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# COMPARATIVE ANALYSIS OF SOFTWARE AND HARDWARE PLATFORMS FOR DIGITAL TWINS AND SIMULATION SYSTEMS IN ROBOTICS EDUCATION

**Abstract**

This article presents a comparative analysis of the architectural and technical characteristics of software and hardware platforms for digital twins and simulation systems used in robotics education. In this study, a three-layer robotic information system architecture was modeled, consisting of a hardware layer (microcontrollers, sensors, and actuators), a communication layer (MQTT, WebSockets, and OPC UA protocols), and a virtual simulation layer (Webots, Gazebo, Unity 3D, NVIDIA Isaac Sim, Tinkercad, and Wokwi). Technical evaluation metrics included data synchronization latency, physics engine fidelity, Hardware-in-the-Loop (HIL) support, computational resource requirements, and telemetry data acquisition capabilities. The results demonstrate that professional simulators provide high-accuracy physical modeling but possess limited hardware integration and telemetry analytics capabilities. In contrast, digital twin platforms based on Unity 3D and NVIDIA Isaac Sim support bidirectional real-time synchronization, IoT integration, and interaction with SQL/NoSQL databases, making them effective architectural solutions for robotic information systems.

**Keywords:** Digital Twin, robotics, simulation systems, MQTT, Unity 3D, NVIDIA Isaac Sim, Gazebo, Webots, IoT, information systems.

## Introduction

The global economy and manufacturing sectors are currently undergoing a paradigm shift toward the Fourth Industrial Revolution, widely recognized as Industry 4.0. This technological transition demands highly qualified engineering personnel capable of developing, managing, and maintaining automated systems, the Industrial Internet of Things (IIoT), and complex robotic architectures. In this technological landscape, technical and vocational education training (TVET) institutions, including colleges, play a critical role as the primary suppliers of technical professionals who must be both adaptable to rapidly evolving market demands and equipped with rigorous practical competencies [1].

However, a significant challenge arises as instruction in contemporary robotics typically necessitates advanced, capital-intensive hardware, such as industrial manipulators, multi-sensor stations, and high-precision actuators. Maintaining up-to-date physical laboratory equipment in educational institutions introduces severe financial and logistical constraints. A viable mitigation strategy for these constraints involves the strategic digital transformation of the educational infrastructure. Specifically, virtual simulation systems and digital twin technologies offer a sophisticated, cost-effective solution while simultaneously enhancing students' cognitive engagement and hands-on comprehension [2].

From an information technology perspective, digital twins extend substantially beyond basic three-dimensional graphics. They constitute integrated, cyber-physical software and hardware infrastructures capable of bidirectional, real-time data exchange with a physical counterpart, thereby accurately mirroring its mathematical models and empirical behavioral characteristics. To foster students' professional aptitude in software engineering, embedded circuit design, and system integration, it is crucial to deploy digital platforms that closely simulate authentic industrial production environments and provide direct interactive feedback loops [3].

Currently, both the commercial software market and the educational sector offer a wide spectrum of options, ranging from professional engineering simulators such as the Robot Operating System (ROS), MATLAB/Simulink, and Cyberbotics Webots, to streamlined, cloud-based web emulation tools like Autodesk Tinkercad and Wokwi. Nevertheless, these platforms exhibit significant disparities regarding their underlying software architectures, computational resource requirements, Hardware-in-the-Loop (HIL) integration capacities, and their capability to capture a student's "digital footprint" for rigorous learning analytics [4].

Consequently, prior to designing an optimized, high-performance information system tailored for educational robotics, it is necessary to systematically classify the architectural features of existing software and hardware platforms and perform a comprehensive technical comparative analysis. This investigation addresses both a relevant scientific challenge and a practical pedagogical necessity. The primary objective of this research is to identify and analyze the structural and architectural characteristics of contemporary simulation systems and digital twin platforms deployed in robotics education. By conducting a systematic evaluation of their technical specifications, this study aims to justify the optimal information technology solutions capable of facilitating the automated monitoring and quantitative evaluation of students' cognitive and learning activities [5].

