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Visualization of particle physics concepts using virtual reality as a learning support tool for physics undergraduate

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Abstract

This research aims to develop a Virtual Reality (VR) application to improve the understanding of particle physics concepts among undergraduate students. Following the waterfall development model, the application integrates a modern and interactive user interface and realistic 3D objects, developed using software such as Figma and Blender 3D. The research process included requirements analysis, user interface design, and implementation of additional features such as a video player and article viewer. These features are designed to enrich the learning experience and facilitate understanding of abstract particle physics concepts. Testing of the app showed that it functioned smoothly and effectively, offering an innovative and interactive learning method. This VR application is hoped to become a significant tool in physics education, helping students understand complex concepts better and increasing their engagement in the learning process.

Keywords: 3D visualization, interactive learning, virtual reality application, waterfall development

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I. Introduction

Physics education is important in shaping students' scientific understanding and critical thinking skills [1]. However, there are significant challenges in learning physics, especially when the material taught is related to the concept of particle physics [2]. Particle physics studies the basic structure of matter and interactions between particles at the subatomic level. This concept is often abstract and challenging for students to understand because it cannot be observed directly [3].

Based on various studies, student interest in physics learning tends to decrease along with the complexity of the material taught, especially at higher levels such as particle physics [4]. In addition, understanding the concept of particle physics is also a challenge because the abstractness of the material is difficult to visualise concretely [5].

On the other hand, virtual reality (VR) technology has experienced rapid development in recent years. VR offers an immersive and interactive simulated environment that can stimulate various senses, including visual and auditory [6]. VR in education has shown great potential in increasing student interest, engagement, and understanding of complex material [7]. However, research on using VR in the context of particle physics learning still needs to be completed. Meanwhile, understanding particle physics concepts is becoming increasingly important in advanced technological research and development, such as nuclear technology, applied particle physics in medicine, and nuclear energy [8], [9].

Therefore, an innovative approach is needed in learning particle physics to increase student interest and understanding. Using VR as a visualisation tool can be an interesting and effective solution to overcome obstacles in learning particle physics [10]. This research aims to explore VR's potential in particle physics learning, focusing on increasing student interest and understanding. By understanding the background of this problem, this research is expected to significantly contribute to developing innovative and effective learning methods for introducing particle physics concepts to students more thoroughly and deeply.

II. Theoretical Basis

Particle Physics

Particle physics, a branch of science that studies the nature and behaviour of elementary particles and their interactions, plays a central role in understanding the universe's origin, evolution, and structure [11]. *Particle Physics in the Context of Cosmology and Astrophysics*. In cosmology and astrophysics, concepts in particle physics provide a basis for explaining a wide range of cosmic phenomena, from star formation to the movement of galaxies in the vast universe [12]. This section will introduce particle physics concepts relevant to cosmology and astrophysics and present research supporting this understanding.

The Standard Model of Particle Physics and Cosmology. The Standard Model of Particle Physics presents a theoretical framework describing three fundamental interactions in the universe: electromagnetism, weak interactions, and strong interactions. Through these concepts, we can understand how elementary particles such as quarks, leptons, and various bosons interact to form matter and mediate their interactions. In cosmology, the Standard Model provides a basis for explaining the formation of the large structures of the universe, including the formation of galaxies and other large-scale structures [13].

The Search for Dark Matter and Dark Energy. One of the main challenges in cosmological physics is identifying the properties of dark matter and dark energy that make up most of the universe. Researchers have sought to understand these properties through particle physics experiments and observations of cosmic phenomena. For example, observations of Type Ia supernovae have provided strong evidence for the existence of dark energy, while particle accelerator experiments such as the Large Hadron Collider (LHC) have sought to find experimental evidence of dark matter [14], [15].

Particle interactions in cosmic structure Formation. Concepts in particle physics also influence the formation of cosmic structures, including the formation of stars, galaxies, and galaxy clusters. For example, the process of star formation involves interactions between particles in molecular clouds that lead to the compression of matter and star formation. Observational studies and numerical simulations have shown how gravity, weak interactions, and other particle physics processes are important in cosmic structure formation [16], [17].

