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VR LAB OF ADDITIVE MANUFACTURING AND 3D PRINTING

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Abstract-- This article presents the Virtual Reality Laboratory for Additive Manufacturing and 3D Printing (VR Lab) developed at the National Technological Institute of Mexico, Ciudad Juárez, and analyzes its potential for education and the manufacturing industry. Its main objective is to explore the feasibility and pedagogical and productive value of virtualizing 3D printing laboratories through virtual reality, allowing for the immersive visualization and manipulation of three-dimensional models, as well as the simulation of additive manufacturing processes and the evaluation of geometries prior to manufacturing. It describes the convergence between 3D printing and VR as a platform for interactive learning where students and professionals can interact with 3D objects, detect faults, optimize designs, and better understand the proportions and parameters of the process in a safe and controlled environment. Among the benefits are improved theoretical understanding and practical skills, reduced risks and costs associated with prototyping, and the possibility of facilitating collaboration and distance learning or in contexts where physical experimentation is limited. Importance is given to key industrial sectors such as automotive and aerospace, as well as education and training, emphasizing that VR can provide a deeper learning experience, encourage design iteration, and support informed manufacturing decisions. It concludes that virtual reality in additive manufacturing laboratories has high transformative potential for education and technological innovation.

Keywords: 3D printing, virtual laboratory, virtualization.

Abstract: This article presents the Virtual Reality Laboratory for Additive Manufacturing and 3D Printing (VR Lab), developed at the National Technological Institute of Mexico, Ciudad Juárez, and examines its potential impact on education and the manufacturing industry. The primary objective is to explore the feasibility and pedagogical and productive value of virtualizing 3D printing laboratories through virtual reality (VR), enabling immersive visualization and manipulation of three-dimensional models, simulation of additive manufacturing processes, and evaluation of geometries prior to fabrication.

The convergence of 3D printing and VR is described as a platform for interactive learning, where students and professionals can engage with 3D objects, identify design flaws, optimize models, and gain a deeper understanding of proportions and process parameters within a safe and controlled environment. Key benefits include enhanced theoretical comprehension and practical skills, reduced risks and costs associated with prototyping, and the facilitation of collaboration and remote learning—particularly in
contexts where physical experimentation is limited.

Special emphasis is placed on critical industrial sectors such as automotive and aerospace, as well as on educational and training applications. The study highlights VR's capacity to deliver a more immersive learning experience, support iterative design processes, and inform manufacturing decisions. It concludes that virtual reality in additive manufacturing laboratories holds significant transformative potential for education and technological innovation.
Keywords: 3D Printing, Virtual laboratories, Virtualization.

INTRODUCTION

Additive manufacturing has revolutionized the industry by offering innovative solutions for creating complex parts with reduced production times and a very high degree of customization. Traditional manufacturing methods start with blocks of material that are cut away to create the object, which is called subtractive manufacturing. Additive manufacturing, on the other hand, builds parts layer by layer, allowing precise control over the geometry of the final product. (López, 2024), (Kumar, 20024).

The ability of 3D printing to manufacture complex structures with greater efficiency and precision has attracted significant attention from various productive sectors. There are increasingly promising trends that stem from new possibilities for innovation, customization, and sustainability. Additive manufacturing has revolutionized product manufacturing methods in various industrial sectors, particularly the automotive, aerospace, and aeronautics industries. This innovative technology allows the creation of three-dimensional objects from digital models, building layer by layer with precision and detail, and above all, offering a wide range of materials for manufacturing (Cardona, 2007).

On the other hand, virtual reality (VR) has emerged as a powerful tool for simulating immersive environments, allowing users to interact with three-dimensional objects intuitively (Abrar, 2016), (Biocca, 1992), (Gigante, 1993), (González, 2013). Currently, virtual reality has been implemented in logistics processes, teaching processes, training processes, industrial processes, and design processes to improve the visualization and analysis of products before their production (Albahbah, 2021), (Asaad, 2021), (Balsam, 2019), (Jerald, 2014).

