Digital Twin-based Flexible System for Intelligent Manufacturing

Zhanhang Lai[1,2,3, a], Shan Hu[1,2,3, *], Zhigang Bing[1,2,3, b], Jia Liu[1,2,3, c], Ying Li[1,2,3, d], Yingzhuang Zhu[1,2,3, e]

[1] School of Automation and Electrical Engineering Tianjin University of Technology and Education, Tianjin, China

[2] Key Laboratory of Information Sensing & Intelligent Control, Tianjin, China

[3] GongJiang Double Carbon Research Institute, Tianjin, China

[a]2745439382@qq.com, [*]lakeshu@163.com, [b]bingzg@tute.edu.cn, [c]liujia0704@126.com, [d]1023841215@qq.com, [e]1975128881@qq.com

Abstract

In this paper, based on digital twin technology for reconfigurable flexible intelligent manufacturing system - a desktop detachable modular and lightweight small machine tool - an intelligent manufacturing flexible twin (VE) is designed to help the operator to understand the structure of the machine tool and its transmission, the roles of the components and their connections, as well as the machine tool's troubleshooting and realization of the digital twin function. The four forms of the machine tool are first modeled using SolidWorks, after which the model is lightweight disassembled in 3dsMax, and converted into FBX. format for importing into Unity to develop the system functions. The system uses TCP/IP communication protocol for data acquisition, and the acquired data is used as the basis for realizing the digital twin function. The test results show that this system can help the operator to understand and learn the features of a reconfigurable flexible intelligent manufacturing system, and can realize the real-time monitoring of the machine tool machining process through the digital twin technology.

Keywords

Digital Twin; Virtual-Physical Interaction; CNC Machine; Intelligent Manufacturing; Virtual Reality.

1. Introduction

The manufacturing industry is an essential pillar of the national economy, and it is also the leading force in promoting industrialization and modernization[1]. The global manufacturing industry ushered in a new wave of technological innovation the background, countries have formulated the corresponding strategic plan[2]. The United States launched the "National Advanced Manufacturing Strategic Plan" and "Advanced Manufacturing Partnership Program", Germany put forward the "Industry 4.0 Strategic Plan", and Japan released the "Industrial Value Chain Reference Framework". Germany put forward the "Industry 4.0 Strategic Plan", Japan released the "Industrial Value Chain Reference Framework (IVRA)", and China, as a global manufacturing leader, also formulated "Made in China 2025"[3][4]. In the process of transitioning to Industry 4.0, China urgently needs to cultivate a large number of high-level manufacturing engineering and technical talents to meet the future development needs of intelligent manufacturing-related industries[5][6].

Digital twin technology is one of the core technologies in the field of intelligent manufacturing[7], first proposed by Prof. Grieves, which is a virtual image of a physical product[8]. The early digital

ISSN: 2414-1895 DOI: 10.6919/ICJE.202311_9(11).0016

twin system contains physical entities, virtual entities, and the connection between them. With the innovation of technical theories and the continuous upgrading of industrial production, Tao Fei et al. proposed a five-dimensional model and construction guidelines for digital twins[9] and cooperated with the Standards and Technology Committee and related enterprises to establish a digital twin standard system architecture, which promoted the further development of digital twin technology[10][11].

Machine tools, as the core equipment of the manufacturing industry, account for 40% to 60% of the total amount of manufacturing products, widely used in aviation, aerospace, energy, and other fields, with basic generality and strategy, is the cornerstone of the development of intelligent manufacturing, but also the key competitiveness in the field of intelligent manufacturing[12]. Therefore, the cultivation of intelligent manufacturing technology talents in related fields is crucial for China's manufacturing industry to move forward in the direction of intelligentization[13][14].

In this paper, based on digital twin technology for the reconfigurable flexible intelligent manufacturing system, a desktop detachable modular and lightweight small machine tool specially developed for the education market, a flexible twin system (VE) for intelligent manufacturing is designed for assisting the teaching of the machine tool and virtual monitoring of the machining process. The reconfigurable flexible intelligent manufacturing system can be assembled into a lathe, a three-axis milling machine, a boring milling machine, or a gantry milling machine and execute the machining process of the machine, which can satisfy the students' requirements for various practical training and experiments. This system deeply integrates digital twin technology with intelligent manufacturing course content, and the real-time feedback and evaluation when operating this system can help students better understand and master the technology and principles of intelligent manufacturing. Compared with traditional teaching methods, this system has the advantages of human-computer interaction performance, self-organization and ultra-flexibility, and multi-dimensional visual interaction, which can provide students with a better learning experience.

