A Case of 3D Virtual Laboratory Design Implementation and Intelligence for Mechatronics Courses

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Abstract

Laboratory courses play a pivotal role in higher education, and with emerging technologies transforming instructional practices, virtual laboratories have become an effective supplement to traditional, face-to-face settings. This paper presents a Unity3D-based virtual production line laboratory platform developed under the ADDIE instructional design model (Analysis, Design, Development, Implementation, Evaluation). The physical assembly line was replicated in a virtual environment and deployed via WebGL on a custom website, enabling students to engage in experimental learning at any time. Additionally, On the student client, we have visualised PLC programs and designed an image recognition module that enables students to visually verify the correctness of their PLC programs. Implementation with second-year undergraduates demonstrated positive impacts on academic performance.

Keywords Educational Technology; Virtual Laboratory; Unity3D; Online Learning; PLC Programming; Visualization; Image Recognition

1 Introduction

In recent years, in order to proactively respond to the latest wave of technological revolution and industrial transformation, the core task of engineering education has shifted to talent cultivation. Crucially, this shift hinges on the pedagogical approaches that instructors adopt to teach scientific skills and on fostering student enthusiasm for learning[1-3]. Within the context of scientific skills acquisition, experiential learning constitutes an indispensable component of educational processes [4-5]. At the undergraduate level, experiential learning often manifests as laboratory coursework: instructors initially demonstrate theoretical principles in the classroom [6-7] and subsequently guide students to laboratory settings for hands-on work and data analysis [8]. This integration of theory and practice cultivates a range of scientific competencies required for teamwork, research, and independent learning [9-10].

Traditional laboratory courses afford students opportunities for hands-on exploration and discovery, whereby unexpected scientific phenomena may ignite their interest in research [11]. However, in conventional experimental instruction, practical engagement with physical equipment is the only modality. However, not all educational institutions have well-equipped laboratories, which means that a huge amount of investment is required [12]. By contrast, computer-based online learning obviates extensive investment in hardware and maintenance, while mitigating risks associated with equipment mishandling and public health concerns such as pandemics [13]. Consequently, this paper proposes a three-dimensional virtual simulation platform for production line cognition and PLC programming, serving as an effective complement to traditional production line simulation laboratories.

The proposed platform delivers cognitive learning via a web interface accessible through standard browsers. It eliminates constraints related to equipment load, laboratory space, and fixed class durations, thereby enabling large-scale classroom experiments. This platform supports mainstream browsers such as Edge, Chrome, and Firefox, through which the website of the experimental teaching management platform can be accessed. Students can engage in interactive activities and conduct self-study on the platform, including downloading materials, watching videos, and completing virtual experiments. Through the experimental teaching management portal, instructors can assign grades and manage participants [14]. For advanced PLC program validation, the client-side Unity application incorporates preconfigured verification nodes to gamify program testing step by step, provide corrective feedback, and assist students in debugging. Moreover, the web portal's modular design affords high extensibility to accommodate evolving instructional needs. Beyond completing virtual experiments, the platform supports courseware downloads, online report submissions, automatic scoring, and user administration.

This paper aims to detail the development of a Unity-based virtual laboratory, supplemented and deployed via a custom website, which not only facilitates production line cognition but also enables hardware - free PLC program verification, fulfilling the pedagogical requirements of laboratory instruction without physical apparatus.

2 Related Work

2.1 Current Status of Virtual Simulation

Contemporary experimental instruction increasingly leverages virtual and remote laboratories for online learning [15]. Virtual laboratories are entirely software-based environments constructed through computer simulation and virtual reality technologies, in which students perform experimental operations and learning activities [16]. These laboratories present digital models of real experiments via a computer interface, enabling observation of experimental procedures and outcomes without physical apparatus [17]. Remote laboratories, by contrast, allow learners to operate equipment located off-site via the web, offering a more authentic experience through direct interaction with physical instruments [18-19]. However, remote laboratories entail additional costs in communication infrastructure and sensory control hardware and software, as well as maintenance overhead, and they permit only one user per workstation at a time, which limits efficiency [20]. Based on prior findings, computer-based virtual simulation laboratories currently appear more attractive for reducing costs and enhancing learning efficiency.

2.2 Impact of Virtual Simulation Technology on Traditional Experimental Instruction

Traditional laboratory pedagogy typically follows a "theory-lecture plus hands-on practice" model: instructors first present theoretical knowledge and fundamental principles, and students subsequently validate and consolidate learning through practical operation in the laboratory. Experimental apparatus usually includes mechanical devices, sensors, controllers, and power supplies, with students required to follow prescribed procedures, observe phenomena, and record data. This conventional approach, however, exhibits the following significant limitations, which virtual simulation technology can effectively address [21].

1) High equipment costs and delayed upgrades. Traditional laboratories require purchase of physical devices (e.g., OSLO-3 process simulators, ABB controllers, etc.), whereas digital twin technology constructs high-fidelity virtual systems by integrating hardware models (costing approximately 5% of real equipment) with simulation software (accounting for 20.9% of license costs). This approach achieves a 95% reduction in hardware investment per device and an overall 26% cost saving in laboratory construction [12]. For control units, digital twin-based PLC controllers cost only 0.6% of their physical counterparts (versus 10% in traditional schemes) and can be upgraded via software to accommodate technological iterations, thus avoiding downtime due to equipment aging.

2) Temporal and spatial constraints and safety risks. Traditional laboratories operate fixed equipment in designated spaces, resulting in limited hands-on time per student. For example, Hou [22] reported that only two students could simultaneously perform a membrane material fabrication experiment at temperatures up to 700 °C, severely restricting instructional progress. By developing a virtual platform, Hou enabled over 50 students to safely conduct the experiment online, resulting in an increase in assessment scores from 60 to 90 points through repeated practice.

