Remote Laboratory as an Educational Tool in Robotics Experimental Course

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Dangfeng Pang[1,2(✉)], Shigang Cui[1], Genghuang Yang[1]
[1]Tianjin University of Technology and Education, Tianjin, China
[2]Tianjin Sino-German University of Applied Sciences, Tianjin, China
pangdangfeng@tsguas.edu.cn

Abstract—A remote lab is a technology that allows participants to efficiently conduct experimental teaching where users can connect to lab equipment from anywhere without being in a specific physical location. The COVID-19 pandemic affects all areas of human activity. As a result, students did not receive face-to-face instruction, and access to the laboratory was limited or practically impossible, and access to laboratory facilities has been limited or nearly impossible. Especially in engineering education, students' practical abilities cannot be developed comprehensively. In this paper, this paper built an online remote robotics experiment system using digital twin (DT) technology and IoT technology and adopted ADDIE (Analysis, Design, Development, Implementation, and Evaluation) teaching method. With these measures, students can design and debug robot programs at home, just like in the laboratory. This study sent questionnaires to 64 students, and 58 were returned. The results show that more than 80% of students believe that the remote labs for industrial robotics courses have improved the efficiency and quality of students' skills training as opposed to virtual simulation and watching videos on the computer.

Keywords—experimental teaching, remote lab, engineering education, e-learning, digital twin

1 Introduction

The remote lab is a practical teaching platform built using Internet and IoT technologies, enabling students to operate the remote lab experimental equipment just like local equipment. It is also an indispensable part of the development of distance education. Previously, hands-on engineering learning was based entirely on face-to-face instruction, with classroom learning taking place individually or in small groups under the guidance of a teacher. However, the COVID-19 epidemic has forced teachers to switch to online teaching strategies hastily. While this transition is demanding for all subjects, it is especially difficult for professors whose courses include hands-on laboratory instruction. Covid-19 has sparked the largest remote work experiment in history [1]–[5]. May et al. (2022) explored the introduction of online laboratories to Electrical Engineering and Computer Systems Engineering courses as part of a quick transition from face-to-face to online experiment from the students' viewpoint [6].

Srinivasan et al. (2021) presented methods for integrating a flexible blended instructional format. They explained four core aspects of a flexible blended teaching format, namely, course design, pedagogical strategies incorporating active learning and offering a sense of online community, infrastructure for delivery and training, and introducing activities that assist student wellbeing [7]. Muhammad et al. (2021) transformed and offered two courses in an online environment in the Winter 2020 semester, including constructivist theory and active learning concepts in the live online lectures. This maintained a healthy level of attendance while also encouraging interactions, the sharing of ideas and thinking, and, eventually, learning [8,9]. In the Biotechnology program, Geng et al. (2022) presented an active digital learning platform that supported undergraduate research-based education in an online space. Students conducted research and innovation on their experiments through learning laboratory methods using online lab exercises and developing the research in a cooperative online environment [10]. Alavi et al. (2022) described the implementation of the completely online Real-time Systems course in the Software Engineering Technology program, along with its positive influence on student learning [11]. Greaves et al. (2022) surveyed McMaster University undergraduate engineering students to discover their preferences for the kind, number, and duration of instructional films, and then made suggestions for the optimal ways of content distribution in an online learning environment [12].

