IMMERSIVE VIRTUAL REALITY FOR CHEMISTRY EDUCATION: SIMULATING EXPERIMENTS FOR SAFER AND ENGAGING LEARNING

Mr. Putluru Rohith,
Post Graduate in Master of Computer Applications, Department of Computer Science and Engineering, Jawaharlal Nehru Technological University Anantapur College of Engineering(Autonomous), Anantapur, Andhra Pradesh, India

Smt. D. Madhuri,
Assistant Professor (Contract), Department of Computer Science and Engineering, Jawaharlal Nehru Technological University Anantapur College of Engineering(Autonomous),Anantapur, Andhra Pradesh, India

Abstract-Virtual Reality(VR) is revolutionizing the field of education by providing immersive and interactive environments that enhance learning experiences. This emerging technology bridges the gap between theoretical concepts and practical application, making science education safer, more engaging, and accessible.

Traditional chemistry labs, while essential for hands-on learning, come with several limitations. Safety risks associated with handling hazardous substances, high operational costs, and then need for extensive infrastructure often restrict their availability, especially in under- resourced institutions. Furthermore, the inability to repeat or modify experiments freely can hinder students' understanding and limit their curiosity-driven exploration. These drawbacks highlight the need for innovative alternatives to traditional lab setups.

This paper, addresses these challenges by creating a VR-based chemistry lab using Unity. The platform allows students to perform experiments safely and repeatedly in a virtual environment that replicates real- world conditions. It eliminates safety concerns, reduces costs, and provides unlimited opportunities for practice, fostering deeper understanding and curiosity. By transforming how students engage with chemistry, this project offers a scalable, accessible, and highly effective solution to modernize chemistry education.

Keywords: Chemistry, Virtual Reality, Unity, Education, Simulation, Immersion, Laboratory Experiments.

I. INTRODUCTION

The integration of emerging technologies in education has significantly transformed traditional learning methods. Among these, Virtual Reality(VR)stands out for its potential to deliver immersive and interactive environments that enhance student engagement and conceptual understanding. In the context of chemistry education, VR offers a promising alternative to traditional laboratory instruction by enabling realistic simulation of chemical experiments without the inherent risks or logistical constraints of physical labs.

Conventional chemistry labs, although crucial for hands-on experience, face limitations such as safety hazards, high operational costs, and limited accessibility particularly in under-resourced institutions. Additionally, restricted opportunities for repetition and exploration may hinder a student’s ability to fully grasp complex chemical concepts. These challenges highlight the need for innovative solutions that preserve the educational value of experimentation while eliminating associated drawbacks.

This project addresses these challenges through the development of a VR-based chemistry lab using Unity and XR technologies. The platform simulates realistic laboratory scenarios where users can mix chemicals, and observe reactions including visual effects for explosions, color changes ,smoke, and more. The system also includes an open-exploration mode, encouraging curiosity-driven experimentation.

By combining immersive interaction with scientific accuracy, the proposed system aims to modernize chemistry education, making it more accessible, safe, and engaging for students.

II. LITERATUREREVIEW

The integration of virtual reality (VR) into education has garnered considerable attention in recent years, especially in STEM fields where practical experience is fundamental. In the domain of chemistry education, VR has been explored as a means to simulate laboratory experiences in an interactive and risk-free manner.

Agbonifo et al. developed a VR-enhanced chemistry laboratory platform aimed at improving adaptive learning among students [1]. Their 2020 study, published in ***Research in Learning Technology***, demonstrated that students using the VR system showed increased engagement and better conceptual understanding compared to traditional methods. The study also highlighted the benefit of real-time interaction in enhancing students' retention and motivation.

In a similar effort**, Aliyu and Talib** addressed challenges faced by science secondary schools in Nigeria, such as lack of laboratory equipment and safety risks, through a virtual chemistry lab system [2].Their findings, published in the ***International Journal of Engineering and Advanced Technology*** in 2019,confirmed that virtual labs could serve as a viable solution to these persistent barriers, enabling students to conduct experiments with greater accessibility and safety.

