Journal of Visualized Experiments

Interactive and Visualized Online Experimentation System for Engineering Education and Research

--Manuscript Draft--

Article Type:	Results Article - JoVE Produced Video
Manuscript Number:	JoVE63342R2
Full Title:	Interactive and Visualized Online Experimentation System for Engineering Education and Research
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Additional Information:	
Question	**Response**
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TITLE:

Interactive and Visualized Online Experimentation System for Engineering Education and Research

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SUMMARY:

This work describes an online experimentation system that provides visualized experiments, including the visualization of theories, concepts, and formulas, visualizing the experimental process with three-dimensional (3-D) virtual test rigs, and visualizing the control and monitoring system using widgets such as charts and cameras.

ABSTRACT:

Experimentation is crucial in engineering education. This work explores visualized experiments in online laboratories for teaching and learning and also research. Interactive and visualizing features, including theory-guided algorithm implementation, web-based algorithm design, customizable monitoring interface, and three-dimensional (3-D) virtual test rigs are discussed. To illustrate the features and functionalities of the proposed laboratories, three examples, including the first-order system exploration using a circuit-based system with electrical elements, web-based control algorithm design for virtual and remote experimentation, are provided. Using user-designed control algorithms, not only can simulations be conducted, but real-time experiments can also be conducted once the designed control algorithms have been compiled into executable control algorithms. The proposed online laboratory also provides a customizable monitoring interface, with which users can customize their user interface using provided widgets such as the textbox, chart, 3-D, and camera widget. Teachers can use the system for online demonstration in the classroom, students for after-class experimentation, and researchers to verify control strategies.

INTRODUCTION:

Laboratories are vital infrastructure for research and education. When conventional laboratories are not available and/or accessible due to different causes, for example, unaffordable purchases and maintenance cost, safety considerations, and crises such as the coronavirus disease 2019 (COVID-19) pandemic, online laboratories can offer alternatives[1–3]. Like conventional laboratories, significant progress such as interactive features[4] and customizable experiments[5] have been achieved in the online laboratories. Before and during the COVID-19 pandemic, online laboratories are providing experimental services to users throughout the world[6,7].

Among online laboratories, remote laboratories can provide users with an experience similar to hands-on experiments with the support of physical test rigs and cameras[8]. With the advancement of the Internet, communication, computer graphics, and rendering technologies, virtual laboratories also provide alternatives to conventional laboratories[1]. The effectiveness of remote and virtual laboratories to support research and education has been validated in related literature[1,9,10].

Providing visualized experiments is crucial for online laboratories, and visualization in online experimentation has become a trend. Different visualization techniques are achieved in online laboratories, for example, curve charts, two-dimensional (2-D) test rigs, and three-dimensional (3-D) test rigs[11]. In control education, numerous theories, concepts, and formulas are obscure to comprehend; thus, visualized experiments are vital to enhancing teaching, student learning, and research. The involved visualizing can be concluded into the following three categories: (1) Visualizing theories, concepts, and formulas with web-based algorithm design and implementation, with which simulation and experimentation can be conducted; (2) Visualizing the experimental process with 3-D virtual test rigs; (3) Visualizing control and monitoring using widgets such as a chart and a camera widget.

PROTOCOL:

In this work, three separate visualized examples are provided to enhance teaching and learning and research, which can be accessed *via* the Networked Control System Laboratory (NCSLab https://www.powersim.whu.edu.cn/react).

1. Example 1: First-order system using circuit-based experimentation protocol

1.1. Access the NCSLab system.

1.1.1. Open a mainstream web browser and enter the URL https://www.powersim.whu.edu.cn/react.

1.1.2. Click on the **Start Experiment** button on the left side of the main page to log in to the system. User name: whutest; password: whutest.

NOTE: This step also suits for other two examples (step 2 and step 3).

1.1.3. Enter the **WHULab** in the left side sub-laboratory list and choose **WHUtypicalLinks** for experimentation.

NOTE: Six sub-interfaces are designed and implemented for different purposes to support simulation and real-time experimentation.

1.1.4. Enter the **Algorithm Design** sub-interface.

NOTE: The user can choose a public algorithm model designed and shared by other authorized users or create a new model.

1.1.5. Choose and click on the **Create New Model** button and enter the web-based algorithm interface. Build a circuit diagram using the provided blocks, as shown in **Figure 1**.

NOTE: Another operational amplifier (op-amp) (Op-Amp2 in **Figure 1**) is used to cancel the 180° phase shift. To ensure that the input, the resistors, and the capacitor are tunable, one variable capacitor and two variable resistors in the ELECTRIC ELEMENTS library and four constant blocks from the SOURCES library are selected from the left-side block library panel.

1.1.6. Double click the corresponding blocks to set parameters as listed in **Table 1**. Set the **X-axis range** of the chart to **8 s**.

NOTE: A popup window will be triggered after a double click to the block, which includes the descriptions of the block and can be used for setting the parameter. An example of the Resistor (R3) is illustrated in **Figure 1**.

1.1.7. Click on the **Start Simulation** button; the simulation result will be provided in the interface, as included in **Figure 1**.

NOTE: This step also suits the two other examples with other test rigs. The simulation results can provide information for users to recheck the designed circuit-based system to avoid a wrong circuit. However, a faulty circuit will cause no harm to the users or the system, so the users do not have to worry about the consequences.

1.1.8. Click on the **Start Compilation** button. Wait until the designed block diagram is generated into an executable control algorithm that can be downloaded and executed into the remote controller deployed at the test rig side to implement control algorithms.

NOTE: This step also suits the following experiments with other test rigs.

1.1.9. Conduct real-time experiments using the generated control algorithm. Click on the **Request Control** button to apply for control of the circuit system.

NOTE: "Request control" is the scheduling mechanism for the system. Once a user is granted the control privilege, the user can conduct experiments with the corresponding test rig. Only one user can occupy the test rig at a time for physical test rigs, and the queue scheduling mechanism has been implemented to schedule other potential users based on the First Come First Served rule[11]. For virtual test rigs, a massive number of users can be concurrently supported. 500 concurrent user experimentation has been tested effectively. For the circuit-based system, 50 users can access the system at a time.

1.1.10. Click on the **Return** button to the **Algorithm Design** sub-interface. Find the executable control algorithm under the **Private Algorithm Models** panel.

NOTE: The executable control algorithm can also be found in the **My Algorithm** panel in the **Control Algorithm** sub-interface.

1.1.11. Click on the **Conduct An Experiment** button to download the designed control algorithm to a remote controller.

1.1.12. Enter the **Configuration** sub-interface and click on the **Create New Monitor** button to configure a monitoring interface, as shown in **Figure 2**. Four textboxes for parameter tuning and one curve chart for signal monitoring are included.

NOTE: The chart on the right in **Figure 2** is the same chart as the one in the left, which was added to demonstrate the data using the **Suspend** button.

1.1.13. Link the signals and parameters with the selected widgets.

NOTE: **Parameter/Input**, **Parameter/R0**, **Parameter/R1**, and **Parameter/C** for four textboxes, respectively, and **Parameter/Input** and **Signal/Output** for the curve chart.

1.1.14. Click on the **Start** button to start the experiment.

NOTE: This step also suits the following experiments with other test rigs. Users can save the configuration for future use.

1.1.15. Set the input voltage to 0 V, tune the capacitor C to 5 µF (0.000005 in **Figure 2**), and then set the input voltage to 1 V; the dynamic process of the output voltage is illustrated in **Figure 2**.

1.2. Calculate the corresponding parameters K and T.

NOTE: The time constant can be calculated when the output reaches 63.2% of the final value K after $t = T$, which is 0.632[12]. From **Figure 2**, it can be seen that the time duration is 1 s, thus, $T = 1$, which is consistent with the theory in which $T = R_1 C = 200000 * 0.000005 = 1$, and $K = R_1 / R_0 = 200000 / 200000 = 1$ (which equals the final value)[12]. Thus, the first-order system can be specified as: $G(s) = \frac{1}{s+1}$.

2. Example 2: Interactive and visualized virtual experimentation protocol

2.1. Use the NCSLab system to conduct simulation and real-time experimentation.

2.1.1. Log in to the NCSLab system. Enter the **ProcessControl** sub-laboratory and choose the **dualTank** test rig, and then enter the **Algorithm Design** sub-interface.

2.1.2. Design a Proportional-integral-derivative (PID) control algorithm using the web interface provided by NCSLab following the steps described in Example 1. **Figure 3** is an algorithm example for the dual tank system.

2.1.3. Double click on the **PID controller**, and tune the parameters for Proportiona (P), Integral (I) and Derivative (D) terms. Set P = 1.12, I = 0.008 and D = 6.6, respectively.

NOTE: The P, I, and D terms should be tuned combined with the simulation result.

2.1.4. Click on the **Start Simulation** button; the simulation result will pop up, which is included on the right side of **Figure 3**.

NOTE: It can be seen that the control performance is good, and the control algorithm is ready for real-time experimentation.

2.1.5. Generate the executable control algorithm following the previously mentioned steps.

2.1.6. Download the control algorithm to the remote controller and configure a monitoring interface with four text boxes for Set_point, P, I, and D, respectively.

2.1.7. Include a chart for monitoring the water level and the corresponding Set_point. Choose a 3-D widget, which can provide all angles of the test rigs and animations of water level connected with the real-time data.

2.1.8. Click on the **Start** button; then, the monitoring interface will be activated as shown in **Figure 4**, which provides a visualized virtual experiment.

2.1.9. Set the Set_point from 10 cm to 5 cm, and then set I = 0.1 when the height of the water level in the controlled tank reaches and stabilizes at 5 cm. Reset the set-point from 5 cm to 15 cm; it can be seen from **Figure 4** that there is an overshoot.

2.1.10. Tune I from 0.1 to 0.01 and reset the set-point from 15 cm to 25 cm. It can be seen that the overshoot has been eliminated, and the water level can quickly stabilize at the set-point value of 25 cm.

3. Example 3: Research with remote and virtual laboratories protocol

3.1. Conduct a real-time experiment in NCSLab.

3.1.1. Log into the NCSLab system and choose **Fan Speed Control** in the **Remote Laboratory** sub-laboratory.

3.1.2. Enter the **Algorithm Design** sub-interface. Drag the blocks to construct the IMC control algorithm diagram, as shown in **Figure 5**.

NOTE: The $F(s)$ and $G_m(s)^{-1}$ is designed as shown in **Figure 5**, in which the designed control algorithm using NCSLab is illustrated to control a fan speed control system in a remote and virtual laboratory mode.

3.1.3. Generate the executable control algorithm and employ the fan speed control system to verify the designed IMC algorithm.

3.1.4. Configure a monitoring interface. Link two textboxes with two parameters, namely, the Set_point and lambda (for λ which is the filter time constant) for tuning, and a real-time chart with the Set_point and Speed for monitoring. Select the 3-D model widget of the fan and the camera widget for monitoring.

3.1.5. Click on the **Start** button to activate real-time experimentation. Reset the Set_point from 2,000 rpm to 1,500 rpm, and then Reset it from 1,500 rpm to 2,500 rpm, the result of which is shown in **Figure 6**.