Digital technology and Internet of Things technology that developing today. Several researchers have used these technologies to develop virtual laboratories that provide students with virtual simulation platforms for experimental learning. In recent years, there has been an increasing amount of literature on online labs. A recent systematic literature review concluded that learners' satisfaction with online learning through questionnaires and differences in learners' satisfaction with different online teaching platforms [13]. Dan, H (2022) applied virtual reality simulation technology to warehouse management's teaching practice, which improved students' skills training and quality [14]. Mohammed (2022) created a smart classroom based on artificial intelligence and the Internet of Things and simultaneously described innovative teaching and intelligent learning [15]. Dominik (2020) introduced the online lab for engineering education to positively impact the application for international students [16]. In Industry 4.0, introducing network technology in the manufacturing technology lab allows for remote laboratory teaching [17]. Reid (2020) assessed the utilization of a remote laboratory with roughly 250 third-year students in the School of Engineering's 'Controls and Instrumentation Engineering 3' course. According to the study, distant laboratories provide fresh chances that aren't attainable with conventional procedures and aren't just a scaled-down version of proximal laboratories [18]. Wuttkeet et al. (2019) proposed remote experimentation as the practical basis for training engineers with disabilities in Computer Science and Information Technologies [19]. Serge (2020) showed steps of design of digital twins upon examples of the master's degree program at the University of Applied Sciences Darmstadt. He described why and how it is possible to use digital twins [20]. However, so far, all researchers have focused on using virtual labs to improve the effectiveness of distance practice teaching. However, virtual laboratory teaching is only a simulation of data, which cannot be measured and controlled for actual equipment. There is a gap between the effectiveness of virtual experiments and hands-on experiments.

In the online teaching process, teachers must innovate their teaching models to adapt to the new changes in the experimental platform. Researchers attempted to evaluate the impact of different teaching processes on the effectiveness of online laboratory instruction. Stapa et al. (2019) employed an innovation in the teaching and learning process that involves transferring knowledge from teacher to student. The use of technology and support can encourage or impede student engagement in online activities [21]. Verma et al. (2020) presented a number of novel solutions, including the flipped classroom approach, which uses previously available online information, online practice problems, and processes [22]. Yao (2021) used Addie teaching design model in a College English class to stimulate students' interest in learning [23]. Rajabzadeh et al. (2020) offered the idea of using UniSim1 software to teach process engineering design in a biology course [24]. Rajabzadeh et al. (2022) investigated the teaching benefits of integrating interdisciplinary open-ended science projects into an undergraduate curriculum to promote students' conceptual comprehension and meta-skill development [25]. Yu (2021) utilized the ADDIE paradigm to create an intelligent virtual reality (VR) interactive system for learning how to make pour-over coffee. The findings revealed that the intelligent VR interactive system matched the participants' learning needs and improved their learning performance [26].

This paper built a remote robotics lab based on digital twin and IoT technology. The lab dynamically presents the robot's operation process; the underlying data and models are derived from the equipment. At the same time, to improve the teaching effect and cultivate students' innovation ability, the study used the ADDIE model in remote experimental teaching. In 2022, due to the epidemic, and used remote experiments to teach industrial robotics experiments to 64 students in their junior year of mechanical and electronic engineering. A questionnaire survey found that 80% of students believe that monitoring and control of actual equipment can be achieved in the remote lab platform, and the learning effect is better than that of the virtual lab. Furthermore, because remote labs allow learning without space constraints, 30% of students think that remote labs are more convenient than hands-on labs.

2 Type of laboratory

2.1 Concept of DT

The concept of the DT was first introduced in 2003 by Professor Michael Grieves of the University of Michigan. In 2010, the "Digital Twin" one word in NASA's technical report was formally put forward. The DT is a digital representation of a physical object in a virtual space. In natural environments, dynamic virtual models are used to simulate and depict physical entities' properties, behaviors, and rules [27]. The U.S. Industrial Internet Consortium has identified the DT as the core key to the Industrial Internet. The German Industry 4.0 has the DT as an essential element.

The essential features of the digital twin are high fidelity, real-time interaction, and real-world symbiosis, which provide learners with an authentic embodied learning experience. Figure 1 presents the structure of the digital twin.