3) Standardized processes inhibiting innovation. Conventional experiments emphasize validation tasks, leaving little room for student-driven design. Broughton [23] argued that traditional methods heavily depend on instructor guidance, hindering independent innovation. In a subsequent virtual platform implementation, Hou provided multiple experimental pathways with immediate feedback, fostering enhanced creativity among students.

4) Unidimensional assessment and delayed feedback. Traditional evaluation focuses on result accuracy, neglecting process-oriented skills. Li [24] introduced Direct Observation of Procedural Skills (DOPS) as a formative assessment tool, combining real-time observation, instant feedback, and dynamic scoring to shift emphasis from outcomes to skill acquisition. The implementation of DOPS raised first-

attempt success rates of students' experiments to 93.3% and reduced average completion time by 7.6 minutes, demonstrating the efficacy of process-oriented evaluation in facilitating skill development.

Drawing on Benjamin Franklin's adage, "Tell me and I forget; show me and I may remember; involve me and I understand," this paradigm underscores the imperative for integrating immersive virtual scenarios into mechatronics laboratory pedagogy. By overcoming high equipment costs, temporal and spatial limitations, safety risks, and assessment constraints, virtual simulation can reduce financial and logistical barriers while providing students with greater opportunities for autonomous exploration and innovation, thereby significantly enhancing pedagogical outcomes.

2.3 Technological Support

The platform integrates several software tools: Unity3D, 3ds Max, NetToPLCSIM, and TIA Portal V18. These components collectively facilitate web-based cognitive learning and local program validation.

1) Unity3D supports importing standard 3D models from software such as 3ds Max, Maya, and Blender, and employs an efficient OpenGL rendering pipeline that ensures satisfactory graphical quality on lower-end devices. Critically, Unity's WebGL support allows users on Windows systems to run simulations directly in a browser without plugin installation [25]. This dual deployment—online via WebGL for cognitive learning and offline via a local Unity client for PLC visualization—makes Unity3D an ideal development environment for virtual laboratories [26-27];

2) 3ds Max is a powerful 3D modeling and animation tool capable of reducing model polygon counts, thereby optimizing resource consumption in simulation environments [28];

3) TIA Portal V18 is Siemens' integrated automation software, providing a unified platform for deploying programs to PLCs [29]. Although no dedicated educational edition exists, a 30-day trial available from the official website suffices for the study's three-week course duration.

4) Given that one of this study's priorities is cost reduction, the course design implements hardware-free validation for students' PLC programming. A critical component of this approach is the NetToPLCSIM software, a freely accessible tool that functions as an S7 protocol converter. By leveraging the TCP/IP standard communication protocol, NetToPLCSIM establishes a communication link between TIA Portal V18 and external software or devices, thereby enabling bidirectional data exchange between TIA Portal V18 and Unity [30]. This configuration allows students to locally verify the correctness of their PLC programs through visualized feedback within the Unity environment. The interconnections among the relevant software components are illustrated in Figure 1. The core architecture involves Unity-based virtual laboratory construction following model importation. On one hand, WebGL technology facilitates online cognitive learning through browser-accessible simulations. On the other hand, NetToPLCSIM serves as a middleware bridge, enabling visual validation of PLC programming logic within the Unity environment.

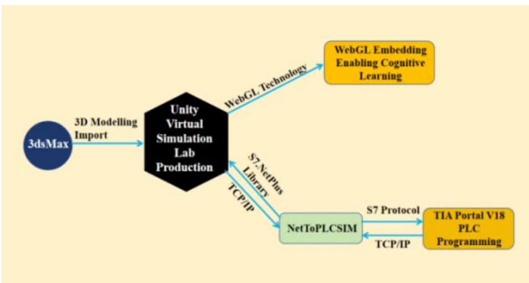


Fig. 1. Networking of software used

3 Method

As noted above, virtual laboratories have become an effective complement to face-to-face labs; however, constructing an instructional virtual laboratory is a complex endeavor that integrates expertise in interaction design, visualization, and pedagogy. To guide this process coherently, we adopted the ADDIE model as our systematic instructional design framework [31], as illustrated in Figure 2.

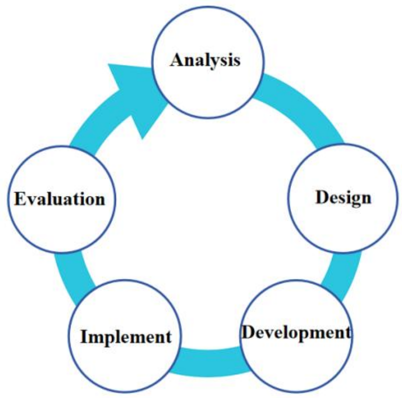


Fig. 2. ADDIE model

The ADDIE model comprises five phases: Analysis, Design, Development, Implementation, and Evaluation. The specific steps for developing the virtual laboratory platform are as follows:

Analysis: Define the learning objectives and list practical activities.

Design: Specify functional requirements for each activity.

Development: Build the virtual laboratory environment and create the PLC program visualization and validation modules.

Implementation: Deploy the platform to the web and integrate all resources.

Evaluation: Assess content and instructional design to inform future improvements.

In the following subsections, we detail the development process, the tools employed, and the rationale for their selection.

