Development of a Unity-Based Digital Twin for Robot Arm Monitoring and Remote Operation

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ABSTRACT

This study presents a Unity-based digital twin for robot arm monitoring and remote operation. Physical robot joint states were transmitted to Unity for real-time visualization, while operator-defined commands were sent from Unity to the physical robot. The two data flows were integrated through User Datagram Protocol (UDP) communication to establish bidirectional real–virtual interaction. The developed system enabled robot posture synchronization and operator-driven remote operation without autonomous closed-loop control.

KEYWORDS: Digital Twin; Digital Shadow; Robot Arm; Remote Operation

1. INTRODUCTION

Industrial robot arms are widely used in manufacturing because of their precision and repeatability. Continuous monitoring is required to observe robot motion and identify abnormal behaviour during operation. Conventional camera-based monitoring, however, may provide limited information regarding individual joint states and overall robot posture.

Digital representations can be distinguished according to real–virtual data exchange [1]. In this study, physical-to-virtual transmission is defined as a Digital Shadow, virtual-to-physical transmission as a Reverse Digital Shadow, and their integration as a Digital Twin. Unity has been applied as a visualization and communication environment for robotic-arm digital twin systems [2] and real-time drone position and attitude monitoring [3]. This study develops a Unity-based digital twin for robot arm monitoring and operator-driven remote operation.

2. MATERIALS AND METHODS

A computer-aided design (CAD) model of the robot arm was converted from STEP to FBX format and imported into Unity (version 2021.3.15f1). The robot components were arranged according to the physical joint hierarchy, and the revolute joints were configured using Unity Articulation Body components. Joint stiffness, damping, force limit, and angular range were assigned to represent the motion of the physical robot.

Communication between the Jetson Nano and Unity was implemented using the User Datagram Protocol. The physical robot transmitted joint-state data to Unity for posture visualization, while Unity transmitted operator-defined target joint angles, velocity commands, and start or stop signals to the physical robot. The physical-to-virtual communication constituted a Digital Shadow, whereas the virtual-to-physical communication constituted a Reverse Digital Shadow. These functions were integrated into a Digital Twin supporting bidirectional real–virtual interaction.

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3. RESULTS

The Digital Shadow reflected the physical robot posture in Unity through continuous joint-state updates. The operator could observe the robot configuration from multiple viewpoints in the virtual environment.

The Reverse Digital Shadow transmitted target joint angles and operator-defined commands from Unity to the physical robot. The received commands were executed by the robot controller, enabling remote operation through the Unity interface.

Integration of the two functions established bidirectional data exchange between the physical and virtual systems. The measured physical-to-virtual synchronization latency was approximately 67 ms. As shown in Figure 1, the resulting digital twin supported real-time robot state monitoring and operator-driven remote operation.

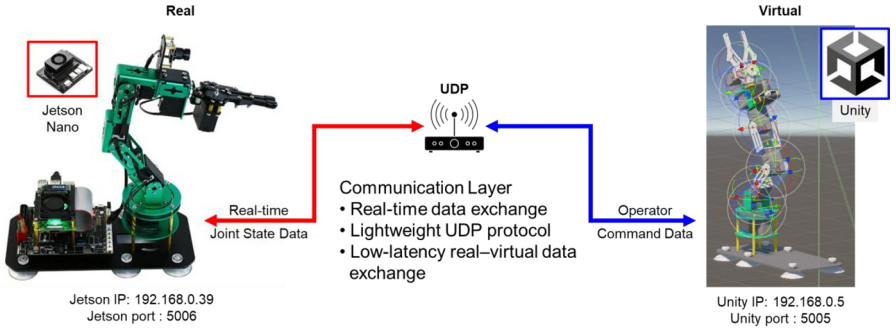


Figure 1. Unity-based digital twin framework for bidirectional robot monitoring and operator command transmission

4. DISCUSSION

The developed system distinguishes physical-to-virtual monitoring from virtual-to-physical command transmission. The integration of a Digital Shadow and a Reverse Digital Shadow enabled bidirectional interaction between the real robot and its virtual model.

The system retains human involvement because the operator evaluates the robot state and enters operation commands. Therefore, the proposed system does not constitute an autonomous closed-loop control system. Manual adjustment of Unity joint parameters is also required to represent the physical robot motion.

5. CONCLUSION

A Unity-based digital twin was developed for robot arm monitoring and remote operation. The system integrated physical robot state synchronization and operator command transmission through UDP-based bidirectional communication. Future work will include robot dynamic-model integration and deep-learning-based abnormal-motion detection.

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