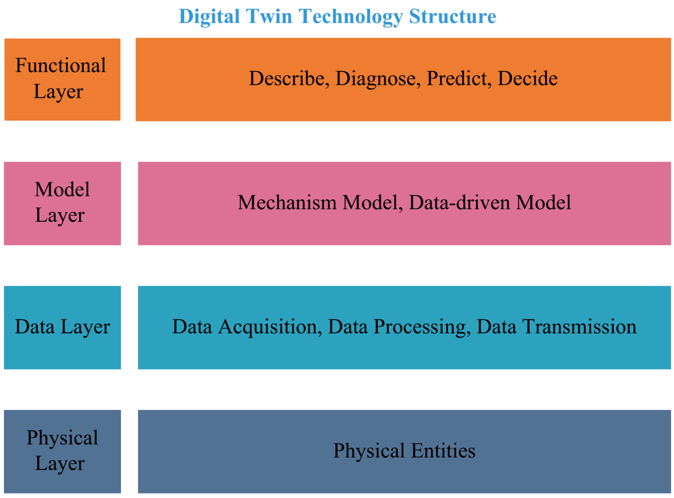

Fig. 1. The structure of digital twin

2.2 Hands-on lab

As we all know, laboratory experiments are essential for education. Hands-on activities have historically been the only way to carry out well-structured experiments. Traditional hands-on laboratory structure and operations have been revamped and expanded to distant laboratories due to advancements in information technology [28]. This type of lab is currently essential for the teaching of technical courses. Thus, virtual laboratories, simulators, and remote labs can be utilized as replacements for traditional hands-on labs in engineering education.

2.3 Virtual lab

In virtual laboratories, the instrument is replaced by a software program that re-creates all of its operations, roughly or totally. As illustrated in Figure 2, a virtual lab can refer to a lab where each simple experiment is simulated and does not need the use of any specific equipment. Furthermore, it can be employed in specific experimental tasks when a simulation is sufficient, and only a standard computer is required. In addition, it can be accessed via an interactive user interface with typically good visual rendering, allowing students to manipulate experiment settings and observe the results.

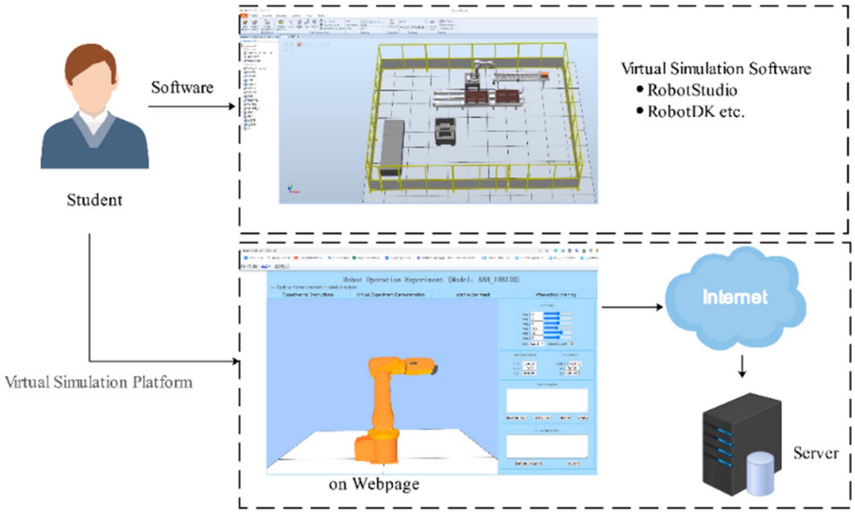

Fig. 2. Virtual lab

2.4 Remote lab

The structure of the remote laboratory designed in this paper is presented in Figure 3. A remote lab is an instructional resource that allows students to engage with genuine workbenches from a distance. These workstations contain experimental equipment such as robots, PLCs, mechanical devices, and pneumatic equipment. Although they are separate from the learner, the experimental equipment can be accessed and controlled by the Internet. Remote laboratories, as opposed to virtual labs, give a useful lab experience by giving extended access to actual hardware. On the other hand, simulators can never perform as well as actual hardware in all circumstances since they cannot incorporate all of the experiment's parameters.

