Digital Twin Systems for Four-Axis and Six-Axis Robotic Manipulators

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Abstract: By building a virtual map of a physical entity or system, digital twins can be tested and optimized without actually manufacturing the product, reducing design iteration costs and time. Then, the existing digital twin robotic arm digital twin system often has the limitation of communication distance, operation efficiency is underground and the work flow is not intuitive and so on. In order to solve the above problems, this paper proposes a modeling scheme for the digital twin system of the robot arm: First, this scheme uses MQTT for remote communication. Then, we built a visual 3D simulation platform. Finally, through the introduction of the screen, this system improves the user experience. This paper proves the validity and rationality of the above content through 3D simulation experiment. Therefore, the system developed in this paper is innovative and has high value both theoretically and practically in the field of digital twin.

Keywords: Digital Twins; MQTT Communication; Message Broker; Message Subscription; 3D Simulation

1. Introduction

Digital Twin technology [1, 2], as an important emerging technology in recent years, involves constructing a virtual representation of physical entities, processes, or systems on an information platform, akin to a digital mirror image of these entities. This technology can be applied across multiple fields. Especially in the manufacturing sector, Digital Twin technology has become one of the key tools driving the transformation of manufacturing towards intelligent manufacturing. It acts as a bridge connecting the physical and information worlds, facilitating the "digitization," "networking," and "intelligence" of manufacturing. Taking robotic manipulatorsas an example, these automated control devices that can mimic the functions of human arms and perform a variety of tasks have a wide range of applications in manufacturing. By integrating the concept of Digital Twin with simulation and monitoring technologies, not only can the working processes of robotic arms be optimized and adjusted, but operational costs and risks can also be reduced, while ensuring the stability and reliability of the production process.

The research history of Digital Twin technology can be traced back to the 1960s when the National Aeronautics and Space Administration (NASA) first proposed the concept of "virtual twin" for simulating and predicting space exploration missions. However, it was not until the early 21st century, with the development of the Internet of Things (IoT), big data, and cloud computing, that Digital Twin gradually became a hot topic in research and application. The "Made in China 2025" plan proposed by the Chinese government has identified Digital Twin technology as an important means to drive the digital transformation of manufacturing. Domestic enterprises and research institutions have also achieved a series of research results in the field of Digital Twin. For instance, Huawei uses Digital Twin technology to remotely monitor and maintain its 5G network equipment, thereby improving the performance and stability of the network equipment. The Shenyang Institute of Automation of the Chinese Academy of Sciences applies Digital Twin to the field of intelligent manufacturing, optimizing production processes through simulation to enhance production efficiency and product quality.

In existing industrial projects, we have identified the following shortcomings:

Communication Distance Limitation. Many robotic arm designs are restricted to operating within specific factories or workshops. This limitation becomes particularly evident when operators are away from their stations or require professional guidance. When operators leave their posts or face complex operational challenges, robotic arms may fail to continue functioning, causing production delays. Furthermore, if expert guidance or technical support is needed, geographic constraints may prevent timely assistance, exacerbating operational difficulties. In such cases, robotic arms lack autonomous operation and remote control capabilities, limiting their use in emergencies or special circumstances.

Low Operational Efficiency. Operators often struggle to precisely understand the position, posture, and trajectory of robotic arms, negatively impacting operational accuracy and efficiency. Without simulation tools, predicting the outcomes of robotic arm movements or planning complex tasks becomes challenging. This may lead to inefficient path planning, task failures, or overall reduced productivity.

Non-Intuitive Workflow. Simulation software's complex operation processes and unclear feedback mechanisms hinder non-professional users from quickly adapting, affecting simulation efficiency and quality. The lack of intuitive understanding of the simulation process and results leads to poor user experiences. Additionally, predicting system behavior or planning effectively during simulations is often difficult.

To address the above issues, we propose the following solutions:

MQTT Remote Communication [3]: Remote operations through Unity-based digital twin robotic arms overcome geographic constraints, allowing operators to control robotic arms located in different locations from a centralized control room. This significantly enhances operational flexibility and response times, enabling operators to work from any location with an internet connection. Additionally, the remote monitoring system ensures real-time oversight of the robotic arms' status, facilitating timely issue detection and resolution, thereby reducing downtime. This approach also fosters collaborative work, enabling multiple operators to work together remotely to complete complex tasks, significantly improving overall efficiency.

Visualization and 3D Simulation: 3D simulation greatly enhances the intuitiveness of robotic arm operations. By utilizing this technology, operators can easily comprehend complex movements and spatial relationships, significantly reducing operational difficulty. Operators can more precisely control robotic arms, leading to improved accuracy and efficiency.

