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NCSLab Remote Experimentation for Control Engineering Education in Wuhan University

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Abstract: The paper introduces the implementation of NCSLab 3D, which is a real-time simulation laboratory based on NCSLab (Networked Control System Laboratory) framework at http://www.powersim.whu.edu.cn/ncslab/. Users can carry out remote experiments anytime and observe the real-time data changes of real test rigs through 3D models or Web cameras. However, an evaluation about the performance of the remote laboratory is often neglected. So this paper makes a quantitative evaluation on the NCSLab 3D. Questionnaires about technical issues, educational issues and added value are made to allow registered users to give their effective feedback. The conclusions drawn from the statistical data of seventy-five students who had performed all the experiments in NCSLab 3D can promote the laboratory's development in the future.

Key Words: Remote laboratory, control engineering education, 3D visualization, questionnaire, evaluation

1 Introduction

In multidisciplinary education especially in engineering education, tests and experiments are very important for teaching, and essential for students as well [1]. Motivated by the interest in experiments, students are willing to obtain a new comprehension on speculative knowledge in classes. Hands-on laboratories are traditional physical forms with real experimental devices. Even though the traditional laboratory enables students to develop the ability of data processing and numerical analysis, its large-scale application is often limited by initial purchase price, the costs of maintenance and insurance. To alleviate this problem, scientific institutions have proposed and established online laboratories [1].

In recent years, online laboratories including remote "hands-on" laboratories (remote labs) [2], virtual laboratories and hybrid remote laboratories [3] have developed rapidly and been deployed widely. With the advance of Internet technology, students benefit a lot from the open-teaching mode with remote autonomous experiments. A remote "hands-on" laboratory is a set of experiments using real devices in a physical laboratory, which connect to the Internet based on software applications and network technologies, thus enabling remote access to the experimental resources. Many automatic control systems have been successfully implemented in remote laboratories [4][5] and furthermore, various software environments have been adopted in remote laboratories, such as MATLAB/Simulink [6][7], LabVIEW [8], Java [9][10] and Ajax[11], *etc*.

Remote laboratories such as the Automatic Control Telelab (ACT) [12] allow users to design their own control algorithms and test it on the real test rigs through a user-friendly interface. MIT iLab [13] provides the services for multiple disciplines. In WebLab-Deusto [14], different kinds of test rigs, which are located diversely in different institutions, were integrated under a single Web interface.

In Networked Control System Laboratory (NCSLab) [15-17], a unified and flexible Web-based interface is provided for various test rigs such as servo motors, magnetic levitation systems, etc. The lab offers remote services to the users with various devices from the institutions all over the world. When browsing through websites, users can design control algorithms and customize their monitoring interface without requiring knowledge of programming. The NCSLab was initially developed in the UK and it has been gradually implemented in several institutions located in both UK and China.

Compared with the remote "hands-on" laboratory, the virtual laboratory is cheaper and safer. The experimental results, which are calculated based on the mathematical models without the model uncertainties and practical disturbances, are closer to the theoretical results. However, the virtual laboratory cannot be applied in experiments focus on data processing.

The hybrid laboratory, enhanced by the development of 3D visualization and virtual reality technologies, has drawn many research fellows' attention. When using Web-based 3D technologies as a complementary of Web cameras in remote laboratories, the limitations of Web cameras can be eliminated. Firstly, it allows the users to zoom in, zoom out or rotate the 3D objects of test rigs without any restriction. Secondly, the users are able to see all details about the test rigs. Thirdly, the real-time simulation is available for users when they try to monitor the process of experiments.

The NCSLab 3D is a hybrid remote laboratory, which is a 3D Web-based control laboratory based on NCSLab framework. When conducting experiments in the NCSLab 3D, the users can observe 3D animations as well as the real-time videos in the Web-based monitoring interface.

In this paper, a brief introduction about the NCSLab 3D in Wuhan University is given, and communication channels are established to guarantee real-time data exchanges between the Web browsers and Control Units. In addition, based on users' feedback, this paper makes an evaluation on the performance of NCSLab 3D, and it implies several conclusions about technical issues, educational issues and added value.

