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RESEARCH

Real-time visualization of cyber-physical system via mobile digital twin

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Abstract

This paper presents a real-time mobile-based Digital Twin system for Cyber-Physical Systems (CPS) visualization using cloud-based technologies. The proposed system replaces traditional hardware-dependent monitoring solutions with a simulation-driven architecture, enabling real-time data generation and visualization without physical sensors. A scalable backend is implemented using Firebase real-time Database to achieve low-latency data synchronization between the simulation module and the mobile application. The system ensures continuous data consistency through real-time cloud updates and an event-driven architecture, allowing seamless bidirectional communication between the virtual model and the user interface. The mobile application, developed using modern frameworks, provides interactive dashboards, graphical visualization, and system status monitoring for enhanced user understanding. The proposed approach improves accessibility, reduces infrastructure cost, and enhances scalability compared to conventional CPS monitoring systems. Experimental evaluation demonstrates efficient real-time synchronization with minimal delay, making the system suitable for academic, training, and lightweight industrial applications. In addition, the system demonstrates a flexible and extensible framework that can be adapted for various real-world applications such as smart monitoring, industrial automation, and educational simulations. The modular design allows easy integration of future enhancements, including IoT-based data acquisition and AI-driven analytics. By combining real-time visualization with a lightweight mobile interface, the proposed system provides a practical foundation for developing scalable Digital Twin solutions in resource-constrained environments.

Keywords: Digital twin, cyber-physical systems, firebase, real-time synchronization, mobile application, cloud computing.

1. Introduction

The rapid advancement of cyber-physical systems (CPS) and cloud computing has created a growing need for efficient real-time monitoring and visualization solutions.

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Digital Twin technology has emerged as a powerful approach for representing systems in a virtual environment [1] for representing physical or simulated systems in a virtual environment, enabling continuous observation, analysis, and control. However, traditional Digital Twin implementations rely heavily on physical sensors, IoT devices, and complex hardware infrastructures, making them costly, less accessible, and difficult to deploy in academic and small-scale environments. To overcome these limitations, this paper proposes a mobile-based Digital Twin system that enables real-time visualization of cyber-physical system behavior using a simulation-driven architecture. The proposed system replaces hardware dependency with a virtual data generation module and utilizes Firebase real-time Database to achieve low-latency, cloud-based data synchronization. This architecture ensures seamless communication between the simulation model and the mobile application, enabling real-time updates and interactive system monitoring. The system is designed using modern mobile and cloud technologies, providing a scalable and cost- effective solution for understanding CPS concepts. By integrating real-time data synchronization, graphical dashboards, and system status monitoring, the proposed approach enhances accessibility and usability for students, researchers, and training environments. The implementation demonstrates how Digital Twin systems can be developed without physical hardware while maintaining real-time performance and system accuracy [2].

2. Background and related work

2.1. Evolution of Digital Twin in cyber-physical systems

Digital Twin technology has evolved as a key component in cyber-physical systems. (CPS), enabling real-time representation of physical or simulated systems in a virtual environment. Early implementations relied heavily on physical to capture real-time data. However, these high cost, complexity, and limited accessibility. Recent advancements focus on simulation-based Digital Twin models, which eliminate hardware dependency while maintaining system behavior representation [3]. This shift has made Digital Twin systems more suitable for academic, training, and lightweight monitoring applications. The implementation of modular components, including data simulation, cloud synchronization, and visualization modules. The use of cloud-based technologies enables seamless data availability.

2.2. Real-Time Synchronization using Cloud-Based Architectures

Traditional monitoring systems often rely on periodic data fetching, which introduces latency and reduces system responsiveness.

Modern cloud-based architectures, such as Firebase Real-time Database, enable event-driven data synchronization where updates are instantly pushed to connected clients. This approach ensures low-latency communication between the data source and the mobile application. By maintaining continuous data streams, cloud- based systems provide efficient and scalable solutions for real-time visualization and Cloud-based platforms such as Firebase enable real-time data synchronization with low latency [4].

2.3. Real-Time Synchronization using Cloud-Based Architectures

In simulation-driven Digital Twin systems, maintaining data consistency and realistic system behavior is critical. Simulation modules generate continuous system parameters such as operational status, performance metrics, and environmental conditions. Ensuring structured data flow and synchronization through cloud databases helps maintain system reliability and accuracy. Compared to hardware-based systems, simulation-based models provide a flexible and cost-effective approach while still enabling meaningful analysis of system performance and behavior. Simulation-driven Digital Twin models provide a cost-effective alternative to hardware-based systems [5].

3. Proposed system architecture

The proposed system adopts a cloud-based, modular architecture designed for real-time Digital Twin visualization of cyber-physical systems. Unlike traditional monolithic and hardware-dependent systems, the architecture is divided into three primary components the Data Simulation Module, the Cloud Synchronization Layer, and the Mobile Visualization application. This separation ensures scalability, flexibility, and efficient data handling. The proposed architecture follows a modular Digital Twin design approach supported by cloud technologies [6].