The ability to share virtual space with a 3D model allows engineers to detect faults, optimize shapes, and better understand product proportions before manufacturing them. Currently, the use of virtual reality in academia has the potential to transform the way students learn, their ability to understand and apply complex processes such as additive manufacturing. Virtual reality (VR) is also seen as a powerful technological tool for education, allowing students to experience environments and situations that would otherwise be inaccessible (Jaynes, 2003), (Kim, 2013), (Gausemeier, 2011). From virtual laboratories to field simulations, virtual reality offers a platform for interactive and practical learning. This tool improves theoretical understanding and also fosters practical skills in a safe and controlled environment. The ability to immerse oneself in a virtual world allows students to face real challenges without the associated risks, facilitating a more comprehensive and effective education (Haba, 2024), (McLellan, 1993), (Nagta, 2002), (Omran, 2024).

The manufacturing industry has experienced significant advances in recent years, especially with the integration of emerging technologies such as virtual reality (VR) and augmented reality (AR) into production and design processes. The integration of these types of technologies allows for the interactive simulation of environments and processes, optimizing training, design, and the execution of industrial processes. However, in the field of additive manufacturing, there are still challenges related to training and the proper use of these technologies, especially in educational environments (Pawassar, 2021), (Roda-Segarra, 2022), (Samala, 2022), (Yunsik, 2022). Despite the growing adoption of these tools, there is no efficient training that allows users to learn comprehensively about the use of 3D printers, much less within an interactive virtual environment.

This project aims to contribute to the development of a virtual training environment that allows students to learn the theoretical and practical fundamentals of additive manufacturing through interactive simulations, CAD design, three-dimensional images, and 3D printing. The goal of this project is to create a virtual environment using Unity and Oculus Quest 2 to simulate the 3D printing process, providing students at the Tecnológico Nacional de México Campus Ciudad Juárez with an innovative tool for their education. This environment will allow users to interact and experiment with the different steps of the 3D printing process safely and without the need for physical access to the printer.

Overall objective

To design an interactive virtual environment for training in the additive manufacturing process, including CAD design and 3D printing phases, in order to improve understanding and practical skills.

Specific objectives

- Conduct a literature review on virtual reality and 3D printing technology.
- Develop a virtual environment that simulates the additive manufacturing process, where users can interact step by step with the 3D printing workflow, from CAD design to print configuration.
- Implement a virtual reality platform that allows users to experience the additive manufacturing process without the need for physical equipment, ensuring an immersive experience.
- Conduct tests to validate the functionality and effectiveness of the virtual environment.

Justification

Currently, the use of technological tools is essential in the training of professionals. Among these technologies are virtual environments, which have become particularly relevant in sectors such as education, engineering, and manufacturing, as they allow complex scenarios to be simulated in a safe, economical, and accessible manner. Virtual Reality, in particular, has established itself as an efficient tool for learning and training, offering immersive experiences that facilitate the understanding of concepts and the development of practical skills. In the context of Industry 4.0 and education, the implementation of virtual environments for training in additive manufacturing processes responds to a growing need for methods that allow experimentation, design, and evaluation without relying exclusively on physical equipment. These environments allow students to visualize prototypes, identify errors in the early stages of design, and significantly reduce material waste and the costs associated with the production of defective physical parts. In addition, remote access to simulation environments expands training possibilities, allowing students to practice at any time, without the need for specialized equipment.

The project uses virtual reality to introduce students to the principles of additive design and manufacturing, providing a tool that allows them to explore 3D printing processes from an immersive perspective, promoting understanding of the process and more efficient evaluation of prototypes.

DEVELOPMENT

The type of research carried out is exploratory-descriptive in nature, focusing on detailing the characteristics of a new training and learning process through the use of virtual reality and 3D printing. The technique used is direct observation and documentary review, which, as researchers, helps us in the collection of information and in the use of the fundamental tools for validation, which in turn helps us in the verification, monitoring, and fulfillment of our objective.