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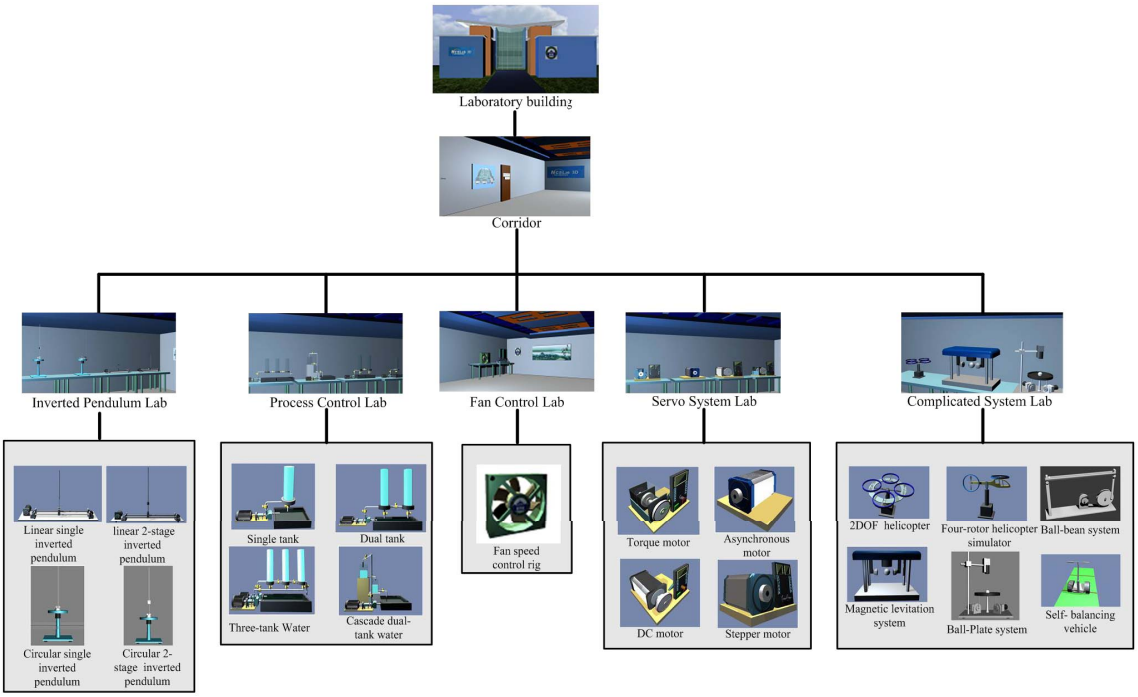

Fig. 1. Logical structure of the laboratory building

2 Implementation of NCSLab 3D in Wuhan University

The NCSLab 3D in Wuhan University was established in 2011. It provides various online experimental services for students in Wuhan University and beyond.

2.1 Structure of the Laboratory Building

At present, in the area of control and automation, the NCSLab 3D has five sub-laboratories including Inverted Pendulum Lab, Process Control Lab, Fan Control Lab, Servo System Lab and Complicated System Lab. Each sub-laboratory is a tree directory structure according to the functionality of test rigs. All the test rigs are cataloged into several sub-laboratory buildings which only exist in the Web-based interface. The logical structure is shown in Fig 1.

2.2 3D Sub-laboratory configuration

Fig 2 depicts an example of how a 3D sub-laboratory room is displayed in the Web page. All test rigs in the sub-laboratory are listed in the XML and their detailed information such as the ID, model name and position are specified. The position of each test rig model is carefully calculated by its real dimensions. The XML is configured in advance by the JSP/Servlet codes and stored in the MySQL database on the server side. The AJAX Scripts running in the NCSLab Web pages get an XML configuration from the Web server, and pass the XMLs to the HTML5 3D engine where the 3D components are displayed properly with these configurations. The HTML5 3D engine parses the received XML, loads the 3D models of the laboratory room and test rigs according to the information obtained from the XML and setup the laboratory room in the Web-based 3D interface.

