3DGeoMuseum: Solid geometry through Virtual Reality

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Abstract: *Mathematics is a subject that has always presented challenges to students. Evolving it through emerging technologies such as extended realities (XR) and artificial intelligence (AI) presents both a challenge and an opportunity for educators and researchers. In this article, we propose the use of a virtual museum to teach spatial geometry, offering students an enhanced understanding of the properties of three-dimensional shapes. We also examine the current classroom context in Cuba, highlighting both the opportunities and obstacles for implementing this research. The proposed solution is the use of 3DGeoMuseum, a virtual reality (VR) application, with an explanation of its development in Unity and its practical operation. The results could be promising, given the novelty of this approach for Cuban students and the use of design elements to enhance its visual appeal.*

Keywords: Mathematics, emerging technologies, extended reality, artificial intelligence, virtual reality.

1. Introduction

The fear of mathematics is a global phenomenon, with students around the world dreading math tests at all levels. Solid geometry, a fundamental area of mathematics, often proves challenging for students due to its abstract nature. This is logical considering the level of abstraction required to analyze 3D objects in two-dimensional (2D) environments.

If we want to explore the 3D world, XR technologies (Çöltekin et al., 2020) are among the most impactful and have gained momentum due to rapid technological advancements. XR encompasses VR (Rubio-Tamayo, Gertrudix Barrio & García García, 2017), Augmented Reality (AR) (Xiong et al., 2021), and Mixed Reality (MR) (qianw211, 2023). These technologies are increasingly utilized across various industries, creating immersive experiences that allow users to engage with digital content instantly. XR has become a preferred option for marketing (Wagner & Cozmiuc, 2022), education (Alnagrat et al., 2022), training (Xi et al., 2022), and entertainment (Xi et al., 2022), offering realistic simulations (Bach et al., 2023) and interactive experiences (Norman, 1990) that enhance user engagement. Although this research focuses on the field of education, impacting mathematics (Yunus & Ali, 2009) directly and specifically solid geometry (Santiago, Zahroh & Darmayanti, 2023).

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In Cuba, access to higher education largely depends on the results obtained in the mathematics entrance exam, and one of the questions that yields the poorest results is spatial geometry due to the level of abstraction it requires from students. Surveys conducted with students and teachers revealed a lack of technological resources and the limited or sometimes non-existent use of digital materials in the classroom.

To make solid geometry more accessible and engaging, we are developing an application (3DGeoMuseum) in the form of an interactive virtual museum using Unity for implementation in VR. This virtual museum allows high school students to explore and learn about three-dimensional geometric shapes by solving puzzles and interacting with an AI that provides information, guidance, and encouragement.

To establish starting points, we pose the next questions:

Q1: How can the integration of XR technologies (VR, AR, and MR) in educational settings enhance student engagement and learning outcomes? What peculiarities are there in the reality of Cuba?

Q2: What are the key technical features and future implementation strategies of the 3DGeoMuseum in a virtual reality environment developed with Unity?

Q3: What would be the best and worst scenarios for the implementation of 3DGeoMuseum?

These questions are addressed in the following sections, providing detailed insights into the educational benefits, the reality of Cuba, and technological implementations of 3DGeoMuseum.

Development

XR technologies combine digital and physical elements to create a hybrid reality (Lai & Cheong, 2022). VR is an interactive, lifelike experience created by a computer program and viewed with the aid of a headset, providing a realistic 3D environment for users to explore and interact with. AR integrates digital information with the physical environment, commonly using handheld devices like mobile phones and tablets. MR merges VR and AR, creating a hybrid reality where digital content is seamlessly integrated into the real world(Çöltekin et al., 2020). By using XR technology, educational institutions can create engaging learning experiences that captivate students in ways that traditional teaching methods cannot. Understanding the potential of these technologies allows us to apply them in our fields, creating more appealing solutions for our target users.

