Digital Twin-based Sim2Real Framework for Real-Time Robotic Task Evaluation

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***Abstract*— This paper presents a digital twin-based simulation to real (Sim2Real) framework for real-time evaluation of robotic task performance through continuous synchronization between physical and virtual environments. The proposed system establishes bidirectional communication between a physical robotic station and its virtual counterpart, enabling task monitoring and evaluation during execution. By capturing real-time task states and maintaining a synchronized digital representation, the framework compares physical and virtual task outcomes to assess execution accuracy and validate Sim2Real consistency. This approach supports reliable performance analysis and contributes to the advancement of digital twin in robotic task verification within automated manufacturing settings.**

Keywords*— *Digital twin, Sim2Real, Robot task performance, Real-time evaluation

I. Introduction

The simulation-to-real (Sim2Real) transfer problem—referring to performance degradation when control policies trained in simulation are applied to real-world systems—has emerged as a key bottleneck in modern robotics [1]. This gap arises from discrepancies in physical modeling, sensor noise, environmental variations, and dynamic uncertainties that are difficult to replicate in virtual environments [1, 2].

Digital twin technology has gained attention as a promising means to address Sim2Real challenges by enabling high-fidelity virtual replicas of physical systems that can be continuously synchronized with real-time operations [3, 4]. Unlike conventional simulation environments, digital twins maintain bidirectional communication with their physical counterparts, allowing real-time updates and ongoing validation of the virtual model [4].

This paper proposes a digital twin-based framework for real-time Sim2Real evaluation, focusing on robotic task performance assessment through continuous synchronization between physical systems and their virtual counterparts. We establish a system architecture that integrates dual-arm robotic configurations with synchronized digital twin replicas and define protocols for real-time data acquisition and comparative analysis.

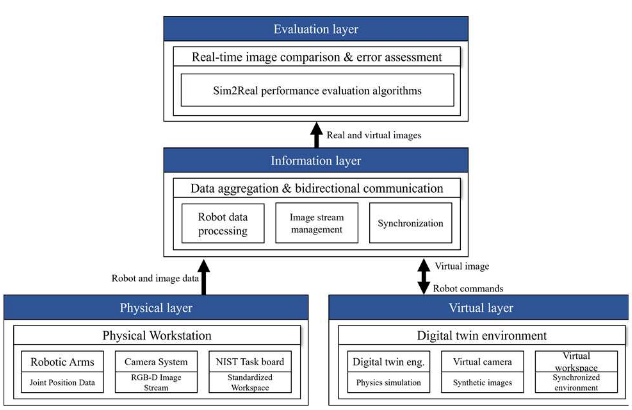

Fig. 1. Four-layer digital twin framework for Sim2Real evaluation

II. System Framework

The proposed system framework integrates hardware, software, and methodological components through a four-layer architecture to enable systematic Sim2Real evaluation. As shown in Fig. 1, the framework consists of four distinct layers with specific roles and responsibilities.

The physical layer encompasses hardware resources including dual robotic arms, depth camera systems, and standardized task boards, generating continuous robot telemetry and visual observation streams. The information layer serves as the central data hub, managing bidirectional communication by receiving robot data and camera images from the physical layer while transmitting robot states to the virtual layer and receiving virtual images. The virtual layer maintains a digital twin simulation environment, updating virtual robot configurations in real-time and generating synthetic camera images through photorealistic rendering. The evaluation layer performs continuous Sim2Real assessment by analyzing synchronized physical and virtual image streams to quantify task execution quality and transfer accuracy.

The architecture supports continuous bidirectional data flow, enabling adaptive synchronization between physical operations and virtual representations for systematic real-time Sim2Real evaluation.

III. Implemented Physical Workstation

To validate the feasibility of the proposed framework for real-time Sim2Real evaluation, we implement a standardized dual-arm robotic workstation that provides the physical foundation for continuous digital twin synchronization and task performance assessment.