An early implementation of interactive virtual laboratories was carried out by **Numan Ali et al**., who developed a 3D VR chemistry lab for high school education [3]. Their 2007 paper highlighted the effectiveness of immersive simulation in fostering hands-on learning and improving student performance in practical chemistry. The interactive environment allowed students to visualize complex chemical reactions more clearly than through conventional methods.

Kolil et al. investigated the impact of virtual laboratory platforms on experimental self-efficacy among university students [4]. Their 2020 study in the ***International Journal of Educational Technology in Higher Education*** demonstrated a significant improvement in students' confidence and understanding after interacting with VR-based experiments. The study emphasized the psychological benefits of virtual labs, including reduced anxiety and increased willingness to explore.

Tatli and Ayas provided a broader overview of virtual laboratory applications in chemistry education [5]. Their work, published **in *Procedia-Social and Behavioral Sciences*** in 2010, concluded that VR technologies offer scalable and flexible teaching solutions. They also pointed out that while virtual labs enhance learning outcomes, their effectiveness depends on the quality of instructional design and user interface.

Collectively, these studies affirm that VR-based learning environments can effectively complement or even substitute traditional chemistry laboratories. The existing research underscores VR's potential to enhance safety, accessibility, and learner engagement, thus forming a solid foundation for the development of advanced virtual chemistry lab systems.

III. System Design

The VR chemistry lab system was designed to simulate real-world chemical experimentation through a modular, interactive, and scalable virtual environment.The design emphasizes usability, realistic interactions, and accurate simulation of chemical behaviors.

A. System Architecture

The proposed VR Chemistry Lab system adopts a modular, layered architecture designed to offer a seamless and immersive educational experience. The architecture ensures clear separation of responsibilities, improved maintainability, and enhanced scalability for future integration of more experiments and features.

As shown in Fig. 1, the architecture comprises a user equipped with a VR headset, interacting in real time with a fully simulated virtual chemistry lab built using the Unity game engine. The virtual lab environment is designed to mimic the layout and tools of a real-world laboratory, supporting hands-on learning through realistic physics, responsive interactions, and simulated chemical behaviors.

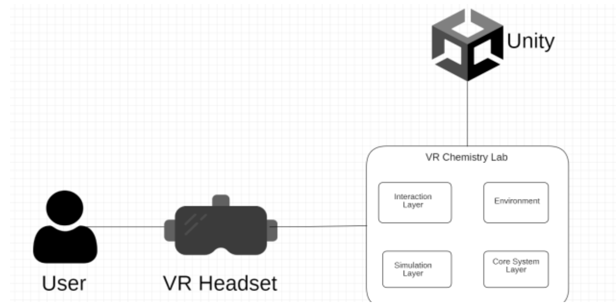


FIG.1.SYSTEM ARCHITECTURE

The system architecture is structured into the following four key layers:

- **Interaction Layer**: This layer manages all user interactions within the virtual lab. It captures input from the VR headset and motion controllers, enabling the user to pick up lab equipment, pour liquids, rotate valves, and conduct experiments naturally. Grabbing mechanisms, and collider- based object handling are implemented here to ensure realistic manipulation of objects.
- **Simulation Layer**: The simulation layer is responsible for executing the core functionality of chemical reactions. Chemical behavior is governed by a custom-built reaction dictionary, which determines the outcomes of interactions between substances. This layer also ensures that reactions are rendered with appropriate visual effects, such as color change, smoke, explosion, or plasma emissions, depending on the experiment.
- **Core System Layer**: This layer acts as the backbone of the application. It includes system logic, data handling, and state management. All modules are coordinated through this layer. It ensures synchronization between layers, real-time updates to UI elements.
- **Environment Layer**: This layer defines the static and dynamic 3D environment of the lab. It includes visual components such as lab chairs, glassware, chemical containers. Sound design and environmental feedback (e.g., bubbling sound fluid pouring, reaction sparks) are also incorporated to heighten immersion.

The system is developed using Unity due to its richsupport for 3D graphics, real-time simulation, and VR integration capabilities. The modular structure allows for future scalability additional chemical experiments, virtual assistants, or multiplayer collaborative features can be integrated without affecting the existing structure.