The research work on the "Virtual Reality Laboratory for Additive Manufacturing and 3D Printing" was carried out at the Technological Institute of Ciudad Juárez, where the graphic interface of the VR laboratory was designed, implemented, and evaluated with higher education students.

The methodological process began with the specific objectives, the first of which was to review the literature on the concepts of virtual reality and additive manufacturing, using articles published no more than five years ago as a reference.

On the other hand, emphasis is placed on the importance of integrating human-machine interfaces between virtual environments, training and continuing education processes, together with current virtual and augmented reality technologies, as a resource for the development of motor and technical skills in student apprentices. As a result, sufficient information was obtained to validate user interaction with the virtual laboratory development.

Finally, to evaluate the impact of implementing the use of the tool, the virtual laboratory allows us to identify the achievement of the overall objective and the project's goals in a quantifiable manner and in comparison with applied characteristics, in order to continue the research as will be shown later.

Immersive technologies refer to the experience created by surrounding the user with a digital environment that immerses them in a virtual world, that is, a reality that is entirely designed through software, capturing sensory stimuli so that the user can interact as they would in physical reality. There are four categories of immersive technologies: Virtual Reality (VR): an experience in which the user can interact with a virtual environment. Augmented Reality (AR) is a technology that superimposes digital information onto the real world through a device such as a smartphone or tablet. Mixed reality (MR) is the creation of a hybrid environment in which virtual objects and real objects can interact with each other; and extended reality (XR) is where all experiences that combine the digital world and the real world are integrated. (Garcia, E, 2023).

Virtual Reality is one of the key technologies in Virtual Prototyping and refers to a technology that has been used for several years as a support tool in different areas of knowledge. It involves easy-to-understand user interfaces in a virtual design space that facilitate interactive exploration of the functionality of a new product, a realistic representation of the product's appearance and, in some cases, its behavior. (Gausemeier, 2011).

The Heilig Sensorama is considered one of the first challenges of virtual reality, which was first presented in 1962 by Morton Heilig. In this concept, the viewer could take a motorcycle ride through New York, with the wind, noise, and smells of the city. Heilig's system had all the characteristics of a virtual reality system, without being interactive, it had a fixed and pre-recorded route. (Gigante, 1993).

Unity 3D is software that centralizes everything needed to develop video games and is known as a development engine; it is a series of programming routines that enable the design, creation, and operation of an interactive environment. It is a tool that allows you to create video games for various platforms using a visual editor and scripting.

On the other hand, additive manufacturing starts with a digital 3D model that is cut into hundreds of thin layers using specific software to export it in G-code format. This 3D printing format is a language that the 3D printer identifies to know precisely when and where to deposit the material. Each layer corresponds to the exact 2D shape of a section or slice of the object. The layers are printed consecutively in 3D, one by one, until the object is completely printed. 3D printing offers a number of advantages, the most important of which is the ability to produce highly complex designs that would otherwise be impossible to achieve. Although 3D printing an object can take hours or even days, it is still much faster than conventional production methods such as injection molding. Prototyping, one of the most popular professional uses of 3D printing, can be done in-house with little or no lead time, and design iterations can be implemented and printed on the spot. This technology also offers many possibilities for 3D printing materials.

DISCUSSION AND ANALYSIS OF RESULTS

Reaching the final phase of the research, we proceed to the development and validation of the virtual 3D printing laboratory. For the proper implementation of this project, the methods and materials were identified.

correct for the design and development of a virtual reality platform for training in the use of 3D printers. The use of Oculus Quest 2 virtual reality glasses was considered, as shown in Figure 1, since this device allows interaction with 3D models and has excellent compatibility with VR platforms. The main features are: a control panel with two internal LCD panels to improve image quality. It has a resolution of 1832 x 1920 per eye and a refresh rate of 90 Hz, achieving greater fluidity. It has a Qualcomm Snapdragon XR2 processor and 6 GB of RAM; and Wi-Fi 6 connectivity with Bluetooth 5.1 and 6 degrees of freedom technology, which allows body movements to be captured without the need for sensors.