Cosmic Movement and Evolution of the Universe. Through astronomical observations and cosmological simulations, we can trace the movement and evolution of the universe from the beginning to the present. Concepts in particle physics, such as the cosmic redshift and inflation theory, help us understand how the universe evolved from a very dense and hot initial state to the complex structure we see today. Recent studies have also shown that the properties of dark matter and dark energy significantly impact the universe's evolution [18], [19].

Virtual Reality (VR)

VR is the result of technological advances. VR technology creates interactive and immersive experiences for users in a simulated environment. In the virtual world created, users can feel and interact with objects and 3D environments that look and sound like in the real world [20]. This technology can make users feel as if they are physically involved to feel they are in a place. VR can present information in detail and interestingly so that users are motivated to see the information presented and can increase the effectiveness of information delivery [21].

In education, VR offers a variety of opportunities to enhance the learning process. For example, VR can create laboratory simulations where students can conduct dangerous or expensive experiments without any real risk. In addition, VR enables virtual visits to historical locations, museums, or hard-to-reach places so students can experience more immersive and contextualised learning. VR in education also supports experiential learning and can increase student engagement, helping them understand abstract concepts better through high visualisation and interactivity [22].

III. Methods

The following are the research results that have been carried out according to the development flow in the waterfall development model, as presented in Figure 1. The research was carried out at the Universitas Ahmad Dahlan Science Learning Technology Laboratory (LTPS) from March 2024 to July 2024.