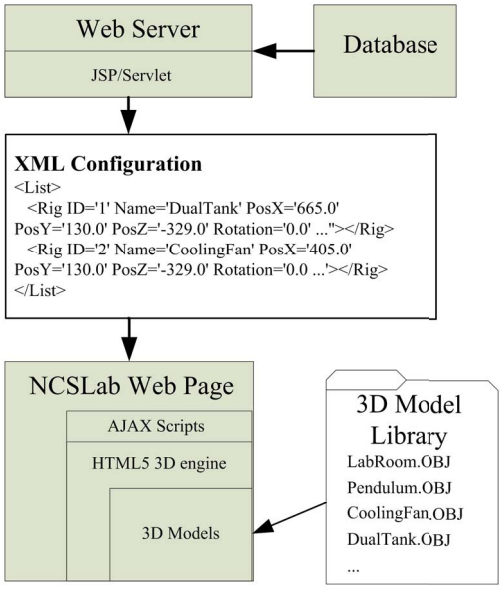

Fig. 2. 3D sub-laboratory configuration

When registered users login the NCSLab 3D system, they are able to access the 3D laboratory with no specific software but a Web browser, and they can “walk into” the virtual building only by manipulating a keyboard and mouse. Inside the building, there is a corridor with many rooms. By clicking the mouse on these room doors, users can “enter” the sub-laboratory. Just like hands-on laboratory, it’s an immersive experience that users can observe the detailed information of test rigs in the remote laboratory. When users point the mouse cursor to the test rig and press the left button, they can pick up any test rig available in the virtual world. If users want to carry out experiments, they may double-left click on the test rig, and the browser will be redirected automatically to the chosen test rig in the experimental Web page, as shown in Fig 3.

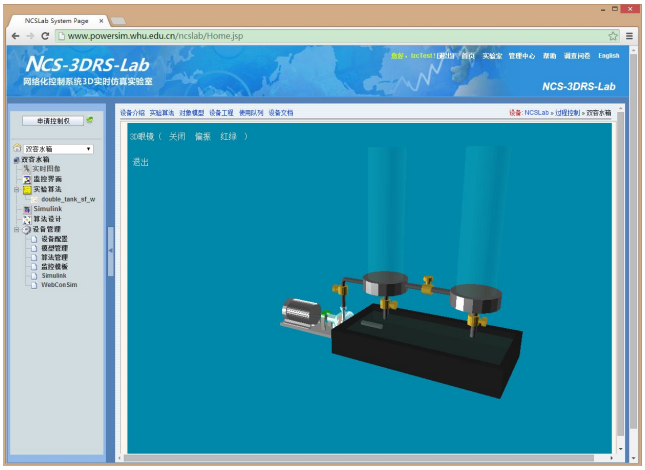

Fig. 3. Experimental Web page with 3D model

2.3 Communication Channels Established in Remote Experiments

The data exchanges between the Web browsers and Control Units as the experiment is being performed. It's essential for the established data link to create communication synchronization mode when exchanging data stream between the widgets (both 3D models and 2D modules) in the Web browser and real test rigs. The NCSLab 3D allows the users to design control algorithms and upload effective control algorithms, then add into the control algorithm page. When the algorithm is downloaded to the target Control Unit, users are able to monitor the process of experiments in the Web-based interface. Meanwhile, the monitoring and supervising interface also can be designed by users. There are 3D models to display the test rigs' motion, 2D modules to show any parameter changes chosen by users in the Web-based interface, and Web camera to transmit real time videos. Therefore, communication channels should link to both side, and guarantee the synchronization of data changes from virtual widgets and real test rigs. In addition, data link is important for users to pass their remote instructions (tuning parameters, changing algorithms, *etc.*) to the Control Units.

Communication channels are the links to guarantee data exchanges in real time as shown in Fig 4.

Experiment Engine is deployed corresponding to each test rig in one of the Experiment Server. The Real Time Data Pool in Experiment Engine is a buffer between the Web browsers and Control Units. With a FIFO (First In First Out) structure, it can store the temporary real-time data in case of network delay, and thus guarantee the continuity of the data stream between the Web browser and Web Server. For campus network, the synchronization of data exchanges between the Web browsers and Control Units is achieved as the result of negligible network delay.

A registered user who had applied for temporary rights to control the test rig can carry out experiments and monitor the experimental process in their PCs. The control algorithms, which are completed in the NCSLab Web-based interface, can be uploaded to the MATLAB Server where the instructions are converted into executable codes. The Control Unit compiles the codes and generates the corresponding actions. When the value of a parameter is changed, the corresponding instructions are passed to the Data Exchange Module as a HTTP request. The Data Exchange Module sends the instructions to the Experiment Execution Module where the instructions are further passed to the Control Unit.

When control instructions are downloaded and executed in the Control Unit, the TCP communication is established automatically between the Experiment Execution Module and the SCADA Server. All control instructions are converted into C codes, which are automatically generated by Matlab/Simulink Real-Time Workshop (RTW), and compiled into executable programs by Visual C++ compiler. API interfaces such as C-API, which are provided by RTW, can access all the internal signals and parameters of the programs running in the control units. The Experiment Engine collects real-time simulation data from the real test rig and temporarily stores them into the Real-Time Data Pool.

