DIGITAL TWIN IN MODELING AND CONTROL OF COLLABORATIVE ROBOTS: ANALYSIS, COMPARISON AND APPLICATION RECOMMENDATIONS

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Annotation: The work examines the Digital Twin concept as a key technological solution for modeling, simulation, and intelligent control of collaborative robots in Industry 5.0 environments. The analysis focuses on mathematical and computational methods underlying Digital Twin systems, including kinematic and dynamic models, probabilistic state estimation methods, environment representation models, sensor fusion techniques, and predictive simulation models. Their mathematical foundations, computational complexity, accuracy, scalability, and suitability for real-time control are compared. The advantages and limitations of each method are evaluated. Practical recommendations are provided for implementing Digital Twin systems in collaborative robotics, autonomous navigation, and cyber-physical production systems.

Key words: Digital Twin, collaborative robots, cyber-physical systems, environment modeling, probabilistic estimation, trajectory planning, Industry 5.0.

ЦИФРОВИЙ ДВІЙНИК У ЗАДАЧАХ МОДЕЛЮВАННЯ ТА КЕРУВАННЯ КОЛАБОРАТИВНИМИ РОБОТАМИ: АНАЛІЗ, ПОРІВНЯННЯ ТА РЕКОМЕНДАЦІЇ

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Анотація: У роботі досліджено концепцію цифрового двійника як ключової технології моделювання, симуляції та інтелектуального керування колаборативними роботами в умовах Industry 5.0. Проведено аналіз математичних і обчислювальних методів, що лежать в основі цифрових двійників, включаючи кінематичні та динамічні моделі, ймовірнісні методи оцінювання стану, моделі представлення середовища, методи злиття сенсорних даних і предиктивні моделі. Виконано їх порівняння за точністю, обчислювальною складністю та придатністю для роботи в реальному часі. Надано рекомендації щодо використання цифрових двійників у колаборативній робототехніці та кіберфізичних системах.

Ключові слова: цифровий двійник, колаборативні роботи, кіберфізичні системи, моделювання, планування траєкторії, Industry 5.0.

A Digital Twin is a virtual mathematical and computational model that accurately reproduces the physical state, dynamics, and behavior of a collaborative robot and its environment in real time. It provides continuous synchronization between the physical and virtual systems using sensor data, mathematical models, and predictive algorithms. This approach significantly increases the reliability, safety, adaptability, and efficiency of robotic systems in cyber-physical environments of Industry 5.0.

The mathematical basis of the digital twin is based on the state space model:

$$x(t) = [x, y, z, \theta, v, w]^T \quad (1)$$

Where: x, y, z - robot position coordinates; θ - orientation angle; v - linear speed; w - angular velocity.

The evolution of the state of the system is described by the equation of dynamics:

$$\dot{x}(t) = f(x(t), u(t), w(t)) \quad (2)$$

Where: $u(t)$ - controlling influence; $w(t)$ - process noise.
Sensor measurements are described by the equation:

$$z(t) = h(x(t), v(t)) \quad (3)$$

Where: v(t) - measurement noise.
These equations (1-3) form the mathematical basis for synchronization, prediction, and control of the digital twin.
The digital twin integrates several fundamental mathematical modeling techniques, including:
– kinematic models,
– dynamic models,
– probabilistic state estimation models,
– environmental representation models,
– sensor data fusion models,
– predictive models.
Kinematic models describe the robot motion without considering forces and are represented by the equations:

$$\dot{x} = v cos\theta, \dot{y} = v sin\theta, \dot{\theta} = w \quad (4)$$

Model 4 provides efficient real-time simulation and is widely used in digital twins for motion prediction and trajectory planning.
Dynamic models describe the robot's motion taking into account forces and inertia:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau \quad (5)$$

Model 5 provides high-precision simulation and is essential for digital twins of manipulators and high-precision robots.
Probabilistic models estimate the state of the robot based on sensor data:

$$P(x_t | z_{1:t}) \quad (6)$$

These include: Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), Particle Filter.
The digital twin uses mathematical models of the environment, such as:
- Occupancy Grid:

$$P(c_i) \quad (7)$$

- Point Cloud:

$$P = \{x, y, z\} \quad (8)$$

- Graph-based model:

$$G = (V, E) \tag{9}$$

Models 7-9 provide a spatial representation of the environment.
Sensory data fusion models are described by the function:

$$x = f(z_1, z_2, \dots, z_n) \tag{10}$$

This method combines data from various sensors such as: LiDAR, camera, IMU, ultrasonic sensors.
Predictive models predict the future state of the robot:

$$x_{t+1} = f(x_t) \tag{11}$$

This allows: to predict the trajectory, avoid collisions, optimize control.
A comparative analysis of digital twin models is given in Table 1.

Table 1 - Comparative analysis of digital twin models

Method	Accuracy	Computational complexity	Real-time operation	Digital Twin suitability
Kinematic model	Medium	Low	High	High
Dynamic model	High	High	Medium	Very high
Probabilistic model	High	High	Medium	Very high
Environmental model	High	Medium	High	Very high
Sensor fusion	Very high	Medium	High	Critical
Predictive model	High	Medium	High	Critical

Digital twin is a key technology for modeling and controlling collaborative robots in Industry 5.0 systems. Kinematic models are recommended for real-time motion modeling and trajectory planning. Dynamic models are required for high-precision systems and manipulators. Probabilistic models are critical for digital twin synchronization and operation under uncertainty. Environment representation models provide spatial awareness of the system. Sensor data fusion methods increase the accuracy and reliability of the digital twin. Predictive models provide prediction and intelligent control. The integration of all these methods ensures maximum accuracy, adaptability, reliability and safety of the digital twin of the collaborative robot.