**Materials and methods**

To investigate the software and hardware platforms underpinning digital twins and simulation tools in educational robotics, a methodological approach based on system analysis, structural decomposition, and multilayer architectural design was deployed. Establishing an optimized information structure during the integration of a robotic complex into an educational framework constitutes a critical requirement, particularly regarding data flow management and the execution of a closed-loop feedback mechanism.

To systematically evaluate the technical and operational functionality of existing platforms, the comprehensive educational robotics framework was modeled as a three-tier architecture. This structural approach provides a rigorous technical foundation to describe and analyze the interactions of users with both virtual and physical environments throughout the learning workflow [6].

The foundational tier is designated as the hardware (physical) layer, which encompasses the physical assets utilized within laboratory environments. The hardware components selected for evaluation represent the computational and mechanical infrastructure standard in contemporary technical colleges. Regarding the microcontroller and onboard computing segment, the analysis incorporated Arduino architectures (Uno and Mega), STM32 microprocessors, ESP32 modules characterized by integrated Wi-Fi and Bluetooth capabilities, and Raspberry Pi 4 single-board computers configured for advanced robotic control sequences. Mechanical actuation was represented by servomotors, stepper motors, and standard DC motors, integrated via L298N and PCA9685 driver circuits. The sensory apparatus comprised ultrasonic distance sensors, infrared modules, MPU6050 gyroscopes, and digital optical cameras.

The intermediate tier comprises the data link and IoT layer, which functions as the primary operational backbone of the integrated infrastructure. This layer facilitates real-time, bidirectional data transfer between the physical hardware components and the corresponding virtual models, serving as a critical prerequisite for architectural stability. Various communication interfaces and protocols were systematically assessed within this framework. Wired data transmission was established via bridge interfaces including USB-UART, I2C, and SPI to facilitate direct communication with the simulation environment. For wireless telemetry, the primary emphasis was placed on lightweight Internet of Things (IoT) protocols. The MQTT protocol was evaluated due to its minimal network overhead, while WebSockets were examined for high-frequency data synchronization with browser-based cloud applications. Additionally, the industrial interoperability standard OPC UA was integrated into the comparative analysis to simulate authentic manufacturing environments [7].

The definitive tier is defined as the virtual (simulation) layer, which constitutes the software environment responsible for executing the mathematical formulations, computing kinematic and dynamic profiles, and rendering three-dimensional graphical assets. For the comparative investigation, a heterogeneous selection of contemporary software platforms was analyzed. Within the domain of professional and open-source simulators, the study evaluated Cyberbotics Webots and the Gazebo ecosystem operated in conjunction with the Robot Operating System (ROS), both utilizing high-precision physics engines such as ODE and Bullet. Within the framework of digital twin development environments, investigations were directed toward Unity 3D, utilized as a versatile engine for synthesizing kinematics and virtual laboratory interfaces, and NVIDIA Isaac Sim, an industrial-grade deployment platform utilizing the PhysX engine alongside photorealistic ray-tracing graphics. Furthermore, cloud-based web emulators, specifically Autodesk Tinkercad and Wokwi, were incorporated to evaluate the execution of microcontroller source code and simplified circuit layouts within standard web browser interfaces. The structural variations distinguishing professional simulators, digital twin environments, and cloud-based emulators are graphically delineated in the user interfaces presented in Figure 1.

