Digital Twin based Visualization Framework for Computer System Monitoring

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ABSTRACT

Digital Twin technology has emerged as a transformative approach for representing and monitoring physical systems through synchronized virtual models. This project presents the design and implementation of an interactive and animated Digital Twin framework developed specifically for computer laboratory system monitoring. The proposed system creates a real-time virtual replica of a physical computer lab by integrating three-dimensional modeling and performance data visualization into a unified simulation environment.The virtual laboratory environment is designed using Blender for detailed 3D modeling and implemented in Unity to enable real-time rendering, animation, and interactivity. Each physical computer system within the laboratory is mapped to a corresponding digital counterpart inside the virtual space. System performance metrics—including CPU utilization, GPU usage, temperature levels, and overall system load—are continuously collected and dynamically visualized through embedded virtual monitors within the Digital Twin environment. These metrics are represented using intuitive visual components such as animated indicators, progress bars, numerical displays, and color-based state variations.

1 Introduction

Digital Twin technology has been recognized widely as an innovative way to represent and monitor physical systems through virtual recreation. [1.1] In computer laboratory environments, the health and performance of the systems must be constantly monitored, but the conventional ways of monitoring are still very much based on the numerical dashboards or descriptive texts that might be hard to interpret especially when there is a need to managing several systems at the same time.The mentioned systems not only restrict the users' intuitive understanding but also prolong the time taken for system faults ~~to~~ ~~be~~ detected.In order to overcome these constraints, the proposed Digital Twin framework utilizes animation and interactive visualization for dynamically depicting the system's behaviour.

The main system performance parameters like CPU and GPU utilization, temperature levels, and system load are integrated into the virtual setting through monitor-based visual displays.

Moreover, besides the performance visualization, the interactive controls will be developed to give the users the power to change the layout of the virtual lab and to see and hear visual state changes that are in sync with the system conditions.Such a combination of features makes it easier to understand, cuts down on cognitive effort and increases the level of user interaction.The new Digital Twin framework not only offers a monitoring solution for computer labs that is practical but is also an educationally valuable one that combines visualization, animation interaction within a unified environment

2 Background

2. 1 Digital Twins usage in physical systems

Animated Digital Twins improve the conventional Digital Twin model by integrating animation effects into the system model for visualization.[2.1] In the context of Cyber-Physic al Systems, animation helps users view the system states dynamically instead of being restricted to snapshots of the data that are static.Systems involving gradualprocesses like the rise in temperature or resource use can be visualized to improve system understanding among users.

2.2 Role of animation in system visualization

Animation can be used to dynamically transform static system information into more understandable visual patterns. In traditional monitoring systems, the system performance metrics like CPU or temperature are displayed either as numbers or graphical representations, which need to be manually translated. Animation enables the visual representation of these changes to be easily tracked.[2.2]
In a Digital Twin computer lab, animation can be used to represent systemstate by meansof visual indicators such as colour change, animations, and animations on virtual computer monitors. .

3 Methodology

3.1 Architecture of general digital twin

The overall architecture of Digital Twin is designedto build a synchronized virtual twin of the physicalcomputer lab. It merges the physical laboratory system, mechanisms of data collection, and the virtualsimulation environment into one framework. Data on system performance is collected on a continuous basis from physical machines and transferred to the Digital Twin, granting real-time monitoring and visualization.[3.1]
It lays great emphasis on modularity, where every single component- data acquisition, visualization, and interaction- works independently within the system and are all interconnected. This design model offers better reliability of the system and makes future enhancements easier to accomplish.
At the physical layer, the actual computer laboratory systems operate as the primary data sources. Each machine continuously generates performance parameters such as CPU utilization, GPU usage, memory consumption, system load, and temperature readings. These parameters represent the operational health and status of the laboratory infrastructure. Sensors, built-in monitoring tools, or system diagnostic utilities collect this performance data at regular intervals to ensure continuous system tracking.

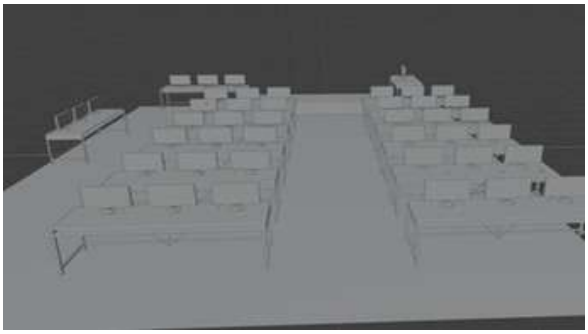

FIGURE1 Change of spatial arrangement of the lab using a toggle button with each click.