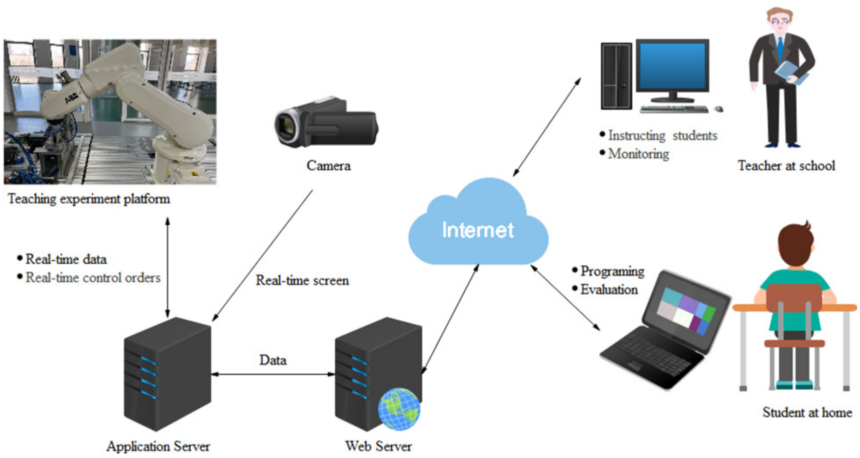

Fig. 3. Remote lab

The structure of the data-driven digital twin model is provided in Figure 4. The display layer is client-side, which uses Unity3D to develop the client-side display interface to display the motion state of the virtual industrial robot through Unity3D. The logic layer uses Unity3D script files to send HTTP requests to the server, which queries the MySQL database information and then returns the query results to the server, using JSON to read and write data in Unity3D. Finally, the data layer returns the collected accurate robot data to the server through the OPC UA communication protocol, and the server writes the data to the database. In contrast, the data twin model calls the database information to realize the motion [29].

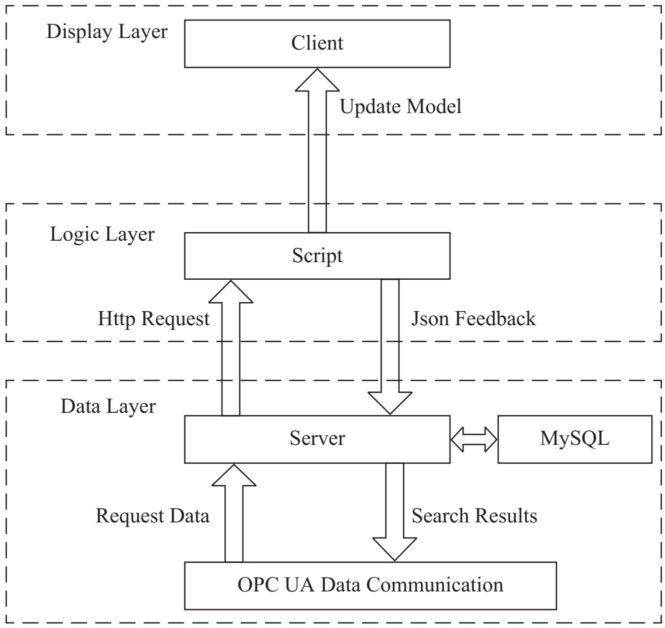

Fig. 4. Data-driven model architecture

Each laboratory style has its advantages and disadvantages. For example, virtual laboratories can be used simultaneously by a large panel, with only processing power as a restriction and no additional charges. On the other hand, remote labs are more expensive to build and maintain because they require real equipment to perform tests and additional Internet access equipment. The hardware and software requirements for a remote laboratory are shown in Table 1.

Table 1. Hardware and software requirements for a remote lab

Hardware/Software	Name	Description
Sound acquisition device	Microphone	Active Noise Canceling
Image acquisition device	High Resolution Camera	Pixels: 32.5 million
Server	Apache Tomcat	6.0
Network connection device	Switchboard	Gigabit network port
Development Language	C#	7.0
Database Core Server	MySQL	5.6