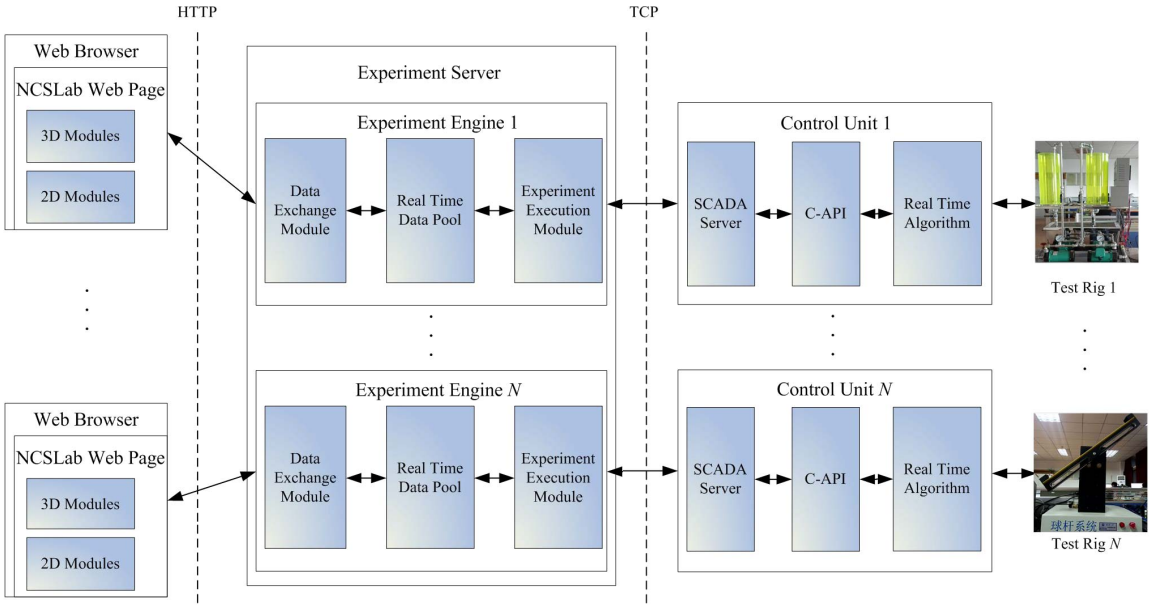

Fig. 4. Logical structure of the laboratory building

The users are able to customize the Web-based monitoring interface, and some widgets like sliders, 3D test rig models are available for users to tune up the control parameters. After downloading process has finished, widgets are displayed in users' interface, the HTTP communication between the widgets and the corresponding Data Exchange Module is created automatically. The data from the Real Time Data Pool is transmitted to the Web browser and delivered to the widgets through the HTTP connections.

3 Evaluation on the performance of NCSLab 3D

In order to evaluate the performance of NCSLab 3D in Wuhan University, students are required to give their feedback. This evaluation employed a sample survey and the results were collected by a Web-based survey. There is a questionnaire in the NCSLab 3D website for users. The students who had chosen the course named *Classic Control Theory* and *Control System Simulation and Computer Aided Design* are junior students from Wuhan University. They were given three weeks to carry out the remote experiments in NCSLab 3D. Five experiments are listed from easy to hard sequence, as shown in Table 1.

TABLE 1
Experiments list

NUMBER	CONTENTS
Experiment 1	Learn to use the remote experiment platform to carry out the automatic control principle experiment
Experiment 2	Closed Loop Control Experimentation on Cooling Fan Rig
Experiment 3	Use PI Algorithms to Conduct Experiments on Cooling Fan Rig
Experiment 4	Write S-function of PI Control Algorithms with Anti-Windup Protection
Experiment 5	Write C-mex S-function to Remotely Control Cooling Fan Rig

Even though one test rig is available for one user within thirty minutes, all students had finished their homework successfully before the deadline and the average mark was 78%. The evaluation of NCSLab 3D involves three aspects. There are technical issues, educational issues and added value, and the data collected from questionnaires is shown in Table 2A, 2B, 2C respectively.

