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Modular Web-Based Interactive Hybrid Laboratory Framework for Research and Education

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ABSTRACT Online laboratories are offering new experimental potential for research and education purposes. This paper investigates the design and implementation of a web-based hybrid laboratory framework for research and education. Based on the previous work of the Networked Control System Laboratory (NCSLab), a hybrid laboratory with a highly modular design providing plug-in free online experiments is discussed. The proposed modular design of the NCSLab is provided in four aspects as hardware, software, control algorithms, and deployment, which covers all of the phases that compose an online experimental platform. The experiments that are integrated into the NCSLab for research and education are also explored in detail. To verify the effectiveness of the proposed modular design, a virtual wiring fan speed control system and a physical wireless power transfer system are deployed as examples to illustrate the virtual and remote experiments, respectively. The modular hybrid laboratory has been applied to research and engineering education at Wuhan University, and the corresponding pedagogical evaluation verified the effectiveness of the NCSLab.

INDEX TERMS Hybrid laboratories, modular design, networked control research, web-based architecture.

I. INTRODUCTION

Online laboratories have been a research interest during the last few decades. As a complement to conventional laboratories where equipment is expensive and cumbersome, online accessible laboratories provide opportunities for students to engage with remote and virtual experiments with flexibility in both time and location while offering high repeatability.

Regarding the classification of online experimental platforms, online laboratories can be classified into remote laboratories [1], virtual laboratories [2] and hybrid laboratories [3], [4], as illustrated in Figure 1. Within the context of this work, a hybrid laboratory is a combination of both a remote laboratory and a virtual laboratory, which is a crucial part of the online laboratory to support online education [5], [6]. Hybrid laboratories' ability to support both remote and virtual experiments distinguish them from remote laboratories or virtual laboratories.

To support different research and educational purposes [7], [8], numerous online laboratories have been successfully designed and implemented. The RELATED framework [9], [10] proposes a structured methodology for developing remote and virtual laboratories, focusing on laboratory definition and built-in facilities such as user management, booking, and basic visualization. Go-Lab portal [11] supported by the Go-Lab project offers a unique and broad set of remote and virtual laboratories that form the starting point for inquiry learning spaces. The Go-Lab project also developed Smart Device [12] to provide interfaces to remote labs for clients and external services through well-defined services and internal functionalities that are quite similar to the Laboratory as a Service (LaaS) approach presented in [13]. Labicom [14] is a commercial architecture that provides an Application Programming Interface (API) for online laboratories built on top of its infrastructure.

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TABLE 1. Online laboratories for education.

Platform	Website	Discipline	Type of Experiment	Collaborative Support	Descriptions by the Authors
Weblab-FPGA-Watertank [3]	weblab.deusto.es	Control engineering	Hybrid	No	The lab provides access to a real FPGA board which can control virtual industrial watertank rather than real, physical ones.
GOLDi [31]	www.goldi-labs.net	Embedded electronics	Hybrid	No	The reconfigurable rapid prototyping platform of the GOLDi system can be used to test all the taught topics of a given lectures in the field of digital system design.
VISIR [32]	openlabs.bth.se/electronics	Analog electronics	Remote	Yes	VISIR is mainly focused on analog electronics: Ohm's law, transistors, passive and active filters, and so on.
Deeds [33]	www.esng.dibe.unige.it/deeds/	Digital electronics	Virtual	No	The Deeds (Digital Electronics Education Design Suite) is a set of tools designed to support learning and laboratory activities in the field of electronic and computer science engineering.
NetLab [34]	netlab.unisa.edu.au	Electronic engineering	Remote	Yes	NetLab is an interactive learning environment that also enables students remote from each other to collaborate.
iSES [35]	www.ises.info	Electronic engineering	Remote	Yes	The iSES is designed for easy creation of real remotely controlled laboratories (RCL) that are accessible from PC, tablets and mobile phones.
UPM 3DLabs [36]	3dlabs.upm.es	Science	Virtual	No	The student or user, through his avatar (your character in the virtual world) can do internships within the space created for this purpose.

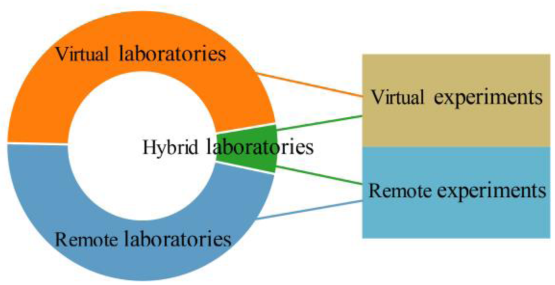

FIGURE 1. Online laboratories classification.

The iLab Shared Architecture (ISA) [15], [16], developed by the Massachusetts Institute of Technology, provides an efficient management framework that can support administration and access to a wide variety of online laboratories at multiple institutions independent of their developed platform. The Virtual Labs project [17] in India supports over one hundred Virtual Labs developed in 9 disciplines by 12 participating institutes. Other projects, such as Library of Labs (LiLa) [18] and Lab2Go [19], also offer easy access to a library of laboratories.