NOTE: It can be concluded that when $\lambda = 1$ the system can be stabilized to a step reference.

REPRESENTATIVE RESULTS:

The proposed laboratory system has been used in several different disciples at Wuhan University, such as the Automation, Power and Energy Engineering, Mechanical Engineering, and other universities, such as Henan Agricultural University[6].

Teachers/students/researchers are provided with great flexibility to explore the system using different virtual and/or physical test rigs, define their control algorithms, and customize their monitoring interface; thus, users at different levels can benefit from the proposed system. The visualized experiments provided by the proposed approach can potentially enhance understanding theories, concepts, and formulas.

The proposed system can be used for different types of algorithm design (**Figure 1** and **Figure 3** are two examples) and multi-purposes such as teaching, learning, and research (three protocols can be regarded as three application examples). The first-order system is an example that the system can be applied to typical system analysis using circuit-based diagrams.

Figure 3 and **Figure 5** demonstrate that the proposed online laboratory can design simple and complex control algorithms using the designed blocks, verified through simulation and real-time experimentation with 3-D virtual and physical test rigs, respectively, as shown in **Figure 4** and **Figure 6**.

The three examples demonstrate that the proposed interactive and visualized laboratory can achieve the following visualization as aforementioned. (1) Theory, formulas, and schematic diagrams can be visualized through web-based algorithm design and implementation, with which simulation and experimentation can be conducted. (2) With the support of the 3-D virtual test rigs, experimental processes can be visualized in the absence of physical test rigs and cameras deployed at the test rig site. In remote laboratories, the integration of 3-D test rigs can also benefit users, allowing users to view the details of the test rigs from different angles. Combining 3-D virtual test rigs with physical test rigs at the remote side can potentially enhance user experience. (3) Using developed widgets such as a chart, a camera widget, and a textbox, the monitoring, and control during the experimental process can be visualized.

FIGURE AND TABLE LEGENDS:

Figure 1: Construction of the first-order system with blocks from the ELECTRICAL ELEMENTS library in NCSLab. The user can drag any block from the left-side block library panel and construct a system by linking the selected blocks properly.

Figure 2: Real-time experiment of the first-order system with the designed control algorithm. The parameters are tunable, and the signals can be monitored with the provided widgets.

Figure 3: Web-based PID control algorithm design and implementation for the dual tank system. The simulation result is included, which shows that the water level of the second tank can be controlled to the set-point value of 10 cm.

Figure 4: Real-time experimentation with the dual tank system. After tuning the integral term from 0.1 to 0.01, the set-point is reset from 15 cm to 25 cm. It can be seen that the overshoot has been eliminated.

Figure 5: IMC control of the fan speed control system. The inverse model of the identified fan model is an improper transfer function (for a proper transfer function, the order of the transfer function numerator must be less than or equal to the order of the denominator), which is constructed with general blocks based on the identified model. To enable a tunable filter, the filter is also built with blocks. The lambda in the figure represents the reciprocal of the λ in Equation 6 and can be tuned easily.

Figure 6: Real-time control and fan speed monitoring using the fan speed control remote laboratory combined with a 3-D virtual fan system. The physical fan system is located at Wuhan University and provides remote laboratory services to users worldwide.

Figure 7: Schematic diagram of the first-order system. The first-order circuit design and

implementation in NCSLab are based on this diagram.

Figure 8: 3-D virtual dual tank system in NCSLab. The purpose of the control is to control the water level in the second tank to the set-point value.

Figure 9: Schematic of the internal model control architecture. $G_m(s)$ is the model of the real plant $G(s)$, $G_m(s)^{-1}$ is the inverse model of $G_m(s)$, and $F(s)$ is the filter. The $F(s)$, $G_m(s)^{-1}$, and $G_m(s)$ constitute the IMC controller.

Table 1: Parameter configurations for the first-order circuit system. R_2 and R_3 are used to cancel the phase shift combined with the op-amp.

Supplementary Figure 1: Simulation warning interface when a user fails to ground a circuit. The result will warn the users, which can help them to recheck the designed circuit.

Supplementary Figure 2: Compilation warning interface when a user fails to ground a circuit. The result will warn the users, which can help them to recheck the designed circuit.

Supplementary Figure 3: Simulation result when a user reverses the polarity of the capacitor. A regular capacitor instead of the variable capacitor has been selected to illustrate this example. No warning message is shown, and the result is similar to **Supplementary Figure 4**.

Supplementary Figure 4: Simulation result when the polarity of the capacitor is correct. A regular capacitor instead of the variable capacitor has been selected to illustrate this example. The simulation result will pop up to help the users to check the circuit.

DISCUSSION:

The present protocol describes a hybrid online laboratory system that integrates physical test rigs for remote experimentation and 3-D virtual test rigs for virtual experimentation. Several different block libraries are provided for the algorithm design process, such as the electrical elements for circuit-based design. Users from control backgrounds can focus on learning without programming skills. The proper design of a control algorithm that can be applied to a suitable test rig should be considered. It is also challenging to design a controller to guarantee a good control performance (considering control performance index, including overshoot, settling time, and steady error) before applying it to the controlled test rig. Before compiling a control algorithm that can be used for real-time experimentation, simulation should be conducted to address potential issues. Control algorithms can be applied to other different test rigs using the system once they are integrated into the proposed system.

The background and theoretical knowledge regarding the three examples are as follows.

For the first-order system, the principle of the first-order system can be analyzed using circuit theory with the provided circuit in **Figure 7**. According to circuit theory[12], the following two equations can be obtained. From the input side view of the op-amp, the current is

$$I = \frac{V_{in} - 0}{R_0} \tag{1}$$

From the output side view of the op-amp, Equation 2 can be obtained

$$I = \frac{0 - V_{out}}{Z} \tag{2}$$

where $Z = \frac{R_1 * 1/sC}{R_1 + 1/sC}$ is the impedance of the RC parallel circuit.

By combining Equation 1 and 2, the transfer function of the system can be calculated as

$$G(s) = \frac{V_{out}}{V_{\mathrm{in}}} = -\frac{R_1/R_0}{R_1 C s + 1} \tag{3}$$

in which the minus sign (–) indicates a 180° phase shift of the output voltage, which is neglected in the analysis in the following steps.

Denote $K = R_1/R_0$, $T = R_1 C$, and then the transfer function of the system can be represented as

$$G(s) = \frac{K}{Ts + 1} \tag{4}$$

For the dual tank system, the designed 3-D water tank system is illustrated in **Figure 8**. The design and implementation of a previous version using Flash have been explored in the work of W. Hu et al. in 2014[13]. The control purpose of this test rig is to control the water level in the second tank to the value of the set point. A PID controller has been used to control the dual tank. Theoretically, the PID can be expressed as[14]

$$u(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t)\mathrm{d}t + K_{\mathrm{d}} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{5}$$

where K_{p}, K_{i}, K_{d} are the coefficients for P, I, and D terms, respectively.

IMC is simple to tune with good set-point tracking performance and has been widely used to control real-life applications[15]. The control architecture of IMC is shown in **Figure 9**, in which $G(s)$ is the real plant and $G_m(s)$ is the model of the plant. $G_m(s)$ is usually obtained through system identification. $G_m(s)^{-1}$ is the inverse model of $G_m(s)$, and $F(s)$ is the filter. $R(s)$, $Y(s)$, and $E(s)$ are the reference, output, and error, respectively. The $F(s)$, $G_m(s)^{-1}$, and $G_m(s)$ constitute the IMC controller. A standard default filter $F(s)$[16] is used in this work as Equation 6

$$F(s) = \frac{1}{(1 + \lambda s)^n}, \tag{6}$$

where λ is the filter time constant, and order n is selected to ensure a proper or semi-proper IMC compensator ($F(s) * G_m(s)^{-1}$).

The IMC control algorithm has been designed and applied to control the physical fan speed system through calculation, analysis, and proper design. In this work, $G(s)$ represents a physical fan speed control system, whose model $G_m(s)$ is identified as a second-order system

$$G(s) = \frac{1.659}{s^2 + 1.849s + 1.566}. \quad (7)$$

The order n of the filter $F(s)$ is set to 1. For tuning purposes, the lambda in **Figure 5** represents the reciprocal of the λ in Equation 6 and can be easily tuned. The filter is set to be the following

$$F(s) = \frac{1}{1 + \lambda s}. \quad (8)$$

Web-based algorithm design allows users at an advanced level to design more complex algorithms with the support of S-function. However, more advanced control strategies for research and education, such as control strategies for multi-agent systems or networked control strategies with time constraints, are under consideration for further upgrading the proposed laboratory system.

The circuit-based system is based on simulation. One of the advantages of simulation is that the users can conduct their operations freely. They do not have to worry about the consequences since their misoperation will cause no harm to themselves and the system and test rigs, especially in an online experimentation system.

After a circuit-based system is designed, the user is supposed to run a simulation. For some cases, such as failing to ground the circuit, the simulation and compilation results will warn the users, which can help them to recheck the designed circuit (**Supplementary Figure 1** and **Supplementary Figure 2**). For other cases, for example, reversing the capacitor's polarity (**Supplementary Figure 3**), no warning message will be shown when a user tries to conduct a simulation or compilation, the result of which is similar to that of a correct circuit as shown in **Supplementary Figure 4**.

Currently, the main limitation of the online experimentation system is that it can primarily be used for users with a control background. The circuit-based system can only be used for simulation with no hardware setups. To cover diverse engineering fields, hardware for circuit systems that can be applied to electrical and electronics engineering can be integrated. More test rigs for other areas should also be considered.

Compared with MATLAB/Simulink, a standalone MATLAB/Simulink for each user is not required using the proposed methodology. Moreover, real-time experimentation with 3-D virtual test rigs and physical test rigs is more than pure simulation in the proposed laboratory. Compared with the MATLAB/Simulink-based remote laboratory presented by I. Santana et al.[9], the proposed laboratory can be used to design controllers and the entire control system with the circuit-based system, 3-D virtual, and physical test rigs. Experimentation environment (EE) offers practical controller design methods with Blockly-based visual design for simple experiments and a JavaScript-based textual design for complex experiments[5]. Considering students are more familiar with MATLAB/Simulink, a block-based algorithm design interface similar to MATLAB/Simulink can be used. An alternative control system could be designed, which can be a good option.

The proposed system can be utilized for teaching, learning, and research for teachers, students, and researchers. Currently, the system has been mainly used in control engineering-related disciplines. The system can potentially be applied to electrical and electronics engineering, industrial electronics, and industrial control.

ACKNOWLEDGMENTS:
This work was supported by the National Natural Science Foundation of China under Grant 62103308, Grant 62173255, Grant 62073247, and Grant 61773144.

DISCLOSURES:
The authors have nothing to disclose.

