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HTML5-Based 3D Online Control Laboratory with Virtual Interactive Wiring Practice

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***Abstract*—This paper introduces the schemes of remote wiring interactions in an online control laboratory using an HTML5-based virtual three-dimensional (3D) interface. Although virtual laboratories have drawn increasing research attention in the last decade, wiring practice, which is a crucial part of experimentation, is normally neglected. In this paper, a practice including 3D modeling, HTML5-based rendering, and control algorithm design is implemented for the interactive virtual wiring based on the NCSLab (Networked Control System Laboratory) framework. The wiring practice is combined with control algorithm design, which is already realized in NCSLab, where users are allowed to customize algorithms using MATLAB/Simulink RTW (Real-Time Workshop). Apart from remotely implementing the control algorithm, the 3D virtual wiring process must be completed correctly before the online experiments can proceed properly. The proposed wiring laboratory is evaluated in practical teaching, with both students' performance and perception considered. The conclusions derived from the report show that the 3D virtual wiring interactions make virtual experimentation complete for simulating a real case, as well as providing an opportunity for a clearer comprehension of control systems.**

***Index Terms*—3D virtual wiring, HTML5, online laboratories, virtual experimentation**

I. Introduction

MASSIVE open online courses (MOOC) provide online courses concerning facts, formulas, and concepts from world-famous universities and professors, which is a crucial part of Campus 2.0 [1]. However, apart from lectures, practical skills can only be acquired through practice and experience, especially in engineering education. Experiments offering experience and practice play a paramount role [2]. However, the sharing of experimental equipment has not yet been addressed by MOOC.

Conventionally, experiments are carried out in hands-on physical laboratories to put theoretical knowledge and ideas into practice. However, limitations such as laboratory space shortages, fund scarcity, and experimental staff insufficiency impose negative effects on the deployment of physical laboratories, which has stimulated the emergence of online laboratories [3]-[6].

Using network communication technologies, the experimental equipment inside the campus can be put online and manipulated remotely, which forms the idea of online experimentation. The definitions of online laboratories [3], [7], [8] can be slightly different judging from different criteria, which are depicted in Fig. 1. For online laboratories, the reliability of communication between users and remote equipment is utterly important, which has been studied in the literature [9]-[11].

With the support of online laboratories, online experimentation could be an important complement to MOOC. Well-established online laboratories are able to constitute the crucial part of education without loss of any level of knowledge [12], [13]. In [14], a review in the fields of science, technology, and engineering on virtual laboratories and virtual worlds was introduced. A great number of existing virtual laboratories are explored using four formulated criteria that follow one crucial requirement; namely, that operating a virtual laboratory for a student must feel like they are working with real authentic devices in a real authentic space. Large-scale virtual worlds like second-life [15], [16] can offer immersive and highly interactive user experiences. Unity3D, which is a powerful virtual reality development tool, is very popular for the design of game-based learning tools [17].

In NCSLab (Networked Control System Laboratory) [18], [19], users can customize the control algorithms and monitor the real-time experiments remotely via a web interface. Based on the NCSLab framework, it is possible to develop virtual 3D interactive wiring practice, which is combined with existing remote monitoring, remote tuning, and remote algorithm implementations.

With the intention of achieving a unified architecture by which to realize complicated remote and virtual experimentation, every link of experimental practice should be integrated. This paper explores a novel architecture covering

Manuscript received June 11, 2017; revised August 30, 2017 and October 13, 2017; accepted October 19, 2017. This work was supported by the National Natural Science Foundation of China under Grant 61374064 and Grant 61673303. Paper no. TII-17-1248. *(Corresponding author: W. Hu)*

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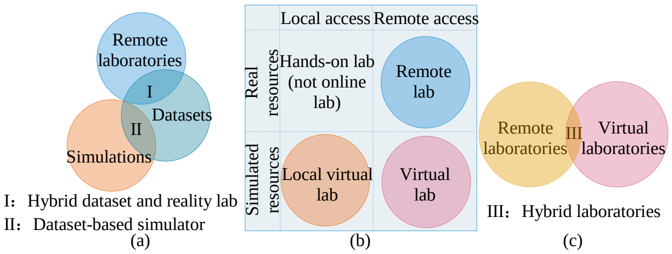

Fig. 1. Online laboratories classification. (a) References [7], (b) [8], and (c) [3].

the entire process of online experiments, i.e., the conducting of experiments and design of control algorithms, in a single online web-based platform using HTML5 technology. The proposed system ensures that the online experiments simulate the entire hands-on process without any loss of knowledge. Moreover, beyond control engineering education, it could be potentially applied to other platforms in which algorithms and the conducting of experiments must be combined.

II. Related Works

In most hands-on experiments, the process of experimentation includes conducting experiments and control algorithm design. As Fig. 2 shows, most online laboratories in the literature realized the process of tuning parameters and monitoring. NetLab [20], [21] and VISIR [22]-[24] developed wiring functionality. Different from control laboratories, the two systems focusing on electric and electronic education require no algorithm implementation. In terms of control algorithms, telelab [25] and UCM EJS-PLC Lab [26] allow users to design their own controller, and SLD [6] allows users to implement the function of user-defined algorithms. However, none of these platforms achieve the architecture simulating the entire process of hands-on experiments in physical laboratories.

