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SpaceXR: Virtual Reality and Data Mining for Astronomical Visualization

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Abstract. This paper presents a project named "SpaceXR" that harmonizes data science, astronomy, and Virtual Reality (VR) technology to deliver an immersive and interactive educational tool. It is designed to cater to a diverse audience, including students, academics, space enthusiasts, and professionals, offering an easily accessible platform through VR headsets. This innovative VR application offers a data-driven representation of celestial bodies, including planets and the sun within our solar system, guided by data from the NASA and Gaia databases. The VR application empowers users with interactive capabilities encompassing scaling, time manipulation, and object highlighting. The potential applications span from elementary educational contexts, such as teaching the star system in astronomy courses, to advanced astronomical research scenarios, like analyzing spectral data of celestial objects identified by Gaia and NASA. By adhering to emerging software development practices and employing a variety of conceptual frameworks, this project yields a fully immersive, precise, and user-friendly 3D VR application that relies on accurate, publicly available databases to map celestial objects.

Keywords: Virtual Reality · Interactive Learning · Astronomical Visualization

1 Introduction

1.1 Background

Technological advancements are continually transforming and enhancing current systems. One such system, education, has seen perpetual improvements following global technological advancements. As an illustration, the widespread adoption of computers transformed basic instructional tools into advanced, interconnected systems, which broadened educational reach and opened new avenues for communication and collaborative learning [1]. A closer examination of education in the subsequent sections reveals how technology influences its effectiveness and the overall learning process of an individual.

Education, by definition, is the process of passing skills, knowledge, or traits to others, typically in a formal setting such as a school or university, to reach a particular

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learning outcome. This learning outcome can be achieved through various learning methods described by popular theoretical models and frameworks, such as those proposed by Kolb, Bergsteiner, Avery, and Neumann. From these theoretical models, three main senses can be derived that facilitate learning based on human perception: visual, auditory, and kinesthetic learning [2]. Despite the lack of evidence supporting the meshing hypothesis, which suggests that focusing on one sense leads to better learning outcomes over another, the incorporation of all three, referred to as cross-modal processing [3], will be implemented by utilizing immersive learning.

Immersion is defined as an objective measure of vividness offered by a system, based on the number of senses that are activated by technology, and the extent to which a system can shut out the outside world [4]. Simply put, you are more immersed as the simulated reality converges with reality. Take learning from a textbook as an example. The experience of reading instructions on fishing from a textbook yields a lower degree of immersion, compared to if you were to go to a physical body of water and experience fishing first-hand. The latter yields a high or full degree of immersion, as you are physically present in the environment and engaging in the actions personally. The idea is that a more immersive experience may lead to improved factual, conceptual, and procedural knowledge acquisition, including transfer of learning and improved learning outcomes [4]. Cross-modal processing does not always mean high immersion, but high immersion typically always includes the use of all sensory inputs.

1.2 XR as a Tool

A technology that has grown exponentially in the past decade is known as extended reality (XR). Extended reality is an umbrella term that encompasses three main branches: virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR is defined as facilitating immersion in a simulated 3D virtual environment. The most common system used for VR is the head-mounted display (HMD). As the name suggests, individuals mount a display onto their heads for visual feedback, frequently paired with speakers on the HMD for auditory feedback, as well as complementary holdable controllers to mimic hand movement and interaction for interactive feedback [5]. In this way, VR can hit all three human senses, effectively enabling cross-model processing and making it an exceptionally immersive tool. Most often, the simulated environment seen through an HMD is created using computer graphics. Expanding on the interaction aspect of VR, interactive elements have shown to be vast. This allows for the cultivation of interactive experiences whilst simultaneously handing the power to the user [6]. Moving on, AR is quickly defined as augmenting the current reality, typically using digital elements overlayed over the physical space, where they are fully independent of one another. MR, on the other hand, like AR, is defined as overlaying digital elements over the physical space, but the elements do interact with the physical environment [5].