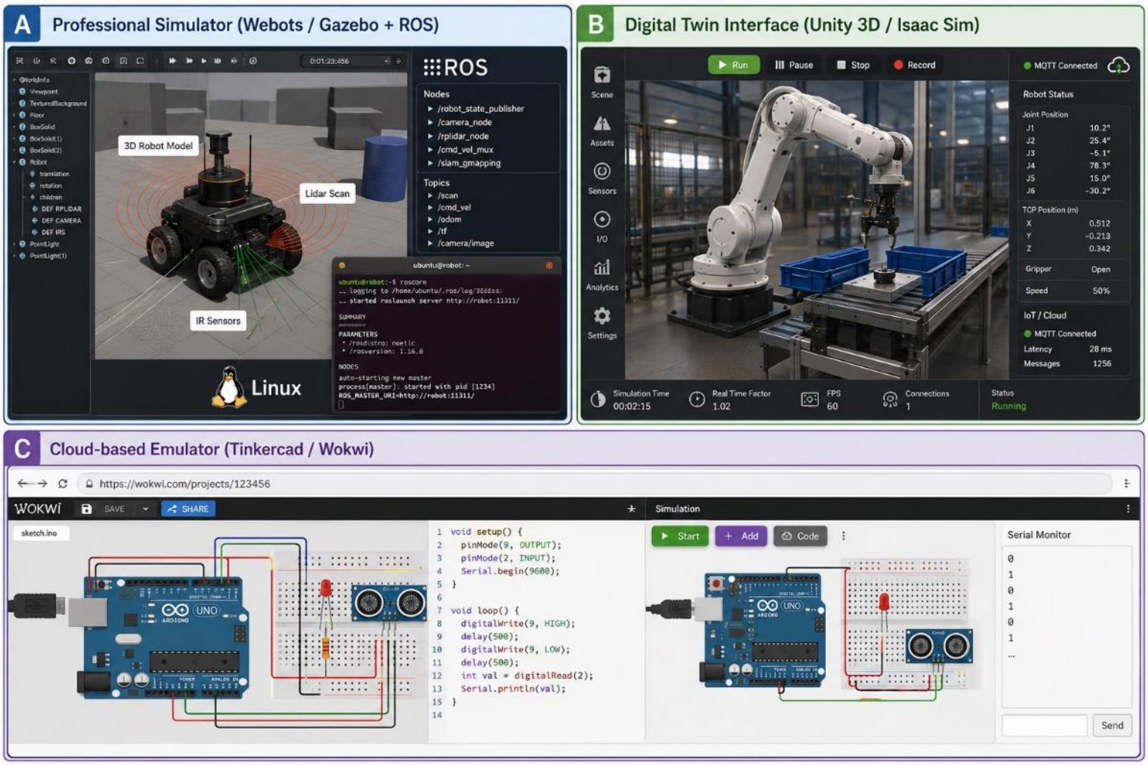


Figure 1 – Graphical user interfaces of the analyzed robotic simulation and emulation platforms

**Evaluation Metrics**

To evaluate the selected platforms from an information systems perspective, a structured framework comprising specific technical criteria and IT metrics was established. This systematic approach ensures a consistent, side-by-side comparative analysis of the software and hardware environments.

The primary evaluative metric was data synchronization latency. This parameter quantifies the temporal delay, measured in milliseconds, between the mechanical execution of the physical robotic asset and the corresponding state update within the virtual representation. Minimizing this latency is critical, as even marginal propagation delays can compromise the user's cognitive immersion and operational precision.

A secondary critical determinant was Hardware-in-the-Loop (HIL) operational support. This capability defines the capacity of a given simulation platform to ingest control signals directly from a physical microcontroller and seamlessly integrate them into the virtual kinematics model. The presence of robust HIL support is vital for validating the structural convergence of physical and digital environments [8].

Furthermore, physics engine fidelity was evaluated to determine the computational accuracy with which the simulation models gravitational forces, kinetic friction, rotational inertia, and spatial collisions. While low-fidelity engines provide purely visual approximations, higher-fidelity alternatives execute precise mathematical calculations of non-linear physical forces, which is an essential prerequisite for rigorous robotics training.

Finally, systematic attention was directed toward telemetry and learning analytics capabilities. This metric assesses the capacity of the platform architecture to automatically log granular user interactions into structured SQL or NoSQL databases. The telemetry acquisition matrix targets variables such as algorithmic compiler errors, simulation execution frequencies, and task completion durations. This dataset functions as a quantitative instrument to analyze and measure student cognitive engagement and learning behavioral patterns [9].