2. Potential implications for education

XR visualization technologies have the potential to transform education by providing immersive experiences that are inherently more engaging than traditional methods such as lectures or readings alone. They also enable better collaboration between educators and students, allowing them to collaborate on interactive tasks in electronic workspaces with access to real-time data and feedback (Nesenbergs et al., 2021). XR can offer personalized learning experiences tailored to individual student needs by integrating assessment data with interactive educational content. It also supports blended learning models that combine traditional classroom instruction with real-world interactive experiences outside of school grounds. Moreover, interactive virtual environments empower educators to deliver more effective instruction by enabling them to create and customize content to enhance each student's learning experience (Ardiny & Khanmirza, 2018).

The use of 3D technology proposes interesting results, primarily based on student motivation, which depends on the interest and application of emerging technologies by teachers in their classes. An example of this is the article (Teplá, Teplý & Šmejkal, 2022), where a 2019 study with Czech middle and high school students found that using 3D models and animations in teaching significantly increased students' intrinsic motivation for learning natural sciences and improved their chemistry knowledge. The study also found that younger students showed greater benefits from dynamic visualizations compared to older students.

The application of XR encompasses all academic disciplines, and specifically, for this research, it has a positive effect on mathematics, producing notable results as demonstrated by the article (Roussou, 2009). The research explores the impact of immersive VR on learning, specifically focusing on fractions in mathematics. Where a virtual environment mimicking a playground was tested with primary school students, revealing that active engagement with the VR environment helped students' problem-solve.

However, it is not only mathematics in general that benefits; specific areas within mathematics are also positively impacted. One such area significantly enhanced is solid geometry, due to the three-dimensional characteristics of the shapes studied. The article (Kovárová & Sokolský, 2011) introduces a VR-based desktop application designed for teaching solid geometry at the high school level. It addresses the challenges associated with displaying three-dimensional space, employing anaglyph technology, and solving the problem of collision detection between 3D objects with precise calculation of collision points.

The concept of the interactive virtual museum aims to motivate students by allowing them the freedom to interact with elements in any order they choose, in a manner that is both flexible and spontaneous, as demonstrated by articles such as (Lepouras & Vassilakis, 2004), which explores the application of 3D game technologies as a cost-effective and user-friendly alternative for developing virtual museum environments. Through a case study comparing an existing virtual museum with a new iteration utilizing game technologies, the findings suggest that game technologies present a viable and effective solution for creating affordable desktop VR experiences.

2. Reality in Cuba. Survey results

In the case of Cuba, it is important to consider that there is a lack of technological infrastructure that often hinders interaction with emerging technologies. A positive point is the abundance of mobile devices among students, which makes it possible to introduce digital components into the classroom. The introduction of emerging technologies like VR would bring novelty to the educational process, not to mention the numerous benefits that could be incorporated, such as: reduced adoption barriers since the cost of VR devices is decreasing and their accessibility is increasing, and integration with other technologies; VR is being combined with emerging technologies like AI, machine learning, and AR, which expands its possibilities and applications.

2.1 Analyzing the survey results

It is presented an analysis with some of the results of two surveys, the surveys were conducted in two high schools in Matanzas, province of Cuba. A total of 52 students were sampled, comprising 33 females and 19 males, along with 5 mathematics teachers, all of whom were male. The primary objectives included the knowledge about XR, and the digital teaching methods.

Focus on VR, although the samples are disparate, as only 5 mathematics teachers were surveyed compared to a sample of 52 students, noteworthy results were obtained. Regarding familiarity with XR in Figure 1, 60% of teachers have heard about XR, although only 20% have used them. In the case of students, 50% have no idea what XR are, which represents a challenge for their implementation, although it becomes a motivation due to the novelty it represents. Support can be found, as the other 50% of them have heard about XR and/or have used it, unlike the previous group. This result highlights a challenge for teachers regarding the implementation of the virtual museum.