Figure 1. *Oculus Quest 2*.

The 3D printer used as the basis for training is a SUNLU T3, as shown in Figure 2, which has the following characteristics: the printing technology is Fused Deposition Modeling (FDM), with a printing area of 220×220×250 (mm), and the ability to print materials such as ABS, PLA, TPU, and PETG. In addition, it has a high printing speed of 250 mm/s, obstruction detection, which allows printing to resume after an obstruction, is considered to be quiet, and has automatic 4*4 bed leveling.

Figure 2. *Sunlu T3 3D printer*.

Unity software is used to create the interactive virtual reality experience, as can be seen in Figure 3. It is chosen for its ease of integration with VR devices such as the Oculus Quest 2 and its ability to create interactive user interfaces and realistic environments. Unity is a multi-platform video game engine created by Unity Technologies, available as a development platform for Microsoft Windows, Mac OS, and Linux. Unity can be used in conjunction with Blender, 3ds Max, and others, and automatically updates changes made to created objects. The graphics engine uses OpenGL, Direct3D, OpenGL ES, and proprietary interfaces.

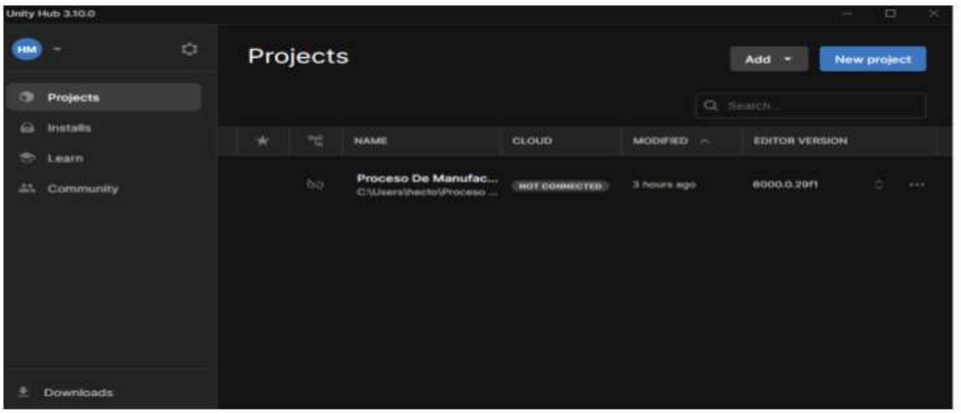

Figure 3. *Unity Engine Platform*.

The application for linking and loading new apps is Meta Quest Link, a platform that allows you to connect the headset to your computer via Wi-Fi or a USB-C cable so you can test your environment. The virtual environment of the 3D printing lab was constructed as follows using elements from Sketchfab. Three walls and a floor were added to define the space in which interaction will take place. To make it more visual, equipment such as a desk, a computer, and work tables were incorporated, as shown in Figure 4.

Figure 4. *Remote 3D Printing Lab*.

Once the lab was organized, the simulation was designed so that the user could interact with the printer and 3D models within the virtual environment. The Sunlu T3 3D printer model was used, as it has the basic components needed to understand how to use the printer. Figure 5 shows this printer placed on a work table within the virtual environment.

Figure 5. *SunLu T3 3D printer model*.

With the printer already in place, the various panels displaying the printer configuration instructions were designed. The simulation includes the following steps: Turn the equipment on/off, Adjust bed movement (X, Y, and Z axes), Load the filament type, Adjust the bed and filament temperature, Load the model to be printed. These instructions were created using Unity's text canvas, which allows the font type and size to be modified and their position to be adjusted as desired, as shown in Figure 6.

Figure 6. *Unity development platform using buttons*.