**Results and discussion**

A comprehensive architectural analysis was executed to evaluate the technical performance, communication protocols, and data acquisition infrastructure of the designated software and hardware platforms. The analytical framework was governed by a central investigative question: the extent to which these virtualized environments optimize engineering cognition and foster proactive learning behaviors within technical education demographics.

To facilitate a systematic evaluation of the analytical data, the investigated platforms were classified into three distinct categories (Figure 2).

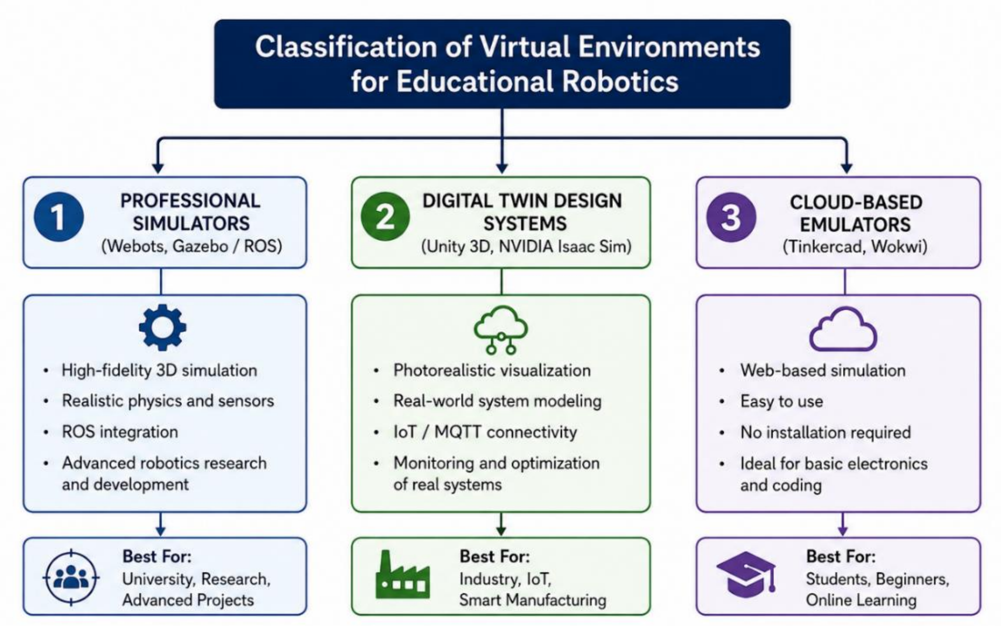


Figure 2 – Classification framework of virtual environments for educational robotics based on professional simulators, digital twin design systems, and cloud-based emulators

As a result of the study, the considered software programs were evaluated based on several technical criteria and metrics. The evaluation was conducted by groups. The summarized results of the performed structural and functional analysis are presented in Table 1.

Table 1 – Comparative analysis of technical characteristics of robotic simulation systems and digital twin platforms

| Technical Criteria and IT Metrics | Professional Simulators (Webots, Gazebo) | Digital Twin Platforms (Unity 3D, NVIDIA Isaac Sim) | Cloud Emulators (Tinkercad, Wokwi) |
|---|---|---|---|
| System Architecture Type | Local (Desktop Application) | Hybrid Cloud (IoT / Client-Server) | Cloud SaaS (Web-based) |
| Data Synchronization Mode (Data Sync) | Limited (Internal software API only) | Bidirectional Real-time (MQTT, WebSockets, OPC UA) | None (Autonomous virtual execution only) |
| Physics Engine Accuracy | High (ODE, Bullet) | Maximum Industrial Grade (PhysX, RTX Ray-Tracing) | Basic (Logical / Ideal physics only) |
| Hardware Integration (HIL Support) | Medium (Requires specific drivers and ROS gateways) | Very High (Direct connection with a physical microcontroller) | Low (Connection of virtual components only) |
| Hardware Requirements | Medium (CPU, basic RAM) | High (GPU, RTX Ray-Tracing support required) | Minimal (Web browser only) |
| Student "Digital Footprint" Collection (Telemetry & Analytics) | Low (Via local log files) | Very High (Automated log transfer to SQL databases) | Low (Task verification level only) |