Simplified User Interface: A simplified operational mechanism, achieved through an intuitive graphical user interface and real-time feedback system, streamlines the robotic arm operation process. This makes operations more intuitive and efficient, reduces learning curves and operational errors, and provides users with a smooth and enjoyable experience.

2. Related Works

2.1 Relevant Modeling Tools

Blender is a powerful open-source 3D creation suite. Its strengths lie in its comprehensive features, enabling users to complete the entire 3D production workflow within a single environment. Its open-source and free nature significantly lowers the barrier to entry. A large community offers extensive tutorials and plugin resources. Customizable interfaces and plugin extensions enhance the software's flexibility. Diverse modeling tools cater to various needs, and real-time preview functionality improves efficiency. Additionally, it boasts excellent cross-platform compatibility.

SolidWorks is widely favored for its parametric design and ease of use. It allows users to modify designs through simple parameter adjustments. Moreover, SolidWorks provides a rich library of standard parts, supporting quick model assembly, and integrates simulation analysis tools, streamlining the process from design to analysis.

AutoCAD holds an unmatched advantage in the field of 2D drafting, capable of creating highly precise engineering drawings. Its high degree of customization and compatibility with a wide range of file formats have made it extensively adopted in the engineering field.

2.2 Digital Twin Development Platforms

Currently, various digital twin development platforms are available on the market, each with unique features and advantages suited to different application scenarios. Below are some common digital twin development platforms.

Azure Digital Twins: A platform-as-a-service (PaaS) solution from Microsoft, enabling the creation of detailed digital models to simulate various environments, such as buildings and factories. It uses the Digital Twin Definition Language [4] (DTDL) to define models and integrates with IoT devices and the Azure ecosystem for real-time data collection and analysis. SolidWorks is widely favored for its parametric design and ease of use. It allows users to modify designs through simple parameter adjustments. Moreover, SolidWorks provides a rich library of standard parts, supporting quick model assembly, and integrates simulation analysis tools, streamlining the process from design to analysis.

IBM Watson IoT [5]: IBM's digital twin technology is built on its powerful Watson IoT platform. By installing sensors on physical objects, it collects data to create virtual models for simulating, analyzing, and predicting the behavior of physical entities.

Siemens MindSphere: An open cloud platform provided by Siemens for the industrial internet, supporting the creation of digital twins. It integrates data analysis, connectivity solutions, and robust security features to help enterprises achieve digital transformation.

2.3 Digital Twin Applications

Urban Planning and Management: Digital twin models [6] of cities can simulate traffic flow, infrastructure usage, and environmental changes. Key Features: Traffic simulation, infrastructure optimization, environmental monitoring, disaster prediction.

Industrial Smart Manufacturing: Digital twins can simulate production lines, predict equipment failures, and optimize production processes. Key Features: Production line simulation, equipment monitoring, fault prediction, supply chain management.

Buildings and Infrastructure: Digital twins can simulate construction and infrastructure projects to optimize design, construction, and operations. Key Features: Building design simulation, energy consumption analysis, structural health monitoring.

Hospital Operations Simulation: In healthcare, digital twins can simulate hospital operations to optimize resource allocation and improve service quality. Key Features: Hospital operation simulation, resource allocation, patient care optimization.

3. Proposed Method

The overall architecture of the digital twin production line for the six-axis and four-axis robotic arms described in this article is shown in Figure 1:

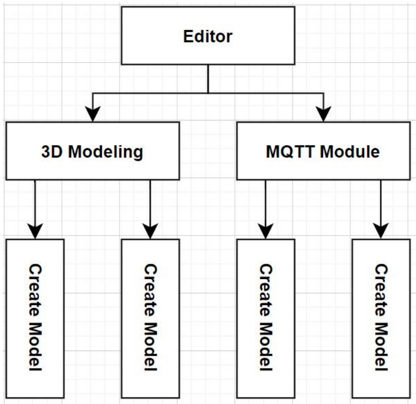

Figure 1. System Architecture Diagram

3.1 3D Model Module

The 3D model is the foundation of digital twin technology. It converts the physical system's shape, geometric features, and other information into digital form, providing accurate input data for the digital twin. Built with the help of modeling software or tools, it ensures that the geometric shape of the digital twin matches the actual object or system through meticulous processing. By accurately constructing the model and applying constraints, the behavior of the digital twin is ensured to align with the real-world counterpart, as shown in Figure 2.