Regarding methodology, HTML5 is regarded as a future trend for the construction of a web-based, secure, cross-platform architecture for online experiments. In recent years, HTML5 has been adopted to develop online experimental platforms [27]-[31]. Watertank FPGA (field-programmable gate array) laboratory [27] develops a 3D virtual water tank controlled by a real FPGA controller, and presents the possibility of a universal hybrid model. Remote panels in LabVIEW for a bipolar junction transistor amplifier are converted to HTML5 [28] in electronic education. Labicom [29], which is a commercial architecture, provides APIs for online laboratories to be built on top of its infrastructure. GOLDi [30] provides fixed 2D graphical interfaces using HTML5. The client side of iSES [31] is also implemented using web technologies concentrated on a modular hardware architecture for quick deployment. As illustrated in Fig. 2, most systems focus on some crucial parts of online experimentation, and there is little existing literature reporting the methodologies of how to use web technologies to systematically build online systems that are able to cover the entire process of control engineering experimentation.

Great importance has been attached to wiring in online laboratories, especially for electric and electronic education, where wiring practice is the main part of the experimentation.

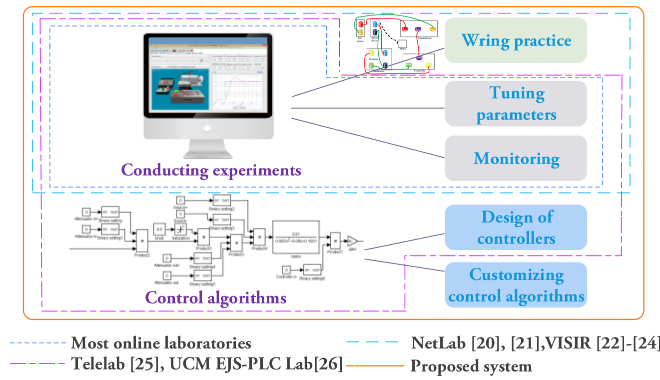

Fig. 2. Architecture of online experiments.

NetLab [20], [21], which is a software client requiring the Java runtime environment, allows the user to wire different circuits using a specific Circuit Builder interface remotely. When conducting remote wiring, the terminal of the component can be clicked and a random color of wire would be led out for connecting. The virtual workbench of VISIR [22]-[24] replicates a breadboard to provide wiring for the electric circuitry required in electric and electronic engineering.

However, as for control engineering, the wiring is supposed to be combined with control algorithm design and implementation. In [32], efforts were made to develop the wiring practice based on the Flash 3D engine with limited interactions. To enhance the functionality of NCSLab proposed in [19], [32], and to develop new wiring functionality to reproduce experimental cases similar to real ones in physical laboratories, and even in industrial scenarios with an improved user experience, an HTML5-based virtual wiring method with 3D interactions allowing users to do the wiring in a 3D virtual laboratory is proposed in this paper.

The wiring process is completed in combination with the control algorithm implementation in MATLAB/Simulink Real-Time Workshop (RTW). To achieve 3D interactions without plug-ins, HTML5 technology is adopted. Specific warning messages are added to provide clearer guidance. During the experiments, wire connecting can be canceled just as in real cases in the physical laboratory. Users are required to correctly set up the wiring connections before the controller, and virtual test rigs can be successfully activated, which reproduces exactly the practical situation in hands-on experiments. With the inclusion of wiring practice, the online experimental system can deliver services that emulate the entire procedure of hands-on control engineering experiments.

III. NCSLab Framework and Methodology for Wiring Practice

NCSLab is a web-based hybrid online laboratory that has been providing both virtual and remote experiments for users for the last decade. Evolved over 10 years, 26 test rigs including six physical test rigs for remote experiments and 20 virtual test rigs for virtual experiments have been integrated into NCSLab. Its architecture as implemented at Wuhan University is depicted in Fig. 3. Before a specific test rig is deployed into NCSLab, the methodology for wiring practice is composed of the three following phases.

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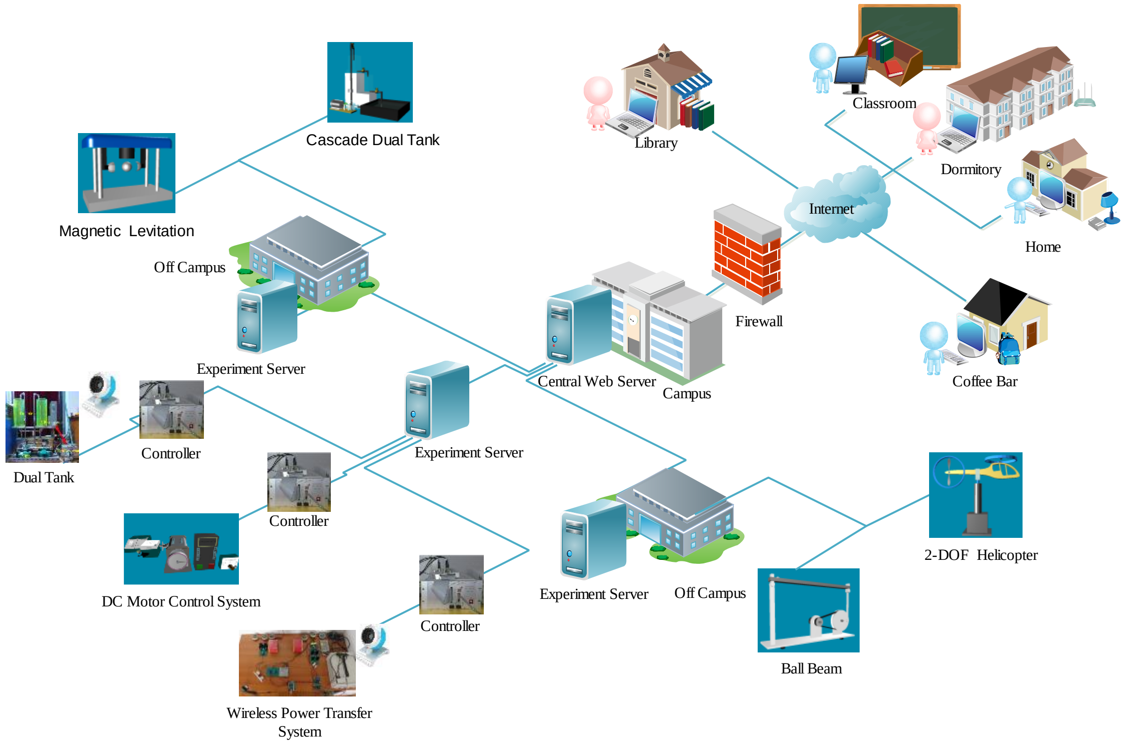