The comprehensive analysis demonstrates that each category of simulation platforms possesses distinct institutional advantages and technical limitations within the contemporary educational ecosystem. Professional simulators, such as Webots and the Gazebo/ROS ecosystem, exhibit high fidelity and precision in computing the complex kinematics and dynamics of physical robotic systems. Despite these mathematical advantages, their underlying software architecture demands an advanced proficiency in the Linux (Ubuntu) operating system, deep competence in C++ or Python programming, and the ability to manipulate intricate system configuration files. For college students navigating the introductory phases of robotic engineering, this structural complexity establishes an excessively high entry barrier. Consequently, such a steep learning curve frequently induces technical frustration and anxiety, culminating in a measurable decline in cognitive engagement and student proactive participation. Furthermore, these professional environments lack integrated telemetry and built-in learning analytics tools, rendering the remote monitoring of student progression and pedagogical intervention highly problematic [10].

In contrast, cloud-based emulators, specifically Tinkercad and Wokwi, offer a highly accessible alternative characterized by low computational overhead and direct browser-based execution. These platforms serve as efficient instructional tools for the rapid acquisition of foundational concepts in electronic circuitry and microcontroller programming. However, their primary pedagogical utility is severely constrained by the absence of a realistic physics engine. Within these virtual environments, students are unable to simulate or experience critical physical variables such as structural mass, kinetic friction, rotational inertia, or stochastic environmental disruptions, including surface roughness and real-world traction variations. The omission of these dynamics poses a significant barrier to the cultivation of practical competencies aligned with actual industrial-grade engineering standards.

The paradigm that aligns most rigorously with the strategic mandates of Industry 4.0 centers on the deployment of Digital Twins developed via Unity 3D or the NVIDIA Isaac Sim platform. These sophisticated frameworks offer profound architectural and hardware-software advantages that bridge the gap between virtual experimentation and physical deployment. A primary mechanism of this architecture is real-time telemetry, driven by robust communication protocols such as MQTT or WebSockets. This framework enables the establishment of a continuous, bidirectional communication loop between a physical robotic manipulator situated in a laboratory and its corresponding high-fidelity virtual 3D model. When a student modifies the underlying control algorithms, the virtual representation and the physical hardware execute synchronized movements. This immediate causal loop generates a powerful gamification effect, thereby substantially multiplying intrinsic student motivation and operational engagement [11].

Furthermore, the implementation of Hardware-in-the-Loop (HIL) simulation technology optimizes both fiscal efficiency and safety protocol compliance. Through HIL configurations, students interface physical microcontrollers, such as Arduino or ESP32 architectures, directly with the workstation to deploy operational source code, while visualizing the resultant kinetic behavior through a highly precise, simulated 3D model. This methodological approach effectively eliminates the operational risks associated with mechanical collisions and structural damage to high-cost laboratory instrumentation. Finally, these digital twin architectures facilitate advanced learning analytics for the continuous monitoring of cognitive engagement. At the core information system layer, every specific user interaction – ranging from simulation execution frequencies and the density of logical errors in the compiled code to granular task completion timelines—is automatically recorded as log data within structured databases such as SQLite or PostgreSQL, enabling objective, quantitative evaluations of the learning process.

**Conclusion**

The comparative investigation into the hardware and software infrastructure of educational robotics highlights a critical architectural divergence between advanced professional simulation environments and entry-level emulation tools. Specialized high-fidelity platforms, specifically Gazebo and Webots, present an overly complex operational overhead, creating an unsustainable entry barrier for undergraduate students during introductory engineering courses. On the contrary, ubiquitous cloud-based environments such as Tinkercad fail to replicate the complex kinematics and multi-body physics intrinsic to industrial-grade robotic applications. This functional disparity validates the necessity of developing hybrid technological frameworks that merge the rigorous mathematical precision of professional simulation software with the accessible, browser-based deployment models of modern cloud systems.