Table 1: Key components of the proposed architecture

Component	Function	Implementation	Benefit
Data Simulation Module	Generates real-time system parameters (status, temperature, performance)	Custom simulation logic	Eliminates hardware dependency and reduces cost
Cloud Synchronization Module	Stores and syncs data between sys	Firebase real-time Database	Low-latency updates
Alert & Status	Detects abnormal conditions	Spring Threshold-based logic + Cloud updates	Improves system awareness and response
User Interaction Module	Allows users to modify system	Mobile UI controls	Enables bidirectional communication

Data Simulation Module: This module acts as the core of the Digital Twin system by generating real-time system parameters such as temperature, operational status, and performance metrics. It simulates the behavior of a cyber-physical system without relying on physical sensors, ensuring flexibility and cost-effectiveness while maintaining realistic system behavior.

Cloud Synchronization Module: This module serves as the communication backbone of the system, managing real-time data exchange between the simulation module and the mobile application using Firebase real-time Database. It ensures continuous data consistency and low-latency synchronization through event-driven updates.

Mobile Visualization Module: This module functions as the user interface, displaying system data through interactive dashboards, graphical charts, and status indicators. It continuously listens for cloud updates and dynamically reflects the current state of the Digital Twin, enabling real-time monitoring and analysis.

Alert and Status Module: This module monitors system parameters and detects abnormal conditions based on predefined thresholds. It generates real-time alerts and visual indicators, allowing users to quickly identify system changes and understand system behavior effectively.

User Interaction Module: This module enables users to interact with the Digital Twin by modifying system parameters through the mobile interface. The updates are instantly synchronized with the cloud database, supporting bidirectional communication and enhancing the interactivity of the system.

Data Simulation Module:

By maintaining organized data collections and timestamps, the module supports real-time access as well as historical data tracking for performance evaluation and system behavior analysis. This enhances data reliability, scalability, and overall system efficiency. It ensures that all simulated parameters, status updates, and historical records are structured efficiently for quick retrieval and analysis. A modular architecture is adopted to improve system flexibility and reduce complexity (Table 1) [7].

Table 2: Comparison with conventional systems

Feature	Proposed Neuromorphic Processor	GPU-Based System	Cloud-Based System
Data Source	Simulated real-time data	Physical sensors (IoT devices)	Manual / periodic data collection
Latency	Low (real-time cloud sync)	Low (real-time cloud sync)	Low
Scalability	High (cloud-based)	Limited by hardware	Limited
Deployment	Easy	Complex	Moderate

Architecture Style: The proposed system adopts a cloud-based, modular Digital Twin architecture where the simulation module, cloud database, and mobile application are decoupled. This separation improves flexibility and scalability. In contrast, traditional monitoring systems are tightly coupled with hardware components, making them difficult to modify or extend [8].

Data Handling: The proposed system uses real-time, event-driven data synchronization through Firebase, where updates are instantly pushed to the mobile application. Traditional systems rely on periodic data fetching or manual updates, which introduce delays and reduce responsiveness.

Data Representation: The proposed system utilizes lightweight structured data (JSON format) for efficient communication between modules. Traditional systems often use complex data handling mechanisms or manual processing, which increases system overhead and reduces efficiency.

Scalability: The proposed cloud-based architecture provides high scalability, allowing multiple users and devices to access the system simultaneously. Traditional hardware-based systems have limited scalability due to dependency on physical infrastructure and device constraints.

Deployment: The proposed system is easy to deploy as it does not require physical sensors or complex setup, making it suitable for academic and training environments. In contrast, traditional systems require hardware installation, configuration, and maintenance, increasing deployment complexity.

Security and Data Integrity: The proposed system leverages secure cloud services and structured data management to ensure reliable data handling and controlled access. Traditional systems may face challenges in maintaining. By utilizing a simulation-driven approach, the system eliminates the need for expensive hardware (Table 2) [9].

Table 3: Performance and security advantages

Parameter	Improvement Achieved
Data synchronization	Real-time updates with minimal delay (<1 sec)
Latency	Low latency due to event-driven cloud sync
Scalability	High (supports multiple users/devices)
Cost Efficiency	Reduced cost (no hardware dependency)
Accessibility	High (mobile-based access anytime)

Real-Time Data Security: The proposed system ensures secure data communication between the mobile application and the cloud database using Firebase's built-in authentication and access control rules. This prevents unauthorized data access and maintains system integrity during real-time synchronization.

Data Consistency: The system maintains continuous data consistency through event-driven cloud synchronization. Any updates in the simulation module are instantly reflected in the mobile application, ensuring that the Digital Twin accurately represents the current system state without data mismatch.