XR can be effective in spatial scenarios and visualization. It opens the opportunity to visualize and interact with different kinds of data [7]. It introduces spatial orientation and awareness, which allows for sensing of scale and space. XR's proficiency in this concept is particularly pertinent to fields that rely heavily on visualizing complex, multidimensional data [8], such as astronomy. Astronomical data is vast, ranging from close-to-home solar system information like orbits and orientation of different planets, to spectrum data of distant stars and galaxies, making astronomy a great candidate to test XR's capabilities.

Each branch of Extended Reality (XR)—Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—has unique applications depending on the context. This research focuses specifically on VR as the primary modality. The choice of VR over AR or MR is influenced by two main factors. First, considering the project's goal of visualizing and interacting with celestial objects, VR was deemed more suitable than AR/MR, which might conflict with the intended immersive environment. Second, among the three modalities, VR is currently the most advanced in terms of development and available support. While the potential for incorporating AR or MR exists in the future, the scope of this research is confined to VR applications.

The discussion thus far suggests that VR, when adeptly utilized and tailored for specific use cases, can serve as a potent tool. It offers a platform for crafting experiences that are not only immersive but also interactive, effectively facilitating cross-modal processing to enhance learning outcomes. Considering optimal areas for applying this technology, the focus shifts to a notable intersection. The inherent adaptability of educational systems to technological changes, coupled with the extensive datasets available in astronomy, posits VR's conceptual framework as a key component. This combination raises an intriguing question: Can the integration of VR technology into educational and academic disciplines, using astronomy as a guiding example, yield significant benefits and advancements in these fields?

1.3 Objectives

This research is committed to developing a multi-disciplinary immersive VR software tool that assesses the feasibility and utility of real-time or imported data interaction within educational and astronomical domains. The focus is on exploring the capabilities of VR in enhancing 3D visualization and improving instructional methods in education. The application is designed to be a versatile tool that not only addresses the immediate requirements of data interaction and visualization in these fields but also delves into the intricacies of VR's interactive design. This exploration aims to establish the application as an innovative solution that strengthens the way complex concepts are visualized and taught, thereby contributing significantly to both educational and astronomical disciplines. The primary objectives are:

Development of a comprehensive. VR application. To develop a versatile and user-friendly VR application that integrates data from multiple astronomical databases for diverse educational and academic use cases.

Astronomical Data Visualization. To effectively visualize a wide range of celestial objects and astronomical phenomena, leveraging data from NASA, Gaia, and other databases, thus facilitating a deeper understanding of space science.

Interactivity and User Control. To implement and refine interactive features such as teleportation, scaling/time manipulation, and object highlighting within the VR environment, ensuring that the application meets the specific needs of various users.

Assessment of Application Performance and Limitations. To evaluate the application's performance, identify and address the challenges faced, such as optimizing for a larger number of celestial objects, and laying the groundwork for future enhancements.

2 Related Works

The intersection of education, astronomy, and Virtual Reality (VR) has been explored in previous works, providing foundational insights into the development of immersive educational tools. Early studies, although not employing immersive VR in the contemporary sense with Head-Mounted Displays (HMDs), have demonstrated the educational benefits of conceptualizing astronomical phenomena in three-dimensional (3D) spaces through non-immersive VR applications. These applications, operating on computer-based interactive windows, underscore the potential of 3D spatial representations in enhancing students' comprehension of complex astronomical concepts. The engagement facilitated by these 3D models, coupled with the perspective shift they offer, serves as a precursor to the development of more immersive experiences [9, 10].

Building on these insights, this project leverages the advantages of real data importation from publicly available databases, enhancing user's engagement using HMDs and controllers. This approach not only introduces spatial awareness and kinesthetic interaction but also utilizes cross-modal processing to foster a comprehensive understanding of celestial bodies and their dynamics. Contrasting with the screen-based methodologies of previous works, this research incorporates real-time solar system data and imported celestial information, offering an interactive exploration environment enriched with scientific metadata.