3 ADDIE teaching model

Instructional design is a crucial factor affecting the effectiveness of classroom teaching. It is the basis for carrying out teaching activities and ensuring teaching quality. As an international common teaching model, ADDIE is quite flexible and can be used for the development and design of teaching models in various fields. Therefore, this paper combined the ADDIE model with remote experimental teaching and constructed a teaching model applicable to industrial robotics experimental courses from five aspects, including relevant analysis, scientific design, effective development, implementation, and objective evaluation. The ADDIE framework was created at Florida State University in 1975. Many instructional designers and training developers utilize the ADDIE framework for instructional systems design while creating courses [30]–[32]. As shown in Figure 5, the ADDIE model initially had numerous steps within its five early phases (analyze, design, develop, implement, and evaluate). The plan was to finish each step before going on to the next. Following practitioners altered the stages, the model finally became more dynamic and interactive than the first hierarchical form. The version first debuted in the mid-1980s.

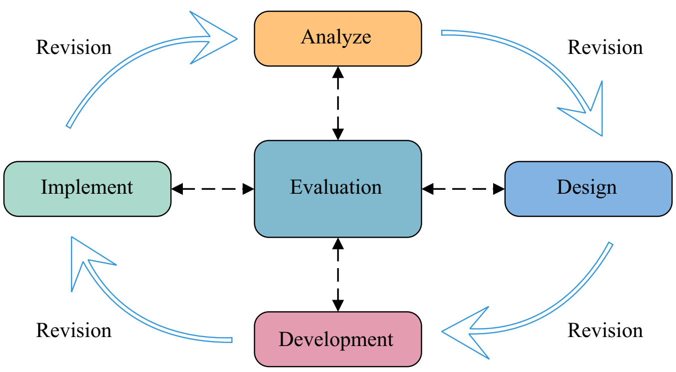

Fig. 5. ADDIE model

3.1 Analysis phase

The analysis phase mainly includes teaching object analysis, teaching objective analysis, and teaching content analysis. Industrial Robotics is a professional foundation course that includes both theory and practice. In addition, it focuses on application-based and research-based experiments. Through this course, students master industrial robots for essential operation, function setting, secondary development, online monitoring and programming, and solution design.

To enhance students' ability to analyze and solve engineering problems through experimental teaching and cultivate innovative and practical skills. Master the ability to program and debug industrial robot control programs and have the ability to apply maintenance and innovative design to industrial robots. The content of the laboratory courses emphasizes basic knowledge while considering an emphasis on innovation. Through the experiment, students will master the essential knowledge points, operation, programming, and maintenance of the robot.

In addition to knowledge and skill objectives, teamwork and communication skills are also important factors in talent cultivation. Rajabzadeh et al. (2022) found that group work improves the communication skills of undergraduate engineering students [33]. Jennifer et al. (2018) emphasized the importance of learning interpersonal skills and teamwork early in engineering education [34].

3.2 Design phase

The main work of the design phase is to design the course content and teaching process based on the analysis phase results, including teaching process organization, learning activity design and teaching media selection. For example, the goal of the laboratory teaching content is to develop student's knowledge and abilities, the contents of the robotics teaching experiment are shown in Table 1. The teaching process is the sequence and way to show the teaching contents, which is designed according to the teaching objectives and contents and determines the students' learning effect. The teaching process is the sequence and way to show the teaching content, designed according to the goal and content. It determines the learning effect, and students' central role should be fully reflected in the design of the teaching process. For example, the robotics experiment teaching content is presented in Table 2.

Table 2. Robotics experiment teaching content

No.	Experimental Project	Experiment Content
1	Build industrial robot workstation	Workstation layout, manual operation of the system, creation of coordinate systems
2	Modeling Features in RobotStudio	Modeling functions, use of measuring tools, creation of mechanical tools and robot tools
3	Robot Programming	Robot trajectory curve and path, robot target point adjustment and axis configuration
4	Application of Smart Components	Dynamic conveyor chain, dynamic clamping with Smart components
5	Online Features of RobotStudio	Backup and restore, online editing of RAPID programs, online monitoring of robot and demonstrator status

3.3 Development phase

The Analyze and Design stages provide a foundation for the Develop phase. Creating the lesson plans and materials is the goal of this stage. This phase of work is the production of online teaching materials, including teaching courseware, experimental instructional videos, and manuals. In addition, remote experiments require the preparation of experimental hardware and software platforms, such as robots and networks. The contents of the teaching materials include experimental purpose, the introduction of experimental equipment, experimental operation methods, and data processing and experimental tasks.