2. Overall System Design

2.1 Introduction to Flexible Twins(VE) for Intelligent Manufacturing

Intelligent Manufacturing Flexible Twin (VE) is a digital twin-assisted teaching system developed for reconfigurable flexible intelligent manufacturing systems with the functions of assembling, disassembling, and twinning, which is used to help students learn and familiarize themselves with CNC machine tools. Through the system's assembling and disassembling functions, students can quickly master the relevant knowledge of machine tools, and the system's twinning function can help students understand the relevant applications of digital twin technology in the field of intelligent manufacturing. The VE system also has a corresponding evaluation system, which can be comprehensively evaluated based on indicators such as the selection of machine modules and the completeness of the construction.

2.2 System Structure

Intelligent manufacturing flexible twin system (VE) is a digital twin-assisted teaching system developed based on digital twin technology for a reconfigurable flexible intelligent manufacturing system, the system framework mainly consists of five parts: physical entity, virtual entity, twin data, service layer, and interaction layer, which together comprise the digital twin five-dimensional model of the VE system as shown in Figure 1, which is the structural diagram of the digital twin five-dimensional model of the system.

ISSN: 2414-1895
DOI: 10.6919/ICJE.202311_9(11).0016

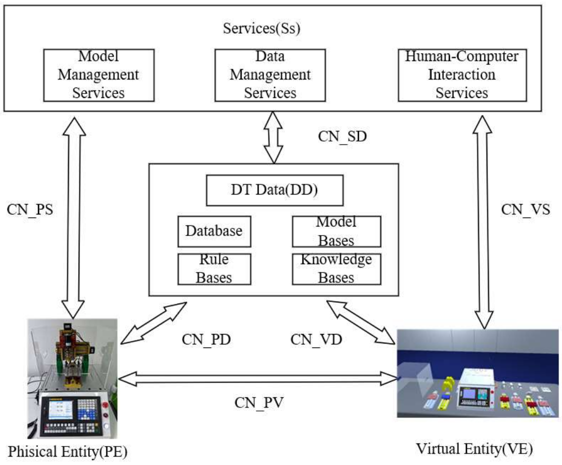

Figure 1. Intelligent Manufacturing Flexible Twin (VE) Architecture Diagram

2.2.1. Physical Entity

In the digital twin five-dimensional model of the VE system, the physical entities play a fundamental role and are responsible for providing the actual functions. As the physical entities in the system, the reconfigurable flexible intelligent manufacturing system consists of stepper motors, linear guides, and high-precision ball screws, which can be assembled to build into a lathe, a three-axis milling machine, a boring milling machine, and a gantry milling machine, respectively, to process non-metallic materials such as substitutes, nylon and so on. In this system, the physical entity is controlled through the numerical control of the machine tool, and the numerical control is utilized to obtain the data processed by the machine tool as a source of data for the virtual linkage of the digital twin. These data are transferred to the virtual end through the communication interface to realize the corresponding work. The physical diagram of the reconfigurable flexible intelligent manufacturing system is shown in Figure 2.

Figure 2. Physical Diagram of Reconfigurable Flexible Intelligent Manufacturing System

2.2.2. Virtual Entity

The virtual entity is the main target object of the intelligent manufacturing flexible twin (VE) system, and its core idea is to transform physical entities into digital forms. In this paper, we use SolidWorks and 3dsMax to model and render the virtual model and create the physical attributes, behavioral attributes, and rule attributes corresponding to the virtual model in Unity software to realize the multi-dimensional mapping of the machine tool in the digital space. By constructing a multi-dimensional digital twin model of the machine tool, the process of physical entity design, manufacturing and operation, and maintenance is made visible in the information space, the operation mechanism is clear, the behavioral capability is complete, the operation law is thorough, and it has a brand-new capability. The virtual model is shown in Figure 3.

Figure 3. Virtual Model

2.2.3. Twinned Data

Data is the key driver of the digital twin and covers data from the physical entity, virtual entity, and service layers. The data of physical entities include the specifications, performance, and related physical attribute data of machine tools, as well as dynamic data reflecting the operating status of machine tools, real-time performance, and environmental parameters. The data of virtual entities mainly include geometric data such as geometric dimensions, assembly relationships, and positions of virtual models, attribute data such as material properties, loads, and features of physical models, and data such as constraints, rules, and association relationships of rule models. In addition, there are simulation data based on these models for process simulation, behavioral simulation, process validation, evaluation, analysis, and prediction purposes. Data in the service layer include algorithms, models, data processing methods, and production management data.