Fig. 3. NCSLab architecture. Test rigs in geographically diverse locations can be integrated into NCSLab.

1) *3D modeling and design.* As mentioned in other NCSLab-related literature, 3D models can be built using any 3D modeling software such as 3ds Max, Solidworks, and Pro/E. However, all of the 3D models for NCSLab are constructed using 3ds Max as there are no restrictions on the constraint relations among each part of the models. Moreover, the tradeoff between the size of the 3D model and the loading time in the web browser can be appropriately handled when using file formats such as OBJ and MTL. Details of the method for 3D modeling and design can be found in [19].
2) *Rendering in the web browser.* Rendering is a crucial procedure as models designed using 3D modeling software cannot be utilized directly in the web browser. Different rendering engines lead to different rendering effects with regard to fluency, plug-in requirements, etc.
3) *Control algorithm implementation.* The control algorithm is used in the web for the control of the test rig. The general control diagram for wiring is shown in Fig. 4. In the case that the Simulink "constant" block represents the wire, the block is parameterized with either "0" or "1". "0" indicates the state of disconnection, while "1" means that the wire is in the connected state. If the block represents a knob, its value is continuously tunable from 0 to 1. The wiring is integrated into the implementation of control algorithms generated by MATLAB/RTW, which is different from NetLab [20], [21] and VISIR [22]-[24]. The general control diagram is made as a template for users to customize their own control algorithm. As wiring is a new implementation combined with control algorithm design, this phase will be explored in detail in Section V.

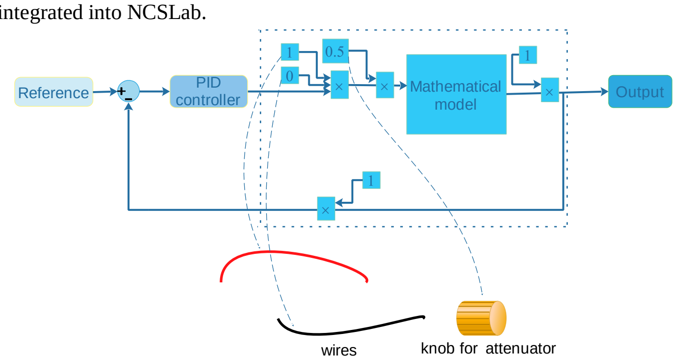

Fig. 4. General control diagram for wiring. If the corresponding wire is connected, the value of the block would change from 0 to 1.

IV. WEB-BASED RENDERING IN HTML5

Among all the experimental equipment in both physical and online laboratories, a DC motor control system [33] has been extensively adopted in research on industrial applications, such as CNC machine [34], robots [35], [36] and electric vehicles [37], [38]. As for control engineering education, a DC motor control system is a typical test rig for the study of closed-loop feedback control and servo control.

In this paper, a DC motor control system containing seven wires is utilized to illustrate the proposed wiring practice methodology. In order to build a virtual system simulating the real one, a virtual DC motor control system is designed on the basis of a real test rig located at the University of South Wales, UK, as shown in Fig. 5(a). The DC motor control system comprises a DC power source, a motor driver, a DC motor, a speed sensor, a controller, and an attenuator. As the pointer of the speed sensor is the only movable part, it is built separately, while other parts are constructed together. As for wires, each individual wire should be built as a separate model since they are supposed to be loaded or canceled separately.

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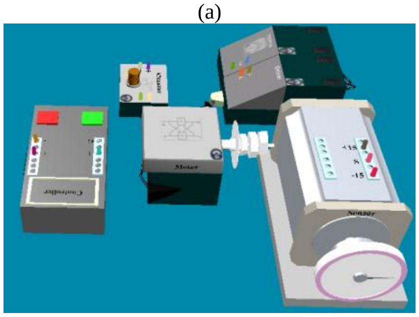
(a)



(b)

Fig. 5. DC Motor control system. (a) Physical test rig and (b) virtual test rig (to be connected).

Flash 3D was used in the previous work of NCSLab [18], [39]; in particular, in [32], in which the researchers used Away3D for position control of the DC motor. To build a service-oriented experimental platform, HTML5 has already been adopted in NCSLab [19], [40], and it is no longer necessary for users to install any plug-ins. Based on the HTML5 framework, 3D wiring that offers wire connections simulating a hands-on experiment is implemented in the web-based rendering process using *Three.js* in this paper.

The main work of rendering is the control of the pointer of the sensor and 3D modeling for terminals. There are several issues to be addressed in terminal rendering, such as the color, size, and position of the terminals in the rendering page, the matching relationship between the number of wires and terminals, and, most importantly, the interactions between users and 3D interfaces. The rendering effect of the virtual test rig in HTML5 is shown in Fig. 5(b), which is the virtual instantiation of the real physical system shown in Fig. 5(a).