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Figure 1

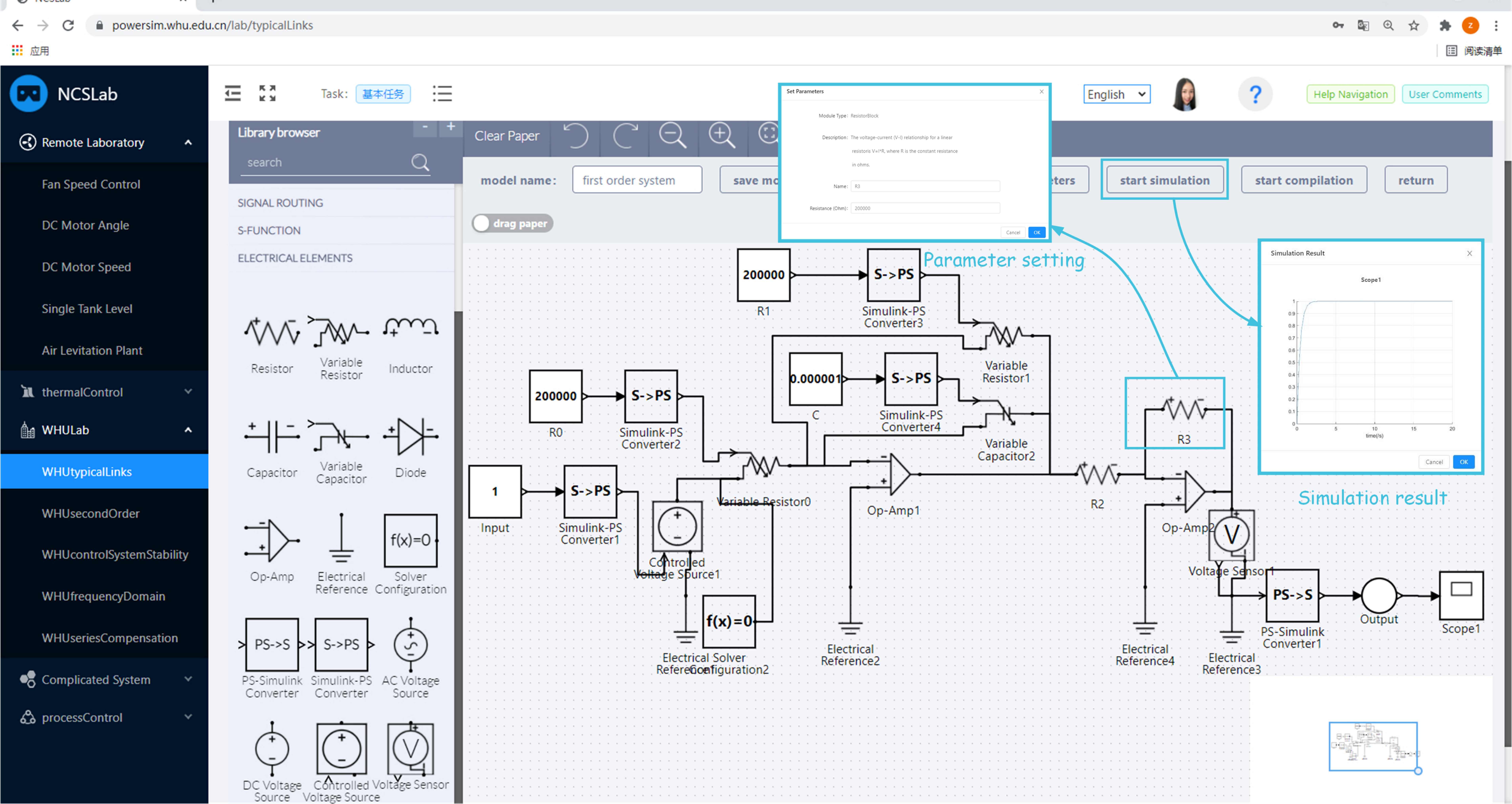

NCSLab
powersim.whu.edu.cn/lab/typicalLinks
Remote Laboratory
Fan Speed Control
DC Motor Angle
DC Motor Speed
Single Tank Level
Air Levitation Plant
thermalControl
WHULab
WHUtypicalLinks
WHUsecondOrder
WHUcontrolSystemStability
WHUfrequencyDomain
WHUseriesCompensation
Complicated System
processControl
Task: 基本任务
English
Help Navigation
User Comments
Library browser
search
SIGNAL ROUTING
S-FUNCTION
ELECTRICAL ELEMENTS
Resistor
Variable Resistor
Inductor
Capacitor
Variable Capacitor
Diode
Op-Amp
Electrical Reference
Solver Configuration
PS-Simulink Converter
Simulink-PS Converter
AC Voltage Source
DC Voltage Source
Controlled Voltage Source
Voltage Sensor
Clear Paper
model name:
first order system
start simulation
start compilation
return
drag paper
Set Parameters
Module Type: ResistorBlock
Name: R3
Resistance (Ohm): 200000
Cancel
OK
Parameter setting
Simulation Result
Scope1
time(s)
Simulation result
200000
R1
Simulink-PS Converter3
Variable Resistor1
0.000001
C
Simulink-PS Converter4
Variable Capacitor2
200000
R0
Simulink-PS Converter2
1
Input
Simulink-PS Converter1
Variable Resistor0
Controlled Voltage Source1
Op-Amp1
R2
R3
Op-Amp2
Voltage Sensor1
PS-Simulink Converter1
Output
Scope1
Electrical Reference2
Electrical Reference4
Electrical Reference3
Solver Configuration2

Figure 2

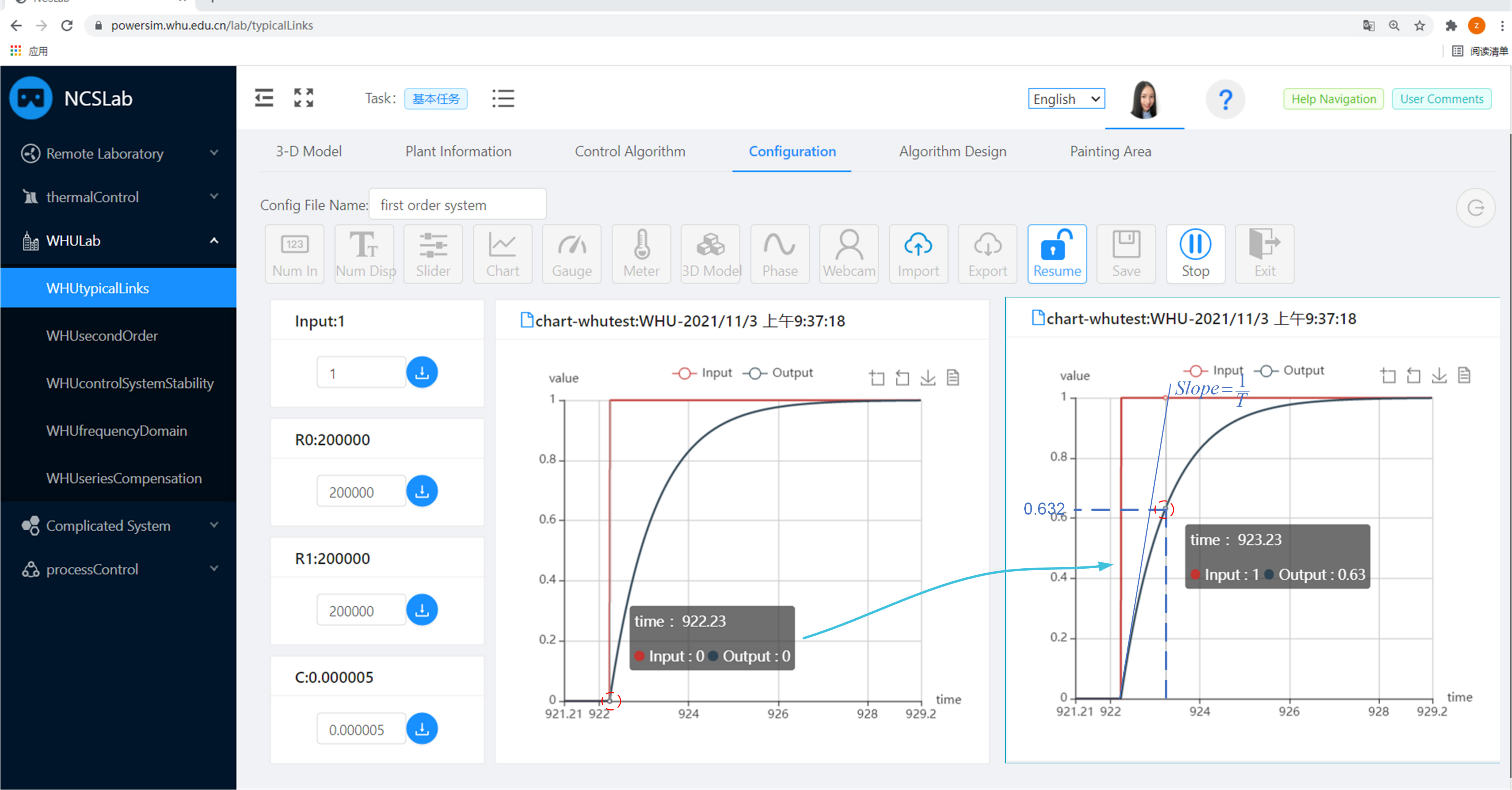

NCSLab
powersim.whu.edu.cn/lab/typicalLinks
Remote Laboratory
thermalControl
WHULab
WHUtypicalLinks
WHUsecondOrder
WHUcontrolSystemStability
WHUfrequencyDomain
WHUseriesCompensation
Complicated System
processControl
Task: 基本任务
English
Help Navigation
User Comments
3-D Model
Plant Information
Control Algorithm
Configuration
Algorithm Design
Painting Area
Config File Name: first order system
Num In
Num Disp
Slider
Chart
Gauge
Meter
3D Model
Phase
Webcam
Import
Export
Resume
Save
Stop
Exit
Input:1
1
R0:200000
200000
R1:200000
200000
C:0.000005
0.000005
chart-whutest:WHU-2021/11/3 上午9:37:18
value
Input
Output
time : 922.23
Input : 0 Output : 0
time
chart-whutest:WHU-2021/11/3 上午9:37:18
$Slope = \frac{1}{T}$
0.632
time : 923.23
Input : 1 Output : 0.63
921.21
922
924
926
928
929.2

