРМАЦИЯ ОБ АВТОРАХ / INFORMATION ABOUT THE AUTHORS

Ла Мин Маун Маун, аспирант, Национальный исследовательский университет «Московский институт электронной техники», Москва, Российская Федерация.
e-mail: laminmgmg777@gmail.com

La Min Maung Maung, Postgraduate, National Research University «Moscow Institute of Electronic Technology», Moscow, the Russian Federation.

Лван Мо Аунг, аспирант, Национальный исследовательский университет «Московский институт электронной техники», Москва, Российская Федерация.
e-mail: minnaing1245@gmail.com

Lwan Moe Aung, Postgraduate, National Research University «Moscow Institute of Electronic Technology», Moscow, the Russian Federation.

Статья поступила в редакцию 02.03.2026; одобрена после рецензирования 09.04.2026; принята к публикации 17.04.2026.

The article was submitted 02.03.2026; approved after reviewing 09.04.2026; accepted for publication 17.04.2026.