The virtual simulation layer represents the core of the Digital Twin framework. Within this layer, a three-dimensional model of the computer laboratory is developed and implemented using advanced visualization tools. Each physical system is mapped to a corresponding digital entity inside the virtual environment. The incoming real-time performance data is dynamically linked to visual elements such as virtual monitors, animated indicators, and color- coded status displays. As system conditions change in the physical lab, the virtual representation updates instantly to mirror those changes.

A key architectural principle of the proposed system is modularity. The architecture is divided into independent yet interconnected components, including data acquisition modules, data processing units, visualization engines, and interaction controllers. Each module operates autonomously while maintaining structured communication with other modules. This modular design improves system robustness by isolating faults within specif~~ic c~~omponents without affecting the entire framework. It also simplifies debugging, maintenance, and performance optimization.

Furthermore, the architecture is designed with scalability and flexibility in mind. New systems, additional performance parameters, or advanced analytics modules can be integrated without restructuring the entire system. This makes the framework adaptable to future technological upgrades, expanded laboratory setups, or enterprise-level deployments.

Another important architec~~tur~~al feature is synchronization control. The system ensures consistency between the physical and digital states by implementing update cycles and event-driven refresh mechanisms. Any variation in temperature, workload, or system utilization immediately triggers visual updates within the Digital Twin. This real-time reflection strengthens system dependability and enhances trust in the monitoring platform.

3.3 Monitor Presence Detection

The monitor presence detection mechanism forms a fundamental component of the proposed Digital Twin system, enabling automatic identification of whether a computer workstation is active or inactive. This is achieved through a camera-based vision system that continuously analyzes the physical environment using either a desktop webcam or a laptop camera. The primary objective of this module is to determine the availability of a monitor on each desk, which directly indicates the operational status of the system.

In the proposed approach, the camera captures real-time visual input of the laboratory workspace. These image frames are then processed using computer vision techniques (image-based object detection methods used to identify objects). The system is trained to recognize the presence of a monitor by analyzing features such as rectangular shape, screen boundaries, and structural appearance. If a monitor is detected within the frame, the system classifies the workstation as active (ON state). Conversely, if no monitor is identified, the system marks the workstation as inactive (OFF state).

The detection process is designed to operate continuously, ensuring real-time monitoring of system availability. Each detection result is transmitted to the backend system through local communication (such as HTTP requests or API calls), where it is logged and updated. The sample output logs, as shown in the system, indicate status updates like "Monitor Detected" and "Monitor Not Detected," confirming the working of the detection pipeline.

This automated vision-based approach eliminates the need for manual monitoring and provides a non-intrusive (no physical contact required) method for determining system usage. It enhances efficiency, reduces human error, and ensures accurate real-time tracking of workstation status, forming a strong foundation for the Digital Twin environment.

4 Result

The implementation of real-time synchronization between the physical monitor detection system and the Digital Twin model produced accurate and consistent results. The system was able to successfully reflect the real-world status of each workstation within the virtual 3D environment. When a monitor was present on the desk, the corresponding digital model displayed the monitor in an active state, while the absence of a monitor resulted in the digital model being marked inactive or hidden. This confirmed that the Digital Twin effectively mirrored the physical laboratory conditions.

The synchronization process demonstrated minimal delay between detection and visualization, indicating efficient data transmission and processing. The backend system reliably handled continuous status updates received from the camera- based detection module and updated the virtual environment in near real-time. The log outputs, such as “Monitor Detected” and “Monitor Not Detected,” validated that the system was functioning correctly and consistently identifying changes in the physical setup.