Fig. 2 shows the implemented physical workstation comprising three key components: a) dual Franka Emika Panda

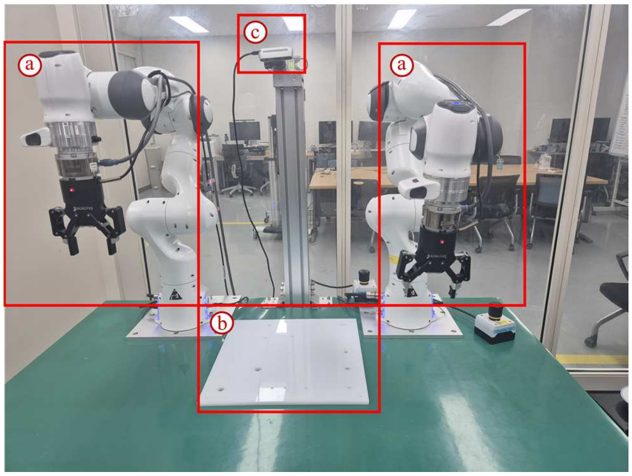

Fig. 2. Implemented dual-arm robotic workstation

robotic arms configured to generate continuous kinematic data streams for future digital twin synchronization, b) National Institute of Standards and Technology (NIST) task board serving as a standardized evaluation platform with precisely defined geometric features and color-coded elements for consistent visual landmarks, and c) an Intel RealSense D435i camera positioned overhead to capture real-time RGB-D image streams with complete workspace visibility while minimizing occlusion.

This configuration establishes the physical data sources required by the information layer of the framework, providing continuous streams of robot telemetry and visual observations necessary for systematic Sim2Real evaluation and digital twin accuracy assessment.

IV. Virtual Environment for Sim2Real Framework

To support the proposed Sim2Real evaluation framework, we develop a Unity-based virtual environment that replicates the physical robotic workstation configuration established in Section 3.

Fig. 3 shows the implemented virtual environment comprising: a) Unity-based virtual environment replicating the physical workstation with identical geometric models of dual robotic arms, NIST task board, and workspace layout, and b) virtual camera view capturing the virtual NIST task board from an overhead perspective that matches the physical RealSense camera configuration.

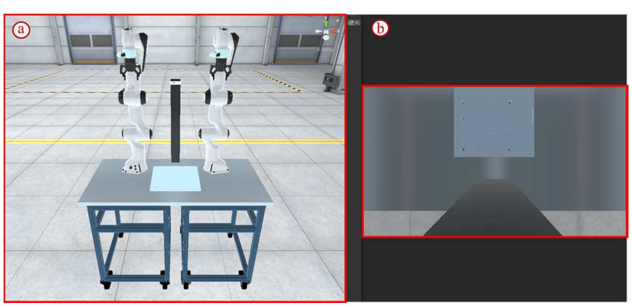

Fig. 3. Virtual environment and camera view for Sim2Real framework

The virtual environment is designed to receive robot kinematic data through the information layer framework, allowing virtual arm configurations to be updated based on physical robot states. The standardized geometric features and color-coded elements of the virtual NIST task board enable future implementation of computer vision algorithms for spatial correspondence assessment.

This virtual environment establishes the foundation for systematic Sim2Real evaluation by providing the necessary infrastructure for comparative analysis between physical observations and virtual predictions, supporting future development of real-time assessment methodologies.

V. Conclusion

This paper presents a digital twin-based framework for real-time Sim2Real evaluation in robotic task performance assessment. The proposed four-layer architecture integrates physical robotic stations with synchronized digital twin replicas, enabling systematic approaches for continuous task evaluation during execution.

The implementation establishes the foundational components of the framework approach through dual Franka robotic arms, Intel RealSense camera systems, and Unity virtual environment. The developed infrastructure components provide the foundation for future implementation of automated task performance assessment and Sim2Real validation methodologies.

Future work includes expanding the framework to support complex multi-robot scenarios, integrating machine learning approaches for predictive evaluation, and developing automated optimization strategies. The systematic approach to digital twin-based task assessment contributes to advancing reliable robotic automation in manufacturing applications.

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