3.1 Analysis of Instructional Content

The instructional platform emulates a real-world assembly line by constructing a virtual counterpart that faithfully reflects the operational states of actual equipment. Through this virtual simulation, students can learn the working principles of machinery and key components, experiencing a safe yet realistic assembly process that fosters comprehensive understanding of automated manufacturing workflows [32]. Additionally, by authoring PLC programs to drive the simulation, students enhance their practical programming skills and problem-solving abilities [33]. Table 1 summarizes the experimental content and sequence.

Table 1. Production line knowledge chain

Sequences	Content
1	Understanding the principle of the experiment
2	Defining the objectives of the experiment
3	Demonstration of the function of the production line simulation
4	Understanding the overall layout of the production line
5	Demonstration of the simulation of the assembly of components
6	The whole process of the assembly of the entire line of experiments
7	Principle of the key components
8	Single-station assembly experiments
9	PLC program single-station visualization experiments
10	PLC program visualization experiments of the entire line of experiments
11	Writing and submitting the experimental report

3.2 Platform Design

The virtual simulation experimental platform typically comprises physical equipment entities, virtual simulation models, communication networks, and data elements. As illustrated in Figure 3, the proposed platform architecture integrates several core components: three-dimensional model development using

3dsMax software, detail optimization of virtual mapping models within the Unity3D environment, virtual simulation model construction, and simulation software programming. The implementation workflow involves importing 3D models created in 3dsMax into Unity3D for virtual laboratory development, subsequently deployed via WebGL to web-based platforms for cognitive learning. Following comprehensive study of component taxonomy, operational principles, and kinematic mechanisms, learners engage in local PLC programming. Final validation of program accuracy is achieved through S7 protocol communication establishing data interoperability between Unity3D and TIA Portal, facilitated by a visualization interface.

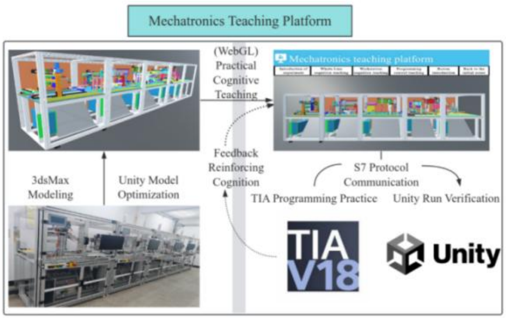


Fig. 3. Production line virtual simulation module framework

3.3 Development

The platform3D Modelling

Modeling of the laboratory environment, virtual equipment, and platform elements involves measurement of real-world data, 3D construction, and texture mapping for scene materials [34]. The fidelity of these models directly affects the rendering quality of the virtual laboratory.

Employing 3ds Max for modeling should pay attention to the restoring of the real scene of the production line. All models on that platform are modeled accord to the structure and size of the actual model. The key modeled components include the micro-control peripheral unit, workpiece trays, cylinders, linear encoders, ball screws, sensors, motors, PLC units, cam indexers, vacuum suction cups, robotic end-effectors, gear-rack transport mechanisms, synchronous belts, and hoppers. During export to Unity3D, attention was paid to scaling: 3ds Max and Unity3D use a default ratio of 0.01:1, and Unity interprets units in meters. Models were exported in FBX format with a 1:1 scale. Figure 4 presents the assembly line model, and a detailed comparison of virtual and physical devices is provided in Appendix A.

Fig. 4. Production line 3D scene

3D Virtual Simulation Interface Development

Unity3D served as the development engine, with the 3D simulation module structured into a presentation layer, an application layer, and a resource layer, as depicted in Figure 5. The resource and presentation layers form the foundational modules. The presentation layer delivers the user interface, interactive elements, and audiovisual effects, while the application layer governs the logic and controls interactions. In essence, the presentation layer provides the stage for human–computer interaction, and the application layer directs its script.

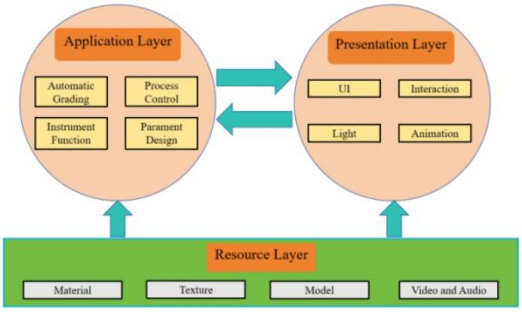


Fig. 5. 3D simulation module framework diagram

The presentation layer critically influences learner's immersive experience and consequently affects student engagement and learning efficiency [35]. Interaction and feedback are key to the Presentation Layer. Interaction and feedback mechanisms—embodied in buttons, audio cues, lighting effects, and text prompts—are orchestrated alongside guidance measures to enhance the learner's immersive experience. The overall interaction structure is illustrated in Figure 6.

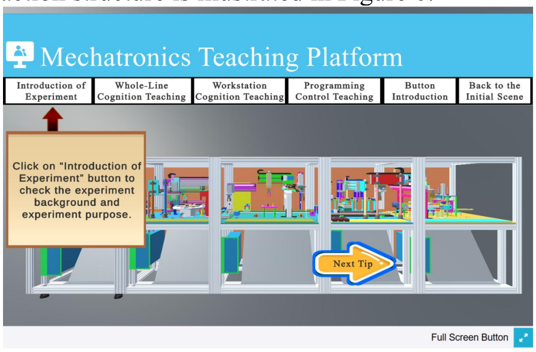


Fig. 6. Interface and performance examples

Development of Equipment Functions

The instructional content focuses on analyzing the operation of a five-workstation assembly line system, where synchronized processes—including component loading/unloading, sequential assembly, quality inspection, and sorting—are executed under coordinated control. As illustrated in Figure 7, the workpiece undergoes progressive integration of four critical components: base, gasket, shaft, and bushing culminating in mechanical integration and unloading at Workstation 5.