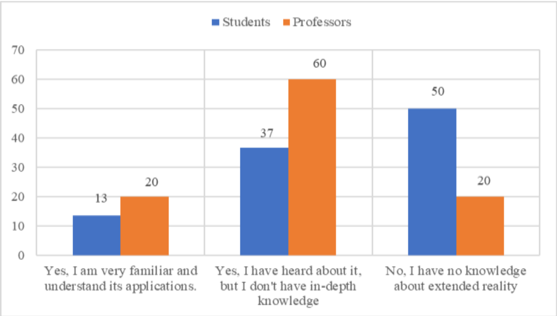

Figure 1. Familiarity with XR Concept

Regarding the use of XR devices in Figure 2, 100% of the teachers have never used them. In the case of students, there are strengths as 58% of them have used VR devices, in addition to 6% who have used AR and/or mixed reality (MR) devices, compared to 36% who have never used them. It is observed that most students have had some previous experience with VR devices, suggesting a decent level of familiarity with this technology among the respondents.

Although the interface of an application should be as intuitive as possible, it is also important for the user to show some interest in interacting with it. Measuring interest in learning more about XR was the intention of this question in Figure 3, showing 100% of teachers interested in learning more, and 47% and 37% of students completely interested and partially interested, respectively. This would facilitate the introduction of an application supported by XR technologies.

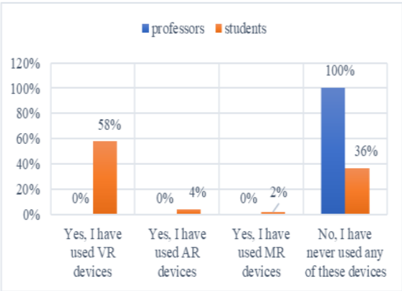

Figure 2. Interaction with XR Devices

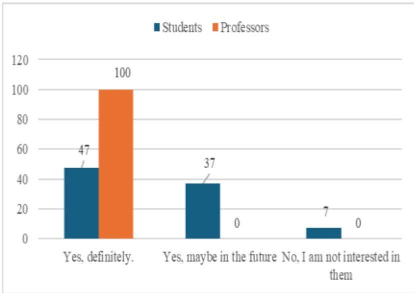

Figure 2. Interaction with XR Devices **Figure 3.** Interest in XR

According to the digital teaching methods, it was known through interviews with the teachers, that the school only provides them with a TV for their classes, which helped to interpret the responses provided by them in the surveys. The frequency of technology used is not optimal, with 60% of the teachers using it occasionally and 40% never using it. Additionally, the 100% of them do not use laptops, tablets, interactive projectors, or interactive whiteboards, limiting them to the mere use of the TV, thus minimizing the utilization of various resources such as software and applications and suppressing student interaction with them.

The survey revealed interesting findings, as shown in Figure 4, where 84% of students reported using their mobile phones for classroom activities, despite it is prohibited by the school administration. For students, it is very appealing to find answers to teachers' questions in various formats (text, image, video), and it keeps them motivated to find different answers online. 8% use computers, referring to their own laptops, which are permitted by the teachers, and 6% mention the TV, which is the medium accessible to the teacher. This challenges us more, but we have a solution running the application on mobile devices, allowing the whole classroom to enjoy the benefits of 3DGeoMuseum.

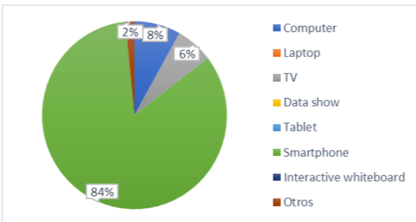

Figure 4. Technological Devices in Classroom

3. Design of the virtual museum

The virtual museum is named 3DGeoMuseum (Figure 5) and is designed as an interactive VR room where students can freely navigate using the camera. The immersion provided by VR offers a unique and engaging educational experience, allowing students to interact with geometric shapes in a tangible manner. The room features various exhibits of three-dimensional geometric shapes that students themselves must assemble by dragging and dropping pieces as if solving a puzzle. It will include shapes such as the cube (Figure 8), sphere (Figure 9), cylinder (Figure 10), cone (Figure 11), pyramid, and prism. Each exhibit presents a set of floating pieces that students must assemble to form the corresponding shape.

Figure 5. Museum view

3.1. Implementation of 3D puzzles

Each exhibition is equipped with a 3D puzzle. As students approach an exhibition, they encounter scattered pieces of the shape. They must drag and drop the pieces into their correct positions to assemble the complete shape. Interaction in VR allows students to manipulate the pieces intuitively and naturally. Once the puzzle is completed, detailed information about the geometric properties of the shape is displayed, including its volume, surface area, and unique characteristics.