A notable progression in this field is the advent of immersive VR applications that gamify astronomical education, such as a recent game-app integrating external data to visualize deep sky objects from Earth's perspective [11]. This application highlights the role of VR in mitigating the constraints imposed by light pollution, enabling users worldwide to experience the night sky in its entirety. Comparatively, the application created in this research distinguishes itself by offering an overhead perspective for user-driven exploration and manipulation, integrating the solar system and extraterrestrial objects into a singular, data-driven VR experience.

In summary, this research synthesizes the core aspects of these pioneering works into a modern, immersive VR application. By combining accurate data visualization, interactive engagement, and educational gamification, it aims to revolutionize the learning experience in astronomy, offering a unique platform for exploring the cosmos.

3 Technical Development

3.1 Hardware

In the realm of current VR technology, there is a wide array of options available, each with its unique strengths and applications. For the purposes of this research, the Meta Quest 2 [12] was chosen for its combination of affordability and functionality. This choice aligns with the goal of preparing for a broad dissemination of the application, where a cost-effective Head-Mounted Display (HMD) is more pragmatic. The Quest 2 stands out for its versatility and ability to meet the minimum standards required for this research. Alongside the HMD, the Quest 2 controllers were essential in introducing interactive elements into the application, enabling users to engage directly with the VR environment and manipulate various aspects of the celestial visualization effectively.

Additionally, a personal Windows computer was essential for the development phase and running the application via PC-VR, rather than as a standalone system. The distinction between standalone and PC-VR system setups is significant in this context. Standalone VR is self-contained, offering convenience and ease of use without the need for external hardware. However, it is often limited by its in-built processing power. On the other hand, PC-VR system setups, while requiring a connection to a computer, offer enhanced graphical fidelity and processing capabilities. This is particularly crucial for the application in question, which demands high-performance computing for rendering detailed 3D environments and specialized data processing tasks.

The decision to utilize PC-VR in this research was driven primarily by the need for higher graphical fidelity, as personal computers generally provide superior performance compared to standalone VR. Furthermore, the data streaming process integral to the application necessitates custom processes only feasible on a PC platform. This approach allowed for a more detailed and immersive visualization of celestial objects, leveraging the advanced computational power available through PC-VR system setups.

3.2 Software

The software infrastructure of the project was built on Unreal Engine 5 [13], a free source-available game engine renowned for its exceptional graphical fidelity and advanced computer graphics capabilities [14, 15], including real-time lighting effects, raytracing, and realistic textures. These features allow developers to focus on application creation without being bogged down by the intricacies of computer graphics, which was particularly beneficial in this research. The engine, primarily based on the C++ programming language, offers a robust framework for developing intricate and visually appealing environments.

A significant aspect of Unreal Engine 5's utility in this project was its integrated visual programming system known as Blueprints. Blueprints facilitated rapid prototyping and interactive design, allowing for a streamlined development process. Most of the application's coding was achieved through this node-based interface, which proved crucial for efficiently implementing the interactive features of the VR environment.

In addition to its core programming capabilities, Unreal Engine 5 played a pivotal role in porting the developed environment onto the Meta Quest 2 HMD. This process involved adapting the 3D environment and interactive elements to be compatible with the VR headset, ensuring seamless integration and user experience. The engine's compatibility with VR hardware, particularly the Quest 2, enabled a smooth transition of the virtual environment onto the headset, providing users with an immersive and responsive VR experience.

Moreover, the capacity for custom C++ coding in Unreal Engine 5 opened avenues for future enhancements, such as integrating live data streaming. The potential for implementing real-time celestial data streams, utilizing technologies like Inter-Process Communication (IPC), a technique used for dynamic data sharing between processes, can significantly elevate the application's interactive and educational value. This dual-language support—combining the rapid development of Blueprints with the customizability of C++ —ensured that the software infrastructure was not only apt for the current scope of the project but also adaptable for future expansions and technological integrations.

Software Development Protocols. The software development for the application was guided by common-day software development models, adapting a strategy that best fit the project's requirements and team structure. Given the project's nature of incremental additions and a small development team, a combination of agile and DevOps methodologies was employed [16].

3.3 Data Research

External Data. This section refers to data on celestial objects outside of the solar system.