B. User Interaction Design

Interaction is based on XR rig components that allow intuitive manipulation of objects within the virtual space. The interaction workflow is designed to ensure that users can intuitively manipulate objects, simulate chemical experiments, and observe real-time reactions within the virtual lab.

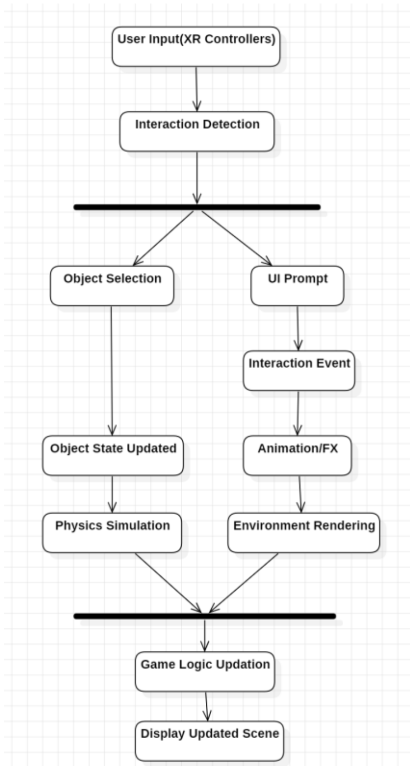


FIG.2.INTERACTION WORKFLOW DESIGN

1. User Input (XRControllers): The interaction begins with user input via XR controllers, which serve as a substitute for real-world hand movements. The controllers capture the user's hand gestures and provide haptic feedback, mimicking the act of grabbing, tilting, or manipulating objects. This input forms the basis for the interaction within the virtual chemistry lab.

2. Interaction Detection: Once the user initiates an interaction, the system detects whether the user is performing actions such as grabbing, tilting, or pointing at objects. Interaction detection is based on tracking the position and movement of the XR controllers.

3. Object Selection and UI Prompt: If an object is

With in reach and deemed interactive, the system allows The user to grab, hold, or manipulate the object. In instances where the user triggers a user interface (UI) prompt, the system presents an interactive response. For example, when a chemical compound is selected, the virtual name of the chemical may appear as a floating text element.

4. Object State Update & Animation Effects: When an object is successfully interacted with, its state is updated accordingly. For instance, if a user grabs a beaker, it can be tilted to simulate the pouring of a liquid. Additionally, when two chemicals come into contact, UI visual effects can be activated to show resultant reactions for chemicals under consideration.

5. Physics Simulation &Environment Rendering: To maintain immersion and realism, physics simulations govern the behavior of objects in the virtual environment. For example, when a user tilts a beaker, the liquid within flows naturally, reflecting the principles of real-world fluid dynamics. The system's physics engine dynamically updates the environment to simulate accurate chemical reactions, such as the formation of new compounds. This level of detail fosters an authentic laboratory experience.

6. Game Logic Update & Display Update: After the user interaction is detected and processed, the system updates the underlying game logic to reflect the user's actions. This may involve changing th estate of objects, triggering chemical reactions, or initiating new sequences within the experiment. Following the game logic update, the display is refreshed to present the most up-to-date visuals, allowing users to immediately observe the impact of their actions.

IV. IMPLEMENTATION

A. VR Environment Setup

The VR Environment Setup is a critical component of the VR Chemistry Lab project, as it provides the foundation for creating an immersive and interactive virtuallaboratory.Thissetupinvolvesacombinationof3D models, realistic textures, physics simulations, and interactive elements, which work together to recreate a believable and engaging chemistry lab.

1. **Designing the Virtual Lab Scene**

FIG.3.ERLENMEYER FLASK3DMODEL

FIG.4.BEAKER3D MODEL

Key laboratory equipment such as beakers, test tubes, sinks, and chairs were imported into Unity from Unity Asset store.