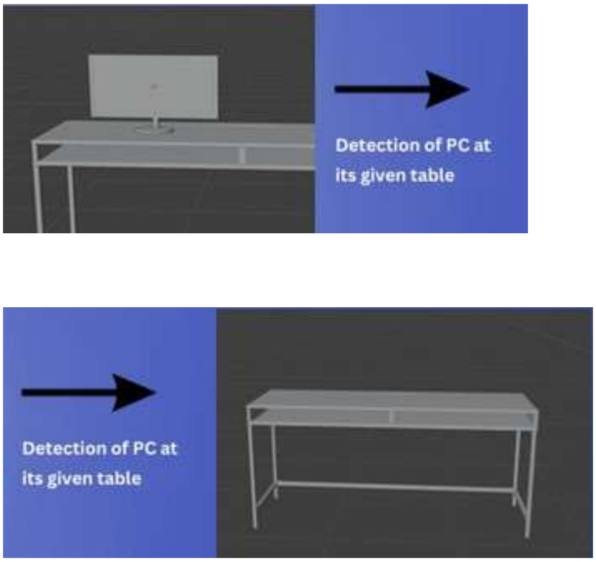

FIGURE2 Detection of monitor’s presence on the table to monitor physical presence of the PC’s

In One of the primary outcomes of the evaluation was improved fault identification efficiency. When simulated stress conditions were introduced—such as high CPU load and elevated temperature levels—the Digital Twin environment visually represented these anomalies through immediate color changes and animated alerts. Users were able to identify abnormal systems more quickly compared to traditional monitoring methods that rely solely on numerical dashboards. The spatial representation of systems within the virtual lab enabled users to associate performance issues with their physical locations, significantly reducing diagnosis time.

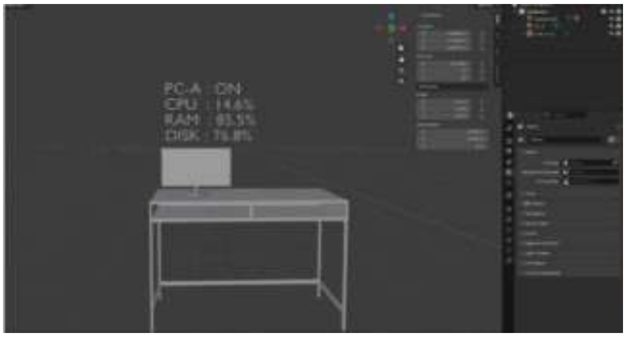

FIGURE3 PC’s on and off status from live data transmitted based on the actual system’s status