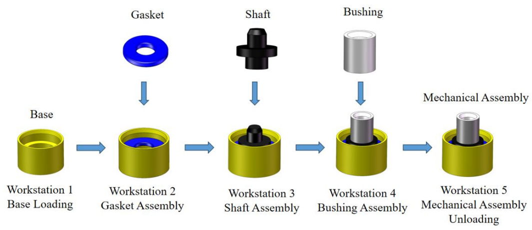
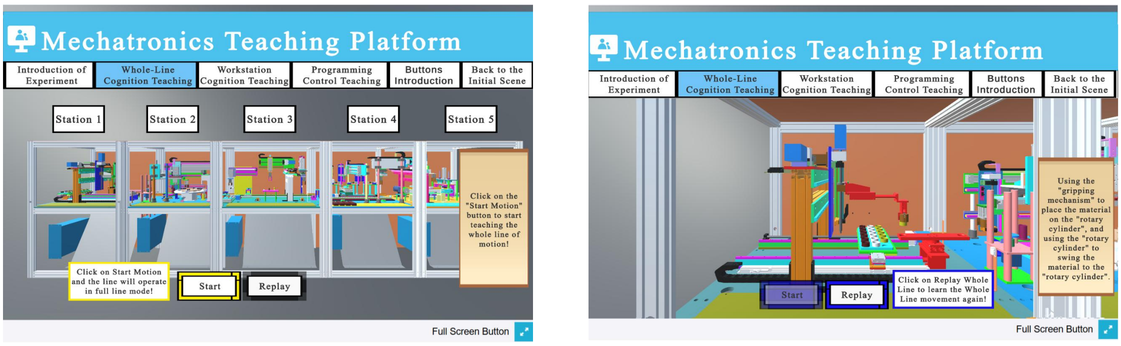


Fig. 7. Product assembly process and the function of each station schematic diagram

Web-based Virtual Laboratory Functions

When learning cognitively on the web site, the complete embodiment of the assembly process is the whole-line cognitive teaching module, in which the learner can completely follow the workpiece to complete the assembly process, during which the learner learns how to collaborate with the various workstations, and learns about the layout of the production line from a holistic point of view, and roughly how the key components work, and at the same time, during the movement of the whole-line of the equipment, there will be a voice broadcast and subtitles display, and the components in motion will have "red markers flashing" to facilitate students to have a clearer understanding of the equipment. The whole-line cognitive teaching interface is shown in Figure 8(a), and the components with "red markers flashing" are shown in Figure 8(b).

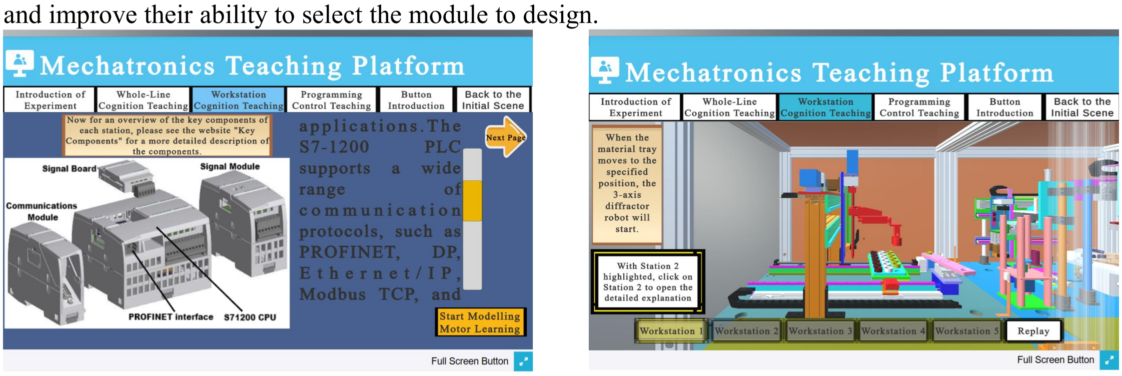


(a) Whole-Line cognition teaching interface

(b) Red markers flashing

Fig. 8. Whole-Line cognitive functions

Whole-Line Cognition Teaching is a macro understanding of the production line operation. In order to give learners a complete knowledge, there is need of Workstation Cognitive Teaching to explain in detail as shown in Figure 9. First of all, it explains the working principle of the key components for the learners, and embodies in the components movement afterwards to give the learners a deep impression and improve their ability to select the module to design.