The analytical outcomes confirm that Digital Twins engineered via Unity 3D or the NVIDIA Isaac Sim architecture yield superior technical and pedagogical outcomes. By establishing a fully synchronized ecosystem structured as a Physical Robot <-> IoT Gateway <-> Virtual Model pipeline, these configurations serve as highly effective mechanisms for expanding cognitive immersion and student autonomy. The integration of an instantaneous, bidirectional telemetry loop eliminates instructional latency, thereby transforming conventional laboratory exercises into highly interactive engineering workflows.

Consequently, subsequent research initiatives will be dedicated to the structural synthesis and system modeling of an optimized digital twin framework engineered for automated technical curricula. The projected architecture is designed to unify a hardware microcontroller topology, an optimized MQTT broker node, and a proprietary Unity 3D visualization canvas. Subsequent empirical investigations will focus on integrating this deployed infrastructure into active university laboratory operations to establish a quantitative, statistically validated assessment of its long-term operational and instructional utility.

**References**

1. Wickramasinghe G., Wickramasinghe V. Institutional Response to Implement 4IR Competencies into Programme Offerings of Technical and Vocational Education and Training in Indo-Pacific // Journal of Technical Education and Training, 2024, T. 16. №3, P. 168-181.
2. Teis N. J. P., Els C. J. Knowledge, competencies and dispositions of lecturers in Technical Engineering in the context of advancing 4IR technologies // Journal of Vocational, Adult and Continuing Education and Training, 2021, T. 4. №1, P. 26.
3. Burkul C., Tajane A., Chavhan P. Implementation of Industry 4.0 Technologies in Technical and Vocational Education in Maharashtra // Asian Journal For Convergence In Technology (AJCT), 2025, T. 11. №1, P. 65-76.
4. MacCraith E., Forde J. C., Davis N. F. Robotic simulation training for urological trainees: a comprehensive review on cost, merits and challenges // Journal of Robotic Surgery, 2019, T. 13. №3, P. 371-377.
5. Camargo C., Goncalves J., Conde M. A., Rodriguez-Sedano F. J., Costa P., García-Penalvo F. J. Systematic Literature Review of Realistic Simulators Applied in Educational Robotics Context // Sensors, 2021, T. 21. №12, P. 4031.
6. Span M. T., Mailloux L. O., Grimaila M. R. Cybersecurity architectural analysis for complex cyber-physical systems // The Cyber Defense Review, 2018, T. 3. №2, P. 115-134.
7. Silva D. et al. A performance analysis of internet of things networking protocols: Evaluating MQTT, CoAP, OPC UA // Applied Sciences, 2021, T. 11. №11, P. 4879.
8. Mihalic F., Truntic M., Hren A. Hardware-in-the-loop simulations: A historical overview of engineering challenges // Electronics, 2022, T. 11. №15, P. 2462.
9. Liao C., Wang Y., Ding X., Ren Y., Duan X., He J. Performance Comparison of Typical Physics Engines Using Robot Models With Multiple Joints // IEEE Robotics and Automation Letters, 2023, T. 8. №11, P. 7520-7526.
10. Fung K. Y., Fung K. C., Lui T. L. R. et al. Exploring the impact of robot interaction on learning engagement: a comparative study of two multi-modal robots // Smart Learning Environments, 2025, T. 12. №12, P. 12.
11. Nambiar S., Paul R. C., Ikechukwu O. C., Jonsson M., Tarkian M. Digital Twin-Enabled Adaptive Robotics: Leveraging Large Language Models in Isaac Sim for Unstructured Environments // Machines, 2025, T. 13. №7, P. 620.