Apart from portals that offer a collection of laboratories, individual laboratory platforms are also a crucial part of online research and education. These platforms cover various engineering fields such as control engineering [20], electronic and electrical engineering [21], mechanical engineering [22], [23], software engineering [24] and industrial electronics education [25]. Some platforms can be accessed through mobile devices [26], [27]. In [28], a cloud-based experimentation platform for scientific inquiry and education was discussed that provides a real-time interactive, fully automated, low-cost and scalable service. Remote laboratories in automatic control systems were investigated in [8], in which the SLD (Sistema de Laboratorios a Distancia, Distance Laboratory System) allowed the learning and adjusting of predefined controllers, the design of new controllers, and other features. Many remote and virtual laboratories for education were reviewed in [29] and [30]. Other accessible platforms [3], [31]–[36] are listed and analyzed in Table 1.

Among the different types of remote experimentation offered, hybrid laboratories may be considered the most efficient for both education and research [4]. Therefore, hybrid platforms are under intensive investigation. Chan and Martin presented a system that combines the use of virtual resources (e.g., virtual machines, virtual switches) with real networking equipment (e.g., routers, switches) to create a hybrid networking laboratory [37]. Henke *et al.* [38], [39] presented a hybrid laboratory for the rapid prototyping of digital systems that evolved into GOLDi (Grid of online lab devices Ilmenau) [31]. Table 2 summarizes some existing hybrid laboratories [3], [31], [40], [41] in detail.

From the perspective of the end users, client applications for developing online laboratories can be classified into two categories; desktop-based clients and web-based clients. An analysis of different software used in the design of remote laboratories is presented in [42], in which web-based applications were explored by the authors for more portability and less intrusiveness than desktop applications. The merits of the web-based online laboratory can also be found in [43] and [44]. More web-based applications are becoming as flexible and powerful as desktop applications, such as integrating 3D graphics into online laboratories, especially when HTML5 was finalized in late 2014.

TABLE 2. Hybrid laboratories.

Hybrid Platform	Algorithm	Monitoring Interface	Interactivity	Client Application	Plug-ins	Server-side Technology	Client-side Technology
Weblab-FPGA-Watertank [3]	Default	Fixed	2D, such as virtual buttons, sliders, and textboxes	Web-based	None	Python	Angularjs, Unity3D and WebGL
GOLDi [31]	User-defined	Fixed	2D buttons	Web-based	None	PHP	HTML5
Micheal [40]	User-defined	Fixed	3D virtual world with high interactivity	Desktop	SL viewer (3D browsing software)	PHP, C++	Second Life
NCSLab [41]	User-defined	User customized	2D and 3D interactivity	Web-based	None	JSP	HTML5

For the ease of designing online laboratory platforms, modular design, which refers to a generic architecture that can potentially be applied to other projects, has been proposed and discussed. In [45], a distributed remote-control framework was presented with regard to a peer-to-peer (P2P) remote access laboratories system, in which a modular design that allows participating nodes to create rigs and host those nodes at distributed locations. However, P2P systems may introduce security risks such as attacks and monitoring by third parties. In [46] and [47], the LaaS, which builds upon the modular remote laboratory concept, was discussed. LaaS implies the development of remote laboratories as a set of independent component modules to allow the interchangeability of components between providers and consumers. Instead of full reliance on the provider's equipment and facilities, the consumer contributes one or more components for remote experiments. Other researchers developed a modular laboratory platform for mobile robotics performing a single experimental task on a reconfigurable mobile robot [48] or an extensible remote electronic laboratory which developed driver adapters to wrap the instrument driver and plug-and-play ISIBoard that allows non-technical persons mounting the circuits on the board [49]. In [35], a modular hardware and software kit ''iSES Remote Lab SDK'' was designed for the easy creation of real remotely controlled laboratories that are accessible from PCs, tablets, and smartphones. However, the design is restricted to a small-scale system with an incompact structure in electronic engineering, thus imposing limitations on its large-scale deployment.

The framework proposed in this paper is a highly modular approach for constructing a hybrid laboratory, which is a plug-in free web-based interactive experimentation platform Networked Control System Laboratory (NCSLab) [41]. The NCSLab adopts a Service Oriented Laboratory Architecture (SOLA) [42]. Designed with a modular structure, the NCSLab is a complex system that covers many experimental projects with various integrated experimental resources. Test rigs that are physically located in different places can be connected and managed together for virtual and remote experimentation. The technical summary was also introduced in [41].

II. PREVIOUS WORK OF NCSLAB

The NCSLab at Wuhan University can be accessed at https://www.powersim.whu.edu.cn/ncslab. Hypertext Transfer Protocol Secure (HTTPS) was adopted for security considerations. Developed as a non-intrusive web-based application, the NCSLab allows the user to safely run the application without worrying about security or privacy issues because the application will not be able to read the information from the hard disk unless explicitly allowed by the user [42]. Moreover, the current NCSLab framework is based on HTML5 that does not use plugins [41]. The HTTPS reliance, non-intrusive approach, and non-dependency on plugins makes the NCSLab a security-oriented architecture satisfying the criteria proposed in [3].

Currently, six physical test rigs and 20 virtual test rigs have been integrated into the system to provide remote and virtual experimentation. The experimental architecture of the NCSLab is depicted in Figure 2. The experimentation platform is real-time, accessible to and interactive for users at geographically diverse locations for control engineering education. The platform allows the user to tune the parameters of the test rig via the web and obtain feedback data such as real-time charts and videos, as long as the Internet is available [see Figure 2a]. For a specific test rig, the components for the experiments consist of a camera (when the test rig is virtual, the camera is not needed), a controller and a control algorithm, which can be monitored through a web-based interface [see Figure 2b]. The platform provides various test rigs allowing users to customize their own control algorithms to carry out different experiments. A ''First Come First Served'' rule is adopted without requiring an appointment; thus, a booking system is not required. The student who has control of the rig can conduct an experiment on the rig, and other students are able to watch the process of the experimentation [see Figure 2c].

