

Development of Machine Tool Disassembly and Assembly Training and Digital Twin Model Building System based on Virtual Simulation

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ABSTRACT

In response to the issues of poor safety and insufficient training equipment in traditional machine tool assembly and disassembly training, this paper proposes a machine tool assembly and disassembly training system based on virtual simulation. The system utilizes Unity 3D to construct an interactive virtual training environment, achieving highly simulated simulations and teaching of the machine tool assembly and disassembly process. Additionally, the system is capable of establishing communication with actual machine tools, achieving bidirectional mapping between digital and physical spaces, allowing learners to observe the dynamic responses of machine tool models through the virtual environment. This virtual-real interaction mechanism enriches the application scenarios of the system, introducing digital twin technology into the virtual simulation of machine tool assembly and disassembly training. This paper also provides a detailed introduction to the design and implementation of core technologies such as the system's overall architecture, scene modeling, and virtual-real interaction, offering significant support for intelligent teaching in machine tool assembly and disassembly.

KEYWORDS

Mechanical Engineering; Manufacturing Technology; Electrical Automation Machine Tools; Disassembly and Assembly Training; Digital Twin; Virtual Simulation; Intelligent Teaching.

1. INTRODUCTION

Machine tools are crucial equipment for realizing mechanical manufacturing processes, featuring complex structures that include the machine body, transmission systems, electrical systems, and other subsystems. For students majoring in mechanical engineering, learning the composition and assembly/disassembly processes of machine tools is of great importance for subsequent courses such as mechanical manufacturing and CNC technology. The assembly and disassembly of machine tools also play a significant role in helping students understand the principles of machine tool design and manufacturing processes. However, direct assembly and disassembly of actual machine tools pose certain safety risks, and the processes are time-consuming and not easily reversible. To achieve safe, efficient, and repeatable instructional training for machine tool assembly and disassembly, the development of a virtual simulation system as a supplementary solution has become a viable option.

In recent years, the field of mechanical equipment has extensively integrated virtual simulation technology into its teaching and training practices. The application of simulation technology has lent an experimental quality to digital twin technology [1], attracting considerable attention and research

from numerous scholars on both simulation technology and digital twins. Song Xiaoyan et al [2] developed a virtual simulation system for automobile structure assembly and disassembly training. Chen Yehang et al [3] utilized VR technology to simulate the assembly and disassembly of CNC lathes. Xie Gang et al [4] implemented gesture recognition for assembling and measuring mechanical parts and integrated VR technology into the process. Sun Shuquan [5] conducted research on key technologies for multi-person collaboration in virtual simulation. Zhang Weixiong et al [6] designed a virtual simulation teaching system for CNC lathe assembly and disassembly. Liu Yonggang et al [7] proposed a remote teaching and training architecture based on digital twins. Zhang Zipeng et al [8] developed a training system for ultra-high voltage converter stations using digital twins and virtual reality technology, which achieves high-fidelity digital replication of equipment and fault scenarios for simulating and analyzing faults in DC systems, thereby enhancing system protection training effectiveness. Li Fu et al [9] established a virtual simulation teaching platform for simulating robots performing high-risk operations.

2. SYSTEM OVERALL ARCHITECTURE

The overall architecture of the machine tool assembly and disassembly training system based on virtual simulation and twin model construction is illustrated in Figure 1. The system utilizes several common types of machine tools as training equipment and constructs a virtual simulation training system for machine tool assembly and disassembly within the Unity 3D environment, facilitating a comprehensive understanding of the machine tool structure, components, and assembly relationships among users. The system is founded on a main framework that encompasses modules for physical entity modeling, assembly and disassembly instruction, assembly and disassembly training, and twin model construction. The assembly and disassembly instruction module provides guidance and reference materials to assist users in comprehending the steps and principles of machine tool assembly and disassembly. The twin model construction module enables users to establish a connection between the model and the physical machine tool by setting properties and interfaces, implementing digital twin technology. Through a designed human-machine interface, the system offers fundamental interaction methods for accomplishing machine tool assembly and disassembly training and the realization of digital twin technology. This modular structural design not only supports parallel development of individual modules but also facilitates future system expansion.