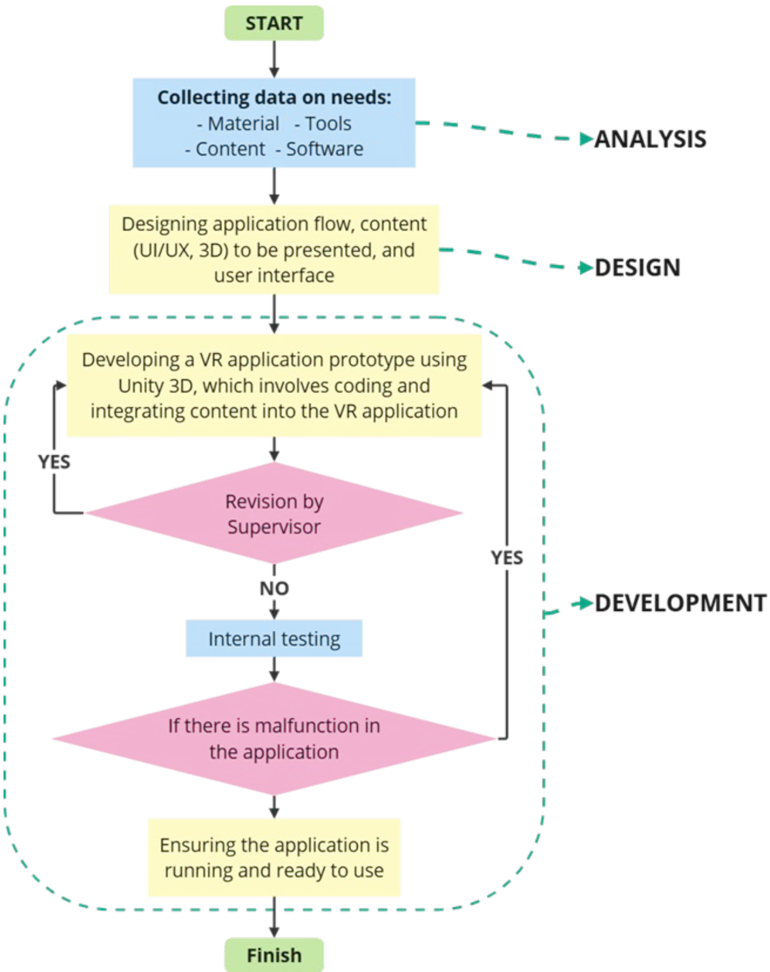

Figure 1. Flowchart of development flow/procedures

Several stages are carried out in this research, including analysis, design, and development, as shown in Figure 1. *First*, Analysis. The initial stage of this research is the collection of needs and analysis of the content or material to be used. In this stage, researchers will identify the functional and non-functional needs of VR applications and analyse the main aspects that need to be considered in designing applications properly. *Second*, Design. After conducting the analysis stage, the next step is to design the system in detail based on the results of the previous analysis. At this stage, researchers will create all the required main components, such as UI/UX design, layout, navigation, and 3D modelling. *Third*, Development. At this stage, researchers build VR applications using Unity 3D software, involving programming and integrating content created at the design stage.

Research uses devices or tools and development materials, which are divided into two parts, hardware and software, as in Table 1.

Table 1. Hardware and software

Item	Description
Hardware	
MSI Alpha 15 A3DDK Laptop	Used as a development centre, providing high performance for data processing, graphics rendering, and running VR development software. Ensures fast, efficient computing.
Oculus Quest 2	Used for testing live VR applications. Allows developers to experience and verify VR applications, ensuring smooth performance and user experience.
Software	
Tldraw	A tool for creating diagrams and sketches to plan and visualise concepts during development.
Figma	A design tool for prototyping and UI design. Enables team collaboration and rapid design iterations.
CorelDraw	Used for graphic design and visual asset creation for VR applications.
Blender 3D	3D modelling and animation tool for creating models and animations to be integrated into VR applications.
Unity 3D	The main platform for VR application development is used for integrating 3D models, scripting, and testing VR applications.
Visual Studio Code	A code editor used for writing and managing code, particularly for developing scripts and interactive components in VR applications.

IV. Results and discussion

The following are the research results that have been carried out according to the development flow in the waterfall development model, as presented in Figure 1.

Analysis Stage

At this stage, the researcher analyses the needs in this study, both the needs for assets, materials, and content and the need for development tools and materials. Based on the results of the data obtained, then the researcher sketches the project to be developed and determines the concepts that will be implemented in the application project developed in this study. All sketches or concepts are recorded in Tldraw software, as presented in Figure 2.

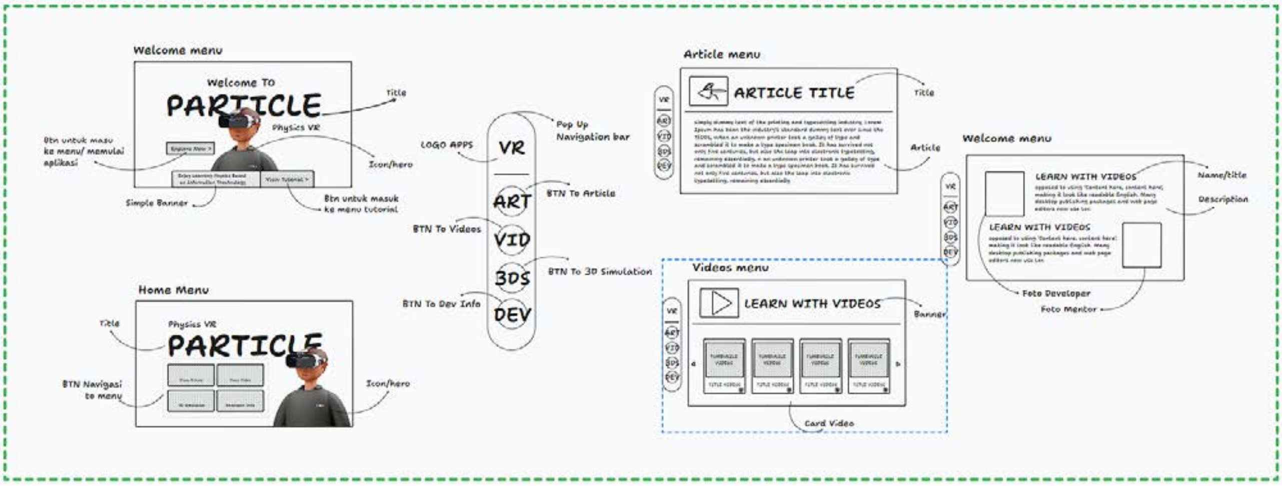

Figure 2. Project Sketch

Design Stage

This stage includes user interface/user experience (UI/UX) design and 3D modelling.