A. VIRTUAL TEST RIGS AND VIRTUAL EXPERIMENTATION

In the NCSLab, virtual test rigs account for the majority of all the test rigs and provide nearly the same experimental experience and outcomes as physical test rigs with much less cost and maintenance. Along with the development of 3D rendering technologies, water level control has been developed

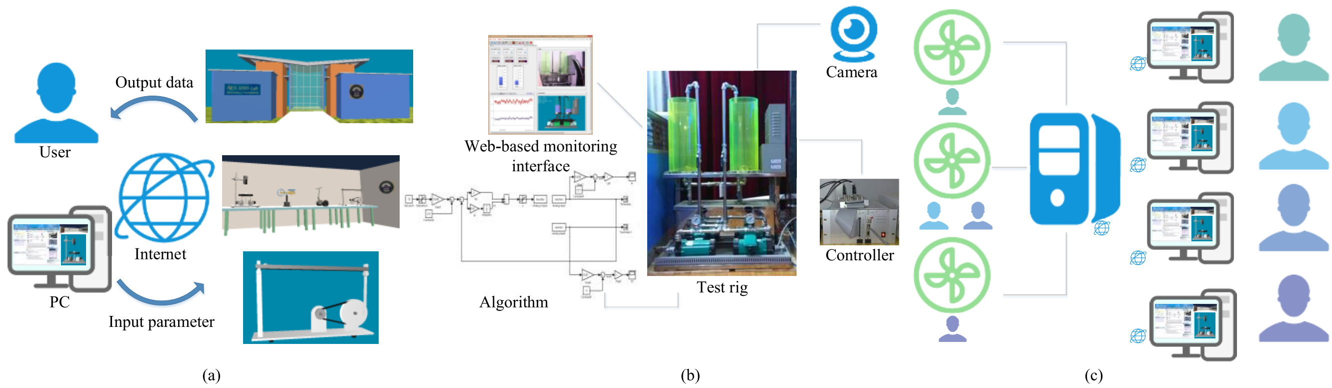

FIGURE 2. Experimental architecture of the NCSLab at Wuhan University. (a) Tuning parameters and monitoring signals. (b) Test rig deployment. (c) "First Come First Served" rule for experimentation.

using Flash Stage 3D and Away3D [50] and HTML5 [51] for the deployment of the virtual dual tank. Other virtual test rigs, including single tank [52] for water level control, DC motor for wiring [53], virtual ball and plate, and virtual ball and beam [41], for position control are also integrated.

For these test rigs, different 3D interactivities can be achieved, and different control algorithms can be designed and verified. For example, the proportional-derivative (PD) control can be demonstrated with the virtual ball and beam system by tuning the parameter for the derivative and observing the results in the 3D interface.

B. PHYSICAL TEST RIGS AND REMOTE EXPERIMENTATION

Compared with virtual test rigs, fewer physical test rigs are currently under deployment. This is due to space, cost and staff requirements. Physical dual tank [41], [51] and fan speed control systems [50] are two test rigs in the NCSLab-related literature. Fan speed control systems integrate easily at a reasonable cost, whereas physical dual tanks can be used as a reference for the virtual one to explore the similarities between the two types of test rigs.

With the help of the MCU (Microcontroller Unit), physical fan speed control systems can display the fan speed digitally for remote monitoring. Additionally, the integral effects in the PI (proportional-integral) controller can be shown by eliminating the steady error.

C. WEB-BASED DESIGN AND IMPLEMENTATION

The NCSLab initially adopted a web-based architecture. To support web rendering, a Java Applet [54] was needed in the first several years. Later, a Flash engine was adopted in [55]. Then, the 3D version of the NCSLab that requires 3D rendering was developed at Wuhan University, thus, Flash 3D engines such as Stage 3D and Away 3D were utilized.

Evolving through four different versions, the NCSLab gradually eliminated plug-ins by adopting the latest HTML5 technology. By using a mainstream web browser, the user can conduct experiments using various widgets with highly interactive features without plug-ins.

III. MODULAR DESIGN

As seen in Figure 3, the NCSLab has a four-tier structure which allows test rigs distributed in different places to be integrated and accessed through a single web address. The modular design methodology of the NCSLab corresponding to the four tiers can be seen clearly. The web interface tier refers to the user access where users can conduct online experiments anytime and anywhere using their web browsers. The server tier is where servers are deployed. In the controller tier, controllers that are employed and allocated with specific IP addresses use one-to-one correspondence with the connected test rigs. Physical and virtual test rigs are integrated into the test rig tier for remote and virtual experiments.

When a user starts to monitor the experimental process, the web page for the experimental interface is loaded by the web browser. After the loading process, an HTTPS communication between the widgets in the web interface and the server is created automatically. The server transmits the latest data to the client side It also processes the users' instructions received from the HTTPS channels.

In a modular design, new and improved experimental setups that are subsequently built may replace older ones. It is not necessary or expected that any of the experiments will be hosted for a long period of time [45]. The modular design discussed in this paper enables the possibility of easy integration of physical and virtual test rigs, easy software implementation and upgrading, easy algorithm customization and ease of cross-institute deployment in the future. Software modular design only involves the web interface, and deployment modular design is related to the server tier. Hardware modular design corresponds to the controller and test rig tiers. The modular design methodology is discussed in detail in the following sub-sections.

