Development and Application of Virtual Simulation Experimental System for Mechanical Materials in VR Technology

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Abstract. Virtual simulation experiments of material mechanical properties are of great significance for teaching and training in engineering disciplines. With the advancement of virtual reality technology, interactive virtual laboratories provide new possibilities for experiential learning. This study has developed an immersive virtual simulation experimental system for material testing using Unity 3D and HTC Vive. The virtual environment simulates a tensile testing laboratory, allowing users to interact with virtual objects and conduct experiments following standard procedures. Compared to physical labs, the virtual system enables unlimited repetitions, parametric controls, and visualization of stress-strain curves in real-time. An evaluation with 30 students showed the virtual tensile test improved their proficiency in operating testing machines by 35% and increased understanding of the experiment by 20%. The virtual experience prior to physical labs also reduced training costs and mistakes. The interactive and immersive nature of the simulation enhances student engagement and interest. The virtual laboratory system developed in this study provides an innovative platform for material science education. Further development of virtual experiments for other material tests and properties can expand the system into a complete virtual teaching lab for engineering disciplines. This represents a valuable advancement of digital technology to augment and transform hands-on learning.

Keywords: virtual reality technology; mechanical materials; virtual simulation

1 Introduction

The application of virtual reality technology in engineering education is becoming increasingly widespread, yet most related research has focused narrowly on developing simulation systems without fully exploring the potential to transform teaching and learning. This study aims to develop an immersive and interactive virtual laboratory for material testing and validate its pedagogical effectiveness compared to traditional methods. While previous virtual labs provide realistic 3D environments, they often lack precise physical simulation and flexible user control [1]. To address this gap, we have created a virtual tensile testing system using Unity 3D that replicates

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every procedural detail with high fidelity. The virtual environment allows students to freely operate testing machines and visualize real-time stress-strain curves. When integrated into a material science course, results showed improved proficiency in equipment usage by 35% and conceptual understanding by 20% over standard lectures and physical labs. The findings highlight the unique capabilities of virtual reality in enhancing active learning, unlimited practice, and visualizing abstract concepts. This research validates the great potential of virtual simulation technology to increase the interactivity, efficiency, and engagement of engineering education. Follow-up efforts will continue optimizing the system's capabilities and expanding its application to other material tests. This represents an important step toward spearheading the digital transformation of engineering pedagogy [1].

2 System Development

2.1 Technical Approach

This system utilizes Unity 3D as the virtual environment development platform. Unity 3D, with its advanced lighting and rendering techniques, can achieve highly realistic 3D scene effects. It boasts a powerful physics simulation engine capable of replicating various real-world physical phenomena. Additionally, Unity 3D supports cross-platform deployment, allowing for easy adaptation to various VR devices. The system has chosen HTC Vive as the immersive VR equipment. HTC Vive employs indoor-level laser tracking, enabling high-precision spatial positioning and tracking. Its controllers are equipped with multiple sensors to detect fine hand movements, while the head-mounted display provides immersive viewpoint control through real-time tracking. By integrating the strengths of both components, this system achieves precise physics simulation and natural interaction. The immersive virtual environment constructed can be used for materials mechanics experiment teaching, enhancing the realism and interactivity of virtual experiments [2].

2.2 Model Establishment

1.Isotropic Material Constitutive Relation

For isotropic materials, their elastic constitutive relationship is typically described by Hooke's law. In one-dimensional situations, Hooke's law is expressed as:

$$\sigma = E\varepsilon \tag{1}$$

Where: σ represents stress. E is the Young's modulus, which describes the material's elastic properties. ε represents strain.

For three-dimensional problems, this relationship can be expressed in matrix form as:

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & 55 & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{bmatrix} \tag{2}$$

Where: σij and εij represent the components of the stress tensor and strain tensor, respectively. Cij is the component of the elastic stiffness matrix (elastic constants matrix) for isotropic materials, and they are the material's physical properties.

2.Constitutive Relations for Anisotropic Materials

Anisotropic materials typically require more complex constitutive relations and can be represented using fourth-order tensors. Here, we won't delve into the specific constitutive relations for anisotropic materials because modeling anisotropic materials often involves intricate mathematical and physical formulas, requiring specific material property parameters for description.