1. UI/UX Design

UI/UX design adopts modern themes and futuristic technology to improve user experience. Researchers use Figma software in the UI/UX design process at this stage, as shown in Figure 3. As shown in Figure 3, UI/UUX design includes several menu sections contained in the application, among them: (1) the landing page or initial menu or opener when you first open the application; (2) the home menu or application homepage; (3) the article menu, where on this menu displays the contents of particle physics material; (4) the video menu, which contains several videos that discuss particle physics material. (5) 3D simulation menu: on this menu, users can observe objects related to particle physics, experimental tools for particle physics, and so on. (6) Dev info menu: this menu displays application developer information and tools used in the VR application development process.

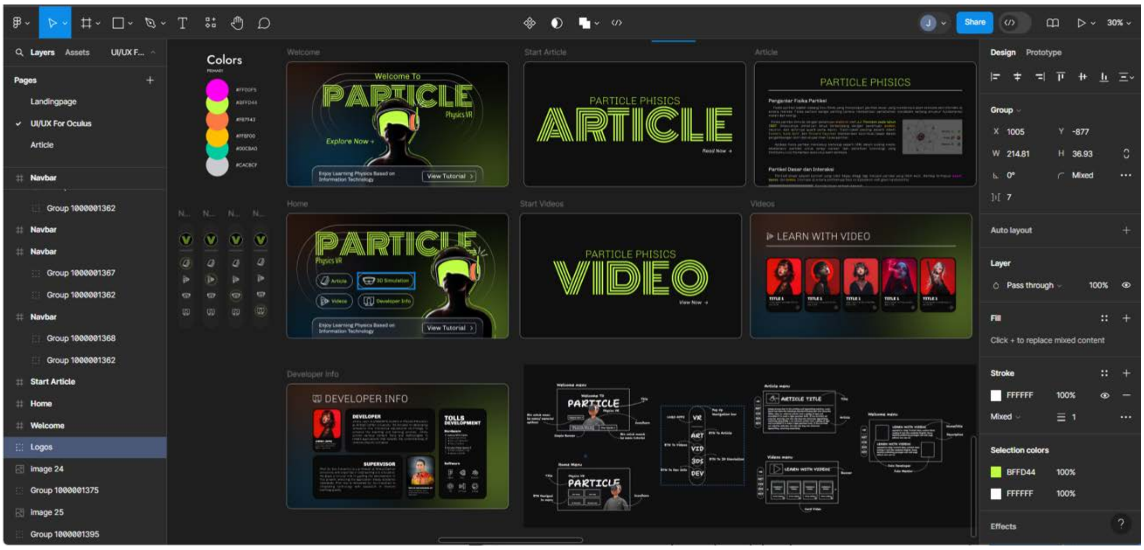

Figure 3. The UI/UX Design Process

2. 3D Object Modeling

In the 3D modeling stage, researchers use Blender 3D software. In making 3D assets, there are several stages for each 3D asset needed, including modeling, texturing, and rendering. Researchers created several 3D object assets for the developed application in this stage, including laboratory rooms, standard particle models, and particle physics experimental tools.

Development Stage

At this stage, the application begins to be built based on the design made in the previous stage. Code implementation uses Unity 3D, and integration between various components ensures the application runs as expected.

1. User Interface Development

The user interface development was done using the Unity UI framework, which allows the creation of interactive elements such as buttons, text, and images, as shown in Figure 4.

Each menu designed during the design stage is implemented in code to ensure intuitive and responsive navigation. The user interface development process involves several key steps:

a. Layouts for each application menu, including the landing page, home, articles, videos, 3D simulations, and developer information, are created using Unity UI.

b. Interactivity is added by assigning functions to buttons and other interactive elements through C# scripts. For instance, the button on the landing page menu directs users to the home menu when clicked, as illustrated in Figure 5.
c. Responsiveness testing is performed to ensure the interface adapts seamlessly to various screen sizes and resolutions.