2.2.4. Service Layer.

The service layer is a serviced encapsulation of all kinds of data, models, algorithms, simulations, and results required in the process of digital twin application, which can efficiently manage the physical entity, virtual entity, and twin data in three parts, and can more intuitively and efficiently display the working process and state of the machine tool to the operator. The service layer has a human-computer interactive function, students can use a PC or wear MR headset equipment to realize the assembling, disassembling, and digital twin function of the intelligent manufacturing flexible twin system (VE) in the virtual scene, and through the multi-dimensional operation students can better master the knowledge related to intelligent manufacturing.

2.2.5. Connection Layer.

The connection layer of the system consists of input and output devices, communication protocols, related technologies, etc. It serves as a medium for the transmission of intermediate data between the physical entity, the virtual entity, the twin data, and the service layer, realizing the interconnection of the data of the various parts of the entire system, and providing support for the realization of human-computer interaction, virtual-reality synchronization, and other functions. Meanwhile, the connection layer, by connecting the various parts, can realize the real-time monitoring of the machine tool machining process and feedback on the complex machining process of the machine tool to the operator, thus realizing the collaborative manufacturing among the personnel, the machine tool, and the digital twin of the machine tool, and the students can also experience the characteristics of the combination of virtual and real of the digital twin in this process.

2.3 Development Process

The development process of a digital twin-based flexible twin system (VE) for intelligent manufacturing is shown in Figure 4. In this paper, firstly, the functions and objectives of the VE system are analyzed in terms of requirements, and then the machine tools are modeled and restored in equal proportions using SolidWorks, 3dsMax, and other software, after that, the functions of the system are developed in Unity, including the functions of assembling, disassembling, and digital twinning, and finally, the functions of the software are tested, especially to experience and test the software from the perspective of students' learning, and adjust and optimize according to the test results, and finally complete the development of all processes.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202311_9(11).0016

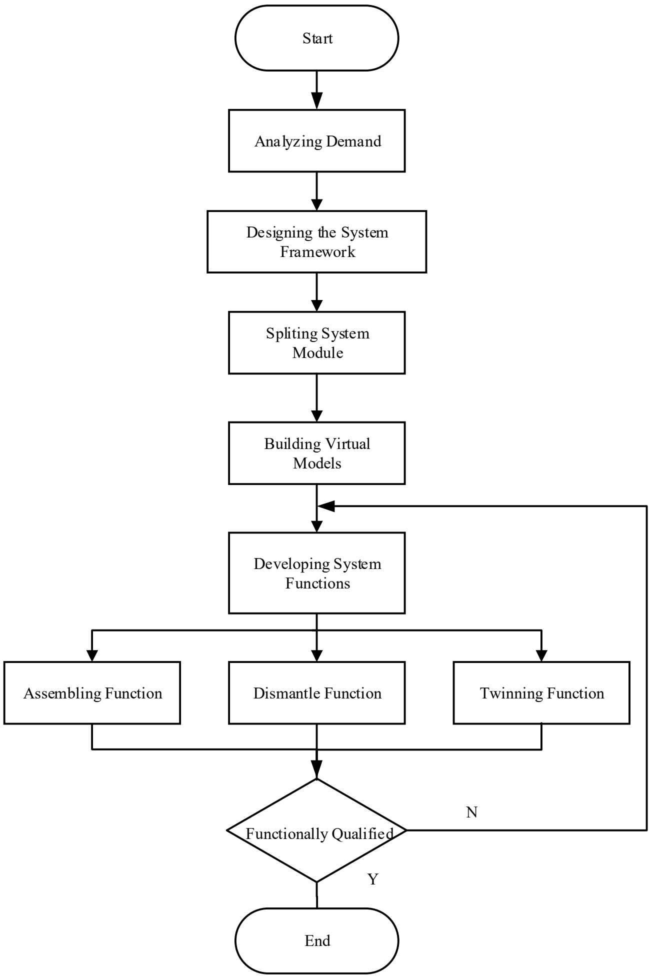

Figure 4. System Development Flowchart

3. Key Technologies

3.1 Modeling Simulation Technology

To realize the modeling simulation of the digital twin, the first step is to ensure that the virtual model material, color, and appearance are consistent with the real device. In this paper, the first use of SolidWorks and 3dsMax for the creation of geometric models and a certain amount of lightweight processing to ensure the user's smooth experience when using the software, and then export the model to the FBX. format and imported into Unity for the development of software functions. The development in Unity uses C# language to write scripts on the Visual Studio 2022 platform, Firstly, we need to add physical attributes, motion logic, and rules for the virtual model of the machine tool, such as collision detection of the model and the complete restoration of the workflow, etc., to create a multi-dimensional model of the machine tool's digital twin, and then finally, we develop the machine tool's assembly, disassembly, and digital twin functionality in Unity. and digital twin functionality in Unity.

