CLASSIFICATION OF DIGITAL TWINS IN COLLABORATIVE ROBOT MODELING PROBLEMS

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Annotation: The paper explores approaches to classifying digital twins in collaborative robot modeling tasks, taking into account the requirements of the Industry 5.0 concept and cyber-physical systems. A multi-level classification of digital twins is proposed, which includes descriptive, diagnostic, predictive, and prescriptive levels that differ in functionality, mathematical models, and level of decision-making autonomy. The mathematical foundations of each type are analyzed, including state assessment methods, dynamic modeling, and optimization control, and their suitability for monitoring, diagnostics, forecasting, and adaptive control tasks is determined. The results obtained can be used to develop effective digital twins in collaborative robotics and intelligent manufacturing systems..
Key words: Digital Twin, collaborative robots, Industry 5.0, cyber-physical systems, modeling, adaptive control, forecasting.

КЛАСИФІКАЦІЯ ЦИФРОВИХ ДВІЙНИКІВ У ЗАДАЧАХ МОДЕЛЮВАННЯ КОЛАБОРАТИВНИМИ РОБОТАМИ

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Анотація: У роботі досліджено підходи до класифікації цифрових двійників у задачах моделювання колаборативних роботів з урахуванням вимог концепції Industry 5.0 та кіберфізичних систем. Запропоновано багаторівневу класифікацію цифрових двійників, яка охоплює descriptive, diagnostic, predictive та prescriptive рівні, що відрізняються функціональністю, математичними моделями та рівнем автономності прийняття рішень. Проведено аналіз математичних основ кожного типу, включаючи методи оцінювання стану, динамічне моделювання та оптимізаційне керування, а також визначено їх придатність для задач моніторингу, діагностики, прогнозування та адаптивного керування. Отримані результати можуть бути використані для розроблення ефективних цифрових двійників у системах колаборативної робототехніки та інтелектуального виробництва.
Ключові слова: цифровий двійник, колаборативні роботи, Industry 5.0, кіберфізичні системи, моделювання, адаптивне керування, прогнозування.

A digital twin is a dynamic virtual model of a physical object or system that reflects its state, behavior, and interaction with the environment in real time based on sensor data and mathematical models. In the context of robotics, a Digital Twin integrates kinematic and dynamic models, sensor data, control algorithms, and the environment, which allows predicting future system states and optimizing its operation.

The architecture of a digital twin of a collaborative robot includes a physical layer, where a real robot with sensors is located, a data acquisition layer that provides information transmission, a data processing and state assessment layer that uses EKF or UKF algorithms, a modeling layer that implements numerical models of motion and the environment, a planning and control layer that determines trajectories and control actions, and an interface for interaction with the operator or other systems. An example of the architecture of a digital twin of a collaborative robot is shown in Figure 1.

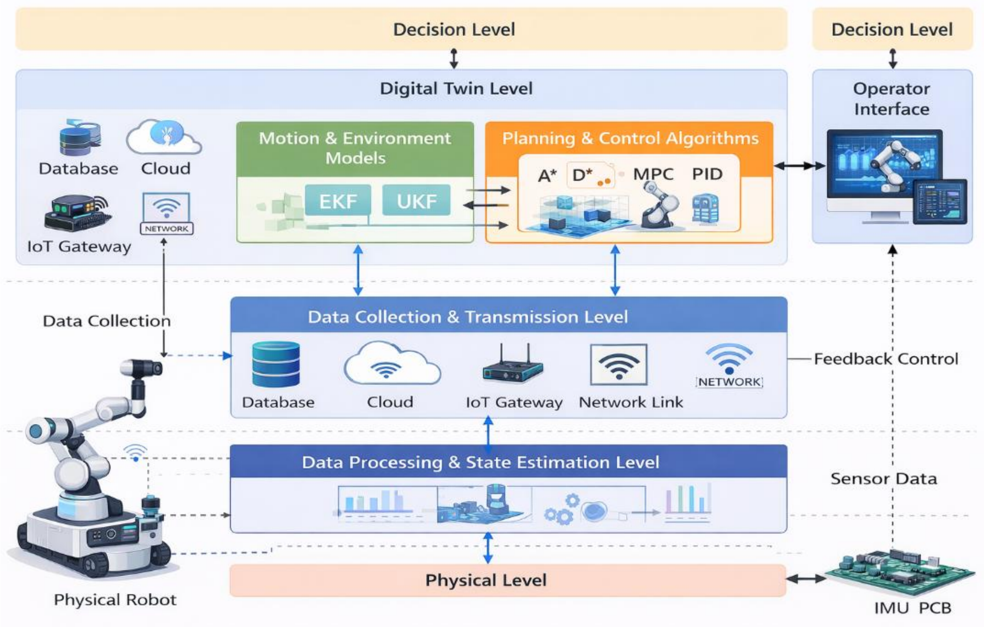

Figure 1. – Example of a collaborative robot digital twin architecture

Digital twins are classified by level of integration and functionality, an example of such a classification is presented in Figure 2.