A. HARDWARE MODULAR DESIGN

The NCSLab is a platform that allows the integration of test rigs with geographically diverse locations. In this subsection, hardware refers to various physical and virtual test rigs that have been and will be integrated into the NCSLab as well

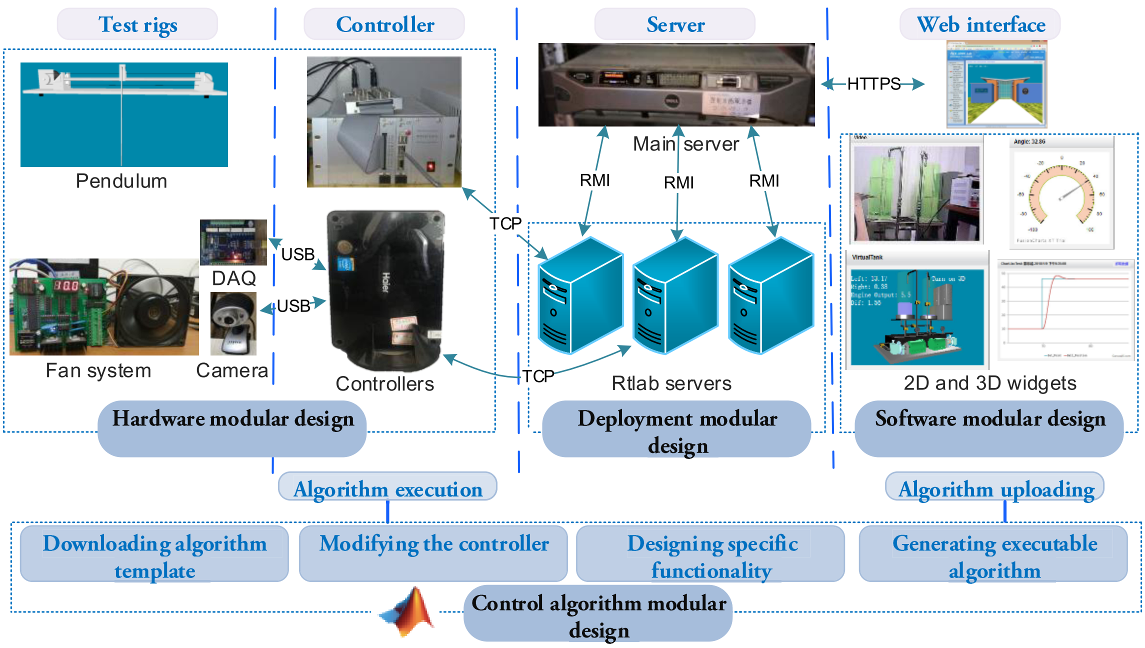

FIGURE 3. Modular design methodology of NCSLab.

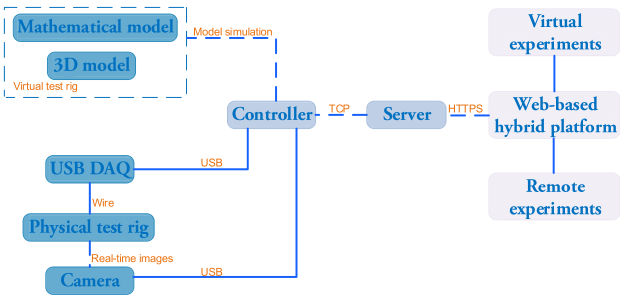

FIGURE 4. Hardware modular design of NCSLab.

as essentials such as the data acquisition (DAQ) card for deployment. Figure 4 illustrates the hardware modular design of the NCSLab. To deploy a test rig in the NCSLab, the following steps must be followed.

1) For a virtual test rig, as there is no physical model, the 3D virtual model is crucial for demonstrating the overall image of the test rig. The control of a virtual test rig is to control its mathematical model, so the mathematical model is vital for the control performance. When the 3D model and the mathematical model are ready, a dedicated controller with a fixed IP address is required for the final integration.
2) For a physical test rig, the controller is also required. A DAQ is also necessary for data acquisition from the physical test rig, such as the speed of the fan. The web camera supplied by the controller is also required, which provides real-time images of the test rigs for remote monitoring.

B. SOFTWARE MODULAR DESIGN

In addition to the hardware, the interface on the user side should be established for experimentation. As mentioned in the preceding sections, HTML5 technology was adopted to provide a plug-in free web-based interactive platform to support hybrid experimentation integrating virtual and physical test rigs. The software modular design of the NCSLab is depicted in Figure 5. Different technologies correspond to different widgets. For example, *CanvasJS*is adopted to demonstrate a real-time chart for signals, and *iframe*is used to display remote real-time images of physical test rigs. The virtual test rig 3D animations are implemented using *Three.js,*and users can interact with the 3D scene by zooming in/out and viewing from any possible angle. More importantly, experiment operations such as valve tuning, cursor dragging, and virtual wiring are also realized in the virtual scene using *Three.js*. Once a new technology arises, it is easy to keep the software in the NCSLab up to date with minor modifications due to the modular design.

