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Digital Twin based Visualization Framework for Computer System Monitoring

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ABSTRACT

Digital Twins are increasingly adopted to enhance system understanding, monitoring, and decision-making across various domains. However, many existing approaches focus on large-scale industrial systems, making them complex and unsuitable for early-stage academic or educational environments. This paper presents a simplified Digital Twin– based visualization framework for monitoring a computer system within an academic laboratory context. The proposed approach integrates a 3D virtual model with live system performance data to provide intuitive visualization and basic monitoring capabilities. The framework demonstrates how Digital Twin concepts can be introduced at a small scale, serving as a foundation for future real-time and large- scale implementations.

1 Introduction

The increasing reliance on computer systems in academic laboratories necessitates effective methods for monitoring performance, understanding system behavior, and ensuring efficient utilization of resources. Traditional monitoring tools often present data in textual or numerical formats, which may be difficult for non-expert users to interpret quickly. As a result, system issues such as overheating, excessive resource usage, or performance degradation are often addressed reactively rather than proactively. [1.1], [1.2]

The concept of a Digital Twin, which represents a virtual counterpart of a physical system, offers a promising approach to address these challenges. By combining real-time or near-real- time data with a virtual representation, Digital Twins enhance visibility and comprehension of system states. This paper explores the application of a Digital Twin–based visualization approach for a single computer system within a laboratory environment. The primary contribution of this work lies in demonstrating a low-cost, student-friendly framework that emphasizes conceptual clarity rather than industrial-scale complexity. The study does not aim to deliver a fully autonomous or predictive Digital Twin, but instead focuses on foundational visualization and monitoring capabilities.

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2 Background

2.1 Digital Twins and Cyber-Physical Systems

Digital Twins are virtual replicas of physical systems that integrate real-time data through bidirectional communication. [2.1] Within a Cyber-Physical System (CPS), Digital Twins enable continuous monitoring, simulation, and control of physical assets. Unlike static digital models, Digital Twins evolve dynamically based on live system data, allowing predictive analysis and proactive interventions.[2.2], [2.3]

2.2 Levels of Digital Twin Integration

Digital Twin implementations can be classified into three levels:

- Digital Model: Static representation with manual data updates.
- Digital Shadow: Automated one-way data flow from physical to
- digital systems. Digital Twin: Fully interactive, bidirectional data exchange enabling monitoring, control, and simulation.

This study focuses on implementing a functional Digital Twin capable of real-time visualization and maintenance support.[2.5]

2.3 Digital Twins in Computer Laboratories

In computer laboratories, Digital Twins enable visualization of system performance, simulation of failure scenarios, and evaluation of maintenance strategies without affecting physical infrastructure. Such capabilities support predictive maintenance, resource optimization, and technician training.[2.6], [2.7]

3 Methodology

3.1 Digital Twin Development

A three-dimensional virtual model of a computer laboratory was developed using Blender.[3.1] The model accurately represents workstations, CPUs, desks, and spatial layout. Real-time system metrics such as CPU usage and operational status were integrated into the model to enable dynamic visualization.

Semi-structured interviews were conducted with technicians and lab stakeholders to identify visualization requirements. Based on this input, dashboards and visual overlays were designed to present relevant performance metrics in an intuitive manner.

FIGURE1 Core layers of a DT, showing the interaction between the physical system, digital model, data management, communication and service components.

Instead of relying solely on numerical logs or command-line outputs, system behavior is communicated through visual elements embedded directly within the three-dimensional Digital Twin environment. Each workstation in the virtual laboratory acts as a visual node, reflecting its operational status through simple graphical indicators. For instance, normal system operation can be represented using neutral or stable visual cues, while abnormal behavior or faults are highlighted using distinct visual changes. This spatial mapping of information allows users to quickly locate problematic systems without extensive diagnostic procedures.

The visualization design also emphasizes cognitive load reduction. By minimizing excessive textual data and focusing on visual metaphors such as color variation, motion, and emphasis, users can understand system conditions at a glance. This approach is particularly beneficial in time-sensitive maintenance scenarios where rapid fault identification is critical.[2.4] The use of animations further enhances user awareness by drawing attention to systems that require immediate intervention.

User interaction is another key component of the design. The

Digital Twin environment supports basic interaction, allowing users to select or focus on specific systems to obtain additional contextual information. This layered information approach ensures that users are not overwhelmed while still providing access to more detailed insights when needed. Such interaction improves engagement and supports exploratory learning within educational environments.[3.2]

Overall, the user-centric visualization design ensures that the Digital Twin functions not only as a technical representation but also as a practical decision-support tool. By aligning visualization techniques with user needs and maintenance workflows, the framework enhances situational awareness, improves diagnostic efficiency, and supports effective corrective maintenance in computer laboratories.