Database Analysis. An integral component of this research was the selection and analysis of appropriate astronomical data.

The objective to develop a data-driven VR application with accurate celestial visualizations necessitated a thorough understanding of the available astronomical data landscape. Initial efforts focused on extensive online research to identify major publicly available databases in the field of astronomy. This exploration revealed several key databases, including Gaia [17–19], the Sloan Digital Sky Survey (SDSS) [20], and the Dark Energy Survey [21].

Gaia, an observatory mission led by the European Space Agency, emerged as a primary data source. It aims to construct the most extensive 3D map of the Milky Way galaxy, containing information on nearly 2 billion celestial objects, representing about 1% of the Milky Way galaxy. The SDSS provides detailed information on distant stars and galaxies using spectral imaging and spectroscopy, while the Dark Energy Survey focuses on mapping celestial objects to enhance the understanding of dark energy.

For the data visualization component of the application, Gaia's Data Release 3 (DR3) was chosen due to its comprehensive range and consistent data on celestial objects. Additionally, consultations with Dr. Bischoff and Dr. Bayliss, associate professors at the University of Cincinnati's astrophysics department, further reinforced the selection of Gaia. Their expert insights aligned with the research's focus and supported the inclusion of Gaia's data in the application.

These discussions also touched on the concept of 'cross-matching' celestial objects between different databases—a common practice in astronomy to combine data from multiple sources [22]. While the Gaia database includes a section for cross-matched objects from other databases, for simplicity, this project focused solely on Gaia-specific objects. However, the potential for implementing custom cross-matching algorithms in future expansions of the project was acknowledged, though it was beyond the scope of the current phase of research.

The process of database analysis and selection was a crucial step in ensuring the application's success. By choosing Gaia DR3 for its extensive and reliable data, the project laid a solid foundation for creating accurate and immersive visualizations of celestial objects.

Data Integration. Following the selection of a suitable data source, the next step was to develop methods for integrating this data into the application.

A critical distinction was made between live or real-time data and imported data. Real-time data involves streaming, filtering, and manipulation during the application's runtime, whereas imported data is pre-loaded and static, without the capability for additional data input during runtime.

To extract information from the Gaia database, the Astronomical Data Query Language (ADQL) was utilized. This programming language allows for querying the Gaia database effectively. While programmatic access to Gaia data in Python was available, it would have required additional work to create an Inter-Process Communication (IPC) between Python and Unreal Engine 5's C + + environment. This integration, although feasible, was earmarked for future development.

For this project, data was queried in advance from the Gaia archive. The algorithm developed for this purpose extracted desired attributes while filtering out non-essential data. Key information such as parallax, inclination, and declination were targeted, enabling the computation of object positionality, which will be described in the following section. Approximately 1000 celestial objects were selected based on these attributes.

It's important to note that the Gaia database provides a wealth of data beyond the selected attributes, including astrometric solutions, G magnitudes, astrophysical parameters from BP/RP spectra, and more. This variety of data can be highly beneficial for individuals interested in visualizing specific astronomical data in a three-dimensional space.

With the celestial positions computed and embedded within a data table, including additional metadata, Unreal Engine 5's Blueprint code completes the mapping process. By parsing the table, each celestial object's positional and metadata are dynamically integrated into the VR environment, enabling an accurate and interactive representation of the astronomical data. This integration empowers the application with the capability to not only depict celestial bodies in their precise locations but also to associate each with its unique data profile, enriching the user's exploratory and learning experience.

Mathematical Conversion. Unreal Engine 5 (UE5) operates within a Cartesian coordinate system, using X, Y, and Z coordinates to define the positioning of objects in three-dimensional space. This system is fundamental for creating realistic and accurately scaled virtual environments.

To translate the celestial data from the Gaia database into this coordinate system, specific mathematical conversions were required. The raw data from Gaia provides the positions of celestial objects in terms of celestial coordinates, which include right ascension, declination, and parallax. These coordinates are based on spherical geometry and need to be converted to Cartesian coordinates for use in UE5.