(a) Description of component principles

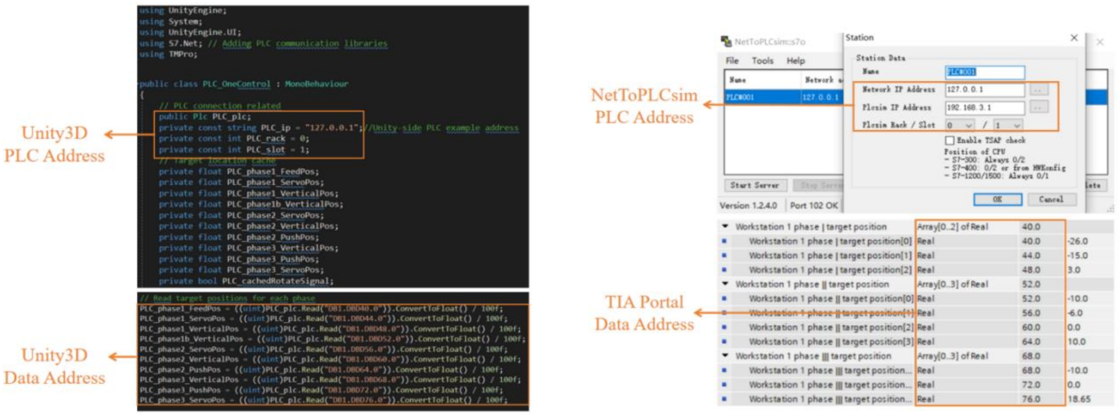
(b)Workstation operating status

Fig. 9. Workstation cognition function

Local Client-based Virtual Laboratory Functions

The PLC programming and control teaching module is carried out in the learner's local client and is based on the communication between TIAPortal and Unity3D, followed by the creation of the corresponding interaction logic that guides the learner to the visual validation of the complete PLC program. As stated in the previous technical support, this paper uses the NetToPLCSIM software as the tool for communication, the reason being that the use of this software enables the data blocks within TIA Portal to be exposed to the outside world without the need for a real PLC, thus achieving data interoperability [36].

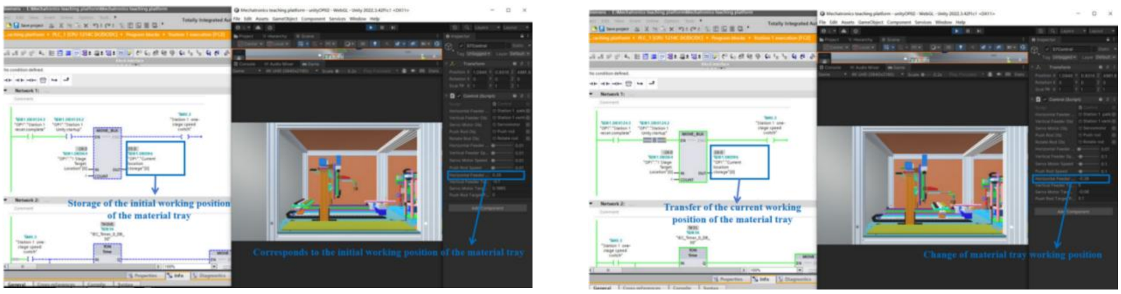
To make TIA Portal communicate with Unity3D, the PLC address of both parties should be determined first. The PLC Address in TIA Portal is created automatically, and it is 192.168.3.1 in the NetToPLCsim PLC Address example in Figure 10(b), and the PLC Address of Unity3D is customized during the creation of the instance in Figure 10(a), specifically 127.0.0.1. In Figure 10(a), the PLC Address of Unity3D is customized during the creation of the instance, specifically 127.0.0.1, and then the addresses of both sides are filled in NetToPLCsim, and then two-way communication can be carried out by executing Start Server. Secondly, the specific data change operation is achieved by modifying the content under the data address. After the definition of the Data Address in TIA Portal is completed, the content of the TIA Portal Data Address will be received and stored in Unity3D. Then, the dynamic change of the data stored in the Unity3D end can be realized only by changing the data content in the Data Address of the TIA Portal, and the movement of the Unity3D components can be controlled by the TIA Portal through using the stored data to drive the components movement.



(a) Unity3D communication related C# code (b) NetToPLCsim and TIA portal related fill-in information

Fig. 10. TIA portal and Unity3D communication situation

The communication effect can be achieved by programming the PLC ladder program to change the position of the material tray as shown in Figure 11, for example, at station 1 the initial working position of the material tray is stored as "35.0", and the corresponding initial coordinate position of the material tray in the Unity virtual model is "0.35". (Because Unity is in metric system, the data is converted from PLC to Unity by dividing it by 100.) When the data in the ladder program is modified to "-26.0", the position coordinate of the material tray in the corresponding Unity virtual model is moved to "-0.26".



(a) PLC program before power-up (b) PLC program after power-up

Fig. 11. Portal programming control results

Compiling and Exporting Scenarios

Unity3D supports packaging projects as WebGL builds for browser deployment. To assess performance impact, we used Unity's Profiler in Game mode, focusing on memory consumption. Because this project will eventually be deployed to a web page, this performance is most likely to cause stuttering or even crashes. The analysis—shown in Figure 12—indicates the virtual laboratory occupies 0.94 GB of total memory, of which 0.64 GB is used by Unity3D. Textures and Meshes are the primary resource consumers, and the scene contains 10,703 objects.

Fig. 12. Profiler performance analysis results

In a browser environment, the WebGL build consumes 0.30 GB (total occupied memory minus Unity occupied memory), which is acceptable for most students' machines with ≥8GB RAM. Additionally, Unity's Statistics panel reports an average frame rate of 99.3 FPS (Figure 13), comfortably above the 60 FPS threshold for perceptual smoothness.

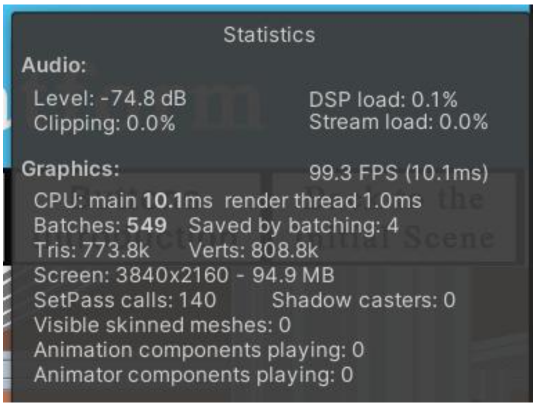


Fig. 13. Scene information in game mode

Website Deployment

We use PHP to build the HTML pages and MySQL for database management, both of which are open-source and free-to-use tools [37], which fits our low-cost theme. Unity automatically creates an Index.html file when exporting WebGL, which is used when deploying the project to the website. When deploying the project to a website, it is necessary to find the core code shown in Figure 14 and insert it into the desired webpage.html file in order for WebGL to work properly.