Figure 3

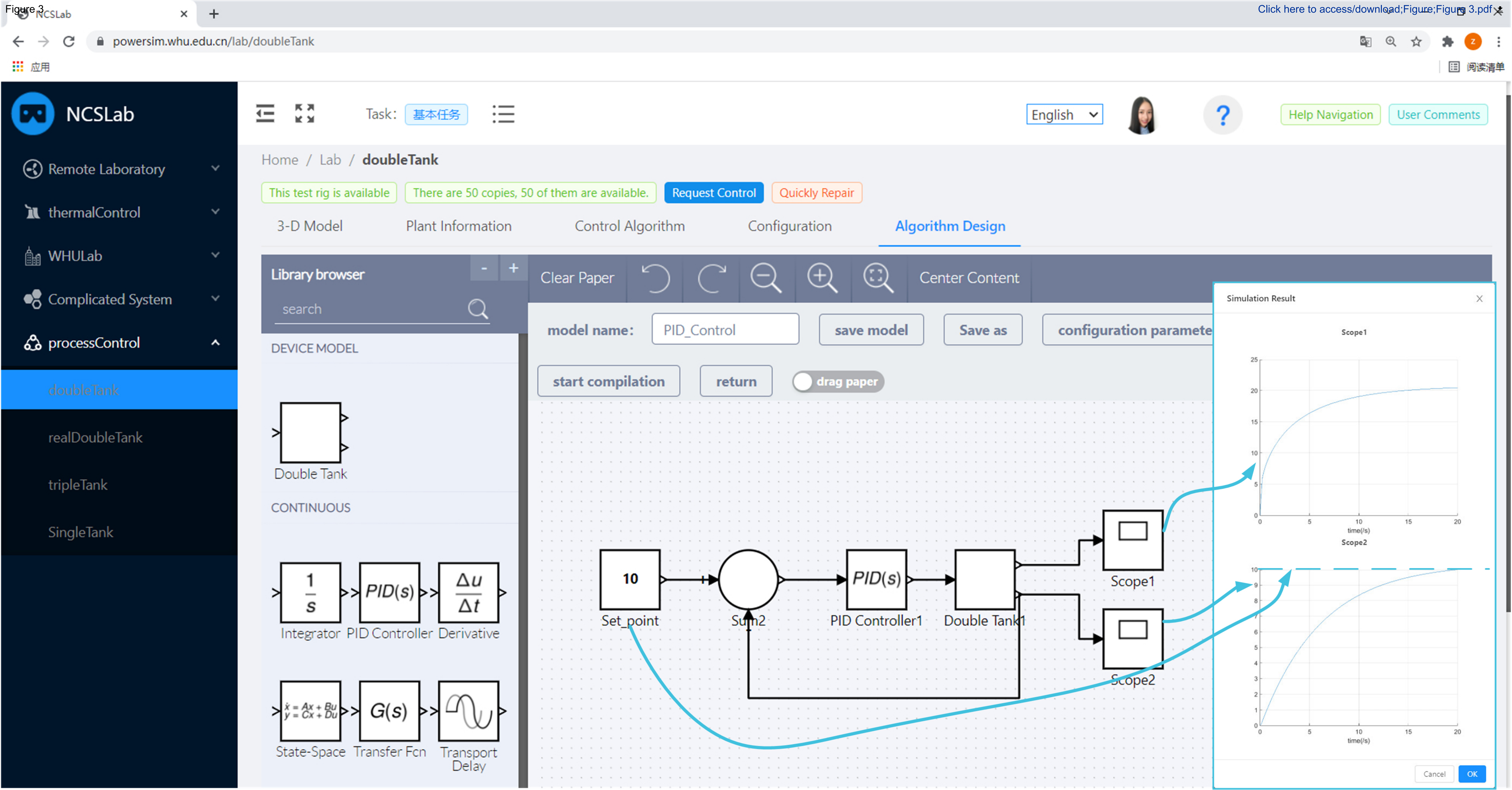

NCSLab
powersim.whu.edu.cn/lab/doubleTank
应用
阅读清单
NCSLab
Remote Laboratory
thermalControl
WHULab
Complicated System
processControl
doubleTank
realDoubleTank
tripleTank
SingleTank
Task:
基本任务
English
Help Navigation
User Comments
Home / Lab / doubleTank
This test rig is available
There are 50 copies, 50 of them are available.
Request Control
Quickly Repair
3-D Model
Plant Information
Control Algorithm
Configuration
Algorithm Design
Library browser
search
DEVICE MODEL
Double Tank
CONTINUOUS
Integrator
PID Controller
Derivative
State-Space
Transfer Fcn
Transport Delay
Clear Paper
Center Content
model name:
PID_Control
save model
Save as
configuration paramete
start compilation
return
drag paper
10
Set_point
Sum2
PID(s)
PID Controller1
Double Tank1
Scope1
Scope2
Simulation Result
Scope1
time(/s)
Scope2
time(/s)
Cancel
OK

Figure 4

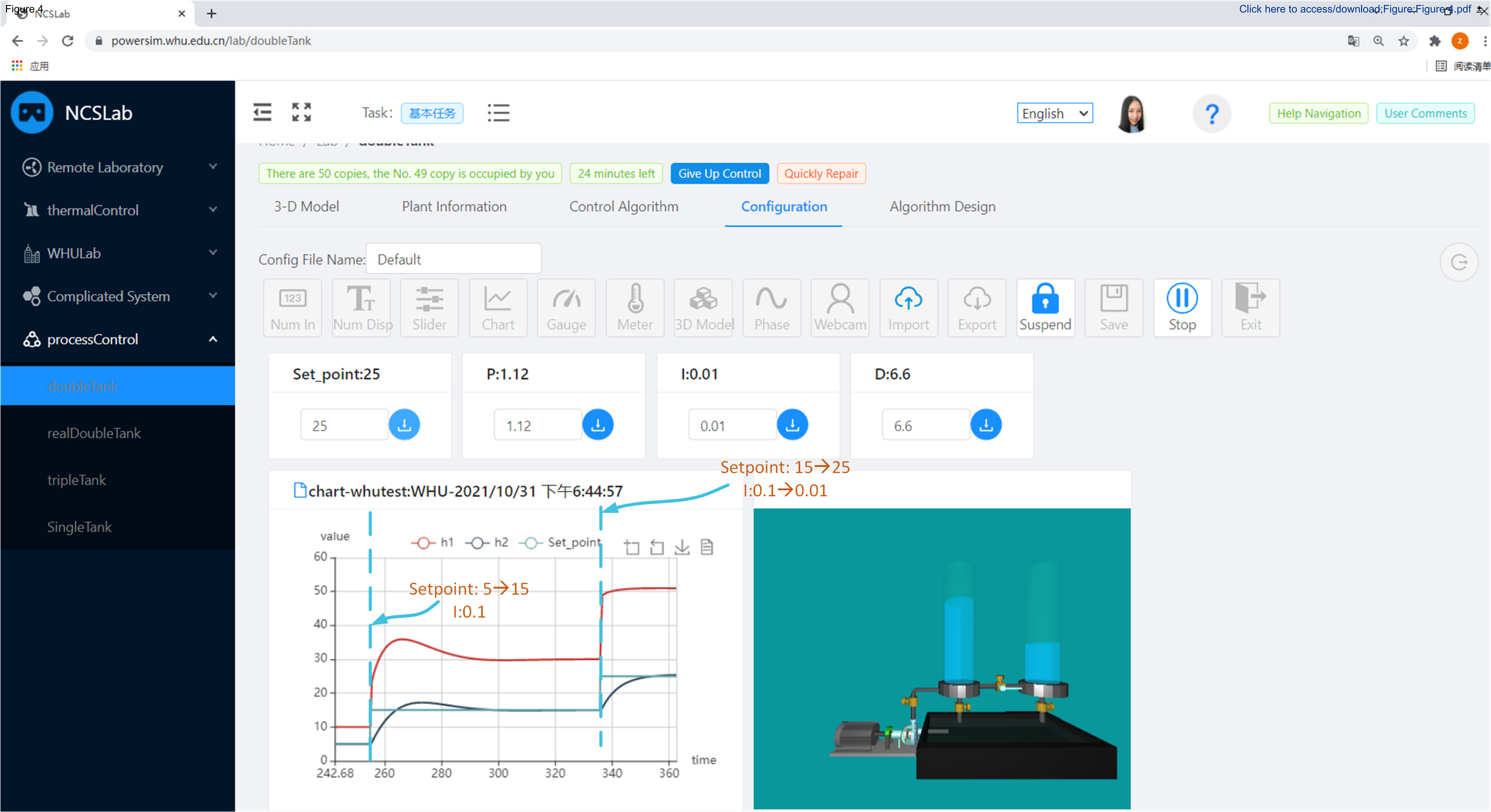

NCSLab
powersim.whu.edu.cn/lab/doubleTank
Remote Laboratory
thermalControl
WHULab
Complicated System
processControl
doubleTank
realDoubleTank
tripleTank
SingleTank
Task: 基本任务
English
Help Navigation
User Comments
There are 50 copies, the No. 49 copy is occupied by you
24 minutes left
Give Up Control
Quickly Repair
3-D Model
Plant Information
Control Algorithm
Configuration
Algorithm Design
Config File Name: Default
Num In
Num Disp
Slider
Chart
Gauge
Meter
3D Model
Phase
Webcam
Import
Export
Suspend
Save
Stop
Exit
Set_point:25
25
P:1.12
1.12
I:0.01
0.01
D:6.6
6.6
chart-whutest:WHU-2021/10/31 下午6:44:57
Setpoint: 15→25
I:0.1→0.01
Setpoint: 5→15
I:0.1
value
h1
h2
Set_point
time
60
50
40
30
20
10
0
242.68
260
280
300
320
340
360