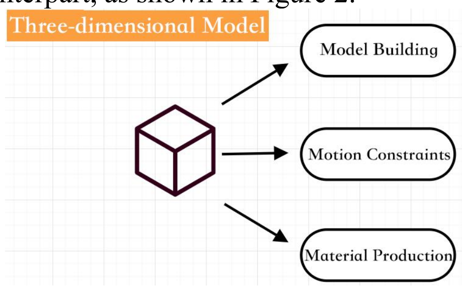

Figure 2. 3D Model Module Use-Case Diagram

3.2 MQTT Module

The overall architecture of the digital twin production line for the six-axis and four-axis robotic arms described in this article is shown in Figure 3:

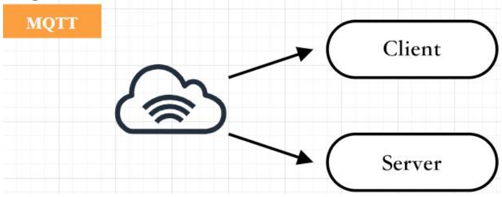

Figure 3. MQTT Module Use-Case Diagram

Subscriber: An application or device using the MQTT protocol. After establishing a network connection to the server, it has several functions: it can publish information for other clients to subscribe to, subscribe to messages published by other clients to receive them, and can choose to disconnect when it no longer needs a connection with the server.

Server: The MQTT server [7], also known as the " broker," plays a key role in the message transmission process. It accepts client network connections, and handles subscription and unsubscription requests. It forwards published application messages to clients subscribed to the relevant topics. The principle is shown in Figure 4.

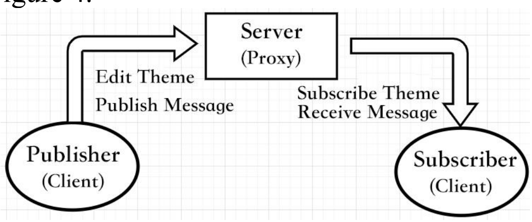

Figure 4. MQTT Principle

3.3 Simplified User Interface Module

Users press function buttons on the operation interface to trigger corresponding functions. For example, pressing the "Grab" button instructs the simulated six-axis robotic arm in the editor to perform the "Grab" operation; pressing the "Move Forward" button makes the simulated cart move to the next target position; pressing the "Detection" button instructs the simulated four-axis robotic arm to perform the "Scan Detection" operation. Through the coordinated control of the four-axis robotic arm, six-axis robotic arm, and cart.

Users can also subscribe to the backend client via the MQTT client. When the backend signal is uploaded to the MQTT server, the MQTT server forwards the backend operation signal to the frontend. Upon receiving the corresponding signal, the frontend executes the simulation animation, achieving linkage in the virtual display. The specific user operation flow is shown in Figure 5.

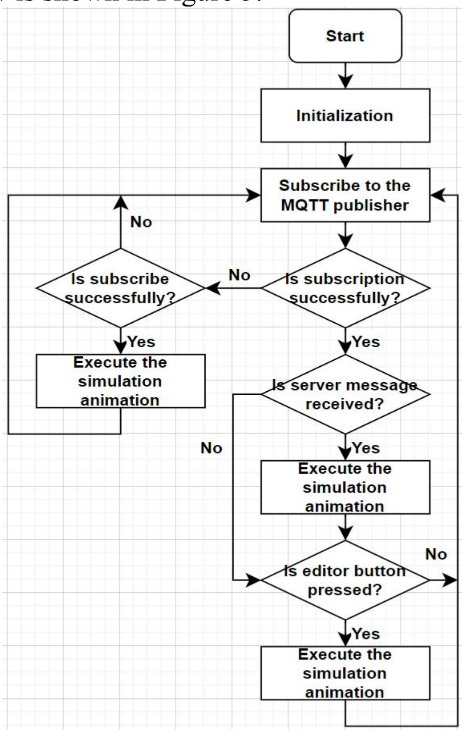

Figure 5. User Interface System Flowchart

4. Experiments

4.1 3D Model Module Modeling

The mechanical structure was accurately digitally modeled using Blender software, creating a detailed 3D model with corresponding materials applied. The specific modeling process is shown in Figure 6. In the software, dynamic parts are constrained using parent-child relationships to prevent moving parts from detaching from the overall model. Additionally, based on the parent-child relationship, a hierarchy of objects can be created, with the affected parts placed above the dynamic parts, as shown in Figure 7.