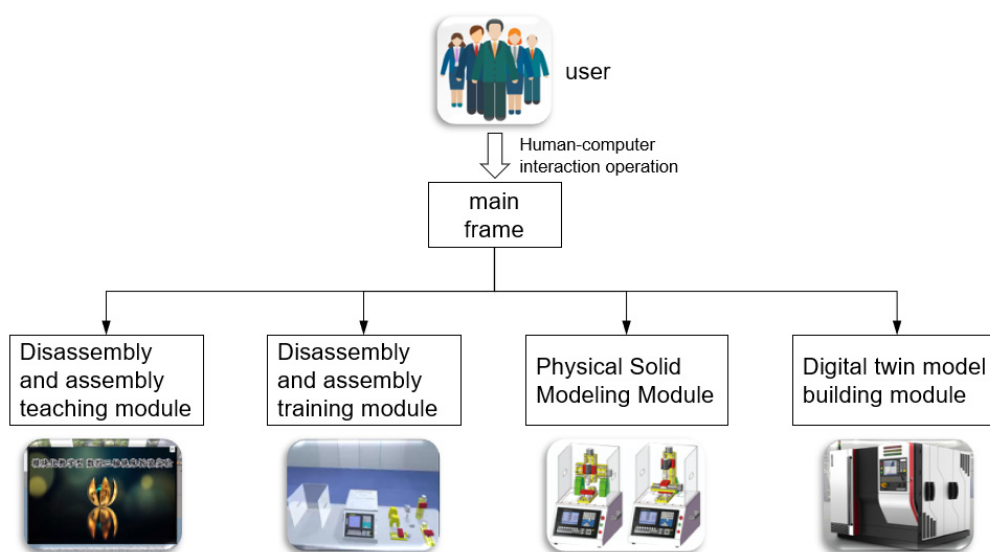


Figure 1. Overall architecture of the virtual simulation system

3. SYSTEM FUNCTIONAL MODULE DESIGN

3.1. Physical Entity Modeling Module

The machine tool is modeled in three dimensions using SolidWorks software. The design of the machine is simplified by removing insignificant elements from the model, reducing its complexity. The completed model is then imported into 3D Max software for rendering and other operations, and exported in FBX format. The FBX format model is imported into Unity 3D, where physical properties, motion axes, and parent-child relationships are set.

The construction of the system scene mainly includes setting the camera perspective, light source position, material properties, and equipment placement. Unity scenes are created by placing and moving objects within a three-dimensional space. Since the user's screen is two-dimensional, a method is needed to capture and "flatten" the view for display. This process is accomplished by the camera. This system adopts a first-person perspective and has added four cameras, positioned directly in front of the machine tool and at two corners of the room. By setting the camera parameters, the cameras can display the content they "observe" on the current screen. When the camera object moves and rotates, the view displayed will move and rotate accordingly, which is the effect of the user rotating, moving, and scaling the three-dimensional scene through the mouse and keyboard.

In order to calculate the shadow effects of a scene influenced by lighting, Unity needs to know the intensity, direction, and color of the light falling on objects. By setting four point light sources at the four top corners of the scene, an ideal lighting effect can be achieved. The specific position and lighting range of the light sources can be achieved by adjusting their transformation matrices. The specific scene construction is shown in Figure 2.



Figure 2. System scene diagram

3.2. Human-machine Interaction Interface Design

The human-machine interaction interface is an essential channel for communication between users and the system, serving as a window to issue commands and receive information. The Unity User Interface (UI) package provides a straightforward UI toolkit for developing the user interfaces of applications. It uses components and the Game View for arranging, positioning, and styling the user interface. A Canvas is an area that can contain all UI elements. When designing the main interface and each sub-interface, a separate Canvas should be created, and then text, images, buttons, switches, videos, and other components and elements are added as needed.

The system login interface is shown in Figure 3. The interface includes elements such as a deep blue background, text, images, and buttons. Users can successfully log in by entering the correct username

and password. A virtual database is established to store user information, and as users register, their information is continually entered. Each time a username and password are input, the system issues a command to search the database.