Figure 5

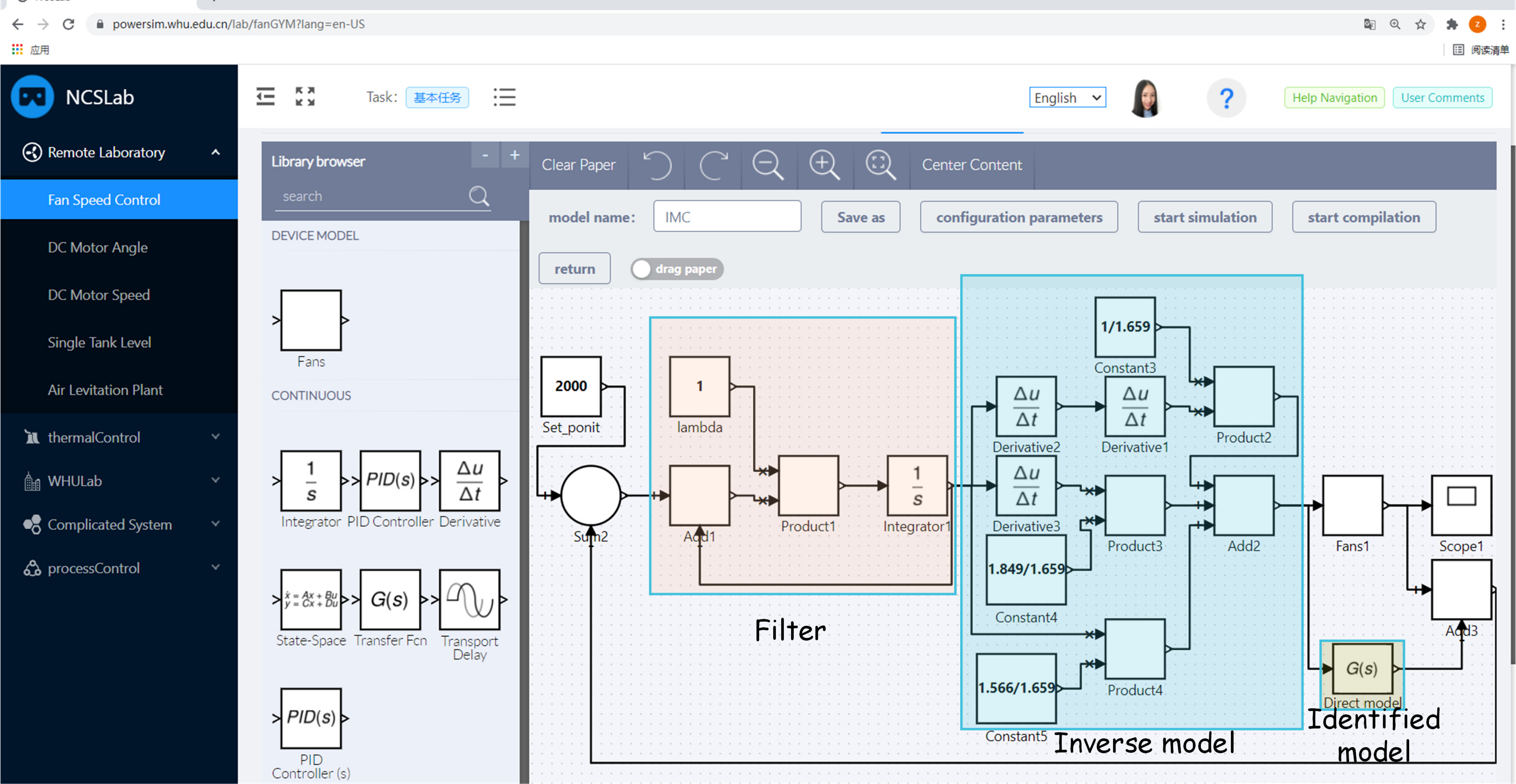

NCSLab
powersim.whu.edu.cn/lab/fanGYM?lang=en-US
应用
阅读清单
NCSLab
Remote Laboratory
Fan Speed Control
DC Motor Angle
DC Motor Speed
Single Tank Level
Air Levitation Plant
thermalControl
WHULab
Complicated System
processControl
Task:
基本任务
English
Help Navigation
User Comments
Library browser
search
DEVICE MODEL
Fans
CONTINUOUS
Integrator
PID Controller
Derivative
State-Space
Transfer Fcn
Transport Delay
PID Controller (s)
Clear Paper
Center Content
model name:
IMC
Save as
configuration parameters
start simulation
start compilation
return
drag paper
2000
Set_ponit
Sum2
1
lambda
Add1
Product1
Integrator1
Filter
1/1.659
Constant3
Derivative2
Derivative1
Product2
Derivative3
Product3
Add2
1.849/1.659
Constant4
1.566/1.659
Constant5
Product4
Inverse model
Fans1
Scope1
Add3
G(s)
Direct model
Identified model

Figure 6

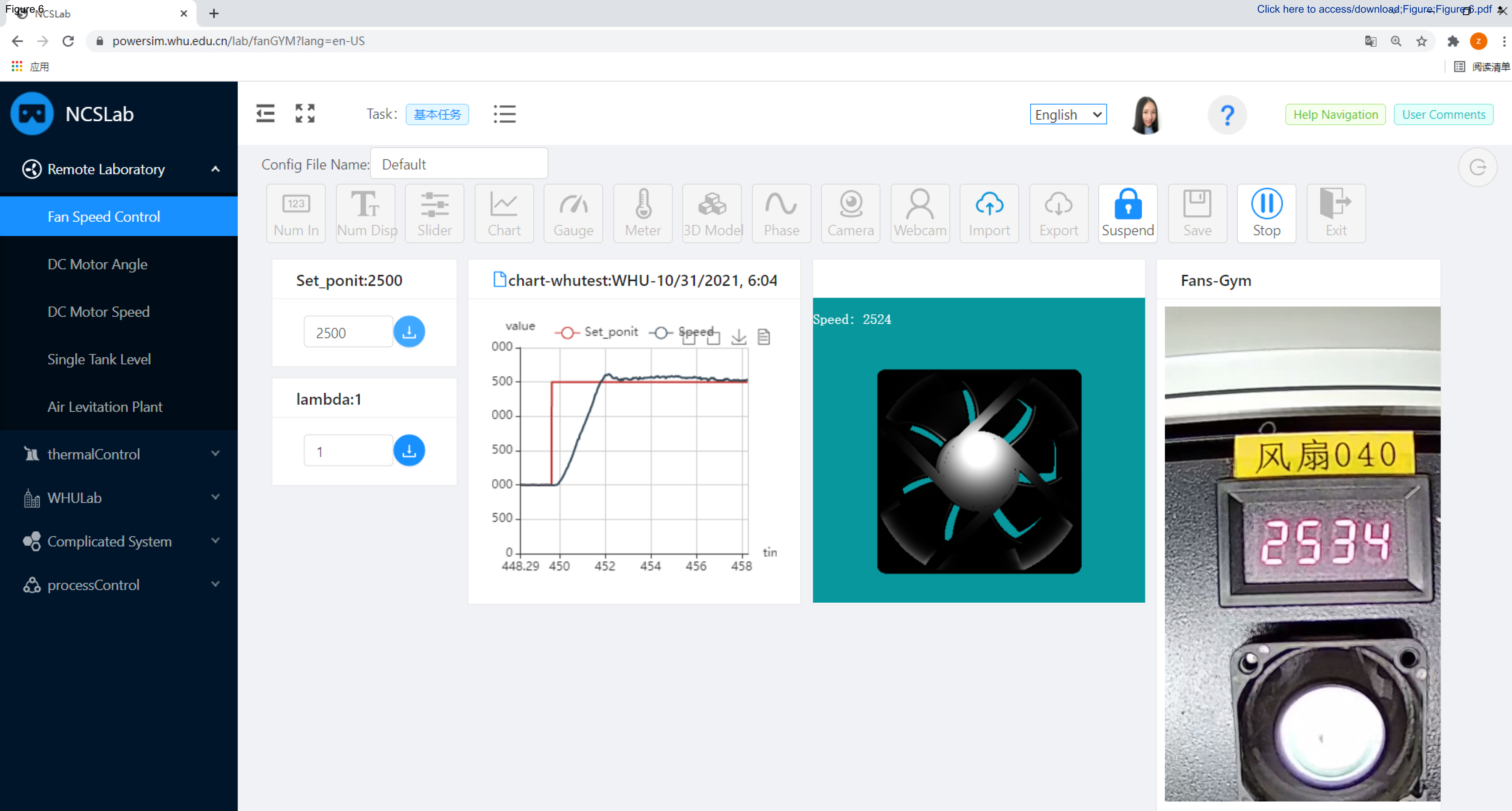

NCSLab
powersim.whu.edu.cn/lab/fanGYM?lang=en-US
Remote Laboratory
Fan Speed Control
DC Motor Angle
DC Motor Speed
Single Tank Level
Air Levitation Plant
thermalControl
WHULab
Complicated System
processControl
Task: 基本任务
English
Help Navigation
User Comments
Config File Name: Default
Num In
Num Disp
Slider
Chart
Gauge
Meter
3D Model
Phase
Camera
Webcam
Import
Export
Suspend
Save
Stop
Exit
Set_ponit:2500
2500
lambda:1
1
chart-whutest:WHU-10/31/2021, 6:04
value
Set_ponit
Speed
448.29
450
452
454
456
458
Speed: 2524
Fans-Gym
风扇040
2534

Figure 7

Click here to access/download;Fig

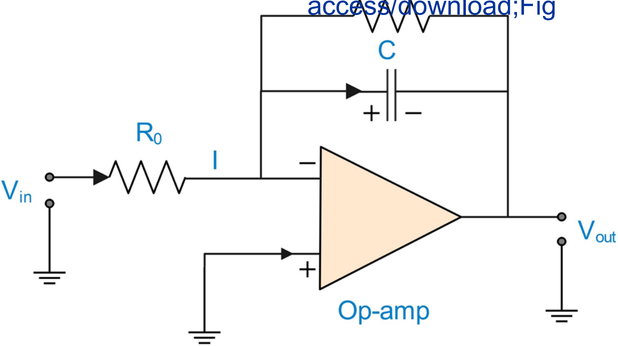


Figure 8

Click here to access/download;Figure;Figure 8.pdf

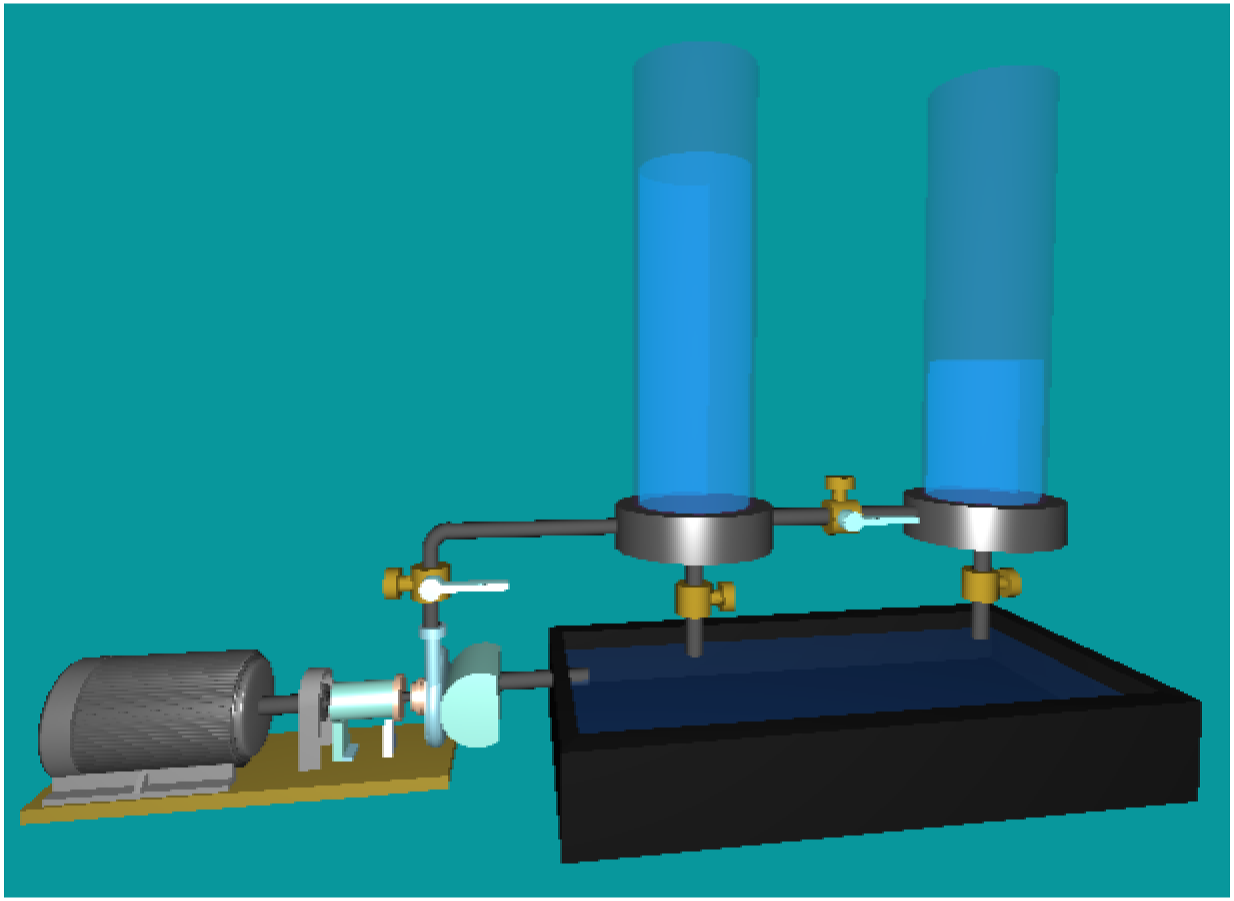
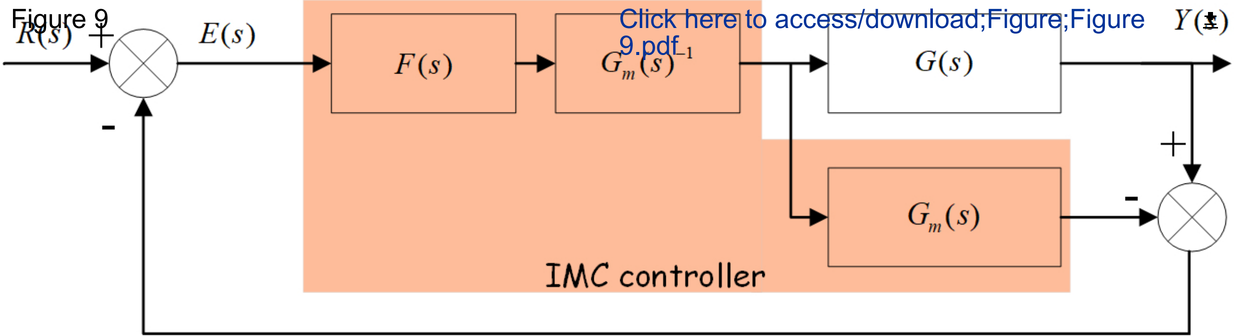