3.2 Data Processing and Real-time Monitoring Technology

In this paper, the intelligent manufacturing flexible twin (VE) system is designed to communicate with the accurate machine tool through TCP/IP communication protocol, periodically collecting data from the machine tool's numerical control system and transmitting it to the Unity side for data processing. Since the multi-dimensional attributes of the digital twin are created for the virtual model of the machine tool in Unity, the DoTween plug-in in Unity can be used to add animation to achieve the effect of virtual synchronization based on the incoming coordinate data, while achieving the purpose of real-time monitoring.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202311_9(11).0016

3.3 Visualization and Interactive Technology

In this paper, a simple UI interaction system is designed through UGUI in Unity, so that students can quickly get started using it and put more energy into learning machine tool-related content. This paper develops a virtual reality operation scenario of intelligent manufacturing flexible twin (VE) based on the Pico4 Enterprise virtual reality headset, where students can wear the headset to complete the assembly and disassembly operations that can be accomplished on the PC side. Compared with the PC side, operating in the virtual reality environment can give students a more intuitive and immersive experience of using the VE, which is useful for helping students understand the structure and transmission mode of the machine tool, the role and connection mode of components, and the troubleshooting of the machine tool from other dimensions. As shown in Figure 5 is the virtual reality end of the development of the software environment.

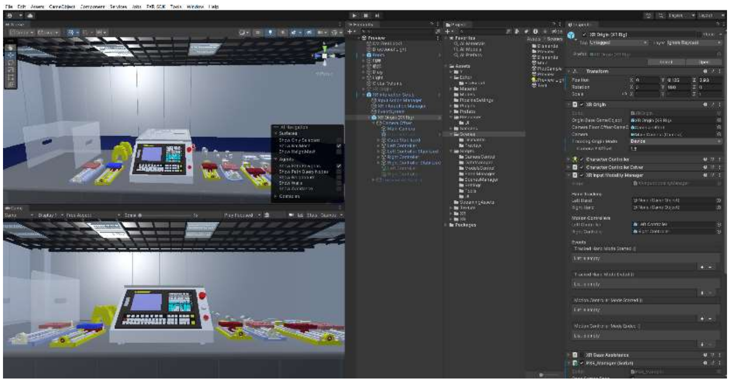

Figure 5. Virtual Reality Development Environment

In addition to this, this paper also develops a mixed reality operation scenario for an intelligent manufacturing flexible twin system (VE) based on Flintlight's Rhino X mixed reality headset. The scene of operating this system using an MR headset is shown in Figure 6. Compared to virtual reality headsets, mixed reality headsets can have more interactivity with the real environment and do not require a completely closed virtual environment, which has a broader range of application scenarios. The development of multiple operating environments in this paper also allows for more choices in actual use, not only limited to the PC terminal, to provide students with a better learning experience.

Figure 6. MR Operating Scene

4. System Main Funtion

4.1 Visualization and Interactive Technology

Students can familiarize themselves with the assembly process of the reconfigurable flexible intelligent manufacturing system through the assembly function of the intelligent manufacturing flexible twin system (VE), which can realize the assembly of the three-axis milling machine, the gantry milling machine, the boring milling machine, and the lathe, and all the assembly steps in the VE system are the same as those of the real equipment. The operator can drag and drop the machine components placed in the scene to complete the assembly of the four types of machine tools, and

Volume 9 Issue 11, 2023
DOI: 10.6919/ICJE.202311_9(11).0016

some of the wrong components, after using the correct components in the correct order of assembly will have the basic information of the corresponding machine tool prompts, as shown in Figure 7.