C. CONTROL ALGORITHM MODULAR DESIGN

Different from hardware and software design, students can participate in the design of control algorithms. The NCSLab system designers try to maintain students' confidence and enthusiasm without just providing shallow knowledge. By customizing their algorithms, students are provided with a comprehensive and profound learning experience. It is able to help them understand more deeply, which requires overall greater mind involvement. Students should not feel that the technology is fundamentally different so they can focus on learning without programming. This can be achieved using MATLAB/Simulink, which is familiar

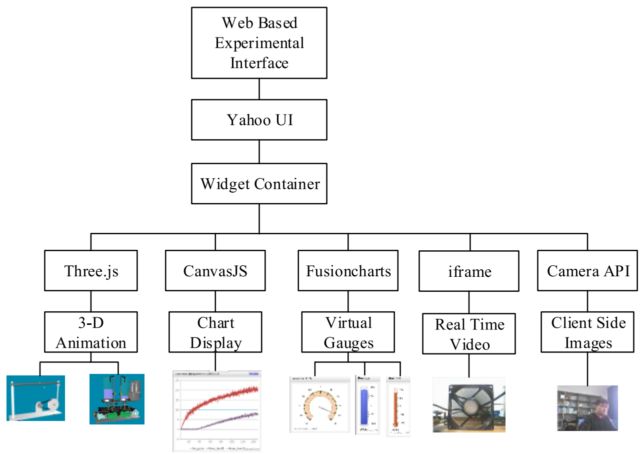

FIGURE 5. Software modular design of NCSLab.

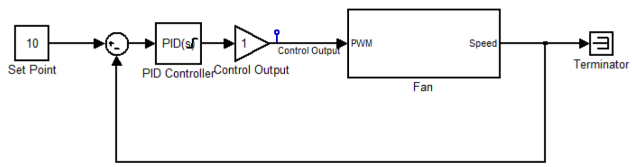

FIGURE 6. Control algorithm modular design in MATLAB/Simulink.

to students in control engineering for designing control algorithms.

For example, if the teacher assigns a task concerning the design of a PI controller with anti-windup protection, the template for an existing algorithm in Figure 6 would be provided. Then, students can modify the template to fulfill the task assigned by the teacher. The detailed technologies involved in the experiment, such as the measurement of the fan speed, are shielded from students so they can focus on the PI design to avoid distractions.

The specific procedure for designing an algorithm is preset by the teacher as follows.

1) *Download the template of the control algorithm.*
2) *Modify the PI controller so P and I can be modified individually.*
3) *Design the functionality of anti-windup for the PI controller.*
4) *Generate an executable algorithm in MATLAB/Simulink RTW (Real-time Workshop) and upload it to the platform for experimentation and verification.*

The algorithm modular design simplifies the process and decreases the time spent to ensure that the student pays attention to learning objectives. After completing the algorithm design process, the executable algorithm can be uploaded to the server using the web interface and then downloaded to the remote controller, where it executes, as depicted in Figure 3.

D. DEPLOYMENT MODULAR DESIGN

In the NCSLab, real-time laboratory (rtlab) servers that are responsible for real-time experimentation can be deployed at any place in the world with a modular structure. Once a rtlab server is deployed at a university or an institute beyond Wuhan University, the test rigs, along with the rtlab server, can be integrated into the NCSLab for online experiments according to their functionalities despite their different geographical locations. This allows for experimentation extension and collaboration with different institutes and universities.

E. ADVANTAGES OF MODULAR DESIGN

Modular design provides valuable advantages to system designers as well as end users. The hardware modular design offers an approach for the easy deployment of new test rigs. With the adoption of a software modular design, all of the complex features and functionalities, such as 3D interaction, evolve without impacting the entire system. Control algorithm design of the proposed system can be used to serve different levels of students. For example, beginners can utilize the default algorithms designed by the teacher, while advanced users can customize their own algorithms. Deployment modular design enables the scalability of the system, i.e., a campus-scale or global-scale deployment. Using the proposed framework, users can tailor their own user interface (UI) to monitor and control the experimentation with various widgets provided by the NCSLab. In this way, multiple hardware works with multiple UI.

IV. INTEGRATION INTO RESEARCH AND EDUCATION

Technology and education drive each other. With the development of technologies such as 3D rendering technology, the NCSLab, which is a hybrid laboratory providing online experiments, aims to offer a better alternative for research and engineering education regarding learning content and user experience.

A. RESEARCH ON NETWORKED CONTROL EXPERIMENTS

The networked control system forms a closed-loop via a network, which has attracted increasing attention in recent years [56]–[58]. In networked control experiments, all nodes that form a control loop, such as the controller, sensor, and controlled test rig, are located in a network environment, and the control and sensor signals are delivered by a network, for example, the Internet.

The NCSLab has been widely used in research on control engineering, particularly, the topic of networked control [54], [55]. Using the NCSLab, the user can control various test rigs in different locations to conduct networked control experiments. In [54], the servo control test rig at the University of Glamorgan, UK has been controlled by the controller at the Chinese Academy of Sciences, China. Both parts are registered to the NCSLab.

Figure 7 illustrates a networked control diagram using test rigs in the NCSLab. The networked control system employs two ARM-9-based NetCons deployed at different locations. One NetCon works as a controller, and the other functions as an actuator/sensor. The two parts are connected using user

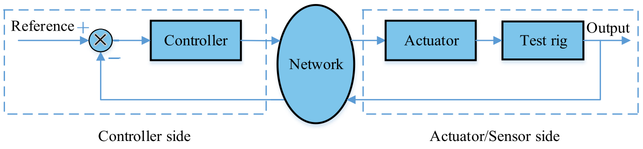

FIGURE 7. Networked control.