3.4 Implementation phase

The goal of this phase is to offer training effectively and efficiently. Furthermore, this phase must increase students' comprehension of the subject and encourage students' mastery of objectives. As a result, the robotics experiment's distant learning is separated into three parts: before, during, and after the experiment.

Before the experimental class, the teacher released the pre-study materials through the class WeChat group, including teaching materials, an experimental instruction video, a practical manual, and experimental task order. At the end of the experiment, students process the recorded experimental data and analyze and discuss the results according to the course presentation method.

3.5 Evaluation phase

The assessment procedure is divided into two parts: formative and summative. Each level of the ADDIE process includes formative evaluation. Summative evaluation is carried out on completed instructional programs or products. For example, the evaluation of the robotics engineering laboratory course consists of two parts: the evaluation of teaching effectiveness and the evaluation of students' performance. This paper uses a questionnaire to evaluate the effectiveness of teaching.

At the end of the course, a questionnaire was posted on the teaching platform. The content of the questionnaire includes students' satisfaction with the experimental content, teaching design, and experimental environment and also investigates students' mastery of experimental techniques and knowledge. Before the operation starts, the teacher demonstrates the operation through video and emphasizes safety precautions. After the demonstration, students start the experiment according to the designed experimental plan and operation steps. Before the operation, the instructor demonstrates the operation via video and emphasizes safety precautions. Then, students access and operate the robotics experiment platform via the Internet at the specified time. During the experiment, the teacher guides the students when they encounter problems.

4 Method

4.1 Questionnaire design

This study aims to understand students' experience and satisfaction with the new learning platform and the factors influencing the learning process, to demonstrate the value and usefulness of the distance laboratory in practical teaching. The questionnaire design consists of four parts: the first part is the learning experience survey, the second part is the learning platform survey, the third part is the learning process survey, and the fourth part is the course learning effect and satisfaction evaluation. Questionnaire contains ten objective multiple-choice questions, and Each question has five answers, including strongly satisfied (SS), satisfied (S), basically satisfied (BS), dissatisfied (D), and strongly dissatisfied (SD). The questionnaires about the effectiveness of remote lab teaching can be seen in Table 3.

Table 3. The questionnaires about effectiveness of remote lab teaching

No.	Items
A	Overall evaluation of the remote laboratory instruction model.
B	Extent to which you like the remote lab lectures.
C	Hands-on sessions stimulate your learning.
D	Remote labs facilitate your knowledge and understanding.
E	Remote labs facilitate interactive collaboration.
F	Remote labs are good for improving analytical problem-solving skills.
G	Remote labs facilitate increased student participation in the classroom.
H	Remote labs have improved your skill level.
I	Satisfied teachers continue to use remote labs for teaching.
J	Satisfied with the ADDIE teaching style.

4.2 Research object

This paper investigated the effect of using a remote laboratory for practical teaching. The target students were junior mechanical and electronic engineering students. The study sent the questionnaire to the class through an electronic link, and the students opened the link through WeChat to complete the questionnaire. The total number of questionnaires distributed was 64, and the number of returned was 60, with a recovery rate of 93.75%, which satisfied the requirement of statistical analysis of the questionnaire.

5 Results and discussion

5.1 Remote lab operation

This paper built a remote robotics experiment platform that allows students to access and operate real industrial robotics equipment from anywhere with an Internet connection. The remote lab also provides a group work function. Two students are divided into groups to complete the experimental project. One student is responsible for 3D model configuration and the other for programming, and they can exchange tasks for training. The industrial robot in the remote lab is an ABB IRB120. As shown in Figure 6, students use RobotStudio software to program and debug the robot. RobotStudio, ABB's simulation and offline programming tool, enable robot programming on a PC at the office without interrupting operations. Students can train, program, and optimize tasks without disrupting production.