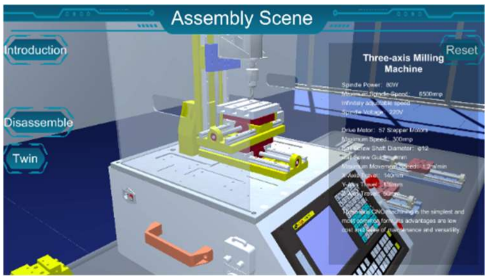

Figure 7. Assembly Scene

4.2 Visualization and Interactive Technology

Students can learn about the disassembly steps of the four machine tools from the disassembly point of view by using the disassembly function of the Intelligent Manufacturing Flexible Twin (VE) to understand the structure of the machine tool and its transmission method, the roles of the components and their connection methods, and the troubleshooting of the machine tool. The disassembly process of one of the three-axis milling machines is shown in Figure 8.

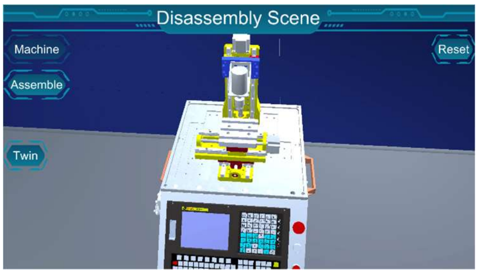

Figure 8. Disassembly Scene

4.3 Twinning Function

The Intelligent Manufacturing Flexible Twin (VE) system develops a digital twin function based on digital twin technology, which transmits data through the TCP/IP communication protocol. Students can realize the digital twin function after configuring the communication connection to achieve the effect of virtual and real linkage and can observe the operation of the machine tool in real-time at the remote end and monitor the machining data of the machine tool. In this learning process, students can experience the real digital twin system workflow through hands-on operation, and have a deeper understanding of the digital twin. In this paper, we consider adding artificial intelligence algorithms in the subsequent optimization and upgrading to make the whole system work more efficiently. As shown in Figure 9 is the scene of the digital twin function realization.

Figure 9. Twin Scene

5. System Testing

Functional testing system testing is a very important part of the entire development process, this paper in the system testing session was carried out in the system functional testing, performance testing, and user experience testing.

5.1 Functional Testing

In the function testing session, firstly, the assembling and disassembling function of the VE system is tested, during which the assembling and disassembling of four kinds of machine tools need to be tested comprehensively, to ensure that these two functions can be fully realized, and potential system problems are found and repaired promptly. Afterward, the twin function of the system is tested, to achieve the effect of virtual synchronization, it is necessary to analyze the coordinates, rotational speed, and other data error analysis of the virtual end, in addition to the need to add interpolation and other algorithms on the Unity side to deal with the twinning of the data transmission interval inconsistencies that may occur. As shown in Figure 10 is the page for debugging the data collected from the virtual end.

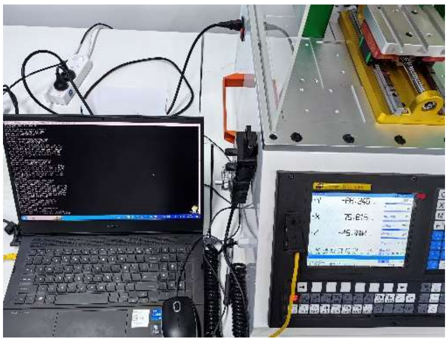

Figure 10. Data Testing Scene

5.2 Performance Testing

In this session, it is necessary to test the performance of the VE system on the PC side and the VR and MR headset side, to ensure that the computer with the minimum required configuration can run smoothly and that there is no obvious delay in the operation of the VR and MR side, and based on this, it is necessary to try to ensure that the system occupies a light amount of memory, and does not create an excessive memory burden for the user.

5.3 User Experience Testing

Finally, we looked for several testers to test and experience the VE system from the student's point of view, to ensure that the students can quickly get started with all the functions when they use it and do not spend too much energy on learning the operation of the system so that they can spend more energy on learning the course content. After several rounds of system testing, it is verified that all the functions of this system can be fully realized and can meet the learning needs of students.

6. Conclusion

In this paper, a flexible twin system (VE) for intelligent manufacturing is designed for a reconfigurable flexible intelligent manufacturing system, which is used to help students understand the structure and transmission mode of the machine tool, the roles, and connections of the components, as well as the troubleshooting of the machine tool and the realization of the digital twin function. After multiple tests, it is verified that the functional requirements of the system can be fully realized, and it is easy to get started. The operating environment in VR and MR headsets can help students experience the system functions in an immersive way, which helps familiarize them with the operation of real machine tools. At present, there are still some places to be optimized in the VE system, and further optimization and upgrading are considered afterwards, such as adding some algorithms for fault prediction of the machine tool during twinning, so that the VE system can reach maturity level of digital twinning that is virtual to preview the real one, and virtual to optimize the real one, and achieve better twinning effects.