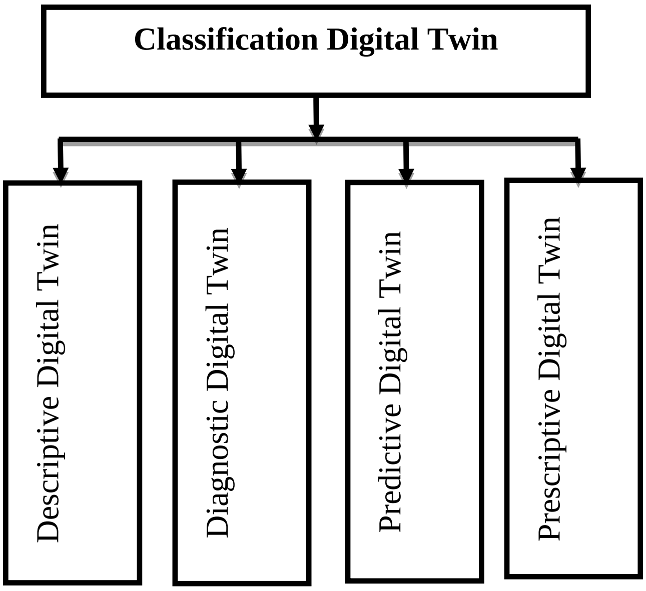

Figure 2 – Classification of digital twins

Let us consider in more detail the proposed classification of digital twins, which is presented in Figure 2:

Descriptive Digital Twin is a basic level of digital twin, which provides a reflection of the current state of a physical system in a digital environment based on data from sensors in real or quasi-real time, where the mathematical basis is presented in the form of a state mapping $x(t) \rightarrow \hat{x}(t)$, which allows forming a digital copy without deep analysis of causes or prediction, and its main purpose is to monitor, visualize and basic analysis of the state of the system, which is critically important for the initial level of digitalization and ensuring transparency of the functioning of robotic platforms as part of cyber-physical systems.

Diagnostic Digital Twin is an advanced level of digital twin that not only displays the state of the system, but also analyzes the causes of changes and deviations, using data processing methods, statistical analysis and state estimation algorithms, such as Kalman filters or Bayesian approaches, which can be mathematically represented as an estimation problem $p(x_k \mid z_{(1:k)})$, where data interpretation and anomaly detection are carried out, and its purpose is to diagnose faults, identify sources of errors and increase the reliability of the system, which is especially relevant for collaborative robots in variable environmental conditions.

Predictive Digital Twin is a level of digital twin that is focused on predicting the future state of the system based on mathematical models of dynamics, statistical methods and machine learning, where a model of the form $x_{(k+1)}=f(x_k,u_k,w_k)$ is used, which allows estimating future movement trajectories, collision risks or component degradation, and its main purpose is to support decision-making, optimize system operation and prevent emergency situations, which is key for traffic planning and control tasks under uncertainty.

Prescriptive Digital Twin is the highest level of development of a digital twin, which not only predicts the behavior of the system, but also generates optimal control actions based on specified performance criteria, using optimization and control methods such as MPC or adaptive algorithms, which is mathematically described as a problem of minimizing the functional $u^*=\arg\min J(x,u)$, where the optimal control strategy is formed, and its purpose is to ensure autonomous or semi-autonomous decision-making, increase the efficiency, safety and adaptability of the system, which is especially important for the implementation of the Industry 5.0 concept and the integration of humans and robots in a shared environment.

CONCLUSIONS. The analysis showed that the proposed classification of digital twins provides a holistic representation of their functional evolution from basic state representation to autonomous decision-making in collaborative robot control tasks. It is established that the use of mathematical models, including state assessment methods, dynamic models and optimization approaches, allows to increase the accuracy, adaptability and reliability of digital twins in cyber-physical systems. It is shown that the integration of different levels of the digital twin is a key factor in ensuring effective monitoring, diagnostics and prediction of the behavior of robotic systems in real time. It is substantiated that the most promising direction is the development of predictive and prescriptive digital twins, which provide intelligent control and support for decision-making under conditions of uncertainty. The results obtained confirm the feasibility of using digital twins as a basic technology for creating intelligent collaborative robotic systems of a new generation.

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