3.3 Experimental Evaluation

User interaction is another key component of the design. The Digital Twin environment supports basic interaction, allowing users to select or focus on specific systems to obtain additional contextual information. This layered information approach ensures that users are not overwhelmed while still providing access to more detailed insights when needed. Such interaction improves engagement and supports exploratory learning within educational environments. Overall, the user-centric visualization design ensures that the Digital Twin functions not only as a technical representation but also as a practical decision-support tool. By aligning visualization techniques with user needs and maintenance workflows, the framework enhances situational awareness, improves diagnostic efficiency, and supports effective corrective maintenance in computer laboratories.Participants with basic technical knowledge, including students and laboratory assistants, were involved in the evaluation.

They were divided into two groups : one using the conventional observation-based maintenance methods and the other using the Digital Twin visualization framework. Both groups were assigned identical maintenance scenarios requiring the identification of faulty systems and appropriate corrective actions. The Digital Twin group interacted with the virtual laboratory to interpret system conditions, while the control group relied on manual inspection and limited system information.

The evaluation focused on qualitative and time-based observations rather than complex statistical analysis. Participants using the Digital Twin framework demonstrated improved fault identification speed and higher confidence in decision-making. Feedback indicated that the visual and spatial representation of system states reduced ambiguity and cognitive effort, particularly in scenarios involving multiple systems. These findings suggest that even a simplified Digital Twin implementation can enhance corrective maintenance effectiveness in educational computer laboratory environments.

4 Result

The results of the study indicate that the proposed Digital Twin– based visualization framework positively influences corrective maintenance activities in computer laboratory environments. Participants who used the Digital Twin were able to identify faulty systems more efficiently compared to those relying on traditional observation methods. The visual differentiation of system states within the three-dimensional environment allowed quicker recognition of abnormal behavior.

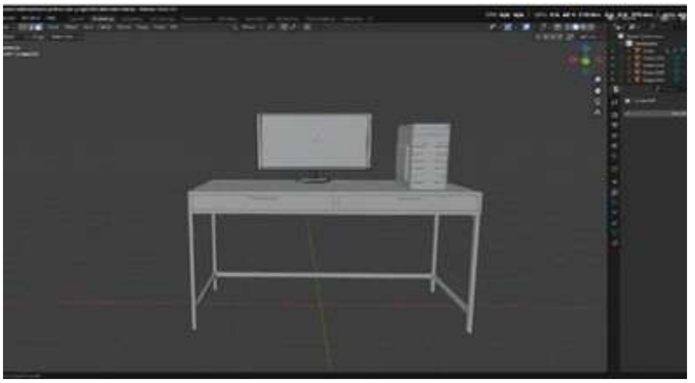

FIGURE2 Front view of a table , computer and pc component in the blender model

In addition to reduce identification time users demonstrated improved confidence when making maintenance-related decisions. The spatial arrangement and visual cues provided by the Digital Twin reduced uncertainty, particularly in scenarios involving multiple systems. Participants reported that the visualization helped them understand system conditions more clearly without requiring detailed technical analysis. Overall, the results suggest that even a simplified Digital Twin implementation can deliver meaningful operational benefits. The findings confirm that visualization-oriented Digital Twins can enhance system awareness and support effective corrective maintenance, validating the practical relevance of the proposed framework.