Despite the robustness of the Gaia dataset, users should be aware that distances obtained through this method are estimates and subject to potential errors inherent in the parallax inversion process and the assumptions made in the conversion formulas. This approximation serves the project's scope for a feasibility study, but for precise scientific applications, additional error analysis and data validation would be necessary [23].

The process begins by calculating the distance of the celestial object from Earth in parsecs using the formula:

$$Distance(parsecs) = \frac{1}{Parallax(arcseconds)} \tag{1}$$

Once the distance is known, the next step is to convert it into X, Y, and Z components. This conversion involves trigonometric calculations that consider the declination and inclination (right ascension) of the object. The formulas used for this conversion are:

$$\text{X} = \text{Distance} \times \cos(\text{Declination}) \times \cos(\text{Inclination}) \tag{2}$$

$$\text{Y} = \text{Distance} \times \cos(\text{Declination}) \times \sin(\text{Inclination}) \tag{3}$$

$$Z = Distance \times \sin(Declination) \tag{4}$$

After calculating the distance of a celestial object in parsecs from the inversion of its parallax, this distance is then converted into lightyears by multiplying by a factor of 3.262. This step is crucial as it translates the astronomical distance into a more universally recognized unit. Subsequently, to align with the Unreal Engine 5 (UE5) environment that operates in kilometers, this value in lightyears is further multiplied by 30,856,775,812,800, the number of kilometers in one lightyear. These calculations transform the spherical astronomical coordinates into Cartesian coordinates that can be directly used in the virtual environment of UE5. The data from Gaia, while extensive, was capped at a certain distance to ensure celestial objects remain visible within the application (Fig. 1).

Fig. 1. Visualization of celestial objects with capped distances for enhanced UX, based on Gaia data

Internal Data. This section refers to data on celestial objects within the solar system.

In the exploration of data pertinent to solar system objects, the research uncovered the utility of NASA's Spice Toolkit (NST) [24, 25]. Recognized within the planetary science and engineering communities, NST stands as a comprehensive information system designed to furnish precise observation geometry. It offers custom application programming interfaces (APIs) that facilitate many functionalities, including but not limited to, time system conversions, precise location and orientation of spacecraft and celestial bodies, transformations of reference frames, and calculation of illumination angles. For instance, consider the NST's application in trajectory planning for space missions. The toolkit's sophisticated algorithms enable researchers to input specific parameters for a spacecraft and project its orbital path around celestial bodies. This functionality extends to the anticipation of spacecraft interactions with planetary bodies, such as gravity-assist maneuvers which are critical for interplanetary missions. Such predictive modeling is theoretical and can be dynamically represented in UE5, offering a visual and interactive experience of the mission's potential trajectory within a virtual reality setting. This wealth of high-precision data renders NST an invaluable resource for solar system mapping applications.

The integration of NST with Unreal Engine 5 (UE5) is facilitated through the MaxQ plugin [26]—a wrapper that enables the seamless implementation of NST's computations within UE5's development environment. Whether utilizing UE5's native Blueprint scripting or the more traditional C++ programming, MaxQ empowers developers to incorporate NST data directly into their virtual creations. This synergy between NST and UE5 paves the way for accurate representations of celestial timing and positioning, enriching the application with interactive elements that enhance user engagement and learning. Key data points, including the position, orientation, and scale of solar system objects are extracted using NST, through MaxQ, and brought into virtual reality. This application inclusively models all planets in the solar system, along with the sun and Earth's moon, thereby offering users a comprehensive and interactive exploration of our celestial neighborhood (Fig. 2). This holistic approach underscores the project's aim to enhance user engagement and educational value through precise, dynamic visualizations of solar system objects.