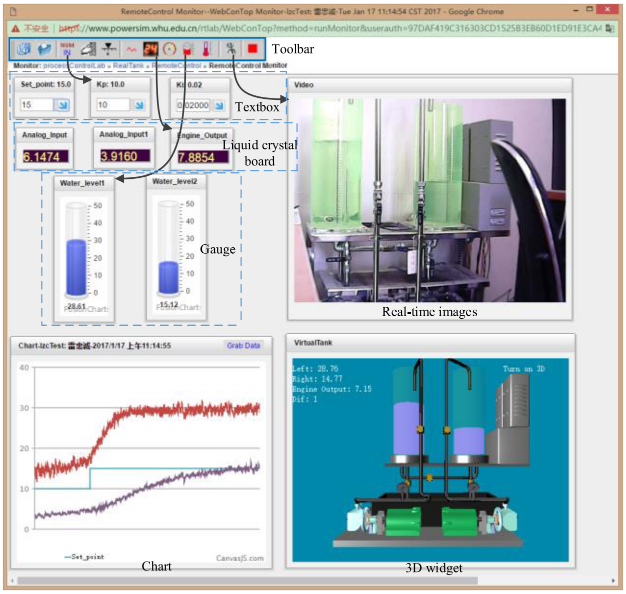

FIGURE 8. Customized monitoring interface of the dual tank.

datagram protocol (UDP) communication protocol through the Internet or a local network environment.

Apart from the networked control research, in the NCSLab, support for education can be concluded as technical support and content support as Sections B and C, respectively.

B. TECHNICAL SUPPORT FOR EDUCATION

Technical support refers to the phase in which certain technology or means are adopted to improve the user experience or enhance students' comprehension. In this paper, technical support shields students from the technical implementation details to allow them to focus on learning.

1) CUSTOMIZING MONITORING INTERFACE AND INTERACTIVE FEATURES

Various widgets have been developed for students to customize their own monitoring interface. As listed in Table 2, most platforms offer 2D widgets such as buttons and textboxes for interacting with the controlled test rigs. In the NCSLab, in addition to the 2D widgets, 3D widgets such as virtual cursors, knobs, wires, and terminals provide a high level of interaction for parameter tuning and wiring in the 3D interface.

Figure 8 depicts an example of a customized monitoring interface for a dual tank. The widgets are arranged in the toolbar for students to select for control and monitoring. Once the widgets are dragged to and placed in certain positions and linked to signals and parameters, they act as a real-time monitoring interface for the remote dual tank, such as in real-time images and real-time curve supported by video and chart widgets, respectively. This method attracts student attention to potentially stimulate their learning interest.

2) PLUG-IN-FREE IMPLEMENTATION

The latest HTML5 technology has been adopted and integrated into the latest version of the NCSLab in Wuhan University. Using mainstream web browsers, the experiments provided by the NCSLab can be conducted without any plug-ins; thus, potential updating issues or crash issues can be avoided by students, which saves student effort and allows them to focus on learning.

3) SUPERVISING STUDENT EXPERIMENTATION

Among the widgets offered by the NCSLab, the client-side images supported by an HTML5 camera API is a deterrent to plagiarism for the continuous capturing of users' photos on the user side [59]. Therefore, students cannot allow other students to conduct the experiments for them, or copy other students' work. With this approach, online experiments are conducted similarly to hands-on ones in a physical laboratory where the teacher can supervise student experimentation.

C. CONTENT SUPPORT FOR EDUCATION

Great importance has been attached to education contents in the NCSLab. The platform is enriched with documentation and custom experiment instructions in both Chinese and English versions available on the NCSLab homepage. Other contents can be included as follows.

1) VARIOUS TEST RIGS

Using the modular structure, test rigs at different locations can be deployed together according to their functionalities rather than their locations. With various test rigs deployed in the NCSLab, process control, servo control, *etc.* can be carried out for different learning objectivities. For example, the fan speed control system can be used for PI control, the inverted pendulum can be utilized for Linear Quadratic Regulator (LQR) control, and the DC motor position control system can be applied to wiring practice.

2) USER-DEFINED ALGORITHMS

Apart from the default algorithms designed by the teacher, students can customize their own control algorithms for various test rigs, which can inspire their creativities and verify their ideas. Templates of control algorithms are provided for them to conserve their efforts so they can concentrate on learning.

3) INTUITIVE INTERFACE FOR COMPREHENSION

Pedagogically, figure and motion demonstrations are easier for students to comprehend than word descriptions and equations. In the NCSLab, with the configurable monitoring

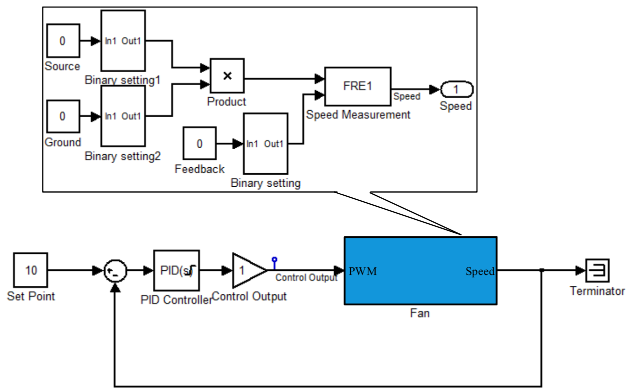

FIGURE 9. Control algorithm with wiring integrated for fan speed control.