CONCLUSIONS. Digital twin is an effective mathematical and software tool for modeling, synchronization and intelligent control of collaborative robots in cyber-physical systems Industry 5.0. The analysis showed that the use of kinematic and dynamic models provides adequate reproduction of the motion and physical properties of the robotic system, while probabilistic methods allow to compensate for the uncertainty and noise of sensor measurements. Models of environmental representation and methods of sensor data fusion ensure the formation of the current spatial state of the digital twin and increase the accuracy of localization. Predictive models allow to predict the behavior of the system and timely adjust the control, which increases the safety and efficiency of work. It was established that the most effective approach is the integration of several mathematical models into a single digital architecture, which ensures adaptability, scalability and high accuracy of the functioning of collaborative robots. The results obtained confirm the feasibility of using digital twins as a basic technology for the development of intelligent robotic systems of a new generation.

REFERENCES

1. Syed Khalid Mustafa, Vladyslav Yevsieiev, Igor Nevliudov, Vyacheslav Lyashenko, Adel R. Alharbi, Wahid Rajeh, "HMI Development Automation with GUI Elements for Object-Oriented Programming Languages Implementation," International Journal of Engineering Trends and Technology (IJETT), vol. 70, no. 1, pp. 139-145, 2022. Crossref, https://doi.org/10.14445/22315381/IJETT-V70I1P215

3. Nevliudov, I., Omarov, M., Yevsieiev, V., Maksymova, S., & Jabrayilzade, E. (2026). MATHEMATICAL MODELING OF TRAJECTORIES CONSTRUCTION, MOVEMENT OF THE GRIPPING DEVICE OF A COLLABORATIVE ROBOT. Advanced Information Systems, 10(1), 11-20.

4. Yevsieiev V. Intelligent Collaborative Control of Mobile Robots for Emergency and Rescue Operations Within the Industry 5.0 Paradigm / V. Yevsieiev // Yevsieiev V. Intelligent Collaborative Control of Mobile Robots for Emergency and Rescue Operations Within the Industry 5.0 Paradigm / V. Yevsieiev // Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations (ICSTRO-2026) : Proceedings of I-st All-Ukrainian Conference, February 12-23, 2026. – Kharkiv, 2026. - P. 144-147.

5. Yevsieiev V. Digital Twins of Collaborative Robotic Systems for Decision Support in Emergency Situations / V. Yevsieiev, S. Svetlana // Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations (ICSTRO-2026) : Proceedings of I-st All-Ukrainian Conference, February 12-23, 2026. – Kharkiv, 2026. - P. 153-156.

6. Model with Neural Network Component for Adaptive Manipulator Control under Variable Load / Amer Abu-Jassar, Mohammad Hamdan, Nowfal Aweisi, Mahmoud Howaidi, V. Yevsieiev, V. Lyashenko // International Journal of Intelligent Engineering and Systems. –19(1). – 2026. – P. 855-868.

7. Yevsieiev, V., Gurin, D., Kulish, S., & Voloshyn, Y. (2025). Development of a partially supervised Markov decision-making model for a 3-link collaborative robot-manipulator. Radioelectronic and Computer Systems, 2025(4), 83-94.

8. Yevsieiev V. Features of the Use of Quantum Computing in Constructing Trajectory of Collaborative Mobile Robot / V. Yevsieiev, N. Demska // Information Technologies and Automation - 2025 : Proceedings of the XVIII International Scientific and Practical Conference, October 30-31, 2025. - Odessa : ONUT Publishing House, 2025 – P. 893-895.

9. Attar, H., Abu-Jassar, A. T., Yevsieiev, V., Lyashenko, V., Nevliudov, I., & Luhach, A. K. (2022). Zoomorphic mobile robot development for vertical movement based on the geometrical family caterpillar. Computational intelligence and neuroscience, 2022(1), 3046116.

10. Yevsieiev, V. Comparative Analysis of the Characteristics of Mobile Robots and Collaboration Robots Within INDUSTRY 5.0. / V. Yevsieiev, D. Gurin // Sectoral research XXI : characteristics and features : collection of scientific papers "SCIENTIA" with proceedings of the VI International Scientific and Theoretical Conference, September 8, 2023. - Chicago : European Scientific Platform, 2023. - P. 92-94.

11. Yevsieiev V. Implementation of STEM education in distance learning conditions during martial law in Ukraine: challenges, tools and prospects for training future engineers / V. Yevsieiev, S. Starikova // Theoretical and Applied Aspects of Device Development on Microcontrollers and FPGA (MC&FPGA-2025) : VII International Scientific and Practical Conference, June 27-28, 2025. – Kharkiv : NURE. – P. 21-25.

12. Невлюдов І. Ш. Технічне та програмне забезпечення розробки малогабаритного мобільного робота : монографія / І. Ш. Невлюдов, В. В. Євсєєв, Д. В. Гурін // Кривий Ріг: Криворізький фаховий коледж Державного некомерційного підприємства «Державний університет «Київський авіаційний інститут», 2025. – 355 с. - DOI : https://doi.org/10.30837/978-617-8332-74-7.