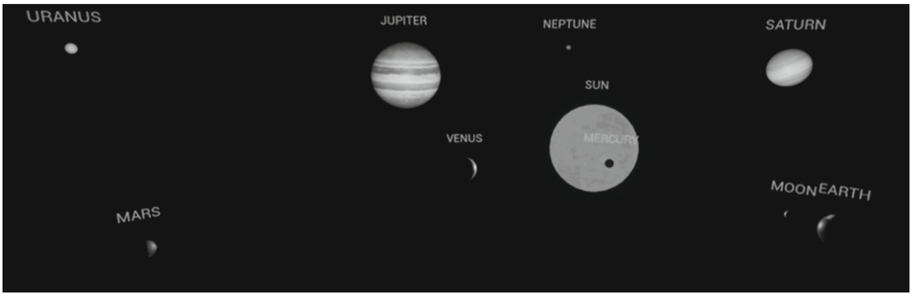

Fig. 2. Representation of solar system objects as integrated using NASA's Spice Toolkit

Differences. Here, it is important to highlight the differences between how external and internal data is treated once within Unreal Engine 5.

The NASA Spice Toolkit (NST) operates on a dynamic data model, forecasting astronomical events based on real-time calculations. For instance, it can predict Earth's relative position to the solar system's barycenter at any given moment. This is a quintessential example of real-time data processing, where predictions are made concurrently with the running application. In stark contrast, external data sources like the Gaia database offer a snapshot perspective. The data from Gaia was collected over a 34-month period, spanning from July 25, 2014, to May 28, 2017. This distinction between real-time predictive data and static historical data is crucial. It influences user interaction with the celestial objects in the VR application and dictates the structural design of the application's framework, enabling users to experience and understand the dynamic nature of celestial mechanics in contrast to the static historical observations.

3.4 Interaction and UX Design

This section delves into the interaction dynamics and user experience (UX) design of the application, focusing on how users engage with the imported astronomical data.

Current Interactive Elements. The application incorporates four key interactive elements, each tailored to enhance the user's exploratory experience within the virtual environment. These elements, detailed below, are currently applicable to internal celestial objects due to specific constraints, which will be elaborated on subsequently.

Teleportation. Activated through a tablet-like interface in the VR space, this feature enables users to instantaneously travel to any celestial object within the simulation. For instance, selecting 'Earth' transports the user to its virtual location. This element effectively addresses VR's inherent limitation of physical space, allowing expansive exploration within a confined area.

Scale Manipulation. Accessible via the same interface, this feature empowers users to adjust the solar system's scale through a slider mechanism. By sliding left or right, the user can alter the solar system's size from smaller to larger scales. This tool is invaluable for comprehending the relative sizes and distances of celestial bodies, offering a tangible sense of the vastness of space.

Time Manipulation. Also housed within the interaction window, this function grants users control over the temporal frame of the solar system. Leveraging the NST's real-time data computations, this feature allows users to select a reference time, prompting NST to calculate and display the current or future positions and orientations of celestial bodies. With three distinct modes of time manipulation, users can either observe significant time shifts or focus on more minute temporal changes. This dynamic exploration tool enables users to witness the motion of planets in their orbits and other celestial phenomena in a three-dimensional space.

Highlighting. By directing the controller towards a celestial object, users can activate a detailed information panel adjacent to the selected object. This panel provides comprehensive details about the object, including descriptive metadata. This feature enriches the user's experience by offering in-depth insights into each celestial body they choose to examine.

These interactive elements are designed not only for engagement but also for educational enrichment, allowing users to gain a deeper understanding of astronomical concepts through direct manipulation and exploration. By providing these tools, the application fosters a more immersive and informative experience, enhancing the user's connection with the vastness of space and the intricacies of our solar system.

User-Centered Design Approach. This approach emphasizes understanding the users' needs, preferences, and limitations to create an experience that is both intuitive and engaging (Fig. 3).

Teleportation was designed to address VR's spatial constraints. Recognizing that physical movement in VR is limited, this feature allows users to navigate vast cosmic distances effortlessly, thus overcoming a fundamental challenge in virtual space exploration.

Scale manipulation responds to the educational need to comprehend the relative sizes and distances in space, which are often difficult to grasp. This tool empowers users to adjust the scale of the solar system, facilitating a hands-on understanding of astronomical scales, and bringing abstract concepts to life.