Acknowledgments

This work was supported by the Tianjin Education Science Planning Project, Subject No.BHE210017, Project Name, Design and Practice of Demonstration Activities for Youth Intelligent Science and Technology Innovation Education, Project leader, Zhigang Bing, Category, Key Project, Organization, Tianjin University of Technology and Education.

References

[1] Bohu Li. et al. "Research on ICT-enabled intelligent manufacturing in industrial environments," China Engineering Science, vol. 24, no. 2, pp. 75-85, 2022.

[2] Jizhuang Hui, Tao Zhou, Kai Ding, Yaqian Zhang, Shuai Wang, and Jinhao Wang, "A digital twin-based unit simulation experiment system for intelligent manufacturing," Experimental Technology and Management, vol. 40, no. 2, pp. 92-97+102, 2023, doi: 10.16791/j.cnki. sjg.2023.02.015.

[3] Shuting Wang, Yuanlong Xie, Zhouping Yin, and Han Ding, "Construction and Practice of Intelligent Manufacturing Innovative Talent Cultivation System for New Engineering Science," Research on Higher Engineering Education, no. 5, pp. 12-18, 2022.

[4] Jinsong Liu, "Research and Application of Digital Twin Key Technology for High-Grade CNC Machine Tools," Ph.D., University of Chinese Academy of Sciences (Shenyang Institute of Computing Technology, Chinese Academy of Sciences), 2022. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CDFD&dbname=CDFDLAST2023&filename=1022718205.nh&v=.

[5] Qiang Cheng, Wenxiang Xu, Zhifeng Liu, and Yu Zhang, "A review of machine tool equipment research for intelligent green manufacturing," Journal of Huazhong University of Science and Technology (Natural Science Edition), vol. 50, no. 6, pp. 31-38, 2022, doi: 10.13245/j. hust.220603.

[6] Wang L. and Lu B., “Research on the Development of Machine Tool Industry in China,” Chin. J. Eng. Sci., vol. 22, no. 2, p. 29, 2020, doi: 10.15302/J-SSCAE-2020.02.005.

[7] Junjun Wu, Haichu Chen, Qinghua Zhang, and Zhifeng Wang, "Research on the teaching mode of intelligent manufacturing practical training based on digital twin technology," Industry and Information Technology Education, no. 2, pp. 72-76, 2022.

[8] Fei Tao et al. "Exploration of digital twin and its applications," Computer Integrated Manufacturing Systems, vol. 24, no. 1, pp. 1-18, 2018, doi: 10.13196/j.cims.2018.01.001.

[9] Fei Tao et al. "Digital twin five-dimensional model and ten domain applications," Computer Integrated Manufacturing Systems, vol. 25, no. 1, pp. 1-18, 2019, doi: 10.13196/j.cims.2019.01.001.

[10] Xiaolong Li, "Research and Implementation of Virtual Monitoring System for Machine Tool Machining Processes Based on Digital Twin," Master's Degree, University of Electronic Science and Technology, 2020.[Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD202002&filename=1020735791.nh&v=.

[11] Jianlin Fu, Jian Zhang, and Dazhi Yang, "An integrated training platform for intelligent manufacturing based on flexible modular reorganization," Experimental Technology and Management, pp. 1-10.

[12] Lei Zhang et al. "Connotation, architecture and key technology of digital twin machine tools," Computer Integrated Manufacturing Systems, vol. 29, no. 6, pp. 1983-1995, 2023, doi: 10.13196/j.cims.2023 .06.016.

[13] Zhaoxiang Zeng, Zhe Liu, and Jinliang Li, "Research on the construction of virtual simulation training base for intelligent manufacturing in vocational colleges and universities in the new era," Education and Career, no. 9, pp. 109-112, 2022, doi: 10.13615/j.cnki.1004- 3985.2022.09.006.

[14] "Research progress of intelligent control system architecture and key technology of machine tools", Journal of Mechanical Engineering, vol. 57, no. 9, p. 147, 2021, 10.3901/JME.2021.09.147. 57, no. 9, p. 147, 2021, doi: 10.3901/JME.2021.09.147.

[15] Fei Tao, Chenyuan Zhang, Qinglin Qi, and He Zhang, "Digital twin maturity model," Computer Integrated Manufacturing Systems, vol. 28, no. 5, pp. 1267-1281, 2022, doi: 10.13196/j.cims.2022. 05.001.