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Interactive panels were also created, allowing users to configure certain parameters as needed. For the on and off buttons, two button canvases were used, which change color depending on the function, such as turning the printer on or off. For the bed axis settings, a canvas with toggle elements was used, which can be checked or unchecked according to the required configuration, as shown in Figure 7.

Figure 7. *Unity development platform using toggles.*

In addition, an interaction was developed for filament adjustment. To do this, several canvases were used: three toggles for selecting different types of preheating and a slider to simulate the increase and decrease in filament and bed temperature, as shown in Fig. 8. A menu was also created with the different models available to choose from. This menu is interactive and was designed to simulate the selection of the model to be printed.

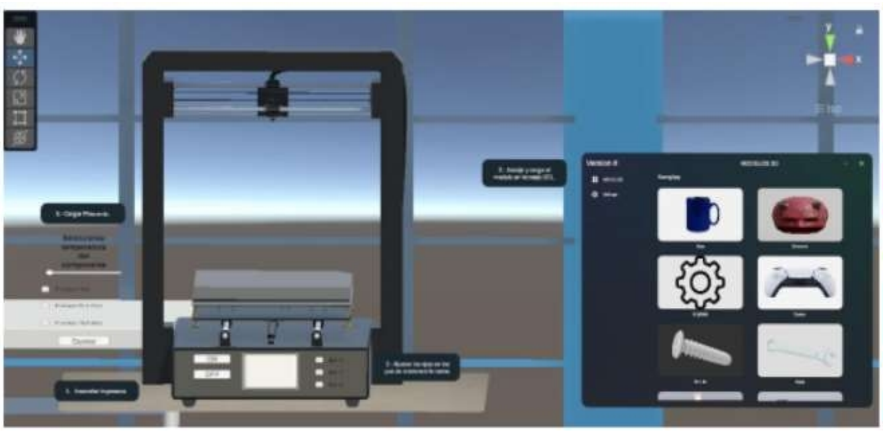

Figure 8. *Unity development platform using sliders.*

Finally, 3D objects were placed so that they could be picked up with the controls and viewed in detail. In addition, the transfer interaction to the printer was designed to simulate how they will be printed in reality. These models are basic, such as a cup, a mask, a gear, a screw, and a key. They were also downloaded from Sketch Fab in .fbx format, as it is compatible with Unity, but they can be designed as needed, as shown in Figure 9.

Figure 9. *Unity development platform using Sketch Fab models*.

The next step was to configure the Unity environment to be compatible with the Oculus Quest 2. A platform change was made, an Android package was downloaded because Oculus is only compatible with this system, and when starting the project in Unity, the default configuration is for development in Windows. Unity is user-friendly software for developing virtual reality simulations, and to achieve this, different packages had to be installed in order to use the VR headset and controls. The main packages were: Meta XR All-in-One SDK groups several Meta SDKs, which include features that offer advanced rendering, social and community building, and provide capabilities to build immersive experiences in both virtual reality and mixed reality. XR Interaction Toolkit is a high-level component-based interaction system for creating virtual reality and augmented reality experiences. It provides a framework between 3D and user interface interactions available from Unity input events. XR Plugin Management is the package that provides easy management of XR plug-ins. It manages and provides help with loading, initialization, configuration, and build support for XR plug-ins. Figure 10 shows the features of the platform.

Figure 10. *Unity development platform using plugins*.

To achieve interaction between objects and canvas, it is necessary to configure them using controls, otherwise they could go to waste if not configured, as shown in Figure 11. Therefore, characteristics had to be added to each object so that they would behave like real elements within the environment and allow interaction. Figure 12 shows the features that were added to each model within the environment: Rigidbody, Mesh Renderer, Mesh Collider, Script Grabbable, Script Hand Grab Interactable, and Script Grab Interactable.