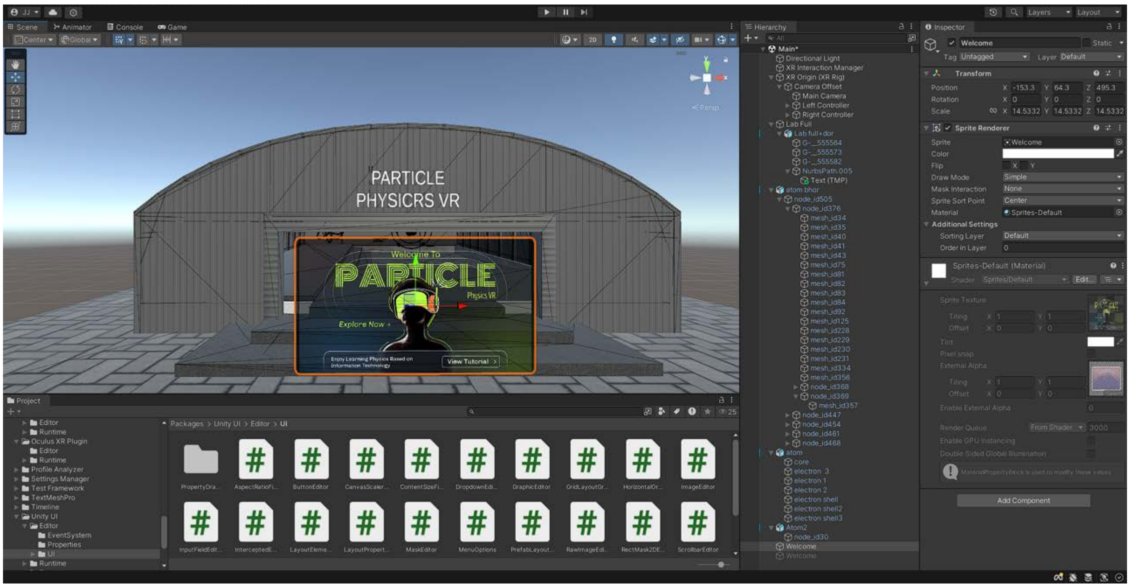

Figure 4. Create a Layout with Unity 3D

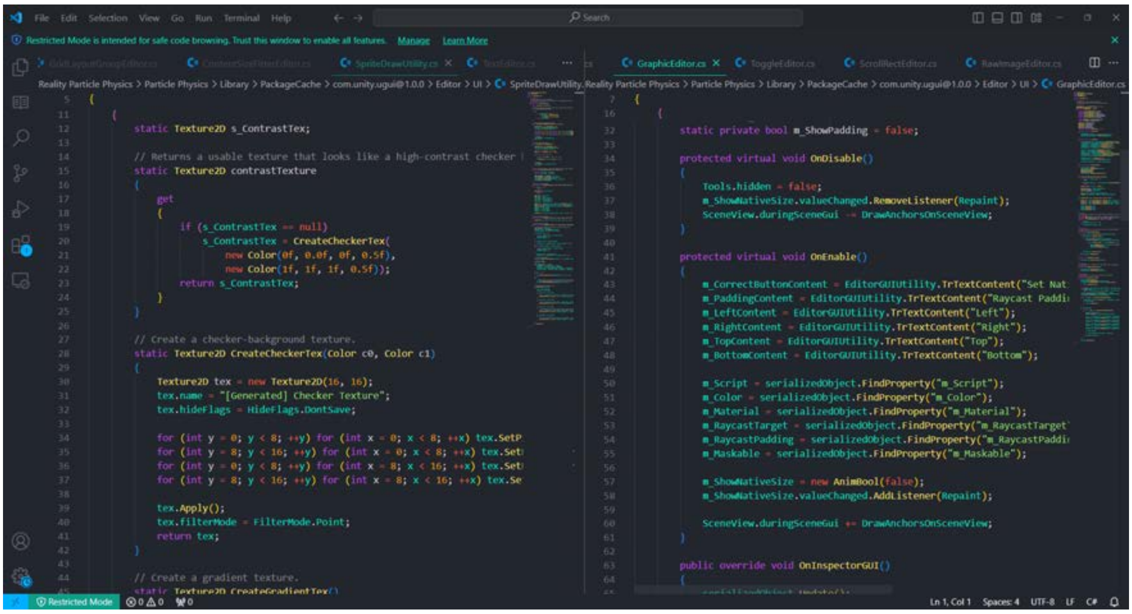

Figure 5. Coding features on buttons with VS Code

2. 3D Asset Integration

3D assets created using Blender are imported into Unity and positioned appropriately within the application. Interactions with these objects are then organized and managed through C# scripts. The 3D asset integration process includes:

a. Asset Import: 3D assets were imported into Unity, including the laboratory room, standard particle models, and particle physics experiment equipment, as shown in Figure 6.
b. Asset Placement: The assets are placed in appropriate positions in the application, e.g., the laboratory room is the main background for the 3D simulation.

c. Interaction Settings: Interactions with 3D objects are set up using scripts, such as the user's ability to rotate, zoom, or manipulate these objects.