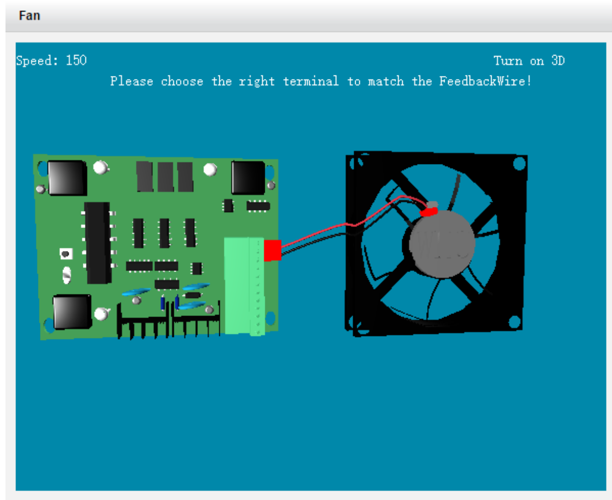

FIGURE 10. Virtual fan speed control system for virtual experimentation.

interface, parameters can be tuned and observed in an intuitive interface. For example, from the textbook, it is stated that derivative action in a controller predicts system behavior and thus improves settling time and stability of the system. However, it may be confusing to understand the true meaning of the derivative from the description. With the help of the NCSLab, the control of the virtual ball and beam system is visually demonstrative when applying the PD controller where P and D can be tuned.

V. CASE STUDY OF TEST RIGS DEPLOYMENT

Various test rigs are deployed in the NCSLab to serve different purposes for research and education following modular design rules. In this section, a virtual fan speed control system and a physical wireless power transfer (WPT) system were selected as examples to illustrate how test rigs are integrated into the hybrid laboratory, offering resources for research and education.

A. VIRTUAL FAN SPEED CONTROL SYSTEM

Physical fan speed control systems exist for remote-control experiments in the NCSLab. Conventionally, a remote-controlled fan speed control system can demonstrate how proportional (P) and integral (I) controls affect the speed control of the fan. Students are supposed to understand the effect of the P and I parameters and learn to tune them to achieve good control performance after carrying out the fan speed control experiment.

However, the students cannot comprehend the working principle of a fan system with the physical test rig. Moreover, hands-on wiring practice cannot be simulated. Thus, a virtual 3D replica that can conduct wiring practice was developed [60]. 3D virtual wiring complements the existing virtual experiments in the NCSLab and other platforms and could potentially be scaled up to other projects.

Figure 9 demonstrates the control algorithm with wiring integrated for fan speed control. C codes were programmed to represent the PWM (Pulse Width Modulation) and speed measurement of the fan system in the S-function module. The block diagram for speed measurement is shown in the upper part of Figure 9, where block "Source", "Ground" and "Feedback" represent the three corresponding wires. The "Binary setting" block can switch its output value to "0" when the input is "0"; otherwise, the output is "1". Block "Product" works as an AND gate to multiply its two inputs, which emulates the source wire and the ground wire working together.

The wiring integrated control algorithm can also be customized by the user using the modular design method proposed in Section III, as long as the definition for the wire in the block diagram is clearly described and understood by the user. For hardware design, a controller that can run the remotely downloaded algorithm is sufficient.

Figure 10 is an example of the experimental interface of the virtual fan speed control system. Using the virtual fan test rig, users were able to explore the control performance of the system by tuning the P and I parameters, which was already possible in the remote experiments. More importantly, 3D virtual wiring can be conducted to figure out how the system works, which simulated hands-on experiments in traditional physical laboratories. For example, in Figure 10, the two wires (source wire and ground wire) were connected, while one terminal of the feedback was clicked. In this case, the activated system was out of control without feedback. Once the other matched feedback terminal was clicked, the feedback wire would be connected and the system gradually adjusted to the set point of the speed.

Wiring fan speed control systems can be a good candidate for conducting networked control experiments. The PID (proportional-integral-derivative) control diagram is downloaded to the controller side, and the wiring related control algorithm is run at the actuator/sensor side deployed at a different location.

B. REMOTE CONTROLLED WIRELESS POWER TRANSFER SYSTEM

WPT technology enables various electronic devices to be charged without cables or wires. In this paper, the

FIGURE 11. Monitoring interface of the remote controlled WPT system in NCSLab.

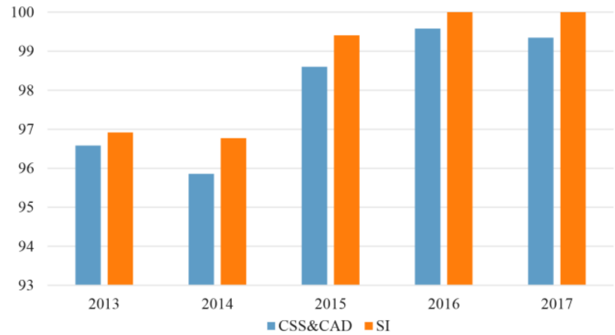

FIGURE 12. Students' assessment (out of 100) for each module from 2013 to 2017. There was a boost in 2015 as NCSLab was brought in.

remote-controlled WPT system [61] consisted of a set of physical WPT system and other needed hardware such as a DAQ card, a controller and a web camera introduced in Section III. The WPT system is a magnetic resonant coupling system with a pair of coupled coils, which caused the transmitter coil and the receiver coil to have the same resonant frequency. The system can be divided into the Tx side, which converts direct current (DC) into alternating current (AC) through an H-bridge inverter circuit, and the Rx side rectifying AC to DC to supply power to the load with bridge rectifier and capacitors.