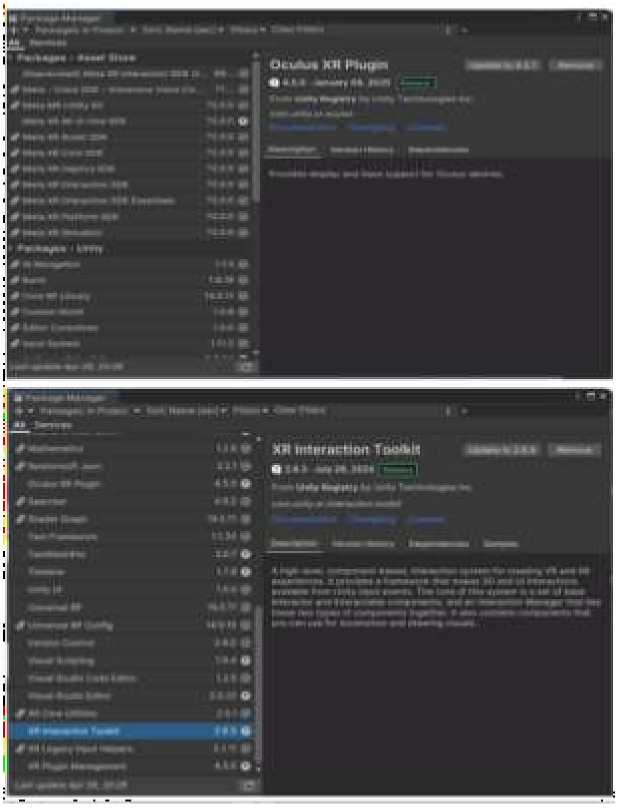

Figure 11. *Unity development platform using packages*.

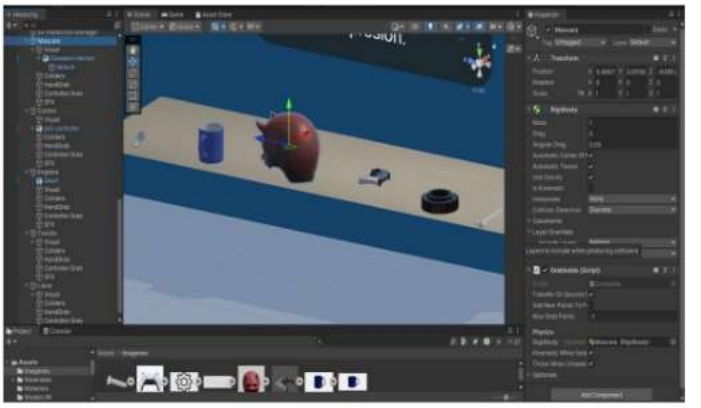

Figure 12. *Unity development platform using 3D models*.

Some features of the object in the inspector, which were useful for giving the objects the effect of gravity, allowed them to be held, moved, and observed closely, as well as moved and placed in different ways in the 3D printer. Movement configuration within the environment To ensure greater user safety, a static virtual environment was chosen, in which the user can interact from a chair or standing up, using only the controls for movement and the glasses to observe the virtual environment. This was achieved thanks to the fact that the previously installed packages provide some pre-configured prefabricated elements that facilitate the handling of the controls and glasses, thus allowing interaction in the virtual environment. It was only necessary to modify the height so that the user could interact both sitting and standing, and to ensure that the view was comfortable, as shown in Figure 13.

Figure 13. *Unity development platform using models and tools.*

To compile and perform the tests, it was necessary to connect the Oculus to the computer via Meta Quest Link on both the computer and a smartphone. This was to ensure that the Unity and Meta applications worked correctly. Once the software was downloaded, a developer account was created and linked to both the phone app and the computer. To connect the Oculus to the computer and view the results, there are two configuration options: Configure Link, which allows the headset to be connected to the computer using a Link cable, and Configure Air Link (Wi-Fi), which allows the headset to be connected using Wi-Fi. Finally, various tests were carried out to verify that the simulation was working properly. These were: Correct functioning of the control buttons, correctly positioned visual aids, and proper positioning of the visual aids.

and optimal mobility within the environment. Once the errors had been corrected and the simulation was working, the scene was downloaded to an .APK file so that it could then be opened directly from the Oculus viewer using SideQuest, without the need to be connected to the computer.