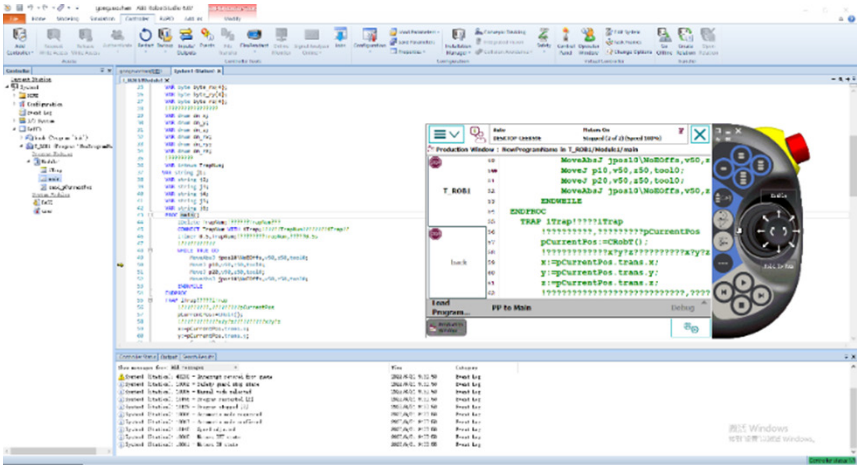

Fig. 6. Robot programming and debugging screen

The Unity3D-based digital twin system includes model building, graphics rendering, script editing, and human-computer interaction interface development. The remote lab uses the industrial communication standard OPC UA protocol to achieve data communication between virtual and real industrial robots, enabling synchronized motion between virtual and real robots. ABB120 robot digital twin diagram is shown in Figure 7. The joint robot positions in the digital twin interface are identical to the physical robot.

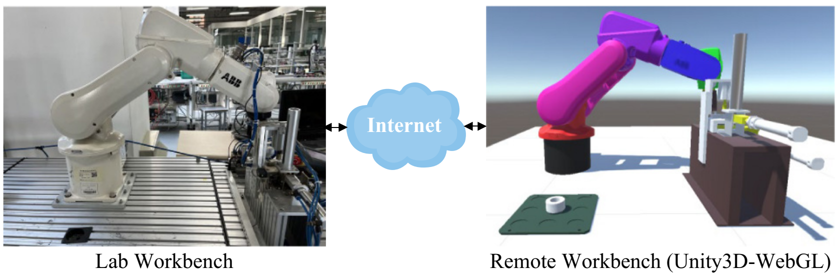

Fig. 7. ABB 120 robot digital twin diagram

The digital twin lab provides an ideal learning environment for experimental courses in automation and dramatically enhances the effectiveness of engineering education. Learners can use the digital twin to control and adjust relevant parameters and remotely manipulate the physical twin, thus conducting remote exploratory experiments and gaining an almost realistic experimental experience.

5.2 Questionnaire reliability test

The validity and reliability of the measurement outcomes were evaluated in this study using SPSS 22.0. According to Table 4, the student survey's reliability coefficient is 0.966, which is higher than 0.9, demonstrating the high level of data dependability in the study. Table 4's item numbers correspond to those in Table 3's.

The reliability coefficient values of the investigated items did not increase significantly after the items were excluded. The value indicates that the reliability of the study data is good, and all items should be retained. Furthermore, the CITC values of the tested items are all greater than 0.7, showing a solid correlation between the studied items and a high level of dependability. The research data's reliability coefficient values were greater than 0.9. When the problem items were removed, the reliability coefficient values did not increase significantly. The data has good reliability quality and can be used for further analysis.