For 3D rendering, there are some similarities between Away3D and HTML5. For example, both are open source with informative help documents and rich tutorials. However, as listed in Table I, although it may seem that only a slight difference exists between the two rendered interfaces on the web, HTML5 rendering requires fewer supporting softwares and exhibits better performance.

V. Speed Control Algorithm for DC Motor Control System

As far as the DC motor is concerned, few studies have focused on speed control of a 3D virtual DC motor. The position control of a 3D virtual DC motor control system with limited interactions is introduced in [32]. In this paper, however, speed control is the priority to be discussed. The control system is designed to drive the pointer of the motor to a preset speed. Without loss of generality, the model of the plant in [41] is selected to design the control algorithm, which is identified as

TABLE I
Rendering Using Different 3D Engines

Category	Away3D	HTML5
Developing software	Flash Builder	Eclipse
Supporting plug-in for web rendering	Flash Player	Plug-in free
Potential issues	Crash/update/compatibility issues	None

$$G(s) = \frac{0.01}{0.005s^2 + 0.06s + 0.1001},$$

where the input of the transfer function is the voltage applied to the DC motor and the output is the voltage of the speed sensor.

The controller can be designed using a typical PI (proportion-integral) controller as

$$\frac{D(s)}{C(s)} = 0.3 + \frac{0.8}{s}.$$

Therefore, the speed control diagram for the DC motor control system is designed using MATLAB/Simulink as shown Fig. 6. The general control diagram is provided so that the PI controller can be customized by the user. The middle part of the diagram is the mathematical model of the DC motor with integrated wiring. In the bottom part, the interconnection between the algorithm and the model is depicted, in which the correspondence of each wire with the block can be clearly seen.

As seen in Fig. 6, there are many “constant” blocks. Each wire is associated with a corresponding “constant” block whose initial values are “0” representing the unconnected state. Each block is multiplied by a certain signal. Therefore, the given signals can be enabled and disabled according to their wire connection states. For example, the block “product4” in Fig. 6 works as an AND gate for the source wires with block “Source+” and “Source−” responsible for connecting the two source wires of the motor. Only when the power supply of the motor is connected in the web interface can the control signals be actually applied to the virtual motor.

The knob of the attenuator is also in the forward channel with a “saturation” block whose upper limit is “1” and the lower limit is “0” to ensure that the system cannot be disturbed. Therefore, the opening degree of the knob is kept at 0 °(input of the knob is “0”) to 180 °(input of the knob is “1”).

If all the values of “constant” blocks for wires become “1” which means all the wires are correctly connected, the PI control algorithm starts to work, and the DC motor control system is activated.

The control diagrams in MATLAB/Simulink are converted into C codes automatically by RTW and compiled into executable programs using C compilers. Once the executable programs are generated, they are supposed to be uploaded to the NCSLab server through a web interface. When conducting the experiment, the executable programs are downloaded to the remote controller. The internal signals and parameters of the RTW-generated algorithm are parsed and normally organized as a tree structure containing all the parameters and signals for control and monitoring. They can be selected to establish the

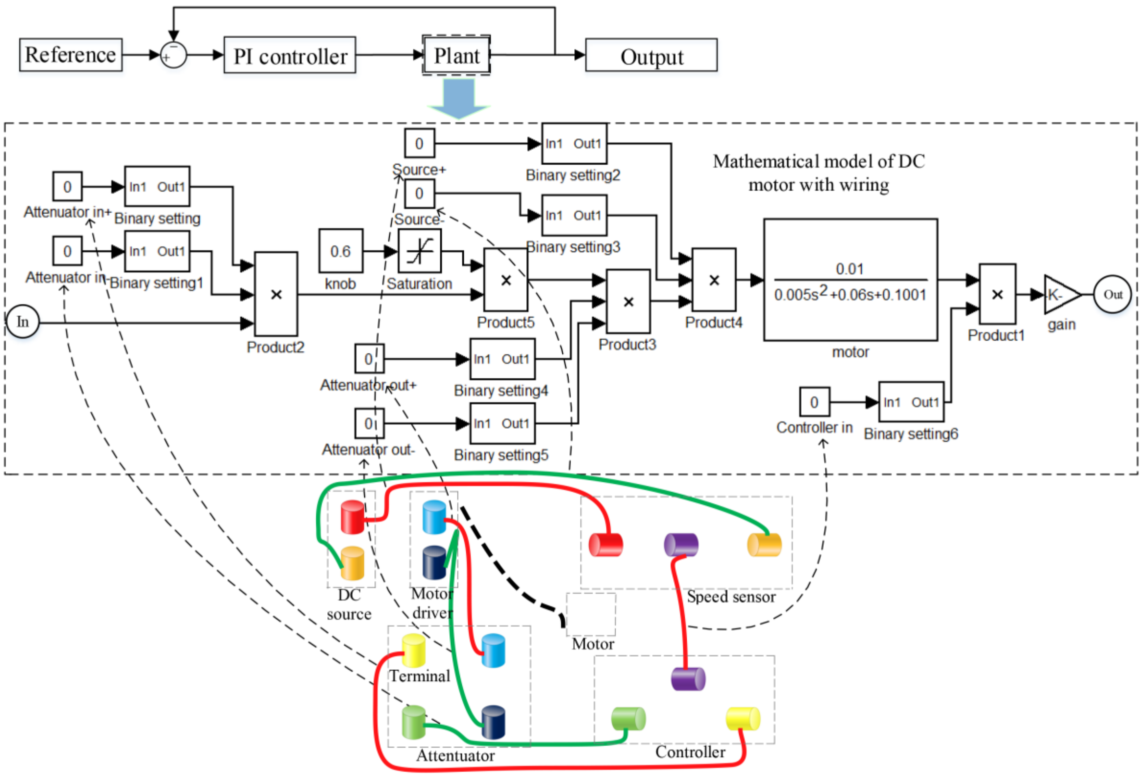


Fig. 6. Control diagram template for users, with a DC motor control system taken as the example; the interconnection between algorithm design and the wiring model is depicted.

interconnections with the widgets of monitoring interface.