TABLE 2A
Questionnaire results: technical issues

QUESTION	Options	NUMBER	Percentage
Is the experiment instructions helpful for you to carry out experiments quickly and correctly in NCSLab 3D?	Helpful	71	94.67%
	Uncertain	4	5.33%
	Not helpful	0	0
What's your opinion on the waiting time for line-up when conducting experiments in NCSLab 3D?	Very short	10	13.33%
	Can be tolerated	49	65.33%
	Very long	16	21.33%
How long is the average waiting time for line-up when conducting experiments in NCSLab 3D?	0~30 minutes	26	34.67%
	30~60 minutes	18	24.00%
	60~90 minutes	5	6.67%
	More than 90 minutes	26	34.67%
Is the NCSLab 3D convenient for you to carry out experiments?	Convenient	71	94.67%
	Uncertain	2	2.67%
	Inconvenient	2	2.67%
Is the NCSLab 3D website fast in response speed?	Fast	57	76.00%
	Uncertain	7	9.33%
	Slow	11	14.67%
Is the NCSLab 3D website stable during experiments?	Stable	54	72.00%
	Uncertain	12	16.00%
	Unstable	9	12.00%
How satisfied are you with the results of your experiments in NCSLab 3D in general?	Very satisfied	60	80.00%
	Neutral	13	17.33%
	Very dissatisfied	2	26.67%

TABLE 2B
Questionnaire results: educational issues

QUESTION	Options	NUMBER	Percentage
Is the NCSLab 3D helpful to motivate your interest in studying?	Helpful	63	84.00%
	Uncertain	11	14.67%
	Not helpful	1	1.33%
Is the NCSLab 3D helpful for you to learn the knowledge from classrooms or books?	Helpful	70	93.33%
	Uncertain	4	5.33%
	Not helpful	1	1.33%
Is the NCSLab 3D helpful for you to master experimental skills?	Helpful	68	90.67%
	Uncertain	5	6.67%
	Not helpful	2	2.67%
Which one is the most difficult experiment in NCSLab 3D?	Experiment 2	1	1.33%
	Experiment 3	3	4.00%
	Experiment 4	25	33.33%
	Experiment 5	46	61.33%
Do you hope to apply NCSLab 3D in others courses?	Yes	62	82.67%
	Uncertain	11	14.67%
	No	2	2.67%

TABLE 2C
Questionnaire results: added value

QUESTION	Options	NUMBER	Percentage
Which one is more interesting for you to carry out experiments, in hands-on laboratories or in NCSLab 3D?	In NCSLab 3D	26	34.67%
	Both the same	26	34.67%
	In hands-on laboratories	23	30.67%
In the case of reservations in advance when conducting physical experiments, which one are you more inclined to carry out experiments?	In NCSLab 3D	47	62.67%
	Both the same	15	20.00%
	In hands-on laboratories	13	17.33%
Which one can help you to learn more knowledge?	Remote experiments in NCSLab 3D	12	16.00%
	Both the same	45	60.00%
	Physical experiments	18	24.00%
Which one can help you to learn knowledge efficiently?	Remote experiments in NCSLab 3D	35	46.67%
	Both the same	25	33.33%
	Physical experiments	15	20.00%
Which one is more difficult for you to carry out experiments, in hands-on laboratories or in NCSLab 3D?	In NCSLab 3D	15	20.00%
	Both the same	25	33.33%
	In hands-on laboratories	35	46.67%
You can learn the knowledge and methods in NCSLab 3D that can't be learned in hands-on laboratories.	Agree	59	78.67%
	Uncertain	13	17.33%
	Disagree	3	4.00%
You will carry out experiments in NCSLab 3D in the future.	Agree	43	57.33%
	Uncertain	32	42.67%
	Disagree	0	0
You will recommend your classmates to use the NCSLab 3D system for the experiments.	Agree	55	73.33%
	Uncertain	20	26.67%
	Disagree	0	0

Some interesting results are worth of analysis. In technical issues, when they were asked questions about the waiting time for line-up during experiments in NCSLab 3D, it turns out that 78.67% of the students can tolerate and wait until the test rig is available, and 34.67% of the students didn't spent more than thirty minutes on waiting for conducting experiments. Because of the queuing mechanism, one test rig is available for one student within thirty minutes, so if students carry out experiments at the same time, the waiting time should be spent. However, with scientific evaluation on the technical issues of NCSLab 3D, enough time is assigned suitable for students to finish experiments, which is an effective way to reduce waiting time. On the other hand, more test rigs will result in less waiting time. The number of test rigs is limited by research funds and storage space. A proper value will be calculated through numerical analysis of users' feedback. The questionnaire results about the response speed and stability of the NCSLab 3D needs to be deeply analyzed. Due to different Web browsers and network environment, the NCSLab Website fast in response speed and stable in operation is supposed to be satisfied. Derived from the results, 94.67% of the students think it's convenient to operate the NCSLab 3D system, and 76.00% of the students' Web browsers receive a fast response from the Web server. In addition, there are 72.00% of the students who had carried out stable experiments recently. In general, almost 80.00% of the students are satisfied with the experimental results in NCSLab 3D.