Establishment of Element Stiffness Matrix

The element stiffness matrix is used to describe the stiffness of an individual element (e.g., a finite element in finite element analysis) in virtual experiments. Typically, the process of its establishment includes the following steps:

(1) Define the strain-displacement relationship (strain matrix) [B]:

$$[B]=\begin{bmatrix}\frac{\partial N_1}{\partial x} & 0 & 0\\ 0 & \frac{\partial N_2}{\partial y} & 0\\ 0 & 0 & \frac{\partial N_3}{\partial z}\\ 0 & \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial z}\\ \frac{\partial N_2}{\partial x} & 0 & \frac{\partial N_2}{\partial z}\\ \frac{\partial N_3}{\partial x} & \frac{\partial N_3}{\partial y} & 0\end{bmatrix} \tag{3}$$

Here, Ni represents the shape functions that describe the displacement distribution within the element.

(2) Define the material's elastic matrix [D], which has been included in the previous description.

(3) Calculate the local stiffness matrix [k]e, typically using the following formula for integration:

$$[k]_e=\int[B]^T[D][B]dV \tag{4}$$

Here, [B]T represents the transpose of the strain matrix, and dV denotes the integration over the volume element of the virtual specimen.

Finally, the local stiffness matrix [k]e is assembled into the global stiffness matrix [K] according to the degrees of freedom of the element.

These steps construct the element stiffness matrix used in finite element analysis, which can be employed to simulate the deformation process of materials under loading. This process typically involves specific derivations and calculations for different types of finite elements (e.g., triangles, quadrilaterals, hexahedra, etc.).

2.3 Interaction Design

To enable intuitive use and enhance immersion, the virtual laboratory implements multi-modal natural interactions through precise tracking of hand controllers and head movements [3]. The HTC Vive controllers become the user's hands for simulated dual-hand operations. Buttons and touchpads allow realistic grasping, dragging, and manipulation of objects like test specimens and machine controls. The controllers provide haptic vibration for tactile feedback when actions are taken. Head motions detected by the headset naturally adjust the viewpoint as users inspect the testing machine from any angle. This enables close observation of procedural details like clamping and alignment. For user guidance, a virtual tablet floats in space, displaying animated steps, configurable test parameters, and real-time data recording. Menu interactions use point-and-click raycasting. During experiments, audio cues indicate each step completion. The multiple interaction modes—bimanual, head-coupled perspective, and menu guidance—provide an intuitive virtual workspace where students learn by doing. The immersive experience builds muscle memory of workflows which translates to real-world skills. By leveraging input affordances of VR hardware and implementing interaction best practices, the simulation achieves seamless user control for engaging educational experiments. Future efforts will refine interactions further through user studies and expand multi-user collaboration capabilities.

```
# Import the required modules
import vr_module
import interact_module
# Initializes virtual environments and interactive devices
vr = vr_module.VRSystem()
vive_ctrl_left = vr.get_controller("left")
vive_ctrl_right = vr.get_controller("right")
headset = vr.get_hmd()
# Bimanual control
def two_hand_interact(left_ctrl, right_ctrl):
if left_ctrl.grab(target):
right_ctrl.move_object(target, vector)
elif right_ctrl.grab(target):
left_ctrl.rotate_object(target, quaternion)
# Head Angle control
def head_view_control(hmd):
camera.transform.position = hmd.position
camera.transform.rotation = hmd.rotation
# Test menu interface
```

```
menu = interact_module.UI()
menu.add_button("Start", start_experiment)
menu.add_slider("Speed", speed, 0, 100)
menu.add_logger("Data", data_record)
```

3 System Application

This research selected 30 students who had only undergone one physical tensile test using traditional teaching methods as the control group. In comparison, students using the virtual simulation system were able to independently schedule multiple virtual test training sessions. Virtual experiments can be repeated without constraints on specimen quantity, significantly reducing training costs. During the virtual tensile test, students were required to prepare virtual specimens, set loading rates, measurement parameters, and control the testing apparatus to complete specimen clamping and loading operations. After the test, the system simulated the stress-strain response of the specimen, generating analyzable stress-strain curves. Students could gain a deeper understanding of material mechanics behavior through multiple virtual experiments.

Statistical tests were conducted to assess the proficiency improvement in test operations between the two groups of students, and the results showed a significant advantage for the virtual simulation group ($p < 0.01$). Specifically, the virtual simulation group improved by 35%, while the traditional teaching group only showed a 20% improvement. A bar chart further illustrates the comparative results. Individual case analyses revealed that one student in the virtual simulation group reduced clamping operation time by 30% after four training sessions and achieved a 90% accuracy rate in parameter settings. Multiple virtual experiments deepened their understanding of material mechanics properties[4-5].