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## РОБОТОТЕХНИКАНЫ ОҚЫТУДА ҚОЛДАНЫЛТЫН ЦИФРЛЫҚ ЕГІЗДЕР МЕН СИМУЛЯЦИЯЛЫҚ ЖҮЙЕЛЕРДІҢ БАҒДАРЛАМАЛЫҚ-АППАРАТТЫҚ ПЛАТФОРМАЛАРЫН САЛЫСТЫРМАЛЫ ТАЛДАУ

**Түйін**

Мақалада білім беру робототехникасында қолданылатын цифрлық егіздер мен симуляциялық жүйелердің бағдарламалық-аппараттық платформаларының архитектуралық және техникалық ерекшеліктеріне жүйелі салыстырмалы талдау жасалды. Зерттеу барысында робототехникалық кешендердің үш деңгейлі ақпараттық құрылымы модельденді. Оның құрамына аппараттық деңгей (микроконтроллерлер, сенсорлар және атқарушы механизмдер), коммуникациялық деңгей (MQTT, WebSockets, OPC UA хаттамалары) және виртуалды симуляциялық деңгей (Webots, Gazebo, Unity 3D, NVIDIA Isaac Sim, Tinkercad, Wokwi) енгізілді. Платформаларды бағалау мақсатында деректерді синхрондау кідірісі, физикалық модельдеу дәлдігі, Hardware-in-the-Loop (HIL) технологиясын қолдау мүмкіндігі, есептеу ресурстарына қойылатын талаптар және телеметриялық мәліметтер мен студенттердің «цифрлық ізін» жинау функциялары сияқты кешенді IT-метрикалар қолданылды. Зерттеу нәтижелері көрсеткендей, кәсіби симуляторлар физикалық процестерді жоғары дәлдікпен модельдегенімен, олардың аппараттық интеграция және телеметриялық талдау құралдары шектеулі. Ал Unity 3D және NVIDIA Isaac Sim негізіндегі цифрлық егіздер платформалары нақты уақыттағы екіжақты синхрондауды, IoT-интеграцияны және SQL/NoSQL деректер қорларымен байланысты толық қамтамасыз ететіндіктен, робототехникалық ақпараттық жүйелер үшін ең тиімді архитектуралық шешім ретінде айқындалды.

**Кілттік сөздер:** цифрлық егіз, робототехника, симуляциялық жүйелер, MQTT, Unity 3D, NVIDIA Isaac Sim, Gazebo, Webots, IoT, ақпараттық жүйелер.

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# СРАВНИТЕЛЬНЫЙ АНАЛИЗ ПРОГРАММНО-АППАРАТНЫХ ПЛАТФОРМ ЦИФРОВЫХ ДВОЙНИКОВ И СИМУЛЯЦИОННЫХ СИСТЕМ В ОБУЧЕНИИ РОБОТОТЕХНИКИ

**Аннотация**
В статье представлен сравнительный анализ архитектурных и технических характеристик программно-аппаратных платформ цифровых двойников и симуляционных систем, применяемых в образовательной робототехнике. В ходе исследования смоделирована трехуровневая архитектура робототехнической информационной системы, включающая аппаратный уровень (микроконтроллеры, сенсоры и исполнительные механизмы), коммуникационный уровень (протоколы MQTT, WebSockets, OPC UA) и уровень виртуальной симуляции (Webots, Gazebo, Unity 3D, NVIDIA Isaac Sim, Tinkercad, Wokwi). Для комплексной оценки платформ использовались такие IT-метрики, как задержка синхронизации данных, точность физического движка, поддержка технологии Hardware-in-the-Loop (HIL), требования к вычислительным ресурсам, а также возможности сбора телеметрии и «цифрового следа» обучающихся. Полученные результаты демонстрируют, что профессиональные симуляторы обеспечивают высокую точность физического моделирования, однако обладают ограниченным функционалом для аппаратной интеграции и телеметрической аналитики. В свою очередь, платформы цифровых двойников на базе Unity 3D и NVIDIA Isaac Sim поддерживают двустороннюю синхронизацию в реальном времени, IoT-интеграцию и взаимодействие с базами данных SQL/NoSQL, что делает их наиболее эффективным архитектурным решением для робототехнических информационных систем.

**Ключевые слова:** цифровой двойник, робототехника, симуляционные системы, MQTT, Unity 3D, NVIDIA Isaac Sim, Gazebo, Webots, IoT, информационные системы.