Fig. 14. WebGL running core code

The final web page deployment effect is shown in Figure 15. Caution Area as notes, Real Equipment Motion Video Area contains the video of the operation of the physical equipment, Critical Components Data Viewing Area contains the introduction of the selection of key components, Virtual Simulation Teaching Area is used as a virtual laboratory to show the learning content.

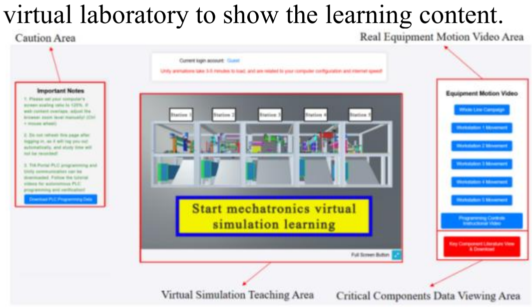


Fig. 15. A complete virtual lab webpage

3.4 Implementation

The platformConfiguration parameters testing

The configuration of this computer is shown in Table 2 below.

Table 2. Computer configuration descriptive information

Form	Element
CPU	AMD Ryzen 7 5800H with Radeon Graphics 3.20 GHz
GPU	NVIDIA GeForce RTX 3060 Laptop GPU
RAM	16.0 GB
OS	Windows 10 22H2
Network Speed	Higher than 3M

Browser Performance Testing

In the local test, without using any plug-ins, the performance test results of the latest version of mainstream browsers are shown in Table 3.

Table 3. Test results of different browsers

Browser Type	First load time	Not clearing cache secondary load time
FireFox	215 seconds	5 seconds
Microsoft Edge	208 seconds	8 seconds
Chrome	312 seconds	6 seconds

According to the test results, when opening WebGL web projects, FireFox or Microsoft Edge browser is preferred, and enable browser caching to significantly save the second opening time.

Results

The final product assembly steps are shown in Figure 16, followed by simply placing the Product into the storage bin to complete the experiment.

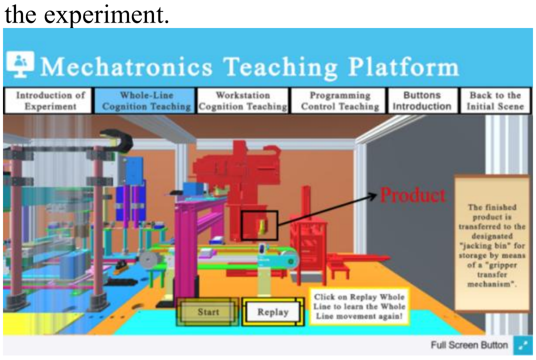


Fig. 16. Cognitive learning experiment completing page

Online Learning Evaluation

In addition to traditional assessment through laboratory reports and a final examination, we implemented two additional evaluation methods tailored to the virtual laboratory format. For online cognitive learning, we recorded the time each learner spent in each module and computed the ratio of actual to expected duration. A ratio greater than one indicates effective engagement, and a ratio closer to one denotes higher proficiency. Timing begins when the learner activates the start button of a module in the WebGL interface and ends upon clicking the module's completion button or navigating away. Upon completion of all modules, the user ID and durations are submitted via HTTP POST to the back-end MySQL database, where a database Trigger executes SQL statements to calculate and store the ratio. Trends in these ratios serve as indicators of student learning progress. The data transfer relationship is shown in Figure 17.

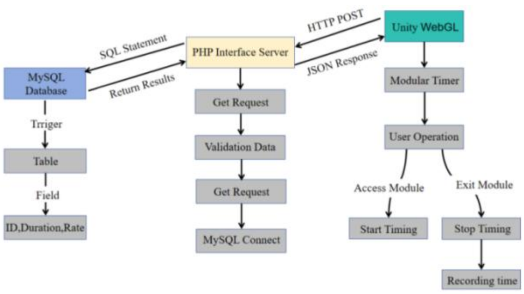


Fig. 17. Virtual laboratory data transfer relationship

In the last semester, the mechatronics experimental course has adopted the virtual laboratory for learning, and all 67 students in the two classes have completed the virtual laboratory, but only 68% of them scored 80 or above, and the ratio of the actual learning time to the necessary learning time is concentrated between 1.5 and 2.0. The analyses of student performance are as follows:

In the online cognitive learning, the time spent by students is generally higher than the necessary completion time, which may be due to the first contact with this mode of learning, suggesting that our virtual labs need to include more guiding information to help students quickly familiarize themselves with the course content.

The Case for Local Learning Assessment and Artificial Intelligence

The local PLC programme assessment requires students to complete a predefined motion sequence, culminating in the assembly of a product. To enable students to visually verify the correctness of their programmes, we intend to integrate the YoloV8 object detection algorithm with Unity. This combination will score the effectiveness of students' PLC programme implementations, allowing them to identify programme errors in real time and make corrections accordingly. Thanks to the YoloDotNet project released by NickSwardh on GitHub (project URL: 'https://github.com/NickSwardh/YoloDotNet/tree/master/YoloDotNet'), we can utilise YoloV8 within the C# environment. We trained Yolov8n as a pre-trained model within the Python environment, converted the best.pt model to ONNX format, and utilised the YoloDotNet library's API to invoke the model, thereby accomplishing image recognition tasks. The results of using a Windows Forms application as the object detection interface are shown in Figure 18. This primarily displays the post-detection image results alongside relevant textual information. The confidence level of 76.5% serves as a quantitative metric and can be directly employed as a scoring basis.