Figure 9



Parameter	**Value**
R_0	200 kΩ
R_1	200 kΩ
C	1 μF
R_2	200 kΩ
R_3	200 kΩ
Input	1 V

Click here to access/download
Table of Materials
JoVE_Table_of_Materials.xlsx

Authors' Responses to the Reviews of JoVE Submission JoVE63342R1

We would like to express our sincere thanks to the Editor for their time and effort in handling our manuscript. We have carefully considered those comments and suggestions, and thoroughly checked and revised the paper accordingly. The revisions are made in the provided 63342_R1.docx which has been uploaded to the system. All comments and suggestions are handled properly. Please refer to the DOC file fr details.

Authors' Responses to the Reviews of JoVE Submission JoVE63342

First we would like to express our sincere thanks to the Editor for their time and effort in handling our manuscript. We would also like to thank the three anonymous reviewers very much for their valuable comments and suggestions on our paper which help us to improve the paper. We have carefully considered those comments and suggestions, and thoroughly checked and revised the paper accordingly. For review convenience, the revised parts in the paper are highlighted with a blue background. The following is a detailed description about how we have addressed the reviewers' concerns in the revised manuscript.

Responses to the Editorial comments

Q - *1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. Please define all abbreviations at first use.*

A - Thank you for your patience and effort to handle this paper. We have revised the manuscript following your valuable comments. The paper has been thoroughly proofread and all abbreviations are defined in the revised manuscript.

Q - *2. Please revise your title to be within 150 characters and describe your paper more accurately. Maybe something like "A circuit-based system for online experimentation in engineering education"?*

A - Thank you for your suggestion. This work discusses three examples for visualizing online experimentation using an online experimentation system, which can be used for teaching, learning and research. Your suggested title can only cover the first example. To cover all three protocols, we have revised the title to "Interactive and visualized online experimentation system for engineering education and research".

Q - *3. Please rephrase the Summary to clearly describe the protocol and results in complete sentences between 10-50 words.*

A - The Summary has been rephrased accordingly, as presented on Page 1.

"This work discusses an online experimentation system that can provide visualized experiments including the visualizing of theories, concepts, and formulas, the visualizing of the experimental process with 3-D virtual test rigs, and the visualizing of control and monitoring using widgets such as a chart and a camera."

Q *- 4. Your protocol describes three modules that are quite specific and can perhaps be used by students and teachers for those specific topics. As stated earlier, please revise your title so that readers understand exactly what the paper and video will show. If you believe that this system is useful for other disciplines (even in engineering), please include brief notes after the steps where modification is possible and explain what the modification should be to be useful to those other fields.*

A - Thank you for your valuable suggestions. We have revised the manuscript accordingly.

Q *- 5. Please ensure that all text in the protocol section is written in the imperative tense as if telling someone how to do the technique (e.g., "Do this," "Ensure that," etc.). Any text that cannot be written in the imperative tense (e.g., provide extraneous details, optional steps, or recommendations) may be added as a "Note." Descriptions, explanations about equations etc should be moved to the introduction or discussion. This will also help keep the video portion (highlighted text) of your protocol within the three-page limit.*

A - Thank you for your comments. We have revised the manuscript accordingly. Descriptions, explanations about equations *etc*. have been moved to the discussion.

Q *- 6. Please adjust the numbering of steps and sub-steps of the Protocol to follow the JoVE Instructions for Authors. For example, 1 should be followed by 1.1 and then 1.1.1 and 1.1.2 if necessary. Please refrain from using bullets or dashes.*

A - Thank you for your comments. Bullets or dashes are not used in the original manuscript. The wrongly numbered section 1 (2.1 and 2.2) in Protocol 2 in the original manuscript have been revised to section 1 (1.1 and 1.2).

Q *- 7. Please format the manuscript as: paragraph Indentation: 0 for both left and right and special: none, Line spacings: single. Please include a single line space between each step, substep and note in the protocol section. Please use Calibri 12 points and one-inch margins on all the side. Please include a ONE LINE SPACE between each protocol step and then HIGHLIGHT up to 3 pages of protocol text for inclusion in the protocol section of the video. We can only film action steps written in imperative tense. We cannot film calculations, derivations, or any mathematical equations. Please ensure that the highlighted steps form a cohesive narrative with a logical flow. To ensure you do not exceed three pages of highlighted text, do not highlight notes and merge shorter, related, highlighted steps so that a step contains 2-3 actions and not more than 4 sentences.*

A - Thank you for your patience and effort to handle this paper. We have revised the manuscript following your valuable comments.

Q *- 8. Please note that your protocol will be used to generate the script for the video and must contain everything that you would like shown in the video. Please add more details to your protocol steps. Please ensure you answer the "how" question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action. Please ensure* *the inclusion of specific details (e.g., button clicks for software actions, numerical values for settings, etc) to your protocol steps. There should be enough detail in each step to supplement the actions seen in the video so that viewers can easily replicate the protocol.*

A - We have checked the protocol steps and any additional necessary steps have been added.

Q *- 9. Please remove all commercial language from your manuscript and use generic terms instead. All commercial products should be sufficiently referenced in the Table of Materials (e.g., Google Chrome, Microsoft Edge, Mozilla Firefox, etc.)*

A - All commercial languages are removed from the manuscript. MATLAB is mentioned in the discussion, we think it can be referenced in the manuscript.

Q *- 10. Line 117: what is this remote controller and where is it located?*

A - The sentence has been revised as "Wait until the designed block diagram is generated into an executable control algorithm that can be downloaded and executed into the remote controller that is deployed at the test rig side for the execution of control algorithms" in Lines 103-105, Page 3.

Q *- 11. Please remove the embedded figures from the manuscript text.*

A - All embedded figures are removed from the manuscript text.

Q *- 12. Please include all the figure legends after Representative Results and upload all figures as separate PDF files.*

A - We have revised accordingly.

Q *- 13. As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3-6 paragraphs with citations:*
a) Critical steps within the protocol
b) Any modifications and troubleshooting of the technique
c) Any limitations of the technique
d) The significance with respect to existing methods
e) Any future applications of the technique

A - Thank you for your advice. The discussion part has been revised accordingly.

Two sentences have been added in Lines 280-283, Page 7 to emphasize the critical steps within the protocol and any modifications and troubleshooting of the technique.
"Before the compilation of a control algorithm that can be used for real-time experimentation, simulation should be conducted to address potential issues. Using the system, control algorithms can be applied to other different test rigs once they are integrated into the proposed system."

Descriptions, explanations about equations *etc.* have been moved to the Discussion part.

***Q** - 14. Is the website https://www.powersim.whu.edu.cn/react open source? Please move all the URLs/ websites to Table of Materials and refer them in the manuscript text wherever needed. Sort all materials alphabetically.*

A - Currently the website is accessible to everyone. The URL has been removed to the Table of Materials and all materials are sorted alphabetically. As suggested by Reviewer 2, the URL has been added in the introduction.

Responses to reviewer 1's comments

Q1 ***-*** *The paper introduces three protocols for online experimentation in Control Engineering through the use of the NCSLab online labs platform. Each protocol is related to a different lab visualization example: 1) visualizing of theories, concepts, and formulas, 2) visualizing of the experimental process with 3-D virtual test rigs, and 3) visualizing of control and monitoring using widgets such as a chart and a camera.*

The protocol is easy to follow and even I was able to reproduce the steps, for Example 1, in the NCSLab website.

Major Concerns:
I have no major concerns to point out regarding this paper.

A - Thank you for your comment. We have thoroughly checked the manuscript again to improve the manuscript.

Minor Concerns:
Q2 ***-*** *A minor concern is that the paper presents three protocols for three different experiments / systems. However, they are all grouped as online experiments, so it makes sense to me to present them together in the same paper and video.*

A - Thank you for your comments. Three separate visualized experiments are provided in this paper for online experimentation, which will be presented together in this single paper and the corresponding video. we have revised the manuscript to avoid confusion.

Q3 ***-*** *A more important minor concern is that authors should make more clear for the reader that Sections 1, 2 and 3 present separate examples. I suggest them to, for example, named them as Example 1: First-Order System Using Circuit-Based Experimentation Protocol, Example 2: Interactive and Visualized Virtual Experimentation Protocol, Example 2: , Example 3:...*

A - Thank you for your good suggestions. We have made it clear that three separate examples are demonstrated in the revised manuscript on Line 74, Page 2. We have also renamed the Protocol names to make it clearer following your suggestions.

Q4 ***-*** *The last thing is that the image quality of some Figures must be improved; especially when they are shown in a one-page scale.*

A - Sorry for the inconvenience. We uploaded clear Figures in the JPG format, but it resulted in blur-generated figures. We have fixed this issue in this revised version.

Responses to reviewer 2's comments

Manuscript Summary:

The paper is generally well-written. My comments are as follows:

Major Concerns:

***Q1 -** Authors mentioned that this online experimentation tool can be used for real-time experimentation using the equipment set up located at Wuhan University. But the authors didn't mention how many users can access the equipment at a time. Is there any scheduler facility available for the users to schedule their experimentation at a particular time. If a scheduler is available, please provide the steps to schedule an experimentation at a particular time.*

A - Thank you for your comments. We have achieved for the experiment. For physical test rigs, a queue scheduling mechanism that is based on First Come First Served rule. While for virtual test rigs, concurrent access scheduling has been achieved, and test verified that virtual experimentation is capable of supporting 500 concurrent users. We had mentioned in the original manuscript that before a user can conduct an experiment, he/she has to apply for the control first, which is the step of scheduling. We have made it clearer in the revised manuscript in Lines 162-168, Page 3.