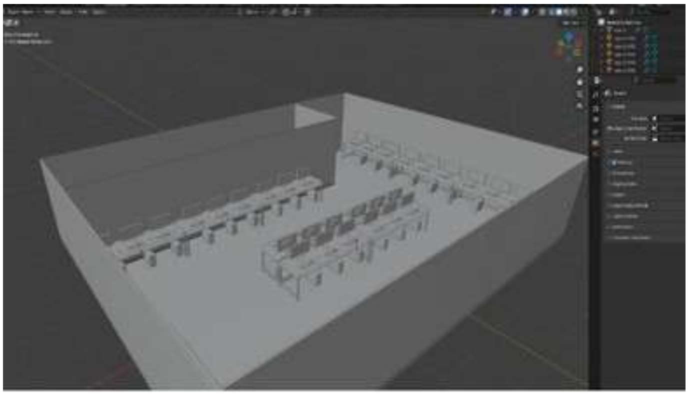

FIGURE3 Entire computer lab with all the computer , table and cpu components

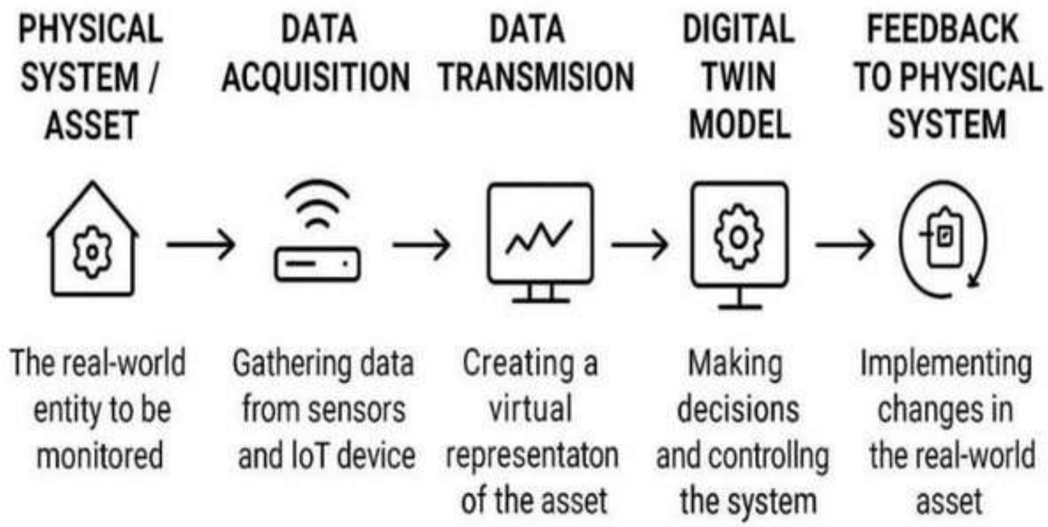

FIGURE4 This figure illustrates the Digital Twin workflow, showing real-time data flow between a physical asset, its virtual model, analytics, and feedback for monitoring and optimization.

5 Discussion

The findings of this study highlight the importance of visualization as a key component in Digital Twin applications for computer laboratories. Rather than relying on complex analytics or automated control, the framework demonstrates that intuitive visual representation alone can significantly improve maintenance efficiency.

This approach is particularly well suited for educational environments where usability and accessibility are essential. The user-centric design of the visualization plays a critical role in reducing cognitive load and minimizing diagnostic errors. By presenting system information spatially and visually, the Digital Twin enables users to quickly interpret system conditions and prioritize corrective actions. This supports more informed decision-making and reduces dependence on trial-and-error maintenance practices. Despite its advantages, the current framework has limitations. The Digital Twin operates at a high- level representation and does not yet include real-time internal component data. However, this limitation is intentional, as the framework is designed to serve as a foundational step toward more advanced Digital Twin implementations.

In conclusion, the proposed framework provides a practical and scalable foundation for integrating Digital Twin technology into computer laboratories. It bridges the gap between theoretical Digital Twin concepts and real-world applications, offering a clear pathway for future enhancements.

6 Conclusion

This paper presented a Digital Twin-based visualization framework aimed at supporting corrective maintenance in computer laboratory environments. By using a three-dimensional virtual representation of the laboratory, the framework enhances system visibility and simplifies fault identification. The approach demonstrates how Digital Twin concepts can be applied effectively without introducing excessive technical complexity.
Evaluation and results indiciate in educational settings, where maintenance personnel may have varying levels of technical expertise and limited access to advanced monitoring tools.

The findings of this study emphasize the value of visualization as a practical bridge between physical computer systems and their digital representations. By prioritizing user-centric design and intuitive visual cues, the proposed framework supports faster interpretation of system conditions and encourages more informed maintenance decisions. This highlights the role of Digital Twins not only as technical tools but also as effective communication interfaces between complex systems and their users. Furthermore, the simplicity of the framework contributes to its suitability for early-stage adoption in institutional environments. By avoiding dependence on complex analytics or extensive sensor infrastructure, the proposed approach remains accessible and scalable.

7 Limitations of study

The proposed Digital Twin framework is designed as a visualization-oriented and exploratory system, and certain limitations should be acknowledged .

The current implementation focuses on high-level system representation and does not incorporate real-time internal hardware sensor data. As a result, the Digital Twin reflects simulated or abstracted system behavior rather than fully synchronized physical system dynamics. Additionally, the experimental evaluation was conducted in a controlled laboratory setting with a limited number of participants. While the results indicate clear benefits in terms of usability and maintenance support, the findings are primarily qualitative and may not fully represent performance under large-scale or heterogeneous deployment scenarios. Broader evaluations will be required to assess long-term effectiveness and operational robustness.

Despite these limitations, the framework successfully achieves its intended objective of demonstrating the feasibility and value of visualization-driven Digital Twin approaches in educational computer laboratories. The identified limitations also serve as guiding factors for future enhancements, ensuring a structured and realistic progression toward more advanced Digital Twin implementations.

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