VI. Implementation of 3D Virtual Interactive Wiring

For the control systems discussed in this paper, great importance is attached to the wiring process. Multiple functionalities are developed to implement 3D virtual interactive wiring. After the completion of 3D modeling, the next step is the definition of interactions. In total, three types of interactions—including *terminal highlighting*, *wire connecting*, and *warning*—are defined for the 3D virtual wiring process. Typically, different interactions work together simultaneously in the entire wiring process.

A. Terminal highlighting

Terminal models are not constructed in 3ds Max, but in the rendering page using *Three.js*. The terminals are built as mesh objects whose color, opacity, and size can be defined. The initial state of the terminal is set to a random color with 50% opacity and appropriate size with regard to the 3D model for a better visual experience. Once it is clicked, the color of the terminal would change according to the click command.

B. Wire connecting

Wire connecting is based on the click of the terminals. A correct click combination for the matched terminals would lead to the corresponding wire connecting. Owing to the specific format of the model loading function, *wire connecting* and *cancel connecting* can be realized in a single function. To connect a wire, an appropriate variable representing the state of wire connecting should be defined and the function concerning wire connecting is supposed to be invoked.

C. Warning for misconducting

There are four types of warning messages for a pair of matched terminals to provide guidance for the users, defined as types 1–4 in Table II. For the entire system, when all wires are correctly connected, a type-5 message would appear. The different moments at which these messages appear are also shown in Table II. For example, when a terminal is clicked and the matched terminal is already clicked and highlighted (marked with a "√" in the table) with no wire connected (marked with a "×" in the table), the message of connecting OK (type 3 in the table) for a specific wire would appear, which informs the user that the wire is correctly connected and wiring process can continue.

Fig. 7 illustrates the interaction logic of 3D virtual wiring for connecting a pair of matched terminals. The wiring process starts by clicking one of the terminals. Once a click action is detected, a determination would be made as to whether the clicked terminal should be highlighted or not, and, at the same time, a judgment made as to whether the matched terminal is highlighted and a corresponding response made accordingly.

As seen in Fig. 7, there are in total four *warning* interactions, which are different from each other. Rather than monotonous words, *warning* interactions are defined and implemented to guide users to connect the wires correctly to make the system function well, which means even the same kind of warning interaction varies from wire to wire for clear guidance.

If more pairs of terminals are taken into account, the interaction logic could be even more complicated, as different pairs of terminals can affect each other. Therefore, more variables should be used to distinguish them. For example, all

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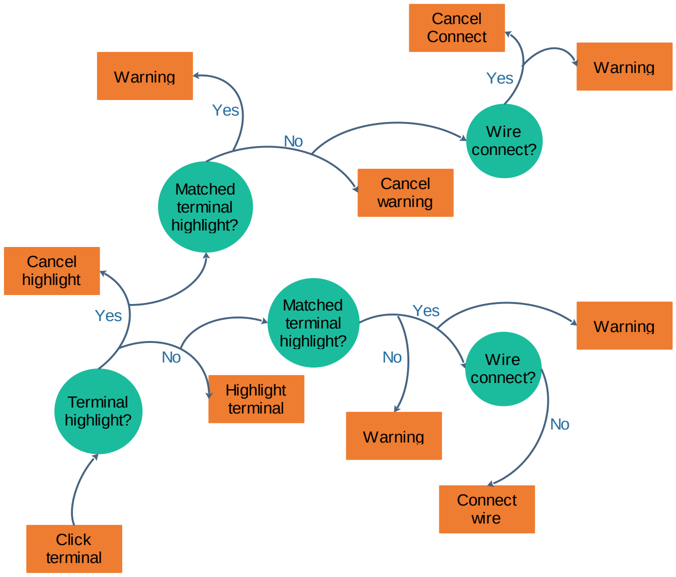

Fig. 7. Interaction logic of 3D virtual wiring.

TABLE II
DIFFERENT WARNING MESSAGES

Type	Warning	Moment of appearance: Matched terminal	Moment of appearance: Wire connecting
1	Match	×	×
2	Connect or cancel	√	√
3	Connecting OK	√	×
4	Cancel connecting OK	×	√
5	All connecting OK, conducting speed control	All wires are connected	

wires share the same variable *stateValue* for the state of the wire connecting, and, thus, to ensure the communication of each wire, *stateValue* should be carefully addressed.

VII. CASE STUDY OF 3D VIRTUAL INTERACTIVE WIRING FOR DC MOTOR AND FAN SPEED CONTROL

The implementation of 3D modeling, rendering, algorithm design, and wiring prepares the work for the control of the system. With the integration of NCSLab, the system can be accessed for experimentation at anytime from anywhere with pre-defined or user-defined algorithms.

The template for customizing of a control algorithm described in Section V can be used for the algorithm design in this section. As long as the number of wires and the connecting relationships are figured out, it is easy to design a control algorithm combined with wiring functionality. Fig. 6 presents a control algorithm example for a DC motor control system.