"Note: "Request Control" is the scheduling mechanism for the system. Once a user is granted the control privilege, the user can conduct experiments with the corresponding test rig. For physical test rigs, only one user can occupy the test rig at a time, and the queue scheduling mechanism has been implemented to schedule other appliers based on the First Come First Served rule [11]. For Virtual test rigs, massive number of users can be concurrently supported. 500 concurrent user experimentation has been tested effectively. For the circuit-based system, 50 users can access the system at a time."

***Q2 -** Another question I had in my mind is what would happen if a user creates a wrong circuit diagram (such as reversing the polarity of the diode, capacitor, failing to ground the circuit). Is there any real-time feedback mechanism available to alert the user regarding this error or the system will calculate the output based on the wrong circuit? Kindly provide the details of the precautions taken to avoid such errors.*

A - Thank you for your comment.

The circuit-based system is based on simulation. For simulation, the great advantage is that the users can conduct their operations freely and they do not have to worry about the consequences since their mis-operations will cause no harm to themselves and to the system and test rigs, especially in an online laboratory.

After a circuit-based system is designed, the user is supposed to run a simulation. For some cases, for example, failing to ground the circuit, the simulation and compilation results will warn the user, which can help them to recheck the designed circuit. For other cases, for example, reversing the polarity of the capacitor, no warning message will be shown when a user tries to conduct a simulation or compilation, but the simulation result may not be as supposed. So the user can re-check the system.

The following is an example of creating a wrong circuit diagram.

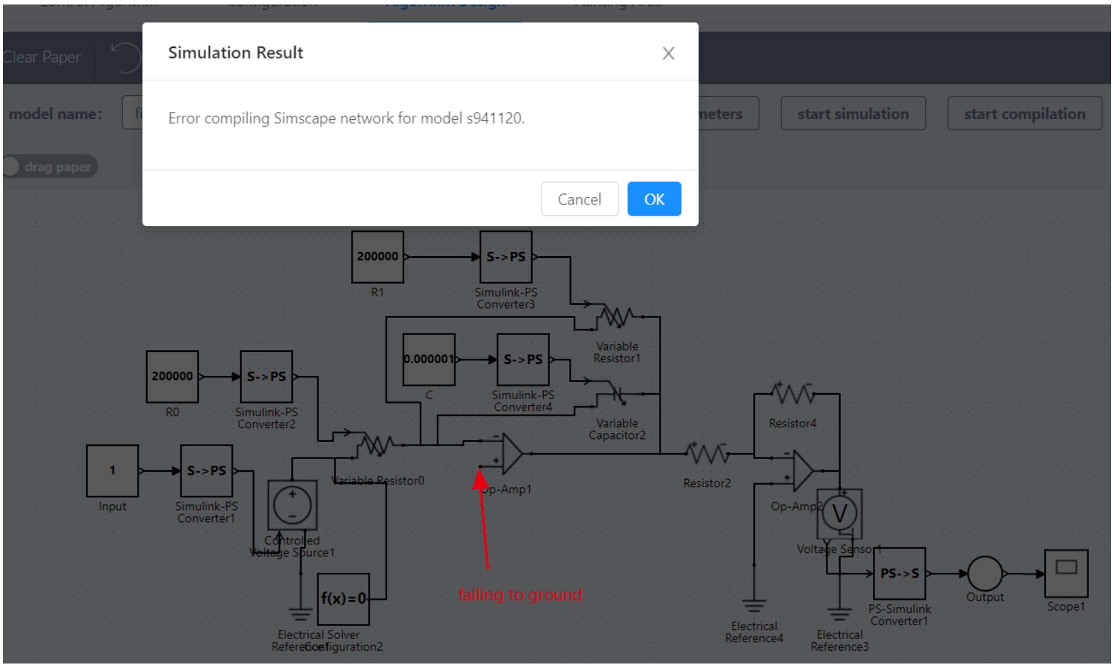


Figure a: Simulation warning when a user fails to ground circuit

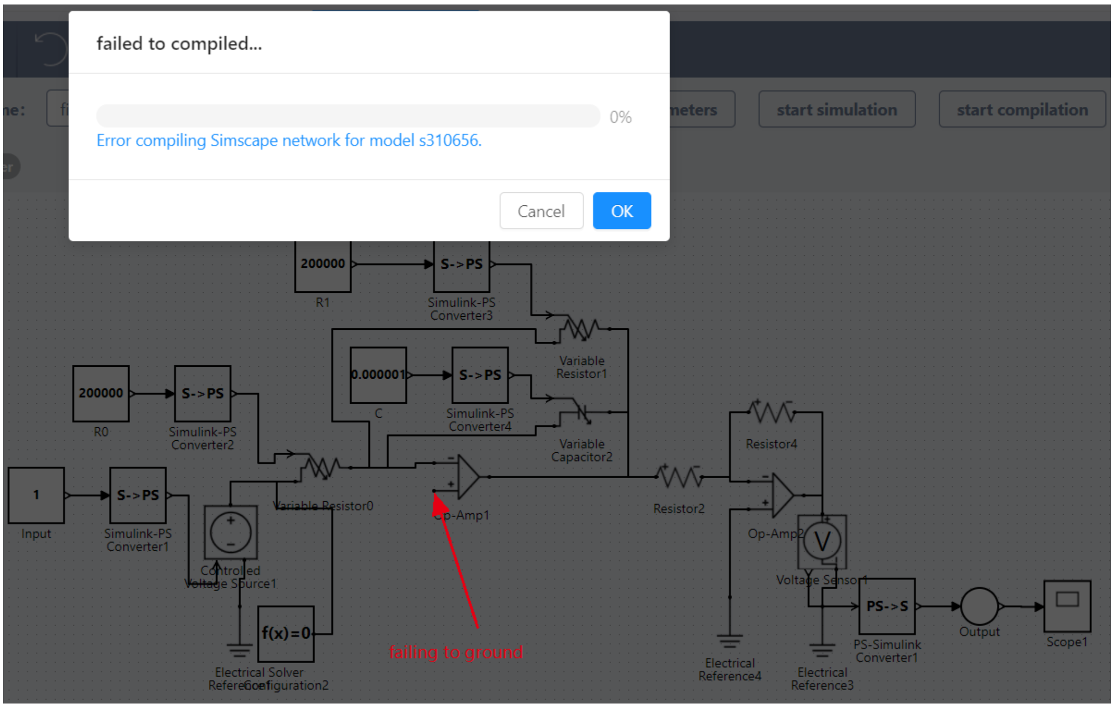


Figure b: Compilation warning when a user fails to ground circuit

In our system, reversing the polarity of the capacity will not cause any error or warning similar to MATLAB/Simulink.

Figure c: Reversing the polarity of the capacity.

Figure d: The polarity of the capacity is correct.

A NOTE has been added in 1.8 in Example 1 in Lines 99-102, Page 3 in the revised manuscript.

Minor Concerns:

***Q3 -** There are typographical errors in Figure 8 and 9. Set point is wrongly written as "setponit" and lambda is written as "lamda".*

A - Thank you for your comment. We have replaced Figure 8 and 9 (Figure 5 and 6 in the revised manuscript) and fixed the two typographical errors. We have revised the main text accordingly.

Q4 - *Lack of consistency in naming parameters in Table 1. Resistor 0 and 1 written as R0 and R1. But 3 and 4 written as "Resistor3" and "Resistor4"*

A - Thank you for your comments. To avoid confusion, we have revised "Resistor3" and "Resistor4" in the original Figure 2 (Figure 1 in the revised manuscript) and Table 1 to "Resistor2" and "Resistor3", and written as R2 and R3 to keep consistency.

Responses to reviewer 3's comments

Manuscript Summary:

Q1 - *The manuscript describes three activities that can be conducted in an engineering class, ranging from completely virtual to remote physical labs. The proposed activities are well-detailed with supporting images.*

A - Thank you for your comment. We have further improved the manuscript following your, the editor's and the other two reviewers' valuable comments and suggestions.

Major Concerns

Q2 - *To me, this reads like step-by-step instructions for a student completing these three particular lab activities. If this is meant for instructors, and not students, then it is unclear what the students are doing as it seems like the instructor would be doing all the work while students watch. I was not able to find anything generalizable in the protocols (ie, I do not see how I can implement this in my own classroom to teach anything other than these three concepts exactly as outlined). Can I vary any of the parameters? If so, which ones and how? The instructions are very well-written as specific examples of how this type of activity can be carried out. But how can this protocol be applied in another classroom that may need to achieve similar (but not exactly the same) learning outcomes? Can it be, or is this the only way that this approach can be used?*

A - Thank you for your comment. The article provides three examples for engineering education and research. Regarding education, both teaching for teachers or instructors and learning for students are possible. The teacher can conduct classroom online experimentation using the proposed system and instructions while explaining the concepts, formulas and theories. In this scenario, the students can watch and learn, and the provided practice can potentially enhance their comprehension of theoretical knowledge. Students can also complete those lab activities in their after-class experimentation using the proposed system and instructions.

Currently, the system is open and can be accessed via https://www.powersim.whu.edu.cn/react at 24/7 basis. Other teachers or students outside Wuhan University can access the system can implement this in their own classroom to teach more than the provided three examples. Of course a user can vary the parameters as demonstrated in the three protocols, for example, Protocol 1 Step 1.16 and Protocol 2, Step 1.7.

The system provides several different physical and virtual test rigs, and allows users to design and implement their own control algorithms, and customize the monitoring interface, thus, it can definitely be applied to different classroom scenarios.

Q3 - *Additionally, is this approach effective? Have students effectively learned from this approach? What evidence is there that they have?*

A - Thank you for your comment. The circuit-based system is newly developed. The other two examples (Examples 2 and 3) have been applied into teaching and learning for several years, and the effectiveness has been verified by the Reference [6] in the revised manuscript.

In the future, we will continue to apply the approach in education and research, and properly evaluate the effectiveness after the applications.