FIG.5.FLORENCE FLASK3DMODEL

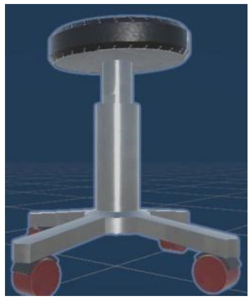


FIG.6.CHAIR3D MODEL

2. Setting Up Physics and Collisions

To replicate real-world interactions, physics simulations were integrated to control object movement, behavior, and collision detection.

- **Rigid body Components**: All interactive objects, such as beakers, test tubes, and other laboratory equipment, were assigned Rigid body components. This allowed objects to respond to real-world physics, such as gravity, collisions, and weight effects.
- **Collider Components**: Collider components were implemented to prevent objects from passing through each other and ensure that interactions remained physically plausible. The colliders were configured to handle both static objects (e.g., lab tables) and dynamic objects (e.g., chemical containers), ensuring accurate detection of interactions when objects were grabbed, moved, or collided.

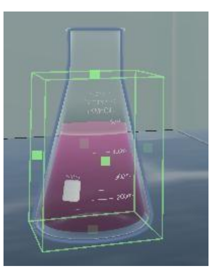


FIG.7.ADDING BOX COLLIDER TO FLASK

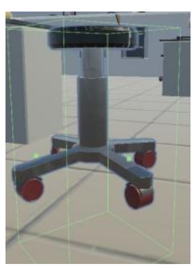


FIG.8.ADDINGBOX COLLIDERTOCHAIR

3. Environmental Lighting and Shadows

The visual atmosphere of the virtual lab is greatly influenced by the lighting setup, which enhances realism and aids in creating an immersive experience. A Directional Light was used to simulate sunlight and provide the primary source of illumination in the lab. This light was configured to mimic the overall room lighting, creating natural shadow effects and giving depth to the scene.

4.VR Player Setup

For the user to navigate and interact with the virtual lab ,an appropriate VR player setup was essential. The XR Rig (also known as XROrigin) was configured to allow smooth movement within the lab environment. This setup ensures that the user can freely explore the virtual space, with controls for teleportation, walking, and spatial orientation. The XR Rig is essential form a intaining immersion, as it accurately tracks the user's head and hand movements, enabling the virtual camera and user interactions to follow in real-time.

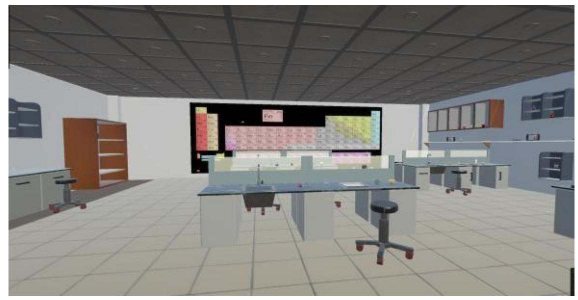


FIG.9.LABENVIRONMENT

B. Hand Interaction and Object Manipulation

Natural and intuitive interaction is a central design goal of the VR Chemistry Lab, allowing users to handle virtual objects using hand-tracking or VR controllers. Leveraging Unity's XR Interaction Toolkit, core functionalities such as grabbing, moving, rotating, and pouring were implemented to mimic real-life laboratory interactions.

1. **Object Pickup and Grabbing:** Laboratory equipment such as beakers, Florence flasks, and Erlenmeyer flasks were made intractable using XR components. Objects respond to user input with realistic motion by incorporating physics constraints and collision detection. Hepatic feedback further enhances immersion by providing tactile responses when grabbing or releasing objects.
2. **Liquid Pouring Simulation:** Pouring actions were simulated by detecting the tilt of containers beyond a defined threshold. When this occurs, a particle system activates to visually represent the flow of liquid. Collision-based logic ensures that poured liquids interact realistically with other substances and surfaces, enabling accurate simulation of chemical mixing and reactions.

C. Visual Feedback

Visual feedback mechanisms are essential in delivering context-aware, real-time responses to user actions within the virtual laboratory. By representing chemical information and reactions through spatial labels and dynamic effects, the system enhances user awareness, supports decision-making, and reinforces learning through immersive visual cues.