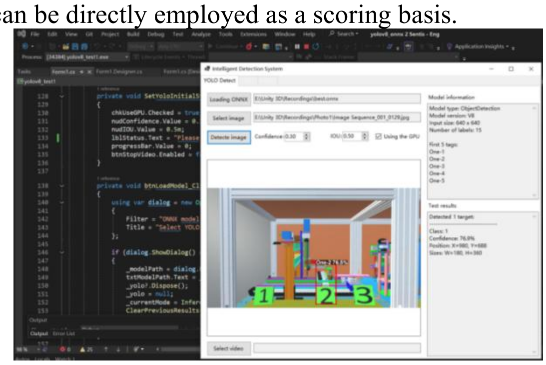


Fig. 18. Course marks statistics

Then we asked the students to send the PLC program and the video containing the test results to the teacher's email address, and the teacher combined the test results with empirical judgement to grade the test, in the assessment of 80 points or more than the expected fewer than expected, the reason may be that the virtual lab itself does not have the function of training PLC knowledge, but only give students a visual expression form, but it is worthwhile to be pleased that all students are in the assignment deadline date, which was difficult in the past, showing that learning in the form of virtual labs can really enhance students' motivation. Meanwhile, in the lab reports written by the students, it is obvious that the students have a clear understanding of the logic of the production line motion, but in the lab reports, most of the students' descriptions of the component motion are similar to our courseware, which shows that the virtual lab enables everyone to have the same learning resources, and the simple learning tasks tend to be more homogeneous, which is capable of narrowing the gap between the students with positive attitudes towards learning and those with average attitudes.

Analysis of Course Scores

The virtual lab was first put into use in 2025, so we kept the offline final exams, and compared the final exam scores of the sophomores of 2023 and 2024 with those of 2025, so as to validate the effectiveness of the teaching and learning in the virtual lab, and the statistics of the scores are shown in Figure 19. It can be seen that the year 2023 is significantly different from the rest of the years, this is because at that time the new crown epidemic of the residual waves still exist, resulting in the interruption of the classes and generally low scores. The scores of 2024 are basically unaffected by the epidemic and are significantly higher. Excluding the effects of the outbreak and focusing on comparing 2024 to 2025, it can be seen that the percentage of students scoring 90 points or higher was slightly higher in 2024 than in 2025, indicating that the virtual labs were not very effective in pulling out the top students who were active learners in their own right. But it can be seen that the effect was significant for students scoring 60-70 points, which was 8.9% lower in 2025 than in 2024, while the number of students with scores of 70-80 increased by 2.6%, and the number of students with scores of 80-90 increased by 7.1%, which means that the use of virtual labs for learning can make students with poor study habits to be engaged in the process, perhaps because of curiosity in the first contact, or maybe the virtual labs prolonged their study time, in any case, all the indications are that the virtual labs as a supplement to the curriculum is effective in improving overall performance of the students.

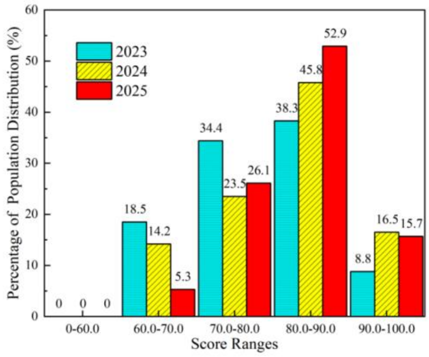


Fig. 19. Course scores statistics

4 Conclusion and Future Work

4.1 Conclusion

The deployment of a virtual laboratory has effectively addressed several limitations inherent in traditional production line cognition and PLC programming instruction—namely, constraints in physical space and lab hours, high equipment costs, limited device availability, and obsolescence. This platform successfully migrates production line cognition to a web-accessible environment, affording students a laboratory experience regardless of location.Moreover,A visual representation of the results of non-intuitive PLC program runs was also made so that students would know not only whether the PLC program was correct or incorrect, but also the specific node where the error occurred.The integration of observational and hands-on learning modalities broadens students' conceptual horizons.

While a virtual laboratory cannot replicate every aspect of a physical lab, it serves as a potent adjunct to in-person instruction. It alleviates the challenges of traditional experimental courses, invigorates student engagement, and guides problem-solving, ultimately enhancing critical thinking and injecting new momentum into teaching quality.

4.2 Future Work

As mentioned earlier, the virtual experiment platform still has a number of problems.

1)The problem of insufficient guidance, which will be a long-term process, need to be improved in the feedback of one student after another, and eventually help students quickly familiarize themselves with the virtual experiment platform.

2)The problem of long loading time of WebGL project, the cloud server currently used only supports 3M bandwidth, which obviously creates a problem for large-scale students to study at the same time, the reason we chose this cloud server is because it only costs $60 a year after discount, and subsequently, we plan to purchase a Linux server by ourselves and then upgrade the broadband, which should significantly improve the students' experience.

3)In this paper, an important element is the visual verification of the PLC program, but it can only be done locally by the students, which not only requires the students to download a lot of software, but also gives the students the possibility of cheating by directly changing the verification procedure. In the future, we will try to use more communication methods to realize the communication between the cloud WebGL project and the local TIA PortalV18, so that students can not cheat without the need to download Unity and C # compiler. The more advantage is that the PLC program can automatically score and reduce the workload of teachers.

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Conflicts of Interest

The authors declare no conflicts of interest.