Reference:

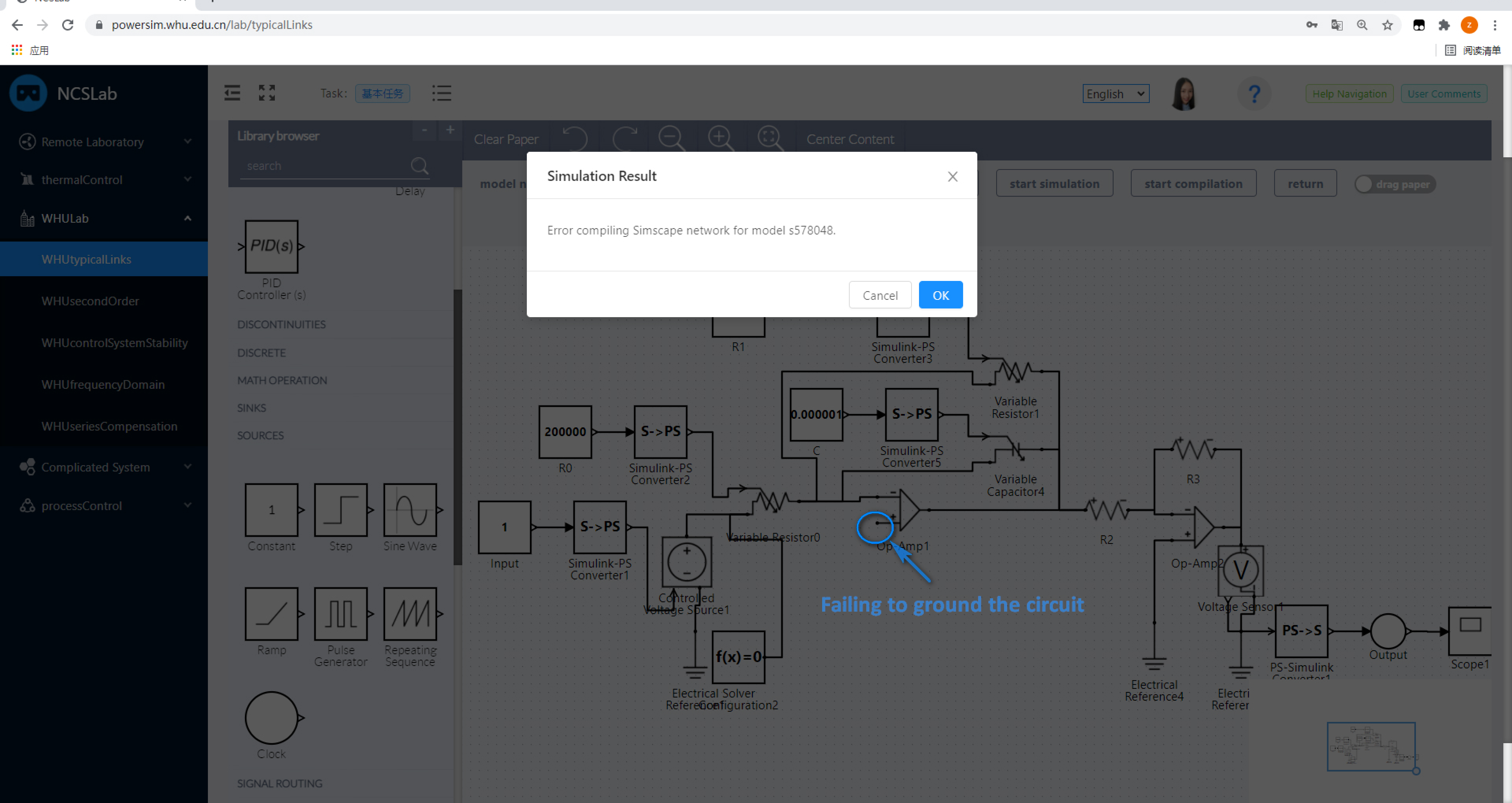
[6] Lei, Z., Zhou, H., Hu, W., and Liu, G.P. Unified and flexible online experimental framework for control engineering education. *IEEE Transactions on Industrial Electronics*. 69(1), 835–844 (2022).

Minor Concerns:

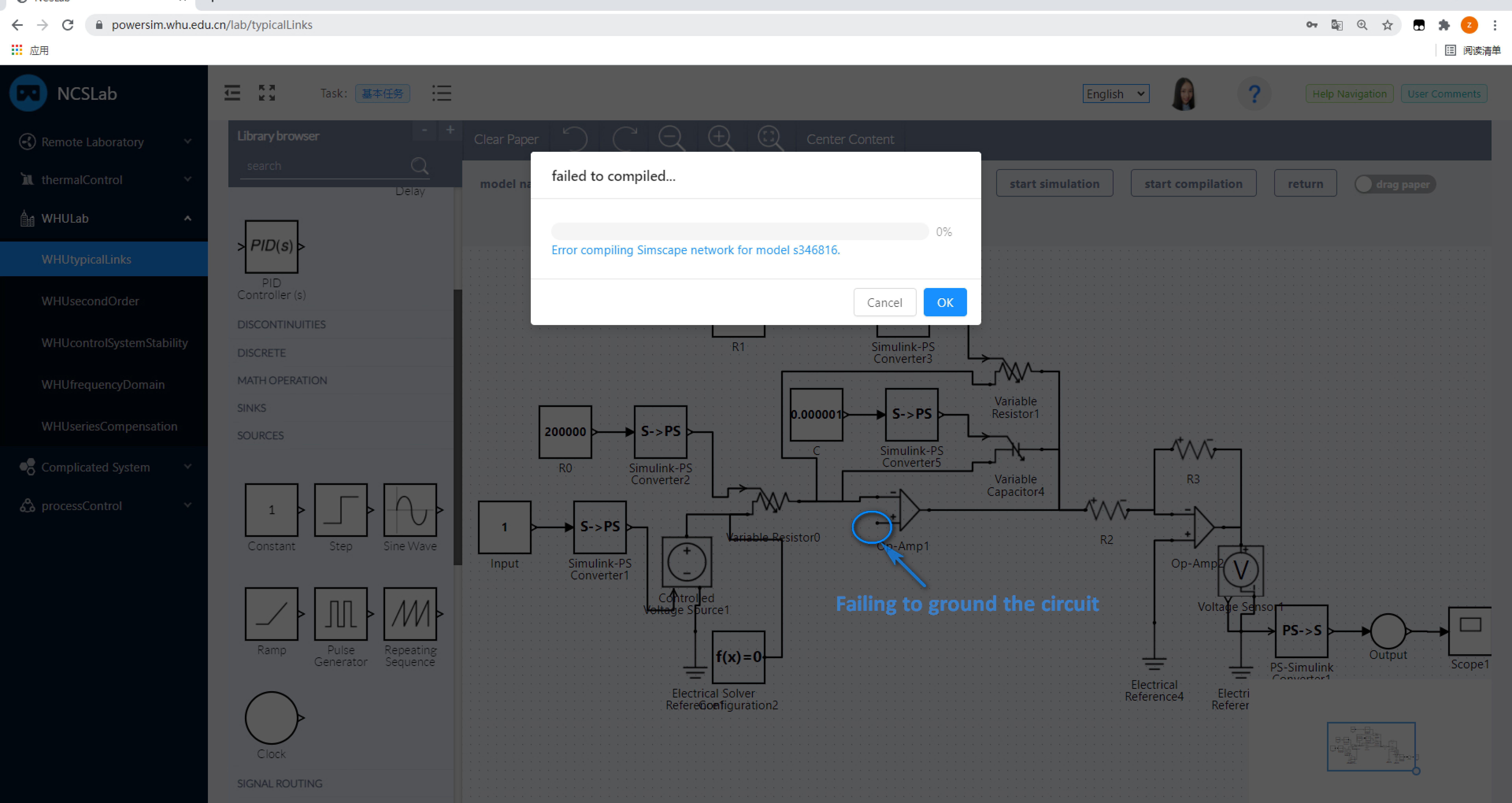
Q4 - *The introduction can be improved by discussing what tools/websites are necessary to execute the protocol. As it reads, I do not have a clear indication of what I would need to execute this protocol.*

A - Thank you for your suggestion. The tools/websites that are necessary to execute the protocol were provided in Protocol 1, Step 2 in the original manuscript. We have improved the introduction by adding the website in Lines 75-76, Page 2 in the last paragraph of the Introduction part in the revised manuscript.

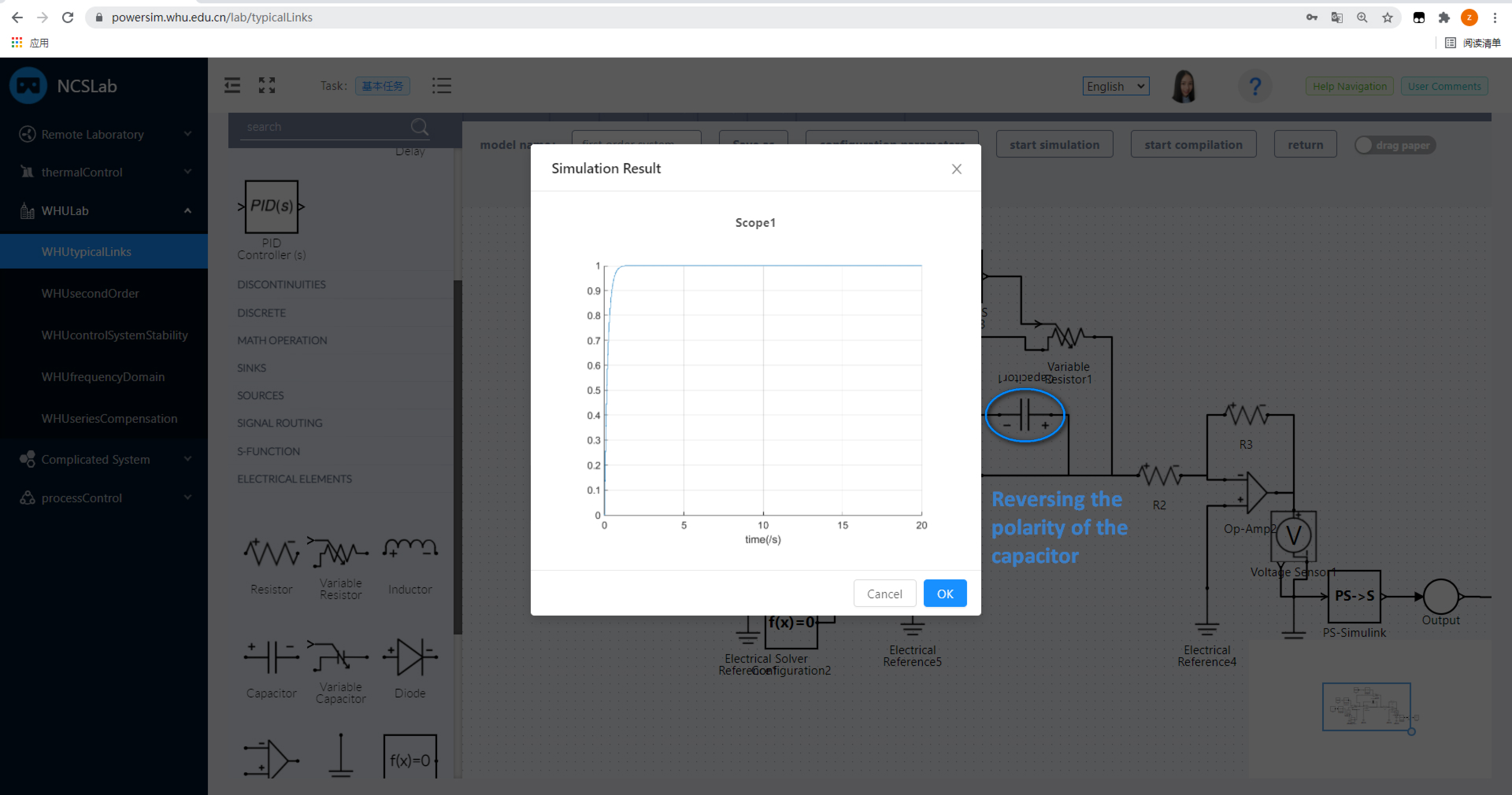
Supplementary Figure 1



Supplementary Figure 2



Supplementary Figure 3



Supplementary Figure 4