Figure 3. System login interface

3.3. Assembly and Disassembly Instruction Module

Within the virtual simulation system for machine tool assembly and disassembly training, the assembly and disassembly instruction module is a key component specifically designed to enhance the user's understanding of the structure and assembly principles of machine tools. This module incorporates multimedia teaching materials, such as instructional videos and animations, to support the user's independent learning process. Effective learning of machine tool equipment requires not only an intuitive understanding of its operation but also a profound comprehension of its internal structure and assembly logic. The disassembly and assembly teaching module is built based on this concept. It enables users to fully master the disassembly and assembly technology of machine tool equipment through rich visual teaching materials and interactive learning experiences.



Figure 4. Video instruction scene

The design of the disassembly and assembly teaching module takes full consideration of user-friendliness and teaching effect. The module interface is intuitive and easy to operate, ensuring that users can get started quickly even if they are first-time users. The layout of the teaching content is reasonable to ensure that users can learn step by step in a logical sequence, from basic to advanced, step by step.

Instructional Videos provides a series of professionally produced video tutorials showing the various components of machine tools, as well as common operation and maintenance procedures. The disassembly and assembly animation shows the machine tool assembly and disassembly process in detail in the form of step breakdown, helping users form an intuitive spatial understanding. Modular learning materials can break down complex machine tool knowledge points into small modular units, which are easy for users to understand and remember. Diversified teaching methods combine visual, auditory and operational learning methods to meet the learning preferences of different users.

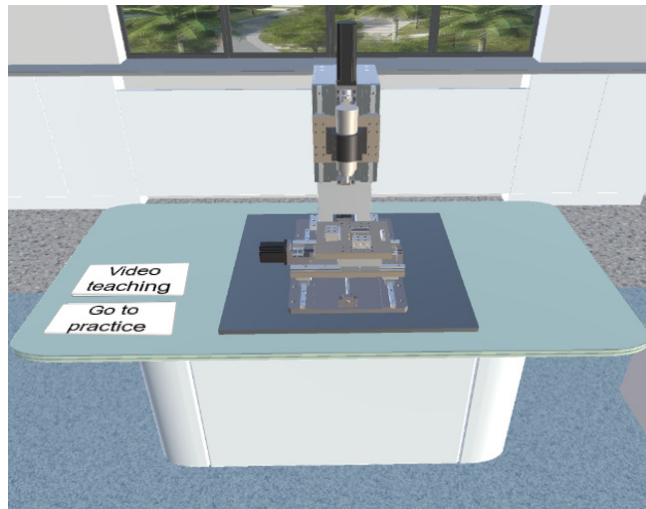


Figure 5. Command selection interface

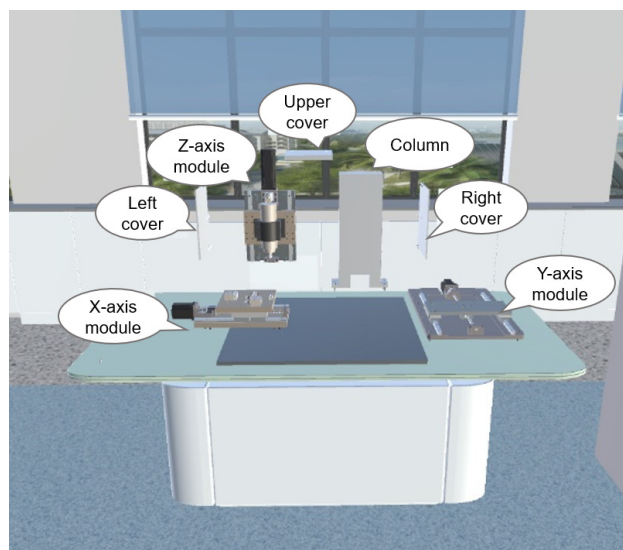


Figure 6. Disassembly animation effect

3.4. Disassembly and Assembly of Training Modules

The disassembly and assembly training module is the core component of the virtual training system. Users can learn and practice the disassembly and assembly process of machine tools through simulated interactive experiences.

In this module, users can perform virtual disassembly and assembly operations on various components of the machine tool through an intuitive user interface. Provide detailed step-by-step guidance to help users understand the specific requirements and execution methods of each step. When a user performs an incorrect operation, the system provides immediate feedback and guidance on how to correct the error. After completing the disassembly and assembly process, users can become familiar with the names, shapes and functions of each component.