1. Chemical Name Display through Floating Labels

To help users identify chemicals during interactions, each chemical container such as beakers and test tubes is equipped with a floating label that becomes visible upon being picked up. These labels display the chemical's name or formula in 3D space using TextMeshPro, a high-quality text rendering tool in Unity.

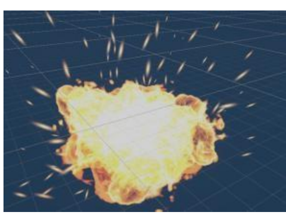
The labels are dynamically positioned relative to the user's viewpoint to maintain readability. By following the camera's movement, the labels remain consistently visible without requiring the user to shift perspective or break immersion.

FIG.10.FLOATING CHEMICAL NAME DISPLAY

2. Reaction Display System

When a chemical reaction is triggered, the system provides immediate visual and textual feedback through the UI. A concise overlay appears, summarizing the result of the reaction.

This display remains briefly in the user's field of vision and is accompanied by particle effects directly at the site of the reaction, ensuring that learners can associate the feedback with their actions. This mechanism not only improves user engagement but also strengthens conceptual understanding by visually representing the outcomes of experimental procedures.



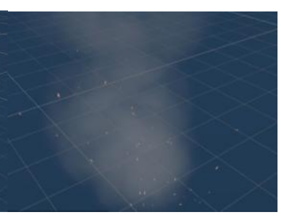
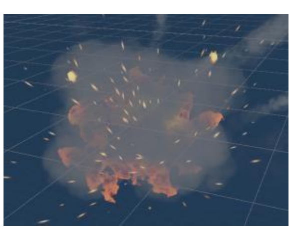


FIG.11.SMALLEXPLOSIONEFFECT

FIG.12.SMOKEEFFECT



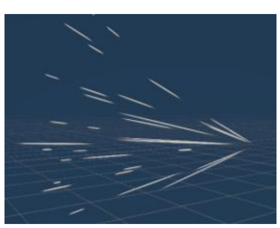


FIG.13.BIGEXPLOSIONEFFECT

FIG.14.SPARKLEEFFECT

C. Reaction Handling in VirtualReality

A key feature of the VR Chemistry Lab is its ability to simulate chemical reactions. The system adopts a dictionary-based approach to manage and process chemical reactions. This structure ensures efficient lookup and extensibility while enabling real-time feedback upon mixing substances.

When two compatible substances are combined within the virtual environment, the system performs the following sequence:

1. **Reaction Lookup**: The system references a predefined dictionary containing chemical reaction rules. Each entry in the dictionary defines a unique pair (or set) of chemicals, their potential reaction, resulting residue (if any), and associated effects.
2. **Resultant Generation**: If a matching reaction is identified, a new virtual substance or residue is generated and visually spawned at the site of interaction. This residue represents a new compound formed as a result of the reaction.
3. **Visual Effects**: To enhance realism and engagement, appropriate visual effects are rendered. These include changes in color, emission of smoke, light flashes, or other particle effects depending on the reaction.
4. **Result Display**: A floating text label briefly appears in the user's view, displaying the result of the reaction.
5. **Audio Feedback**: Complementing the visual representation, spatial audio cues are played to match the type of reaction.

V. FUTUREENHANCEMENTS

Although the current implementation of the virtual reality chemistry lab achieves its core objective of delivering an immersive and educational experience, several enhancements can be explored to extend its pedagogical scope, realism, and user engagement. These prospective developments aim to align the system more closely with authentic laboratory practices and evolving educational standards.

1. **Realistic Chemical Transfer and Volume Tracking:** An advanced liquid transfer system can be introduced to enable accurate pouring between containers, with real-time volumetric changes. By in-cooperating physics-based volume tracking, dynamic fill levels, and realistic mixing behaviors, users could perform complex experiments such as titration and serial dilution with greater fidelity and control.
2. **Expanded Chemical and Reaction Database:** The existing system supports a limited set of chemicals and reactions. Future iterations may include an extensive database comprising acids, bases, salts, indicators, and organic compounds, enabling a broader range of experiments and chemical interactions to be simulated within the virtual environment.
3. **AI-Powered Virtual Assistants:** The integration of AI-driven lab assistant scan offer personalized guidance

And real-time educational support. These assistants may facilitate learning by explaining reaction mechanisms, answering user queries, suggesting next steps, and ensuring procedural accuracy during experiments.