Before beginning experimentation, the connecting schematic would be provided to the students. For example, Fig. 8 presents the diagram for a DC motor control system [see Fig. 8(a)] and the actual wiring result in the 3D virtual interface [see Fig. 8(b)]. It can be seen that there are seven wires for the virtual experiments, which is the exact configuration of the physical system.

Incorrect connections would not cause any damage to the virtual system, but could also not result in the wire connecting, which means that the system cannot be activated for experimentation. When an incorrect connection occurs, a warning message would appear to provide clear guidance.

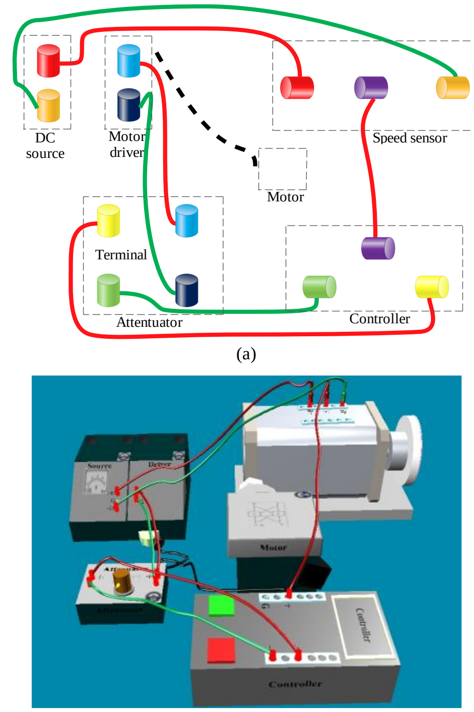

Fig. 8. Wiring diagram. (a) The schematic for wiring, in which the motor driver and the motor is already physically connected using electric wire (shown as a dashed line). (b) The actual wiring result in the 3D virtual interface.

In carrying out the wiring experiment, students' interest in experimentation is supposed to be stimulated, while, at the same time, they are expected to have a clear comprehension of the system to a similar degree as they do in hands-on experiments. For the final speed control, the following user procedures are required.

A. User-defined monitoring interface

The monitoring interface is supposed to be set up by the user in advance of conducting the experiment. NCSLab offers a freely customized monitoring interface for the user with a set of widgets for different control and monitoring purposes. For example, charts can be used to monitor the real-time trend of any selected signal, and virtual sliders can be utilized to set the value of any parameters chosen by the user. The web-based rendering discussed in Section IV is implemented in the 3D widget. In the rendered page, the initial state of the system is unconnected, so the user must virtually connect the system using a PC mouse before carrying out the virtual experiment.

B. Wiring practice

Although users have the freedom to customize the monitoring interface, the 3D widget displaying the rendered 3D model is supposed to be selected for the virtual experiment, especially when the wiring process is also completed in the 3D widget. The wiring implementation has been described in Section VI in detail in terms of terminal highlighting, wire connecting, and warnings.

In this subsection, another wiring test rig is considered as an example. The virtual fan speed control system is illustrated in Fig. 9, where it can be seen that three wires are to be connected, which makes a total of six terminals. Fig. 9 illustrates a

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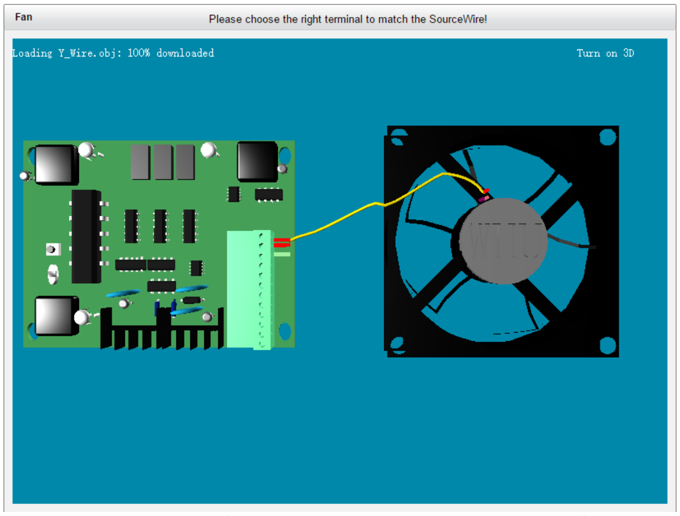

Fig. 9. Warning message for connecting the source wire when one of the source terminals is clicked and highlighted.

situation in which the feedback wire is connected while the source wire and the ground wire are not connected, and one of the source terminals is clicked and highlighted. The warning message is shown in the figure. The interactions involved in the wiring of the fan speed control system are as follows.

1) *Terminal highlighting:* For a single terminal, for example, one of the source terminals, the terminal can be clicked and highlighted with connecting warning guidance. When it is already highlighted, another mouse click would cancel the highlighting and the warning at the same time.
2) *Wire connecting:* For two matched terminals, the correct combination of mouse clicks would contribute to wire connecting. For instance, in Fig. 9, to connect the source wire, the user must click the matched terminal. If two terminals are already connected with a wire, the click action would cause wire canceling. This would happen if the two feedback terminals in Fig. 9 are clicked.
3) *Warning and guidance:* Warning and guidance appears along with other wiring interactions. Every single click of the terminal would lead to the appearance of the warning message with clear guidance for correct wiring.