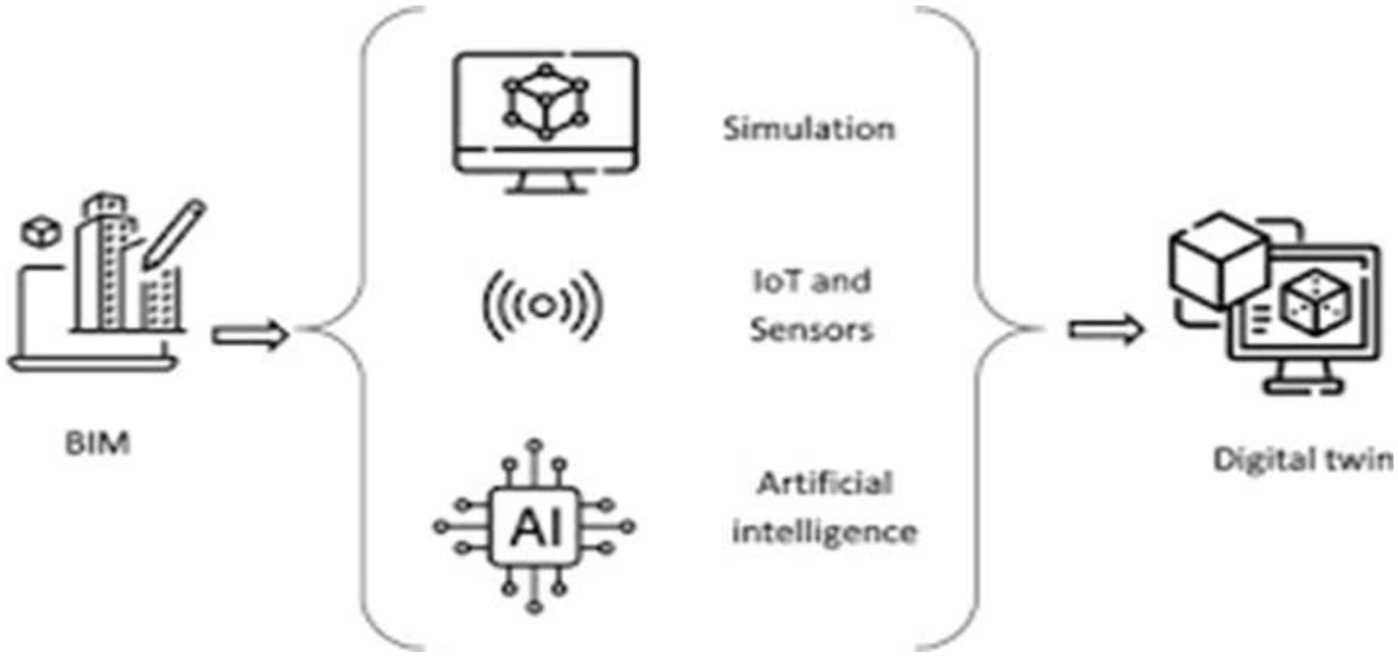

FIGURE4 This figure illustrates the Digital Twin workflow, showing real-time data flow between a physical asset, its virtual model, analytics, and feedback for monitoring and optimization.

5 Discussion

The results of this study emphasize the role of structured system integration in enhancing the practical relevance of Digital Twin applications within computer laboratory environments. Instead of focusing solely on predictive algorithms or automated intervention mechanisms, the framework validates that accurate synchronization between physical infrastructure and its digital representation can substantially improve operational transparency. The strength of the system lies in its ability to merge spatial modeling with live performance data, thereby transforming raw technical parameters into context-aware insights.

This approach proves particularly valuable in academic institutions where laboratories are shared by multiple users with varying levels of technical expertise. The Digital Twin environment reduces the learning curve associated with traditional monitoring tools by embedding performance metrics directly within a familiar three- dimensional layout. Users are not required to interpret abstract dashboards or switch between multiple monitoring windows. Instead, the integrated environment allows simultaneous observation of multiple systems, encouraging proactive system supervision and better resource managementFurthermore, the integration of interactive visualization within the Digital Twin framework enhances collaborative usage in shared laboratory environments. Multiple users, including students, lab assistants, and technicians, can collectively interpret system conditions with minimal confusion, as the visual representation standardizes the understanding of system states. This reduces dependency on highly skilled personnel for routine monitoring tasks and enables quicker response to potential issues.

6 Conclusion

The development of the proposed Digital Twin–based system monitoring framework successfully demonstrates how interactive visualization and real-time synchronization can transform traditional computer laboratory management. By creating a three- dimensional virtual replica of the physical lab and integrating live performance metrics such as CPU utilization, GPU usage, temperature, and system load, the framework establishes a reliable and intuitive monitoring environment.

The project validates that effective visualization, when combined with accurate data mapping and modular architecture, can significantly enhance system awareness and maintenance efficiency. Unlike conventional monitoring systems that depend heavily on numerical dashboards and fragmented tools, the Digital Twin environment presents system information in a spatial and visually contextualized format. This approach simplifies interpretation, reduces cognitive load, and enables faster identification of abnormal system behavior.

The modular and scalable architecture ensures that the framework can adapt to future expansions, including the addition of new systems, advanced analytics modules, or predictive maintenance capabilities. Real-time synchronization between physical systems and their digital counterparts further strengthens reliability and ensures consistent representation of operational conditions. The experimental evaluation confirms improved fault detection speed, enhanced user engagement, and better situational awareness compared to traditional monitoring practices

7 Limitations of study

The Despite the successful implementation and validation of the proposed Digital Twin framework, certain limitations must be acknowledged.

One of the primary limitations is that the current system focuses mainly on high-level performance metrics such as CPU utilization, GPU usage, temperature, and system load. It does not yet incorporate deep hardware diagnostics, component-level failure prediction, or advanced performance analytics. As a result, the Digital Twin functions primarily as a monitoring and visualization platform rather than a fully predictive maintenance system.

Another limitation lies in the scale of experimental evaluation. The framework was tested within a controlled laboratory environment with a limited number of systems. Large-scale deployment across multiple labs or enterprise-level infrastructure may introduce challenges related to network latency, data synchronization delays, and increased computational overhead in the simulation engine.

The current implementation also relies on simulated or periodically refreshed data streams rather than fully optimized real-time industrial-grade data pipelines. In high-frequency monitoring scenarios, this may affect synchronization precision between the physical systems and their digital counterparts.

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