Time manipulation enables users to interact with celestial dynamics over time, a key aspect in understanding astronomical phenomena. This feature not only enhances the immersive experience but also serves an educational purpose by allowing users to observe and comprehend the movement of celestial bodies and their positional changes over time.

Highlighting was incorporated to satisfy the curiosity-driven nature of learning. By providing detailed information about celestial objects on demand, this feature supports exploratory learning, allowing users to delve deeper into subjects of interest.

Fig. 3. User Interface with VR headset and motion controllers.

Impact on Learning and Engagement. The interactive features of the application significantly enhance its educational value.

Teleportation engages users by making space exploration accessible and exciting, encouraging exploration and discovery.

Scale manipulation offers a practical tool for visual learning, helping users visualize and understand the vastness of space and the relative sizes of celestial bodies—concepts often challenging to convey through traditional educational methods.

Time manipulation provides an interactive way to understand celestial mechanics. By observing the movement of planets and other celestial bodies over different time frames, users gain a dynamic understanding of the solar system, fostering a deeper grasp of astronomical concepts.

Highlighting enhances engagement by catering to the user's immediate curiosity. It serves as an on-demand educational resource, enabling users to learn more about specific celestial objects, thereby supporting individualized learning paths.

Overall, these interactive elements enrich the learning experience by fostering an environment of exploration and active participation. They encourage users to engage deeply with the content, leading to a more profound understanding of complex astronomical concepts, and enhancing the overall educational impact of the application.

4 Discussion

4.1 Implications and Challenges

In reviewing the development, architecture, and user experience of the VR application created in this research, several key implications and challenges emerge:

Data Integration Complexity. The process of integrating data into the application has proven to be highly context dependent. Databases, particularly in astronomy, exhibit a diverse range of structures and formats. This diversity necessitates a tailored approach for effective cross-integration within each specific application context. In this project, the distinction between 'external' and 'internal' data sources required meticulous development to ensure seamless integration. The foundational principle for data validity in this context hinged on the commonality of three-dimensional spatial representation, allowing for the unique projection of each data point within Unreal Engine 5 (UE5).

Technological Limitations and Opportunities. UE5, while a powerful tool, imposes limitations on the number of objects that can be simultaneously represented in a spatial environment. Considering the extensive scope of the Gaia database, which contains over 2 billion objects, the limitation to approximately 5000 objects through instanced meshes poses a significant challenge. Alternative, more optimized approaches, such as using UE5's Niagara particle system, may offer viable solutions for representing large-scale data in future project phases.

User Experience and Learning Engagement. The interactive elements integrated into the VR application significantly enhance user engagement, aligning with the principles of cross-modal processing. The application's immersive environment offers an innovative approach to learning, potentially transforming traditional educational methods. An initial comparative study to assess the application's effectiveness against conventional teaching methods in astronomy education was envisaged. However, time constraints precluded this analysis within the current research phase. Future studies focusing on this comparative analysis could provide empirical evidence on the impact of VR in educational settings, offering insights into its pedagogical efficacy.

Preliminary User Feedback and Future Directions. Early user feedback indicates high levels of engagement and interest in the application, which may be attributed to the novelty of VR or other factors. Without a formal evaluation in an educational context, definitive conclusions about the application's impact on learning outcomes remain elusive. However, this initial response suggests a promising direction for future research. Future studies should focus on evaluating the application's effectiveness in enhancing learning outcomes and user engagement, potentially harnessing VR's novelty to elevate the educational experience.

In conclusion, while this research has laid a strong foundation in developing a VR application for astronomical education, it opens avenues for further exploration in understanding the full implications of immersive learning technologies in educational settings.

5 Future Work and Direction

As this research project progresses into its next phases, several areas of future work have been identified, each presenting opportunities to enhance the application's capabilities and impact. These areas can be categorized into immediate priorities and broader, exploratory objectives.

5.1 Immediate Priorities

Evaluating Educational and Visualization Effectiveness. A critical next step involves empirically assessing the application's impact in educational settings and its effectiveness in astronomical visualization. This evaluation could include studies comparing the VR application's learning outcomes against traditional teaching methods, focusing on user engagement, comprehension, and retention of astronomical concepts.