Conventionally, a WPT system is cumbersome and difficult to set up requiring carefully tuned circuit parameters, which creates sharing issues. It would be difficult for the teacher to bring it to the classroom for teaching. Additionally, if the user would like to experiment with the system, an appointment is required before he can go to the physical laboratory, resulting in limitations on time and location.

Inspired by the functionality of online laboratories, a WPT system was deployed in the NCSLab with the intention of sharing state of the art technology and integrating it into classroom teaching. Thus, for the teacher, the difficulty of bringing a WPT system to the classroom for teaching purposes is addressed, which makes it possible for classroom online demonstrations using a web browser.

The monitoring interface of the remote-controlled WPT system in the NCSLab is illustrated in Figure 11. The parameters such as the excitation frequency and sweeping amplitude can be tuned and real-time signals such as output voltage can be monitored with various widgets provided by the NCSLab. By using the real-time video widget, the hardware of the WPT system can be clearly observed.

Through the experiment with the remote-controlled WPT system, the user can estimate the output power through the brightness of the bulb or extract the data from the monitoring interface and then precisely analyze the transmission efficiency and other factors.

VI. PEDAGOGICAL EVALUATION

The proposed hybrid laboratory has been applied to several teaching and experiment modules both in and out of the classroom for engineering education by around 200 students per year at Wuhan University. The use of the NCSLab in class is for classroom demonstration together with descriptions of concepts and formulas from textbooks, which achieves a positive result for intuitive presentation. For after-class experimentation, NCSLab has been utilized for online experiments.

TABLE 3. Student performance.

Module	2013~2014			2015~2017		
	Participants	Mean	S.D.	Participants	Mean	S.D.
CSS&CAD	169	82.44	12.80	222	84.98	7.09
SI	156	81.78	8.84	219	82.57	7.36

Every year, students in control engineering take several modules using the NCSLab as the platform for remote experimentation.*Control System Simulation and Computer Aided Design (CSS&CAD)*in the Autumn semester, and *System Identification (SI)* in the Spring semester were selected for the pedagogical evaluation. Since 2015, the NCSLab has been applied to the teaching of the two modules on a large scale. For each teaching module, the students are required to conduct several related experiments such as PID control, LQR control and SI on the remote and virtual test rigs. Within a one-month deadline, students are free to carry out the online experiments before they submit their laboratory reports. Table 3 shows student performance (mean and standard deviation (S.D.) of the score) regarding different modules with and without the application of the NCSLab. It can be seen that students earned better grades for both modules after the application of the NCSLab in 2015 than they had in 2013 and 2014.

As a regulation in Wuhan University, all teaching modules are assessed online by the students at the end of the semester. Their marks are important criteria for the university to judge the effectiveness of the modules. Figure 12 illustrates the general average marks of students' assessment for the two related modules in the past five years. There was a strong boost in the student marks in 2015, as the NCSLab was widely brought in that year.

Apart from the module assessment, a survey on the NCSLab platform had also been conducted in 2015 and 2016,

TABLE 4. Results of survey (scale 1-5).

	Question	2015 ($n = 75$)		2016 ($n = 78$)	
		Mean	S.D.	Mean	S.D.
Usability	Q1. NCSLab was easy to use?	4.84	0.717	4.56	1.191
	Q2. I was satisfied with the NCSLab system?	4.55	0.963	4.69	0.726
	Q3. I would recommend NCSLab to other people?	4.47	0.890	4.44	1.064
Educational Value	Q4. NCSLab was able to inspire my learning interest?	4.65	0.830	4.62	0.856
	Q5. NCSLab helped me to understand the course contents?	4.84	0.638	4.56	0.831
	Q6. NCSLab helped me to improve the laboratory skill?	4.76	0.803	4.38	1.131
Stability	Q7. NCSLab was working stable with no software bugs?	4.20	1.395	4.64	0.897
	Q8. There was no sense of time delay?	4.23	1.467	4.59	1.086

involving 75 and 78 students, respectively [41]. The results are shown in Table 4, in which eight questions related to usability, educational values, and stability are included. It can be seen that the acceptance of NCSLab is notably high, and most of the students thought NCSLab was easy to use and can help them understand the course contents.

VII. CONCLUSION

In this paper, a web-based interactive hybrid laboratory for research and education was introduced. The modular design of hardware, software, control algorithms and deployment were explored in detail. Hardware design offers an approach for the easy deployment of new test rigs. The modular software design enables the NCSLab platform to remain current with the latest technologies while requiring only minor modification. The full technical and content support for education offers students a service-oriented platform focused on learning. The effectiveness of the proposed modular design was verified by deploying a virtual wiring fan speed control system and a physical WPT system that represented the remote and virtual experiments, respectively. The modular hybrid laboratory has been successfully applied to networked control research and engineering education at Wuhan University. The pedagogical evaluation involving student performance and assessment of the two class modules in the past five years showed that the proposed system can be useful for control engineering education.

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