Figure 14 shows the virtual 3D printing laboratory in Unity, where walls were integrated to delimit the work area, computer equipment, and a 3D model simulating a 3D printer. Interactive panels were programmed to allow the user to perform basic configurations of the 3D printer, such as turning it on/off, moving the bed, loading filament, and adjusting the temperature. Complete integration of Oculus Quest 2 with the Unity environment was achieved (see Table 4), using Meta XR SDK, XR Interaction Toolkit, and XR Plugin Management. Object grasping and manipulation functions were enabled, as well as locomotion in the virtual environment using the controls. Each of these interactions was evaluated and validated using the platforms, as shown in Figure 15.

Figure 14. *Remote Lab 3D functional tests*.

Figure 15. *Functional testing of buttons on the 3D printer*.

Functionality tests were performed to verify the correct operation of each interaction developed. Figures 16 and 17 show that the virtual printer was first turned on and off, which worked properly using interactive buttons. This function can be performed remotely from the panel with the control or with the index finger of the synthetic hands. Figure 18 shows the simulation of selecting the type of bed movements on the X, Y, and Z axes, which was executed correctly. Figure 19 shows the selection and loading of different filament and bed preheats, which was carried out using toggles and sliders, allowing the appropriate temperature to be set, which worked well. Figure 20 shows that the simulation of selecting the 3D model file to "print" worked correctly and also works remotely with the controls or by dragging the index finger on the panel. In addition, objects within the environment could be manipulated for better visualization and positioning when printing, as shown in Figure 21. The index finger and thumb are used on the controls to pick up objects.

Figure 16. *Printer on/off functional tests*.

Figure 17. *Functional tests of 3D printer with viewer*.

Figure 18. *Functional tests for selecting the x, y, and z axes*.

Figure 19. *Functional tests for filament selection*.

Figure 20. *Functional tests for 3D model selection*.

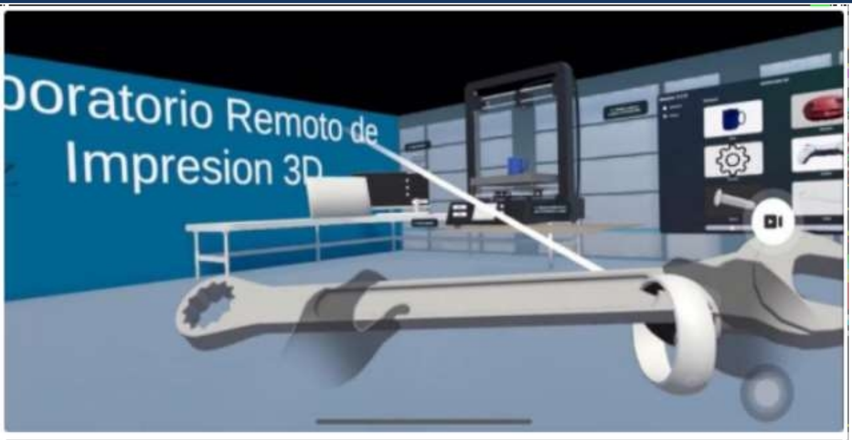

Figure 21. *Functional tests for manipulating 3D models*.

The stability of the connection between the Oculus Quest 2 and the Unity environment was also ensured, minimizing disconnections or errors. The overall interpretation of the results indicates that the virtual environment is functional and meets the objectives of providing immersive and effective training in the additive manufacturing process. Once the functionality tests have been completed, this file can be compiled in .APK format and may be shared with other Oculus headsets.