Wiring practice can help students better comprehend the system. For example, when the fan speed control system works properly with all wires connected, if the user clicks the two corresponding terminals to disconnect the feedback wire, the feedback channel would be disconnected, and the speed of the fan would be out of control, which is exactly what happens in the real test rig. Through this kind of practice, the students can better understand the importance of the feedback.

C. *Speed control experiment*

Once the wires are correctly connected in the 3D interface, the system is available for speed control experimentation. Considering different control purposes, the wiring experiments can be carried out in various network environments with a varied number of ARM9-based NetCon controllers using the NCSLab experimental platform. Two examples follow.

1) LAN-based remote local control experiment

In a remote local control experiment, one NetCon acts as the controller and sensor/actuator at the same time. The NetCon and controlled test rig are connected to a local area network (LAN). The executable programs generated from the designed control algorithms can be uploaded to the server database and downloaded to the remote controller.

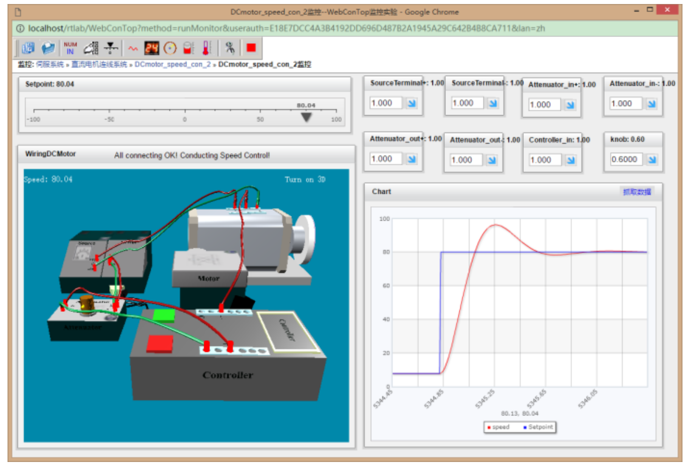

Fig. 10. Speed control monitoring interface for DC motor control system.

Fig. 10 shows a typical monitoring interface of a DC motor control system. The uppermost part is the toolbar containing various widgets. The lower left-hand part is the virtual slider for the tuning of the set point for speed, and the 3D widget displaying the entire virtually connected system. The lower right-hand part includes the chart depicting the real-time speed and its set point versus time, and eight numeric input widgets showing the value of the wires and the knob. Fig. 10 also shows that the system can work properly with all wires correctly connected in the remote local control experiment.

The wires can also be disconnected by canceling the wire connecting. If the user would like to find out what would happen when one of the wires is disconnected, the two matched terminals of a wire can be clicked, and then the wire connecting would be canceled.

2) Internet-based networked control experiment

NCSLab is not only used for teaching, but has also been widely used in research on control engineering, especially for the topic of networked control [42]-[46]. Using NCSLab, the user can easily control test rigs in different locations to carry out networked control experiments. In [47] and [48], the concept of cloud control systems has been briefly demonstrated as an extension of networked control systems, which states that the research on cloud control systems will make new contributions to control system theory and practical applications in the near future. Currently, cloud control in which the controller is in the cloud and can be physically located anywhere in the world is being researched. The virtual DC motor with wiring functionality could be a favorable candidate for such research.

To verify the effectiveness of networked control, joint research is being conducted at Wuhan University (WHU) and Harbin Institute of Technology (HIT). In the joint research practice, two NetCon controllers are employed, one of which is deployed at HIT working as a controller, with the other at WHU serving as a sensor /actuator connected to the test rig. The real-time data are exchanged between the two NetCon controllers via the Internet, which forms a closed-loop control.

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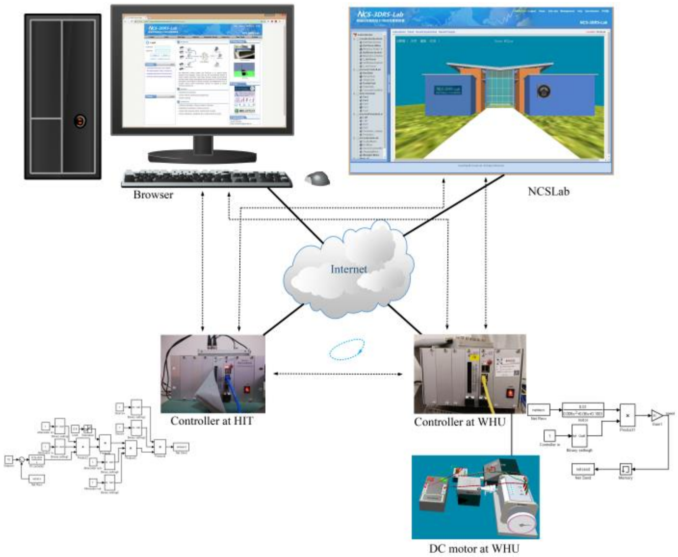

Fig. 11. WHU's joint research of networked control on virtual DC motor wiring with HIT based on the Internet.

Fig. 11 illustrates the joint research practice. The test rig of the Internet-based networked control system is a DC motor wiring system mentioned in the preceding sections. The control algorithm is redesigned to be split into two parts, in which one part is downloaded to the remote controller at HIT and the other part is in the sensor/actuator at WHU. Using an ARM9 UDP sender and receiver, the two algorithms inside the NetCon controllers can communicate with each other through the Internet by IP address and a port number.

The detailed technology and architecture of the LAN- and Internet-based environments are shielded from the user. Thus, from the user's point view, there is no difference regarding the experimentation method and monitoring compared to the LAN-based case.

The Internet-based joint research indicates that virtual wiring methods could potentially be applied in research and industrial scenarios apart from being used in teaching practices.