Example: cube puzzle

In the cube exhibition, students find scattered pieces positioned on a stand labeled "cube". Upon solving the puzzle and forming the cube, they are provided with information about its volume, surface area, and general properties (Figure 8). This information remains accessible for future visits without the need to solve the puzzle again. However, fostering a community where students can collaborate and communicate enables them to collectively analyze and resolve the properties of the shapes. Periodically disassembling the shapes encourages students to reassemble them to access their properties

Since it is still a demo, essential elements within the shape have not been included yet. For instance, when displaying volume information, the elements used to calculate it will be highlighted in the shape, as well as for area and perimeter. Furthermore, qualitative properties such as edge lengths and the relationship between cube faces will also be highlighted when presenting that information, allowing not only textual information but also providing a description relevant to that information.

3.2. Software architecture and development of 3DGeoMuseum (table 1)

Table 1. 3DGeoMuseum technical explanation

Unity and VR Setup	**- Unity Version:** The project was developed in Unity 2022.2.12.f1, which is compatible with modern VR SDKs such as OpenXR or platform-specific SDKs like Oculus SDK for Oculus devices. **- VR SDK Integration:** The first step is setting up the VR environment. Using Unity's XR Interaction Toolkit, you can easily create interactions for VR controllers and hands, enabling movement and interaction within the 3D space. **- XR Rig:** The XR Rig acts as the camera and controller setup for users in VR. This allows users to look around and interact with objects using VR controllers. **- Locomotion:** Implementing teleportation or smooth locomotion for movement, depending on the hardware being used (e.g., Oculus, HTC Vive), ensures smooth navigation in the museum.
3D Model Creation and Import	**- Geometric Models:** The shapes (cube, cylinder, sphere, pyramid, cone, orthohedron) are modeled in 3D software such as Blender (Cone, Pyramid) or directly within Unity using built-in primitives (Sphere, Cube, Cylinder, Orthohedron). These models are then imported as assets in Unity. **- Puzzles:** Each geometric shape is divided into parts that can be assembled. These pieces are created by breaking the original models into smaller components. **- Textures and Materials:** Apply materials using Unity’s Shader Graph or the Standard Shader to give the shapes realistic or educationally relevant appearances. For example, shapes could have a transparent look or a grid texture to highlight edges and faces during the assembly process.
Interaction System for Puzzle Assembly	**- XR Grab Interactable (dragged pieces):** Using Unity’s XR Interaction Toolkit, the puzzle pieces are configured as XR Grab Interactable, allowing users to grab and manipulate objects in VR. **- Snap Zones (targets):** To guide the assembly of the shapes, snap zones are created. These are regions where puzzle pieces automatically snap into place when dragged close to their correct positions. **- Feedback Mechanism:** Add visual or auditory feedback (color changes) when pieces are correctly placed to improve user engagement.

Displaying Geometric Information	**- UI Elements:** Information about the shape's geometric properties (volume, surface area) is displayed using Unity's Canvas UI System and by overlaying 3D text objects in the scene. This information is triggered when the puzzle is completed. **- Dynamic Highlights:** When properties like volume or surface area are displayed, the corresponding elements of the shape (e.g., edges, faces) are highlighted in the 3D model using material changes and line renderers to visualize these aspects.

3.3. Future implementations and considerations

Future implementations for 3DGeoMuseum include the incorporation of collaborative and persistent features that allow puzzle progress to be saved and enable multiplayer interactions, allowing users to solve puzzles together or observe each other's progress. To optimize performance, Level of Detail (LOD) techniques will be used to manage model complexity, and pre-baked lighting will reduce the required processing power, ensuring smooth VR performance. Enhancements in audio and immersion will include spatial audio for realistic sound effects, haptic feedback for tactile responses, and hand tracking for natural interaction with the pieces, replacing controllers if the hardware allows.