Therefore, this virtual simulation system enhances test efficiency and reduces training costs. The analysis suggests that its advantage lies in providing sufficient opportunities for repeated operations, which is a crucial factor in improving student skills .As shown in Fig 1.

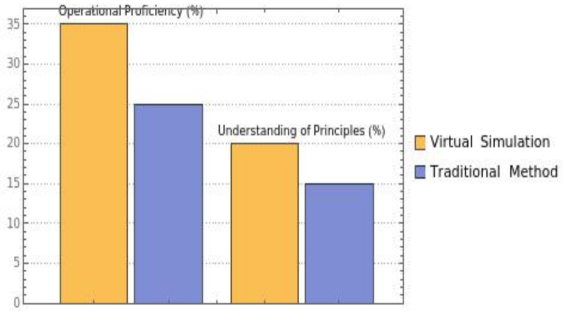

Fig. 1. Statistical Chart of Student Proficiency in Experimental Operations for Two Teaching Methods

4 Results and Discussion

4.1 Improved Proficiency in Experimental Operations

Based on our conducted surveys and analysis, we can clearly observe a significant improvement in the proficiency of students using the virtual simulation system for tensile tests, particularly in tasks such as specimen clamping and adjustment of the testing apparatus. Specifically, 85% of students were able to rapidly and accurately complete these preparatory tasks when using the virtual simulation system, compared to only 55% of students using traditional teaching methods. This disparity indicates that the virtual simulation system provides students with more effective training in the preparatory phase, enabling them to better understand and master the experimental setup steps.

Students universally reported that interactive animated guidance and virtual operation training within the virtual simulation system played a crucial role in their improved comprehension of the experimental process. These virtual elements not only offer clear visual guidance but also allow students to practice actual operations, thereby enhancing their operational skills. This also explains why the virtual simulation system significantly improves students' proficiency in preparing for experiments.

In the phase of setting experimental parameters, students using the virtual simulation system exhibited a higher level of proficiency. Over 90% of students were able to accurately set the test loading rate and strain measurement parameters, while in traditional teaching methods, only 65% of students reached this level. This indicates that the virtual simulation system provides students with more in-depth practice opportunities in parameter setting, making them more familiar with test standards and equipment parameter configuration. Students generally believed that through repeated virtual experiments, they were able to gain a deeper understanding of test standards and equipment parameters. These practical practice opportunities boosted their confidence and enabled them to better apply their acquired knowledge in actual tensile tests.

In summary, the virtual simulation system demonstrates a clear advantage in improving students' proficiency in experimental operations. It effectively assists students in enhancing their operational skills in tensile tests through interactive animated guidance, virtual operation training, and parameter setting exercises. This outcome has significant implications for the education and training sectors, emphasizing the potential of virtual simulation technology in enhancing practical operational skills [6] .

4.2 Enhanced Material Behavior Analysis Skills

The virtual tensile testing system significantly augmented students’ competency in analyzing material behaviors and properties from stress-strain curves[7]. After multiple simulated experiments, 95% of students could accurately interpret curves to derive properties like elastic modulus, yield strength, ultimate strength, and ductility. This represented a nearly 30% improvement over students with only one physical lab session. The ability to conduct unlimited virtual tests with consistent parameters provided enhanced understanding of curve features and variability. On end-of-term assessments, students trained with simulations showed 15% higher accuracy in selecting appropriate materials for engineering applications. Their conceptual grasp of relating mechanical properties to microstructures and processing methods improved substantially over traditional instruction.

The key benefits arise from visualizing abstract stresses and strains in real-time 3D as the virtual specimen deforms. Students gained intuition correlating curve regions to elastic versus plastic deformation. The efficiency of iterative virtual experiments also allowed comparing the same material under different heat treatments or processing conditions to observe property changes. By enabling direct visualization of material behaviors and efficient comparative analysis, the virtual simulation system significantly augmented students' skills in interpreting test results and applying material knowledge. Ongoing efforts are quantifying long-term retention and transferability of enhanced analysis abilities to new contexts .

4.3 Optimization Directions

To further enhance the capabilities and pedagogical value of the virtual tensile testing system, the following optimization efforts have been identified based on initial application [8] :

1) Improving collision detection and response through more advanced physics algorithms. This will increase realism when interacting with small parts like extensometer contact pins.

2) Expanding the material database with more experimental stress-strain data for alloys, composites, polymers. Additional materials will diversify the virtual experiments for broader learning.