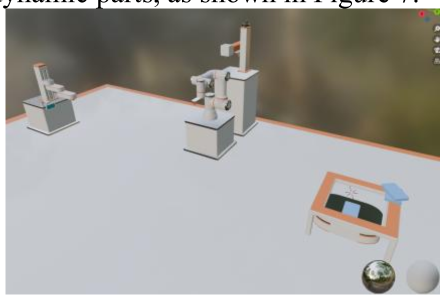

Figure 6. 3D Model Module Modeling Diagram

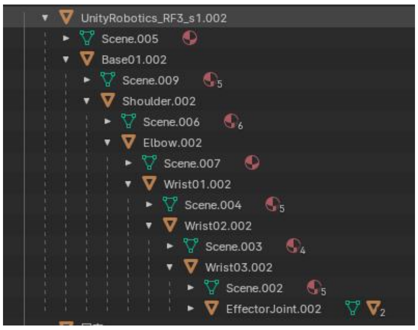

Figure 7. Setting Parent-Child Relationships

4.2 Model Optimization and UI Interface Construction

After importing the static model into Unity, issues such as material ball loss, color change, and material alteration may occur due to compatibility problems with the original material balls. Therefore, it is necessary to re-edit the material balls in Unity and apply them to the corresponding models. The model's color is appropriately unified to make the visuals more harmonious.

Operation buttons for backend communication are created in the lower left corner. These buttons trigger related functions, allowing users to familiarize themselves with the production line workflow even without backend data transmission. Additionally, an automatic demo function is provided for automatic production line demonstration. On the right side, view angle switch buttons are set up, allowing users to quickly change the perspective by pressing the corresponding key or directly clicking the desired view for detailed observation of the operation flow, achieving the effect shown in Figure 8.

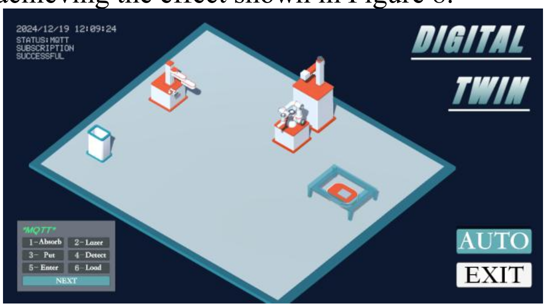

Figure 8. Optimized Model Interface

4.3 MQTT Communication Experiment

Server Selection and Setup: MQTTnet [8] is an open-source .NET library that provides an easy-to-use API for quickly setting up an MQTT server in the .NET environment. The server built with MQTTnet can easily interact with various MQTT clients, making it suitable for building IoT applications, mobile apps, and other real-time communication scenarios. Setting up an MQTT server with the MQTTnet library involves creating an MqttServer instance, configuring a connection validator to handle client connection requests, adding event handlers to listen for events like client connections, disconnections, and message receptions, and finally starting the server by calling the StartAsync method to accept network connections from clients, process published information, and forward messages to clients subscribed to relevant topics [9].

To implement the MQTT protocol, communication between the client and server must be completed. In the communication process, there are three roles in MQTT: Publisher, Broker (Server), and Subscriber [10]. The publisher and subscriber are both clients, while the broker is the server. The message publisher can also act as the subscriber. Thus, based on requirements, the roles of publisher and subscriber can be switched freely. In the Unity editor, relevant code is written to connect to the server, and as a subscriber, the client receives operational information published by the publisher and executes various commands. A visual operation interface for the publisher is set up, as shown in Figure 9.

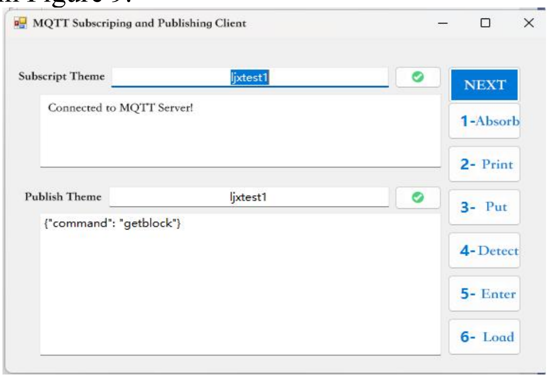

Figure 9. Publisher Operation Interface

5. Conclusion

This paper explores the application of digital twin technology in the field of smart manufacturing. By utilizing Blender software for precise 3D modeling and optimizing model materials and the user interface with the Unity3D engine, combined with the MQTT protocol to ensure efficient data interaction, the design, development, and functional testing of a robotic arm digital twin system were successfully achieved. The system innovatively integrates remote communication technology, high-precision 3D simulation, and an intuitive, user-friendly interface, effectively enhancing the monitoring and control capabilities of the smart manufacturing process. The paper also provides a detailed analysis of the system's shortcomings in practical applications and proposes targeted improvement strategies, offering practical insights and theoretical guidance for the digital transformation and efficiency improvement of the smart manufacturing industry.

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