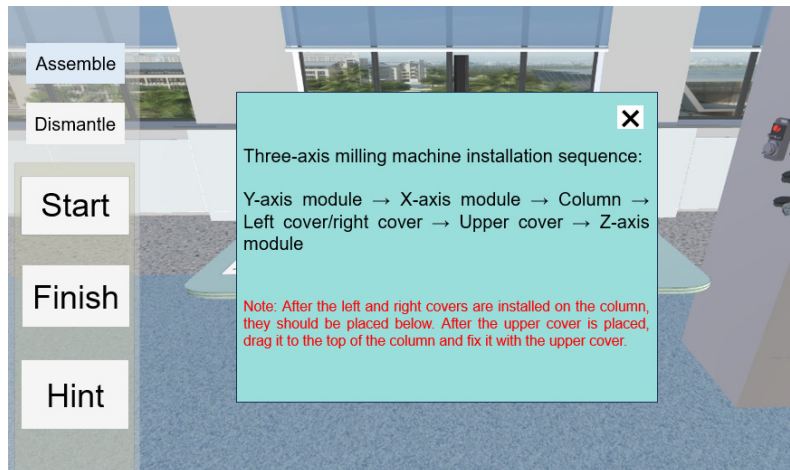


Figure 7. Disassembly and assembly steps guide



Figure 8. Feedback interface after completion

Through simulation, users can practice repeatedly without the constraints of time and physical space, thus mastering disassembly and assembly skills more efficiently and improving learning efficiency. The teaching of assembly principles is realized, and the assembly principles are systematically explained based on the disassembly and assembly process, allowing users to understand the role and relationship of each component in the machine tool. Compared to actual operations, virtual assembly and disassembly avoid damage to the machine tool and repair costs due to mishandling, thereby reducing learning costs. Moreover, users operate in an environment free of physical risks, also avoiding potential safety accidents that could occur during real-life operations.

In short, the disassembly and assembly module is not just a virtual operation tool, it is a brand-new teaching method that combines traditional teaching and modern technology to provide users with an all-round, multi-dimensional learning platform. It not only enables immersive hands-on practice, but also ensures the safety, efficiency and economy of the learning process. Learning machine tool disassembly and assembly skills through this simulated environment can significantly improve users' operational abilities and application level of theoretical knowledge, laying a solid foundation for future careers.

3.5. Digital Twin Model Building Module

The twin model construction module is one of the extended technologies of the virtual training system, mainly responsible for creating and maintaining the digital twin of the machine tool equipment. After

users have fully practiced and mastered the disassembly and assembly process of the machine tool, the assembled model can be directly used to implement digital twin technology.

To achieve the digital twin effect, the geometric shape, physical properties, motion characteristics, and functional behavior of the physical machine tool are accurately mapped to the digital model. The key step is to establish communication between the physical machine tool and the twin model, using sensors and CNC systems, among other means, to achieve real-time data synchronization between the physical machine tool and the twin model. First, the parent-child relationships of the machine tool components are set based on attributes such as the machine's motion axes and path range, and C# scripts are assigned to the components.

In terms of hardware connection, the configuration file of the supervisory computer program predefines the IP address and port information required for communication with the CNC machine tool, as well as the data item commands read through the Modbus protocol. Under this configuration, the CNC machine tool acts as a Modbus server, and the supervisory computer acts as a client, with the two exchanging data over Ethernet. The supervisory computer periodically sends Modbus requests, such as reading feed speed, spindle speed, and system status parameters, and the CNC machine tool responds to these requests and returns the corresponding data.

On the simulation model side, the communication interface is implemented based on the C# programming language. C# scripts attached to the simulation environment listen for data connections from the supervisory computer on a specific port on the local host. The supervisory computer sends data to this port using the TCP protocol, and the C# script is responsible for receiving the data and controlling the machine tool model in the simulation environment accordingly. To ensure efficient and stable network communication, a Socket-based programming approach is adopted. Using the TCP/IP protocol, the Socket is configured in server mode to listen for connection requests from the client. Each connection request is identified by a unique IP address and port number to ensure the accuracy of data transmission. The core responsibilities of the C# script include parsing and encapsulating communication data and manipulating the behavior of the simulation model. In the technical implementation, special attention is given to key aspects such as data subscription and reading, network exception handling, data decoding, and deserialization. The received data is used to promptly update the state of the simulation model, achieve dynamic synchronization with the physical machine tool, and complete the construction of the digital twin, as shown in Figure 9.