In terms of technical learning through immersive simulation, the test results showed that users were able to correctly perform the configuration and operation tasks of the 3D printer within the virtual environment. This experience coincides with the findings reported by (Villalobos López, 2024), who conclude that virtual reality environments improve the retention of technical skills by enabling safe, repeatable practices without the risk of damage to real equipment. In this project, the sequence of simulated steps from power-up to model loading reinforces procedural learning, aligning with the principles of experiential learning.

Interaction with virtual objects and motor skill development has allowed the integration of manipulable 3D objects with realistic physics (Rigidbody, Collider, Grabbable), enabling users to experience the manipulation of printed parts, which promotes spatial understanding and visomotor coordination. (Ferreira et al., 2021) highlight that this type of interaction in virtual environments improves preparation for assembly and technical operation tasks. In the tests carried out, users were able to hold, move, and position objects with precision, validating the effectiveness of the interactive design implemented.

The portability and accessibility of technical training makes it possible to run the simulation directly on the Oculus Quest 2 headset, without the need for a constant connection to a computer, which represents a significant advantage in terms of accessibility. (Pinargote Castro et al., 2024) emphasize that autonomous VR environments allow for expanded access to technical training in contexts with limited infrastructure. In this case, exporting the environment in .APK format and deploying it using SideQuest demonstrates the feasibility of implementing this solution in educational institutions with limited resources.

ANALYSIS OF RESULTS

The integration of virtual environments into the learning process has proven to be an effective strategy for developing technical skills, while protecting both the physical integrity of students and laboratory equipment. This implementation has contributed significantly to reducing incidents, such as burns or cuts from sharp tools, which often occur during practices such as 3D printing.

The use of simulations allows specific operating conditions to be recreated in a controlled and safe environment, facilitating student exposure to complex scenarios without real risks. Simulated situations include fires, critical equipment failures, and other events that require immediate response. This not only strengthens students' ability to react to emergencies, but also gives teachers and lab managers the ability to design training experiences aligned with the challenges engineers face in real industrial contexts.

CONCLUSIONS

According to research on the subject:

The literature review allowed us to establish a solid conceptual framework on the use of virtual reality technologies applied to additive manufacturing processes, identifying their potential to improve technical training in educational environments. Based on this analysis, an interactive virtual environment was developed that simulates the 3D printing process in detail, from CAD design to final equipment configuration, allowing users to go through each stage in a guided and safe manner. The implementation of the virtual reality platform proved to be an effective alternative for experiencing the additive manufacturing process without requiring physical equipment, offering an immersive experience that promotes practical learning. The tests carried out validated the functionality of the environment, showing an improvement in the understanding of technical procedures and a significant reduction in the risks associated with the direct handling of machinery, such as burns or cuts.

Overall, the results confirm that the use of virtual environments not only optimizes the teaching-learning process in engineering, but also contributes to the training of professionals who are better prepared to face real situations in safe and controlled conditions.

FUTURE WORK

Based on this research, the aim is to strengthen the subject in the near future with the design and implementation of strategies that promote the optimal development of motor skills, among which play will be the main focus, given the age and characteristics of the students being taught.

Integration of various equipment and operating conditions to build a catalog of specific faults and scenarios, aimed at strengthening students' academic training by exposing them to real situations typical of industrial environments. This tool will enable more detailed training, focused on developing technical skills and decision-making in complex contexts.

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COLLABORATIVE WORK TABLE

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Validation	Zapata de Santiago Israel Emmanuel, Moreno Mercado Héctor Javier
Formal Analysis	Rodríguez Mejía Jeovany Rafael, Quiroz Merino German
Research	Rodríguez Mejía Jeovany Rafael, Quiroz Merino German, Zapata de Santiago Israel Emmanuel
Resources	García Morales Paula Verónica
Data curation	Quiroz Merino German, García Morales Paula Verónica
Writing - Preparation of the original draft	Rodríguez Mejía Jeovany Rafael
Writing - Review and editing	Quiroz Merino German, Zapata de Santiago Israel Emmanuel
Visualization	García Morales Paula Verónica
Supervision	García Morales Paula Verónica
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