VIII. Pedagogical Evaluation

The developed wiring practice outlined in this paper is similar to hands-on experiments in which necessary wiring with experimental test rigs is familiar to students. Before the deadline, students are free to use the test rig in NCSLab to carry out their wiring experiments to obtain satisfactory results.

A. Courses and background

Inspired by [6] and [49], the use of NCSLab in wiring practice has been applied in the teaching module *Control System Simulation and Computer Aided Design (CSS&CAD)*, which is a major module for students with a control engineering background at WHU. 73 students attended the course in 2017. *CSS&CAD* is a module combining theoretical knowledge and practical skills. One half of the module are lectures that teach the students how to use computers to help them simulate and design control algorithms. The other half is the online experimentation on NCSLab. The students are required to complete five online experiments (including two related to wiring practice) to verify the control algorithm design methodologies learned from the lectures.

TABLE III
STUDENT PERFORMANCE

Year	Participants	Mean	Standard deviation.
2016	74	79.99	7.78
2017	73	83.72	10.33

Correspondingly, the assessment of student performance in the module also consists of two parts. It includes the written examination, which accounts for 50% of the score, and the experimental reports, which account for the other 50%.

B. Student performance analysis

In 2016, the students were only required to design and implement the control algorithms using the online experimental platform. In 2017, two new wiring experiments have been added. The students were required to work on the virtual DC motor control system and fan speed control system. In order to get the two virtual control systems working, they needed to design the control algorithms in Simulink, implement them remotely on the remote controller, and, above all, complete the wiring in the web-based virtual 3D environment.

Because the required experiments in 2016 and 2017 are different, the students' scores on the experimental part are not actually comparable. Table III shows the student performance on the theoretical examinations in 2016 and 2017. The examination papers for both years are created from a general question bank. Therefore, the difficulty levels of the papers are similar.

With the introduction of virtual wiring in 2017, NCSLab can create a virtual experimental environment emulating the entire process of control engineering experimentation. Through virtual experimentation, students have a better understanding of the control system. It can be seen that the students' average score increased from 79.99 in 2016 to 83.72 in 2017.

C. Student perception analysis

The survey focused on the perception of the newly implemented wiring practice. Both the questions and frequencies of each response value are listed in Table IV, and the survey results are graphically depicted in Fig. 12, in which the percentages of each question response are analyzed and calculated. From the results, it can be seen that general acceptance of the wiring practice is notably high.

The easy to use issue needs to be improved. Even though most of the students had acknowledged that the wiring practice is easy to use, 10 students reported a bad user experience. Since this is a first attempt at combining wiring practice and control algorithm implementation, the user experience data gathered can be used to carry out future improvements.

IX. Conclusion

In this paper, an HTML5-based 3D online control laboratory with virtual interactive wiring practice is presented. Using HTML5 technology, the rendering of the 3D model is implemented without plug-ins. The wiring process is combined with the design of the control algorithm using

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TII.2017.2769883, IEEE Transactions on Industrial Informatics

TABLE IV
SURVEY QUESTIONS AND FREQUENCIES OF ANSWERS

Questions	Frequencies				
	Poorly	Slightly	Moderately	Very	Extremely
Were the virtual wiring experiments effective and easy to use?	7	3	1	11	51
Can the wiring practices stimulate your interest in experimentation?	2	2	1	4	64
Were the wiring practices useful in enhancing your comprehension of the system?	2	1	1	11	58
How do you value virtual wiring practice developed through NCSLab?	0	1	3	14	55
Would you recommend the use of wiring in NCSLab to students for the next course?	1	1	1	19	51

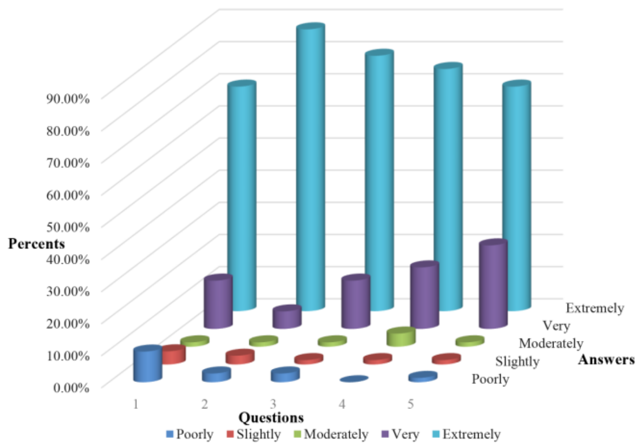

Fig. 12. Survey results.

MATLAB/Simulink, which provides a template for customizing control algorithm with wiring integrated. 3D virtual wiring interactions including terminal highlighting, wire connecting, and warning are realized with high interactivity using *Three.js*. As experiments without wiring processes are incomplete, the rules of wire connection can help a user better comprehend a system during an experiment. The wiring method and test rigs could be potentially applied to research on networked control, distributed control, and cloud control. The proposed architecture can cover the entire process of online experiments, which simulates the hands-on experiments in physical laboratories very well within a single web-based online laboratory framework. The results obtained from the pedagogical evaluation show that the proposed wiring system is useful for study. The wiring combined control algorithm design and 3D interactive wiring such as terminal highlighting and wire connecting, are generic components that can potentially be scaled up to other research or industrial projects using the method proposed in this paper.

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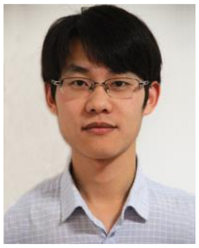

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