4. **Learning Assessment and Progress Monitoring:** To enhance academic integration, the system could incorporate features for evaluating student performance. This may include experiment completion tracking, in- lab quizzes, interactive checkpoints, and analytics to measure engagement and conceptual understanding over time.

5. **Advanced Fluid Dynamics Simulation:** To improve physical realism, future versions may replace basic particle systems with high-fidelity fluid simulation techniques. GPU-based or VFX Graph-powered simulations could support properties such as viscosity, flow rate, temperature responsiveness, and realistic mixing enhancing both visual and scientific accuracy.

6. **Collaborative Multi-User Environment:** Enabling multi-user capabilities would allow multiple learners to collaborate in a shared virtual lab. This feature could support teamwork-based activities, group experiments, and remote instructional demonstrations, thereby fostering social learning in virtual contexts.

7. **Support for Advanced Chemistry Domains:** While the current system focuses on foundational reactions, it can be expanded to cover advanced topics such as organic chemistry, electrochemistry, redox processes, and thermo-chemistry. This would allow the platform to scale from secondary education to undergraduate coursework and specialized research-based applications.

VI. Conclusion

The journey of building this virtual reality chemistry lab has been both challenging and rewarding. What originated as a conceptual initiative to merge virtual reality with chemistry instruction has materialized into a fully functional, interactive simulation that enables experiential learning in a safe and engaging manner.

By allowing students to actively engage with virtual chemicals, perform experiments, and observe real-time reactions, the system moves beyond passive learning models. It offers a hands-on environment where users can explore complex concepts without the risks and limitations associated with physical laboratories. This approach not only enhances conceptual understanding but also fosters curiosity and sustained interest in the subject.

The outcomes of this project illustrate the potential of VR to serve as a powerful educational tool particularly in disciplines like chemistry where practical access can be constrained. The platform provides a scalable, repeatable, and cost-effective alternative to physical labs, reinforcing the value of immersive learning in promoting deeper comprehension and retention.

While the current system meets its primary objectives, it also lays the ground work forfuture advancements. Opportunities for expansion include the integration of advanced fluid simulations, AI-driven tutoring systems, broader chemical reaction libraries, and collaborative multi-user environments. These enhancements will further strengthen the platform’s relevance and adaptability across various educational levels and institutions.

VII. REFERENCES

[1] O. C. Agbonifo, O. A. Sarumi, and Y.M. Akinola, "A chemistry laboratory platform enhanced with virtual reality for students adaptive learning, "*Res. Learn. Technol.*, vol. 28, 2020.

[2] F. Aliyu and C. A. Talib, "Virtual Chemistry Laboratory: A Panacea to Problems of Conducting Chemistry Practical at Science Secondary Schools in Nigeria," *Int.J.Eng.Adv.Technol.(IJEAT)*,vol.8,no.5C, pp.126–130, May2019.

[3] N.Ali,S.Ullah, A.Alam, and I.Rabbi,"3DInteractive Virtual Chemistry Laboratory for Simulation of High School Experiments, "*J. LaTeX Class Files*, vol. 6, no. 1, Jan. 2007.

[4] V.K.Kolil, S.Muthupalani, and K.Achuthan, "Virtual experimental platforms in chemistry laboratory education and its impact on experimental self-efficacy,"*Int.J.Educ. Technol. High. Educ.*, vol. 17, no. 1, pp. 1–18, 2020.

[5] Z. Tatli and A. Ayas, "Virtual laboratory applications in chemistry education, "*Procedia-Social and Behavioral Sciences*, vol. 9, pp. 938–942, 2010.

[6] Unity Technologies, *Unity*[ComputerSoftware].

[7] Meta Platforms Inc., *Oculus XR Plugin* [Software Library].

[8] Unity Technologies, *XR Interaction Toolkit* [Software Library].

[9] Microsoft Corporation, *Visual Studio Code*[Computer Software].