3.3.1 Global accessibility and educational collaboration in 3DGeoMuseum

3DGeoMuseum has great potential to be used in any international context due to its global accessibility and collaborative features. By incorporating multilingual support, any user, regardless of language, could interact with the museum in their native tongue, making the learning experience more inclusive. Additionally, being a virtual museum, people from all over the world can access it without traditional geographical limitations, making it a valuable global educational tool.

The inclusion of multiplayer features would allow users from different countries to collaborate, fostering intercultural learning and teamwork. Furthermore, 3DGeoMuseum could be adapted to the curricula of various international educational systems, making it useful for schools and universities worldwide. Exhibits could also include content on the history and use of geometric shapes across different cultures, enhancing its relevance in global educational and cultural contexts.

4. Use of Artificial Intelligence

4.1 Technical specification for the 3DGeoMuseum chatbot

Objective: The 3DGeoMuseum chatbot will assist users by answering questions related to 3D geometry, providing examples of geometric shapes, and offering guidance on how to interact with the virtual museum app. This chatbot is text-based and will enhance the learning experience through interactive support.

Table 2. 3DGeoMuseum Chatbot Technical Specifications

Frontend Integration: The chatbot will be embedded within the Unity 3DGeoMuseum application as a UI component.	- **Platform:** Unity 2022.2.12.f1 (the app's development environment) - **UI Implementation:** A simple chat window using Unity's UI system. Components: Input field (for user queries), chat display area (for responses), and send button. Chat interface will appear as a floating panel or be integrated into the HUD (Head-Up Display). - **Frameworks and Tools:** Unity's Canvas system for the user interface. Unity's TextMeshPro for high-quality text rendering.
Backend and Processing	- **Backend Platform:** Python-based chatbot using Flask as the API server. Flask handle communication between Unity and the chatbot's logic. - **NLP Engine:** Hugging Face Transformers for natural language understanding and generation, specifically tuned to handle questions related to geometry. The chatbot will be trained or fine-tuned on geometry-related data to ensure it can respond accurately to user queries.
Communication Protocol	- **Unity to Backend:** Unity will use UnityWebRequest to send user queries from the app to the Flask server, which will run on a local server or be hosted in the cloud. - **Response Handling:** Flask will process the user's question, pass it through the NLP model, and return a response to Unity. Unity will display the text response in the chat UI.
Key Features	- **Text-Based Interaction:** Users will type geometry-related questions into the chatbot. - **Question Handling:** Geometric properties (e.g., "What is the volume of a cone?") Instructions on interaction (e.g., "How do I interact with the cube?") - **Response Generation:** The chatbot will generate natural language responses based on pre-trained data, focusing on geometry concepts. - **Interactive Guidance:** It will offer step-by-step instructions on how to manipulate the 3D shapes in the virtual museum.
Data Storage and Security	- **Data Management:** The chatbot will not collect or store any personal information. It will only handle real-time question processing. - **Security:** Communication between Unity and the backend server will be secured using HTTPS.

Testing and Deployment	**- Testing:** Unit testing will be conducted for both the frontend integration in Unity and the backend response accuracy. **- Deployment:** Once tested, the chatbot will be deployed as part of the main Unity project. Debugging tools within Unity will be used to ensure smooth integration and real-time responsiveness.

5. Best and worst scenarios for the implementation of 3DGeoMuseum. Methodology.

5.1 Best scenarios for the implementation of 3DGeoMuseum

In the best-case scenarios for implementing 3DGeoMuseum, the widespread availability of VR technology in schools would allow the museum to be fully integrated into classrooms, providing an immersive and engaging way for students to learn geometry. Ideally, each school would have access to virtual reality labs, not just for mathematics but for all subjects, enabling the creation of a wide array of VR resources. The curricular integration of the museum into math or science classes would allow teachers to use it to teach spatial reasoning, geometric properties, and problem-solving skills. For this to happen, the museum would need to encompass all possible 3D geometric figures and their properties, forming an interactive database.