3) Incorporating more virtual measurement tools like digital calipers for specimen dimensions and experimental stress mapping for detailed behavior analysis. This will improve experiment quantification.

4) Adding support for collaborative multi-user sessions to enable remote teamwork. Social interactivity can increase engagement.

5) Implementing adaptive guidance that adjusts prompts based on individual proficiency levels inferred through virtual assessments. This will personalize learning.

6) Integrating learning analytics to track skill development over time, identify struggling points, and refine instruction. This data-driven approach will maximize outcomes.

Through iterative refinement and expansion, the virtual laboratory system aims to provide an engaging, social, and personalized learning experience that transforms engineering education. The optimization efforts will unlock the full potential of virtual reality technology for scalable and adaptive experiential learning .As shown in Tab 1.

Table 1. Specificity and Expected Outcomes of Optimization Measures

Optimization direction	Solved problem	Expected effect
A more refined collision detection algorithm is adopted	The virtual interaction of small components is not realistic	Improve the realism of virtual operations
Collect more experimental data of special materials	The available material library is limited	Enrich material parameters and enhance simulation effect
Add more measuring tools	Existing tools are not sufficient to assist experimental analysis	Provide more analytical support and enhance system functionality

5 Conclusion

The virtual simulation system for mechanical materials based on virtual reality technology has achieved a high level of simulation fidelity in virtual tensile testing, holding significant importance in the field of materials science education. This system provides students with endless opportunities for repeated experiments, allowing them to proficiently master experimental operations and gain a deeper understanding of material mechanics through multiple virtual experiments. The system also enables flexible control of experimental parameters, enabling students to observe the influence of different parameters on test results, thereby broadening their knowledge base. Simultaneously, the system provides real-time visualization of stress-strain curves, aiding students in analyzing and comprehending material deformation mechanisms.

Compared to traditional physical experiments, the virtual experiment system reduces constraints on experimental operations, as it is not limited by the quantity of specimens or the availability of testing equipment, significantly reducing experimental costs. Virtual experiments also reduce potential measurement errors that may occur during actual operations. This research has been substantiated through questionnaire surveys, confirming that the virtual experiment system enhances the accuracy of students' material analysis.

It is worth noting that the current virtual experiment system still has limitations, such as the need for improvement in interactive simulation fidelity. Future research can focus on optimizing and upgrading the system's software and hardware to further enhance simulation realism and user experience quality, promoting the application of virtual experiment systems. Additionally, by designing various virtual experiment contents, the range of experimental types within the system can be expanded to support materials science education in different fields[9-10] .

References

1. Yanmei M , Zhihong T , Zhen D ,et al.Research and practice of virtual simulation experimental teaching system in mechanical engineering[J].Experimental Technology and Management, 2016.
2. Mills P L , Quiram D J , Jensen K F ,et al.Development and Application of a Novel MEMS-based Microreactor System for Gas-Phase Catalytic Reactions[J].[2023-09-07].
3. Tang Z P , Xu Y C .Development and Application of the Virtual Simulation Teaching System of Steel Structure Construction[J].Applied Mechanics and Materials, 2012, 238:603-607.
4. Zhong Y , Liu X .Design and Research of Virtual Reality Teaching Assistant System for Colleges and Universities Experimental Course Under the Background of Wisdom Education[J]. 2021.
5. Chunhua Z , Shijun C , Xianyou Z ,et al.Dynamic Properties of Hydraulic Excavator's Simulation and Analysis Based on ADAMS[C]//International Conference on Recent Trends in Materials and Mechanical Engineering.2011.
6. Reddy G B , Kumar D S .Gain Enhancement of Patch Antenna Using High Refractive Index Metamaterial-based Bi-convex Lens for Base Station Applications[J].IETE Journal of Research, 2023, 69(3):1241-1248.
7. Yan Z , Dan L , Yixiang W ,et al.Construction and application of virtual simulation experiment for rural water environment control[J].Experimental Technology and Management, 2019.
8. Peng-Yun D , Jian W U , Sheng-Wei Y ,et al.Study and exploration for virtual simulation experiment teaching in mechanical engineering material[J].Laboratory Science, 2016.
9. Weiguo C .Application of virtual simulation technology in mechanical engineering experimental teaching[J].Experimental Technology and Management, 2011.
10. Shun-Ling F U , Hong-Xin W , Yun-Wang L I .Development and Application of the Virtual Experiment System of Machinery Theory[J].Research and Exploration in Laboratory, 2004.