Optimization of Data Representation. Improving the application's ability to handle and display large datasets, such as those from Gaia, is essential. This includes enhancing data processing efficiency and exploring more effective visualization techniques for representing vast numbers of celestial objects.

Enhanced Interaction with Imported Data. Developing methods to allow interactive engagement with imported data, such as that from Gaia, will enrich the user experience. This could include features that enable users to query, manipulate, and explore this data dynamically within the VR environment.

Expansion of Interactive Elements. Introducing more comprehensive and diverse interactive elements can significantly improve the application's educational and exploratory value. This includes tools for data analysis, simulation controls, and narrative-driven educational experiences.

Incorporating Story-Driven Teaching. Utilizing narrative techniques and story-driven approaches to present astronomical concepts can enhance user engagement and make learning more impactful and memorable.

Upgrading Graphical Fidelity for Immersion. Investing in higher-quality graphics and more detailed visualizations will enhance the overall immersion and realism of the virtual environment, making the educational experience more compelling.

5.2 Broader, Exploratory Objectives

Integration of a ChatGPT Bot Helper. Incorporating an AI assistant like ChatGPT [27], which users can interact with via voice commands and receive responses through text-to-speech, would add a new dimension of interactivity and support within the application.

Exploring AR/MR Integration. Expanding beyond VR, integrating augmented reality (AR) and mixed reality (MR) could offer alternative ways of experiencing and interacting with astronomical data. This could involve overlaying celestial data onto physical environments or blending virtual and real-world elements.

These future directions aim to not only refine and expand the current capabilities of the VR application but also to explore new frontiers in interactive learning, user engagement, and data visualization within the realms of education and astronomy.

6 Conclusion

This research project embarked on a journey to harness the transformative power of Virtual Reality (VR) in the realm of education and astronomy. By developing a multidisciplinary immersive VR software tool, the project aimed to revolutionize how celestial data is visualized and interacted with, thereby enhancing the learning experience in educational and astronomical studies.

Throughout this journey, the project navigated the complexities of integrating vast astronomical datasets, like those from Gaia, into an interactive VR environment. This integration was pivotal in creating an immersive platform where users could engage with celestial objects, experiencing the vastness of space in a tangible and meaningful way. The development process underscored the necessity of a tailored approach to data integration, emphasizing the uniqueness of each dataset and its requirements for effective visualization.

The Unreal Engine 5 (UE5) served as the backbone of this endeavor, providing the necessary tools and frameworks to bring celestial data to life in a virtual space. Integrating the NASA Spice Toolkit (NST) via the MaxQ plugin further augmented the application, allowing for precise and dynamic representations of celestial objects within the solar system.

The VR application, enhanced by its interactive elements like teleportation, scale manipulation, time manipulation, and highlighting, successfully bridged the gap between complex astronomical concepts and user-friendly educational tools. These features were not only instrumental in enhancing user engagement but also played a crucial role in fostering a deeper understanding of astronomical phenomena.

Reflecting on the project's journey, it is evident that the application has set a strong foundation for future exploration in immersive educational technologies. The initial user feedback has been promising, indicating high levels of engagement and interest.

However, a formal evaluation in an educational context remains a future goal and is vital for understanding the full impact of this VR tool on learning outcomes.

Looking ahead, the project has outlined several avenues for future work. These include empirical studies to assess the educational effectiveness of the application, optimization of data representation for larger datasets, expansion of interactive elements, and exploration of narrative-driven teaching methods. Additionally, the integration of technologies like ChatGPT and the expansion into Augmented Reality (AR) and Mixed Reality (MR) realms hold the potential to further revolutionize the user experience.

In conclusion, this research has not only demonstrated the feasibility of integrating complex astronomical data into an immersive VR environment but also opened the door to a new era of interactive learning. The journey of this project highlights the endless possibilities that lie at the intersection of technology, education, and space science, inspiring future endeavors in these dynamic fields.

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