Table 4. Questionnaire reliability of students

Item No.	Correction Item-Total Correlation (CITC)	α Coefficient with Item Deleted	Cronbach α
A	0.782	0.965	0.966
B	0.762	0.966	
C	0.739	0.967	
D	0.878	0.962	
E	0.862	0.962	
F	0.904	0.961	
G	0.876	0.962	
H	0.910	0.960	
I	0.810	0.964	
J	0.934	0.959	

As shown in Table 5, the Kaiser-Meyer-Olkin (KMO) value of the student scale is 0.920, which meets the above requirements and is suitable for factor analysis. In addition, Bartlett's sphericity test value is less than 0.05, and the data are spherically distributed.

Table 5. KMO and Bartlett tests of student questionnaires

KMO measurement sampling adaptability		0.920
Bartlett's sphericity test	Approximate cardinality	674.731
	Degree of freedom	45
	Significance	.000

5.3 Analysis of student satisfaction

The item numbers from A to J in Figure 8 are consistent with those in Table 3. Looking at Figure 8, more than 80% of the ten indicators were satisfied, indicating that students were more satisfied with this new experimental teaching mode. From the indicators, more than 90% of the students think that remote laboratory teaching stimulates learning interest. More than 85% of the students think that using remote labs is helpful for knowledge acquisition. Nearly 90% of the students accepted that the instructor continued to use the distance lab for teaching. 85% of the students were satisfied with the ADDIE model of teaching. Although most students were satisfied with the remote lab, more than 13% were unsatisfied with the hands-on lab. In the future, this paper needs to optimize the laboratory environment and teaching mode to improve students' satisfaction.

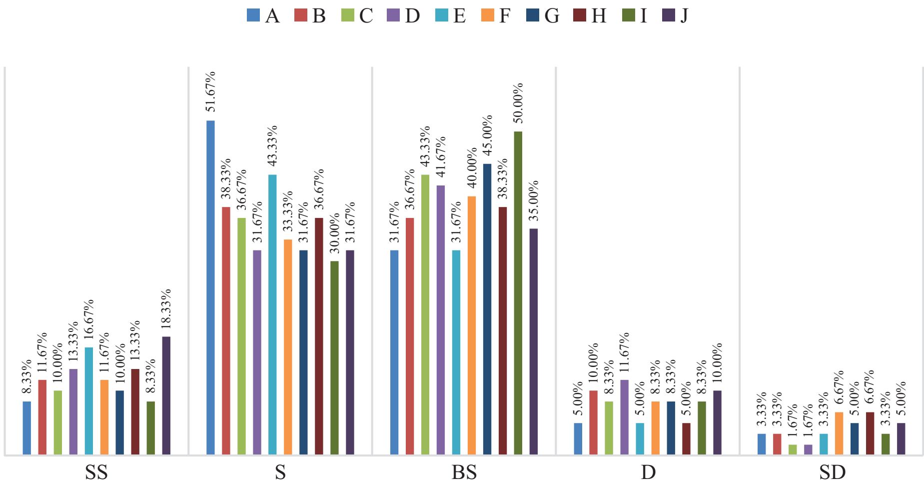

Fig. 8. Survey data of the questionnaire

Note: SS = Strongly satisfied, S = Satisfied, BS = Basic Satisfied, D = Dissatisfaction, SD = Strongly dissatisfaction.

6 Conclusion

This paper outlines the details of this online distance experiment platform and curriculum design, as well as students' feedback on the experience and perceived value of this method, based on the data collected from the survey feedback. Based on the questionnaire results, more than 80% of the participants felt that the expected learning outcomes of the distance labs were comparable to traditional lab work. Students want to sustain and expand the deployment and use of distance labs. Currently, the remote lab does not support mechanical and electrical maintenance experiments. In the future, the study will improve the experimental platform and teaching mode to enrich the teaching content.

7 Acknowledgment

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9 Authors

Dangfeng Pang is a lecturer at the School of Mechanical Engineering, Tianjin Sino-German University of Applied Sciences. He has participated in several international conferences and published research papers.

Shigang Cui is a professor at School of Automation & Electrical Engineering, Tianjin University of Technology and Education, Tianjin, China.

Genghuang Yang is a professor at School of Automation & Electrical Engineering, Tianjin University of Technology and Education, Tianjin, China.

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