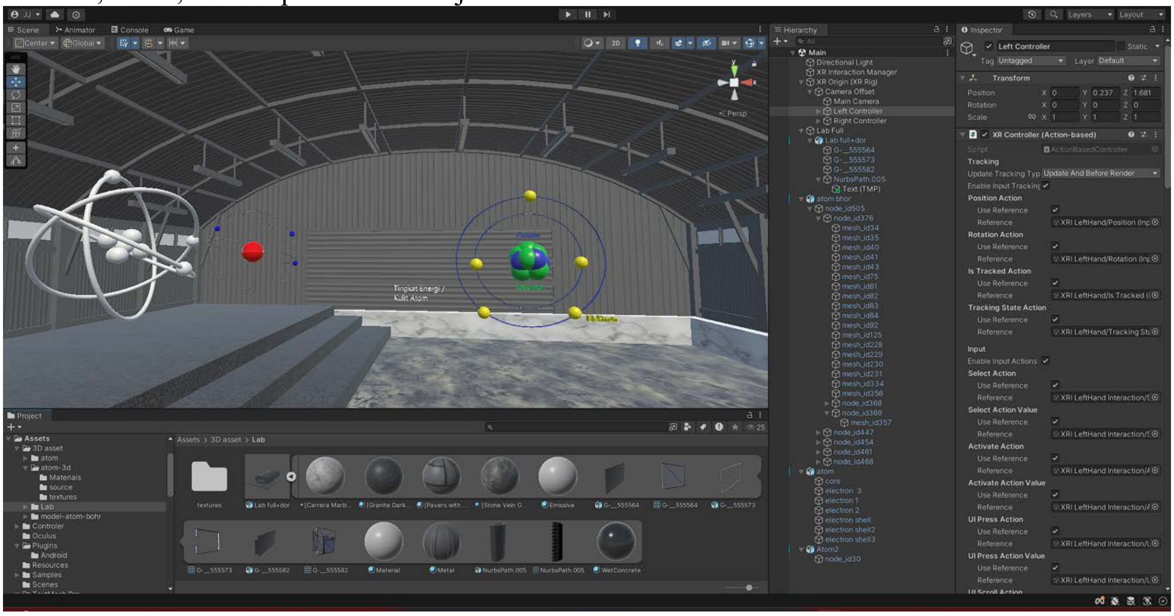

Figure 6. Import 3d assets into Unity 3D

3. Implementation of Additional Features

Additional features, such as a video player for the video menu and a viewer for the article menu, are implemented, as shown in Figures 7 and 8. Users can play educational videos and read articles provided without leaving the application. The steps in implementing additional features include:

a. Video Player Integration: The video player component was added to Unity and configured to play the prepared videos.
b. Article Viewer Implementation: The article viewer was created using Unity UI, allowing users to read the text easily.
c. Additional Functionality Testing: Each additional feature was tested to ensure its functionality runs well and without bugs.