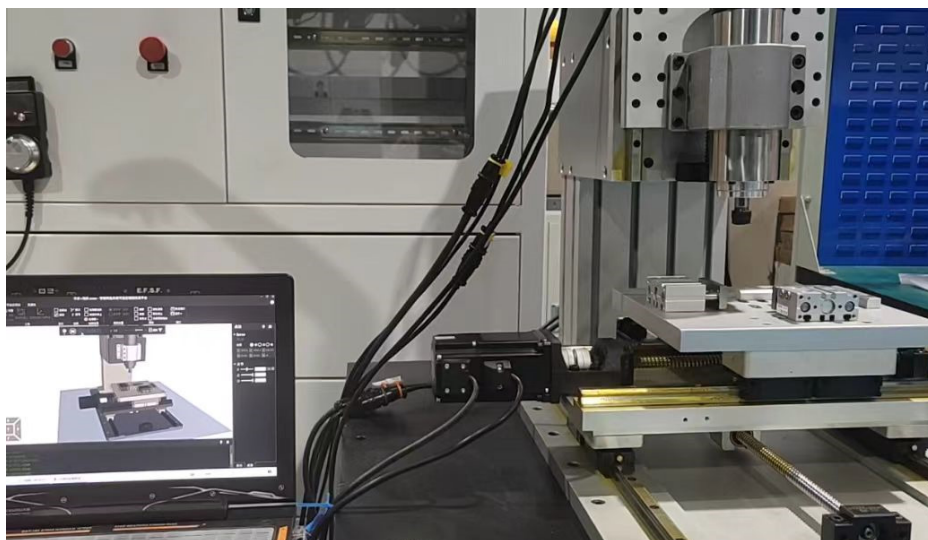


Figure 9. The twin model is completed

4. PROGRAM STRUCTURE AND OPERATING ENVIRONMENT REQUIREMENTS

4.1. Program Structure and Process

The overall program structure of the virtual simulation system is shown in Figure 10.

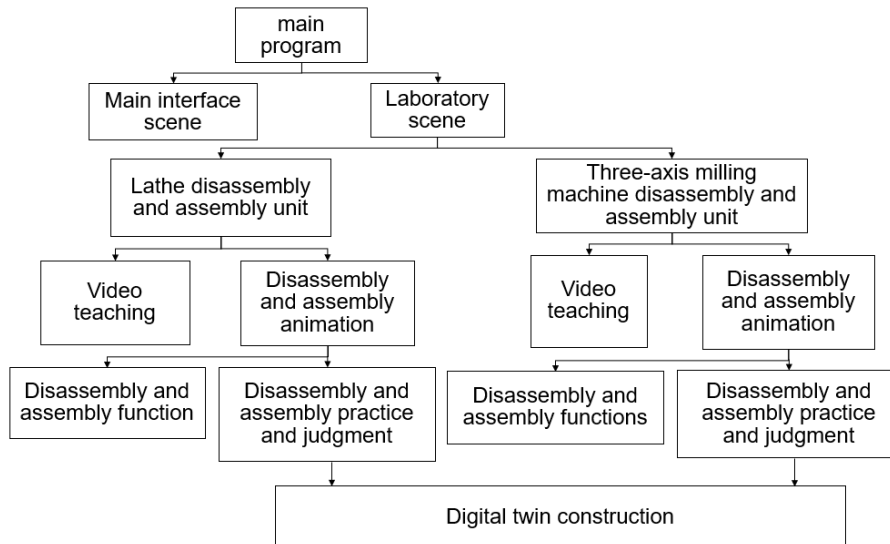


Figure 10. Program structure diagram

The overall process of the virtual simulation system is shown in Figure 11. Learners log in to the system through their account and password, come to the corresponding device through keyboard and mouse control, select the button on the desktop to enter the usage scenario, and conduct independent learning and disassembly and assembly training. At the end of the training, the results are judged and recorded.