Partnerships between schools and VR developers could ensure continuous updates and improvements, enhancing the platform based on educator feedback. Furthermore, in the context of remote learning, 3DGeoMuseum could serve as an important tool for teaching geometry to students who cannot attend in-person classes. The addition of interactive and collaborative features, such as multiplayer puzzle-solving, would foster teamwork and increase engagement, aligning with the goal of creating a collaborative and motivating learning environment.

5.2 Worst scenarios for the implementation of 3DGeoMuseum

In the worst-case scenarios for implementing 3DGeoMuseum, limited access to VR technology could hinder its success, as schools or students may lack VR headsets or compatible hardware due to cost or logistical challenges. While mobile devices can offer a limited virtual reality experience, providing a 360-degree view of 3D geometric shapes, this cannot fully match the immersive benefits of VR headsets, though it remains a viable alternative. Teacher resistance or lack of training in VR technology could also pose a challenge, reducing the platform's educational impact if educators are unwilling or unable to incorporate it into their teaching.

Additionally, technical issues such as lag, poor graphics rendering, or a complex user interface may frustrate users and lead to disengagement. Without sufficient content or regular updates, the app risks becoming stagnant, causing students to lose interest after the initial novelty wears off. Finally, some students may experience VR-induced motion sickness, making it difficult for them to fully engage with the learning activities, potentially reducing the adoption rate of the platform.

5.3 Cuban scenario

There are no VR laboratories in Cuba, nor has this technology been introduced into classrooms. We face limitations with technological resources, although the novelty of the new technology works in our favor, as does the acceptance of using mobile devices in the classroom. The app will be made available to math teachers at the surveyed schools, providing them with training on its functionality. The intention is to use it during space geometry classes, especially when introducing new three-dimensional geometric figures. Both students' and teachers' mobile devices will be used, providing a VR experience that, although limited, will offer a better view of the properties and visual characteristics of each figure.

5.4 Methodology

The methodology of **3DGeoMuseum** is grounded in the principles of **experiential learning**(Lewis & Williams, 1994) (McCarthy, 2016) (Anon, n.d.), as proposed by david kolb (Kolb, 2014), by offering students the opportunity to interact actively with three-dimensional geometric shapes. This immersive environment allows users to manipulate, rotate, and observe the properties of the shapes from different angles, thus fostering a direct and concrete learning experience. through hands-on interaction with the forms, students not only receive visual and spatial information but also apply geometric knowledge in real-life situations, encouraging reflection and consolidation of their understanding. This active and reflective experience is at the core of experiential learning, enabling students to construct their knowledge through direct engagement with objects.

3DGeoMuseum also incorporates a methodology centered around the use of **three-dimensional puzzles**, which challenge students to apply geometric concepts to solve problems within the virtual space. While it does not employ traditional gamification, the puzzles offer a form of learning based on the **problem-solving principle**, motivating students to think critically and experiment with different solutions. This methodology of active and constructive learning aligns with pedagogical theories that promote autonomy and guided exploration, providing a deep learning experience focused on understanding space and form.

6. Conclusions

This research demonstrates that integrating XR technologies, such as virtual reality, can transform traditional solid geometry teaching into a more immersive and engaging experience for students. The virtual museum 3DGeoMuseum motivates students and facilitates the visualization and manipulation of abstract concepts through interactive 3D environments.

In the Cuban context, the results highlight the feasibility of implementing XR-based educational tools despite technological limitations. While classroom infrastructure is limited, the widespread availability of mobile devices offers an effective way to adopt emerging technologies, with both students and teachers showing interest in learning more about XR.

The design of the 3DGeoMuseum allows students to actively engage with three-dimensional shapes, improving their spatial reasoning and problem-solving skills. The inclusion of an AI-powered chatbot further enhances the experience by providing immediate assistance, deepening their understanding of 3D geometry.

This research highlights both the potential and challenges of implementing the 3DGeoMuseum. While access to VR technology in schools promotes immersive learning, limitations such as a lack of equipment, technical issues, and teacher resistance remain obstacles. In Cuba, mobile devices provide a feasible alternative, though with less immersion. The use of experiental learning offers students the opportunity to interact actively with three-dimensional geometric shapes and understand their properties and visual aids.

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