Figure 7. Additional features layouting

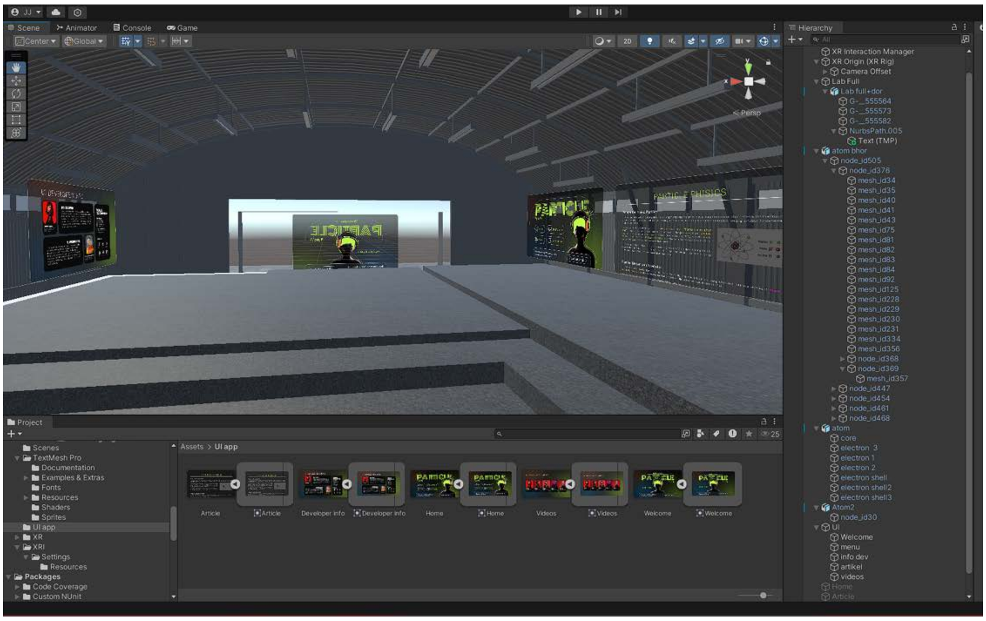

Figure 8. Implementation of additional features

4. Testing and Debugging

Once all the components are integrated, a testing phase ensures the application runs without issues. Any bugs found during testing are then identified and fixed. Testing involves real usage scenarios to ensure end users can use the application smoothly. The testing and debugging process includes:

a. Unit Testing: Each application component is tested separately to ensure its functionality works as planned.
b. Integration Testing: All application components are tested simultaneously to ensure no conflicts or integration issues.
c. Debugging: Bugs found during testing are logged and fixed. The debugging process is done using debugging tools provided by Unity and Visual Studio.
d. The results of the development stage show that the application runs according to the design that has been made and meets the needs of users to learn particle physics through VR technology.

V. Conclusions

This research successfully developed a Virtual Reality (VR) application for visualising particle physics concepts as a learning aid for undergraduate students. Following the waterfall development model, the application integrates a modern and interactive user interface with realistic 3D objects, developed through analysis, design, and implementation stages using software such as Figma and 3D Belender. Additional features, such as a video player and article viewer, enrich the learning experience. The application runs smoothly and effectively based on internal testing that researchers have carried out. It is hoped that the VR application developed can improve user understanding of particle physics and become an innovative and interactive learning media.

This research contributes to developing VR applications for learning particle physics, but some limitations must be considered. First, the currently developed app only covers basic particle physics material without including more complex topics. In addition, the impact of using VR on students' long-term understanding and engagement in learning has also yet to be tested in depth. Therefore, further research is recommended to expand the available learning materials. Further research could also focus on a deeper analysis of the effects of using VR in improving the understanding of particle physics concepts sustainably.

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