In educational issues, from users' perspective, remote control engineering education exerts a positive influence on teaching and scientific research. When students were asked whether experimentation in NCSLab 3D can stimulate their interest in studying, 84.00% of the students chose "Yes". What's more, 93.33% of the students agree that it is helpful to enhance the understanding of the knowledge learned from classrooms or books. Moreover, 90.67% of the students think it can strengthen their experimental skills. To promote the large-scale application of NCSLab 3D, 82.67% of the students hope to use it in other courses.

In contrast to traditional hands-on laboratories, NCSLab 3D receives more positive feedback from users. In terms of interest on experimentation, the students are in favor of NCSLab 3D almost the same as hands-on laboratories. However, when students are required to make reservations in advance in hands-on laboratories, their attitudes lean to one side, which 62.67% of the students are inclined to carry out experiments in NCSLab 3D. More interestingly, the supporters of hands-on laboratories are nearly as many as the other one about which one can help students learn more knowledge, and 60.00% of the students hold unbiased opinions. When it comes to the efficiency, students' attitudes lean to one side again, which 46.67% of the students tend to carry out remote experiments in NCSLab 3D, where only 20.00% of the students still insist on conducting physical experiments. The data changes as a result of hands-on laboratories' inherent shortcomings. Firstly, hands-on laboratories are limited by location and management, so it can't always keep open. On the contrary, NCSLab 3D provides users the freedom to access to conduct experiments at any time, thereby students can carry out experiments many times without limitation of time until they master the knowledge. Secondly, online experiments can make students learn actively, positively, and thus improve their learning efficiency and practical ability. Therefore, 46.67% of the students agree that physical experiments are more difficult. In the future, no one believes that he or she will never carry out experiments in NCSLab 3D, and 73.33% of the students will recommend their classmates to use the NCSLab 3D system for the experiments.

Some conclusions are made according to analysis of statistic results above.

1) A user-friendly interface: With the experiment instructions and teaching in classes, students can finish experiments independently in NCSLab 3D. NCSLab 3D

gives users the freedom to customize their own monitoring interface, in which they can choose the signals to be observed and parameters to be tuned during experiments. The major problem when conducting experiments in NCSLab 3D is the waiting time for line-up. If suitable time is assigned for students to carry out experiments as their homework and a proper amount of test rigs are located in the remote laboratory, the waiting time can be very short. The remote experiments in NCSLab 3D require less restriction conditions, i.e., students carry out experiments without constraints of time and places. In total, remote experimentation in NCSLab 3D is easy for students to carry out experiments with more freedom to decide when and what to learn.

2) Web-based remote education and autonomous Learning: Remote experimentation in NCSLab 3D can help students to consolidate the key knowledge points learned in classes. Moreover, conducting experiments in NCSLab 3D can motivate students' studying interest on further knowledge beyond classes. Just like physical experiments, students can observe experimental results in real time, so they can master experimental skills through remote control. The construction of NCSLab 3D can contribute to the sharing of experiment resources and relive the burden of heavy funds.

3) Higher satisfaction at NCSLab 3D: Derived from the questionnaire results, NCSLab 3D displays prominent advantages in teaching compared with hands-on laboratories. Firstly, NCSLab 3D offers more flexibility to users and it can develop their ability of autonomous learning, thus improve their learning efficiency. Secondly, remote experimentation in NCSLab 3D improves students' concentration on the experimental principle and develops their creative ability and scientific research ability. Therefore, students can learn the knowledge and methods in 3D Web-based control laboratories, which is difficult to learn in hands-on laboratories.

4 Conclusion

In this paper, the technology implemented in NCSLab 3D is briefly introduced. From users' feedback, there is a positive evaluation on the performance of NCSLab 3D. Firstly, it is very convenient for students to carry out experiments in NCSLab 3D without any constraints of time, and thus obtaining a high degree of acceptance. Secondly, it can enhance the practical education of control engineering, which is able to improve students' interest in learning and develop their ability of autonomous learning. Thirdly, in contrast to hands-on laboratories, the NCSLab 3D receives more positive feedback from users. In the future, more comprehensive and objective evaluations will help to build a 3D Web-based control laboratory with users' satisfaction.

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