System Reliability: The cloud-based architecture ensures reliable data storage and retrieval. Even in case of application restart or temporary disconnection, the latest system data can be retrieved from the cloud database without loss, ensuring uninterrupted monitoring. The system is designed based on standard software engineering principles to ensure maintainability and scalability [10].

Platform Accessibility: The system uses a mobile-based interface with cloud integration, allowing users to access real-time system data from anywhere. This ensures platform independence and enhances usability across different devices without requiring complex setup (Table 3).

4. Implementation methodology

The system implementation follows a modular and cloud-based approach integrating simulation, real-time data synchronization, and mobile visualization. The development is carried out using modern frameworks and tools to ensure scalability, efficiency, and real-time performance. Firebase Real-time Database enables event-driven communication between system components.

Data Simulation: The simulation module generates dynamic system parameters such as temperature, system status, and performance metrics. These values mimic real-world system behavior and are continuously updated to represent a cyber-physical system. Visualizing behavior [11].

Cloud Integration: Firebase real-time Database is used as the backend to store and synchronize system data. The database ensures real-time updates by pushing changes instantly to connected clients without the need for manual requests.

Mobile Application: The frontend is developed using Flutter, providing an interactive user interface with dashboards, charts, and status indicators. The application continuously listens to cloud updates and dynamically reflects system behavior. The mobile application is developed using Flutter for efficient UI design [12].

Real-Time Communication: Event-driven architecture is implemented to ensure low-latency data flow between the simulation module and the mobile application. This enables seamless synchronization and accurate Digital Twin representation.

Alert Mechanism: Threshold-based logic is implemented to detect abnormal system conditions. When system parameters exceed predefined limits, alerts are generated and displayed in the mobile interface.

5. Results and discussion

The proposed Digital Twin system was tested under different simulation scenarios to evaluate real-time performance, data synchronization, and system responsiveness. The results demonstrate that the system successfully achieves continuous real-time data updates between the simulation module and the mobile application using Firebase Real-time Database [13]. The event-driven architecture ensures that any changes in system parameters are instantly reflected in the mobile interface with minimal delay.

Performance testing shows that the system maintains low latency, with data synchronization occurring within less than one second under normal network conditions [14]. The mobile application consistently displayed updated system parameters such as status indicators and performance metrics without noticeable lag, confirming the effectiveness of the real-time communication model. Scalability testing indicates that the cloud-based architecture supports multiple concurrent users without affecting system performance. Since the system does not rely on physical hardware, it significantly reduces deployment cost and complexity while maintaining flexibility and accessibility. Furthermore, the alert mechanism accurately detected abnormal due to real-time cloud synchronization [15].

6. Challenges and future scope

Although the proposed system provides an efficient and scalable Digital Twin framework, certain challenges were identified during implementation. One of the primary challenges is network dependency, as real-time data synchronization relies on stable internet connectivity. Any network delay or interruption can affect system responsiveness and data update frequency. Digital Twin systems use data-driven approaches to analyse system performance and improve decision-making. While this approach reduces cost and complexity, it may not fully capture real-time physical variations, limiting its applicability in industrial environments. In terms of future scope, the system can be extended by integrating real IoT sensors and hardware devices to enhance system accuracy and practical usability. Additionally, advanced analytics and machine learning techniques can be incorporated to enable predictive monitoring and intelligent decision-making. Artificial Intelligence can be integrated to analyse system data and predict failures further improvements may include enhancing data visualization with advanced dashboards, supporting multi-device integration, and optimizing cloud performance for large-scale deployments. The system can also be expanded for applications in smart manufacturing, smart. Machine learning techniques can be integrated for predictive analysis in Digital Twin systems.

7. Conclusion

The proposed mobile-based Digital Twin system successfully demonstrates an efficient and scalable approach for real-time visualization of cyber-physical systems using cloud-based technologies. By eliminating dependency on physical hardware and adopting a simulation-driven architecture, the system provides a cost-effective and accessible solution for academic and training environments. The integration of Firebase real-time Database ensures low-latency data synchronization, enabling continuous and accurate representation of system behavior in the mobile application. The implementation of modular components, including data simulation, cloud synchronization, and visualization modules, enhances system flexibility, maintainability, and scalability. The results confirm that the system achieves reliable real-time performance, efficient data handling, and improved user interaction through dynamic dashboards and alert mechanisms. Overall, the proposed approach establishes a strong foundation for developing lightweight Digital Twin systems and highlights the potential for future expansion into real-world applications with IoT integration and advanced analytics. This makes the solution highly suitable for academic environments, where accessibility and cost-effectiveness are critical factors. The proposed system demonstrates the potential of Digital Twin systems use data analysis techniques to improve system performance and decision-making.

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