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機電一體化課程的3D虛擬實驗室設計實施和智能化案例

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摘要：實驗課程在高等教育中起著舉足輕重的作用，隨著新興技術改變教學實踐，虛擬實驗室已成為傳統面對面教學的有效補充。本文介紹了根據 ADDIE 教學設計模式（分析、設計、開發、實施、評估）開發的基於 Unity3D 的虛擬生產線實驗室平臺。此外，在學生客戶端上，我們將 PLC 程序可視化，並設計了一個圖像識別模塊，使學生能夠直觀地驗證其 PLC 程序的正確性。在本科二年級學生中的實施對學習成績產生了積極影響。

關鍵詞：教育技術；虛擬實驗室；Unity3D；在線學習；PLC 編程；可視化；圖像識別

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Appendix A

This appendix systematically illustrates the component structures and functional comparisons between the complete production line and five workstations of mechatronic system equipment through the mapping relationships of virtual simulation models and physical equipment. These figures aim to supplement the details of Figure 4 in the main text, offering readers an intuitive restoration of virtual-physical interaction scenarios.

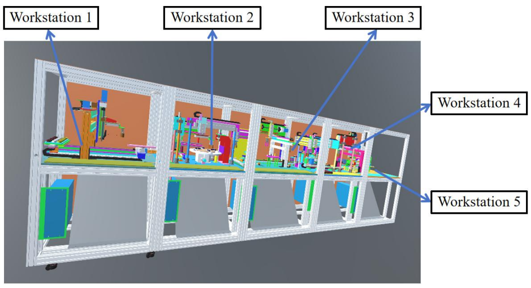

Fig. 1. Complete production line virtual model

Fig. 2. Physical equipment model of the complete production line

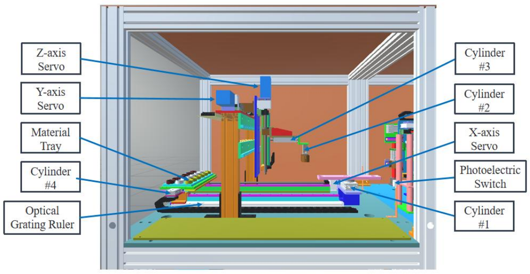

Fig. 3. Introduction to the components of a virtual model for workstation 1

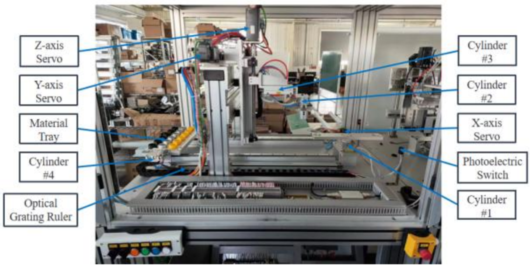

Fig. 4. Introduction to the components of physical equipment for workstation 1

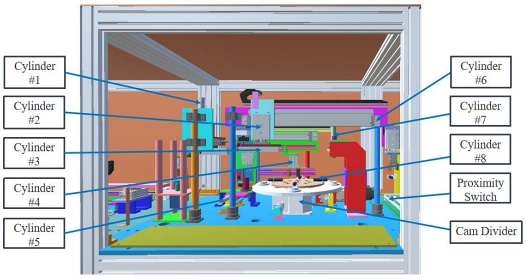

Fig. 5. Introduction to the components of the virtual model for workstation 2

Fig. 6. Introduction to the components of physical equipment for workstation 2

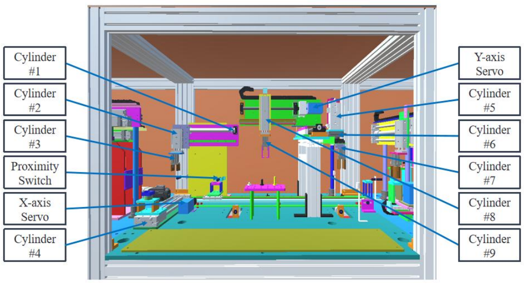

Fig. 7. Introduction to the components of the virtual model for workstation 3

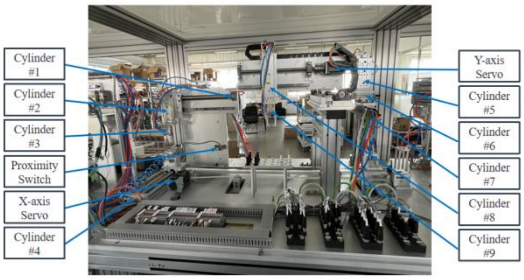

Fig. 8. Introduction to the components of physical equipment for workstation 3

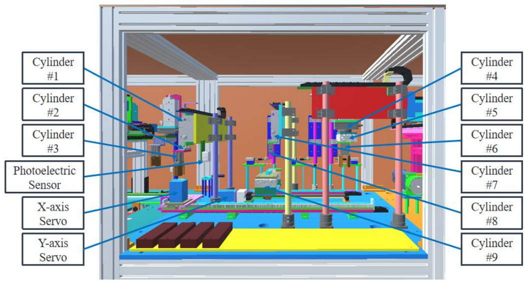

Fig. 9. Introduction to the components of the virtual model for workstation 4

Fig. 10. Introduction to the components of physical equipment for workstation 4

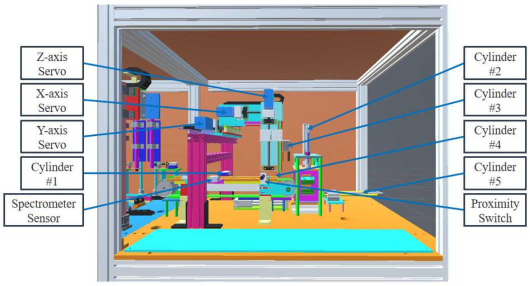

Fig. 11. Introduction to the components of the virtual model for workstation 5

Fig. 12. Introduction to the components of physical equipment for workstation 5