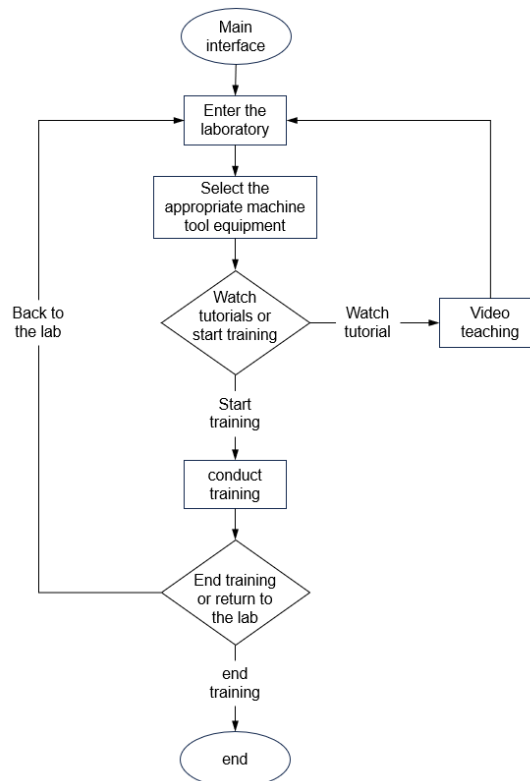


Figure 11. Program flow chart

4.2. Requirements for Operating Environment

To ensure the efficient operation of the virtual training system, this article recommends that the operating environment be equipped with high-performance computing resources. Systems should be equipped with multi-core processors, high-speed random access memory (RAM), solid-state drives (SSD), professional-grade graphics processing units (GPUs), and high-bandwidth network interfaces. The integration of these hardware resources will provide a solid foundation for complex data processing, real-time simulation rendering and stable network communication. In terms of operating system, it is recommended to use the latest 64-bit Windows operating system and keep all software updated in a timely manner to ensure system stability and security.

In terms of software configuration, an integrated development environment (IDE) that supports C# development and simulation software that is compatible with it must be installed to ensure the effective writing and execution of C# scripts. At the same time, appropriate Modbus communication tools and network monitoring software should be configured to facilitate accurate network debugging and communication protocol analysis.

5. SUMMARY AND OUTLOOK

The Unity3D three-dimensional engine development platform can be installed and run independently after the .exe file is directly generated or the installation file is released. The machine tool virtual simulation system development plan proposed in this article has wide applicability; the Unity 3D three-dimensional engine development platform can realize all movements of the machine tool virtual simulation system, and comes with many functional modules, so users do not need to spend a lot of time to master advanced programming knowledge; making low-cost The machine tool virtual training system becomes possible under hardware conditions; the dynamic data of the model movement is converted into machine tool movement parameters through the data acquisition module, making the system more practical. In future research, we will apply this solution to the development of other machine tool virtual teaching and training systems, and develop a virtual training and teaching system covering more general machine tools.

This article successfully explores the feasibility and efficiency of using the Unity 3D three-dimensional engine development platform to build a machine tool virtual simulation system. Through Unity3D's highly integrated environment, developers can directly generate independent executable files (.exe) or installation packages, which users can then install and run independently without a development environment. The development solution proposed in this article not only has wide applicability, but also because Unity 3D has a large number of built-in functional modules, users can realize all dynamic movements of the machine tool virtual simulation system without in-depth learning of complex programming knowledge, significantly reducing the development threshold and time cost. In addition, through the data collection function in the digital twin module, the dynamic data of the model is effectively converted into machine tool motion parameters, which greatly improves the practicality and educational value of the system.

Future research will further expand the application scope of this system and develop a virtual training and teaching system that comprehensively covers general machine tools. This will greatly enrich the application of virtual simulation technology in the field of education and training, and at the same time promote the standardization and teaching of machine tool operating skills. modernization. At the same time, the optimization of real-time data processing and advanced user interaction functions is also the focus of future work to further improve the interactivity and immersion of the simulation system. Through continuous technological innovation and teaching model reform, it is expected to provide a more efficient, more intuitive and safer learning platform for machine tool operators.

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