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NEUMATIC-FERROLAB VR:
LABORATORY OF PNEUMATIC
SYSTEMS IN VIRTUAL REALITY FOR
RAILWAY ENGINEERING

NEUMATIC-FERROLAB VR:
LABORATORIO DE SISTEMAS
NEUMÁTICOS EN REALIDAD VIRTUAL
PARA INGENIERÍA FERROVIARIA



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ABSTRACT

This contribution introduces Neumatic-FerroLab VR, an immersive, virtual-based laboratory for railway pneumatic systems designed to train engineers in this sector. Its development arose from the need for alternatives to traditional physical laboratories, which are often limited by high costs and associated risks. *Neumatic-Ferrolab VR*'s architecture includes modules for theoretical learning, interactive simulation, immersive practice, and automated assessment. It also facilitates instructor support by allowing students to visualize, manipulate, and gain an understanding of the operation of pneumatic components, all within a safe and controlled environment. From a transdigital perspective, *Neumatic-Ferrolab VR* is a hybrid techno-pedagogical device that virtualizes the existing laboratory at the Interdisciplinary Professional Unit of Engineering and Social and Administrative Sciences of the National Polytechnic Institute in Mexico, enabling the combination of physical and digital practices. In this sense, it expands learning opportunities through pedagogically mediated, immersive educational experiences.

Keywords: virtual reality, engineer, pneumatic systems, education, simulation, educational technology

RESUMEN

En esta contribución se da a conocer el recurso *Neumatic-FerroLab VR*, que es un laboratorio de sistemas neumáticos ferroviarios de carácter inmersivo basado en realidad virtual orientado a la formación de ingenieros de este sector. Su desarrollo surgió para contar con alternativas a las carencias de laboratorios físicos tradicionales por los altos costos y riesgos asociados. *Neumatic-Ferrolab VR* consideró en su arquitectura módulos de aprendizaje teórico, de simulación interactiva, práctica inmersiva y evaluación automática. Asimismo, se facilitó el seguimiento docente con lo que le permite al estudiante visualizar, manipular y aproximarse a la comprensión del funcionamiento de componentes neumáticos, todo ello en un entorno seguro y controlado. Desde una mirada Transdigital, *Neumatic-Ferrolab VR* es un dispositivo tecno-pedagógico de carácter híbrido que virtualiza el laboratorio que existe físicamente en la Unidad Profesional Interdisciplinaria de Ingeniería y Ciencias Sociales y Administrativas del Instituto Politécnico Nacional, México, con lo que pueden combinarse prácticas físicas y digitales. En este sentido, se extendieron las posibilidades de aprendizaje con experiencias educativas inmersivas pedagógicamente mediadas.

Palabras clave: realidad virtual, ingeniería ferroviaria, sistemas neumáticos, educación técnica, simulación, tecnología educativa

1. INTRODUCTION

In Mexico, higher education is undergoing a digital transformation, with advanced technological tools increasingly being integrated into learning environments. This is particularly true of virtual reality (VR), which is an educational tool with great potential for training in all areas of knowledge, particularly engineering, given its cost and safety for technical training. In the case of railway engineering, this technology allows for an understanding of pneumatic systems, which are fundamental to the development and skills related to train control and suspension (Lampropoulos et al., 2025; Soliman et al., 2021).

Studies such as those by Šiđanin et al. (2020) and Damaševičius and Sidekerskienė (2024) have shown that using immersive VR-based learning scenarios facilitates deep and sustained understanding of complex concepts. Furthermore, it allows students to experiment with real-life situations through simulated mechanisms, suggesting that using VR in technical education accelerates the learning process in safer and more controlled environments.

However, the practical teaching of pneumatic systems faces challenges in terms of infrastructure and equipment at universities (Hernández-Rodríguez & Guillén-Yparrea, 2023; Wilkerson et al., 2022). This results in limited laboratory practices that do not reflect the complexity of real-life situations at the time of learning, as incorporating two-dimensional simulations does not bridge the gap between theory and practice (Asad et al., 2021; Gittinger & Wiesche, 2023). In this regard, Qolamani and Mohammed (2023) pointed out that the lack of resources for comprehensive practices limits the ability of trainee railway engineers to experiment with pneumatic systems.

In this vein, the virtualization of pneumatic systems laboratories becomes an innovative proposal from an educational point of view, as the implementation of immersive technologies creates safe learning environments by extending traditional methods (Hu et al., 2024; Marks & Thomas, 2021). In this sense, as education moves toward transdigital perspectives (Escudero-Nahón & Mercado López, 2025), immersive experiences will never replace physical practice, as they should be considered an extension of learning possibilities. To this end, both physical and digital scenarios should be integrated in a synergistic and contextualized manner. In this regard, Williams et al. (2021) and Okolie and Okoye (2023) recommended instructional designs that connect theoretical and practical knowledge through simulation, thereby promoting cohesive and holistic learning.

From this perspective, *Neumatic-Ferrolab VR* can be considered a transdigital resource that exemplifies the potential of assessment in technical training in pneumatic systems. This tool allows interactive simulations and pedagogical mediation to be integrated into a single experimental environment (Katz et al., 2020; Chmyr et al., 2024). This synergy promotes efficient and dynamic learning guided by reflection. This allows students to take an active role in their learning process (Dogutan et al., 2025; Lampropoulos et al., 2025). In this way, educational practices in this discipline are being transformed towards the emerging pedagogies of the digital age.

This article analyzed the design and implementation of *Neumatic-Ferrolab VR* as an educational solution for railway pneumatic systems, aimed at students in the Railway Engineering program at the Interdisciplinary Professional Unit for Engineering and Social and Administrative Sciences (UPIICSA) of the National Polytechnic Institute (IPN) in Mexico. The proposed tool combined interactive modules in a VR environment, supporting theoretical and practical learning through the same program for better understanding. Virtual support can be replicated in other training programs for railway engineers and even in other areas of engineering that face similar challenges with this subject matter. This opened up a range of opportunities to improve training in other technical disciplines, as they meet the demands of the professional environment (Soliman et al., 2021; Anjos et al., 2020).

2. METHOD OF RESEARCH

The study was carried out using an exploratory qualitative approach, through a case study focused on the design, implementation, and analysis of a transdigital educational resource based on VR. In other words, through a situated educational experience. For this reason, no causal relationships or statistical generalizations were established. To ensure the relevance and scalability of the platform, prior to the instructional design and implementation of the virtual reality educational resource, a comparative analysis of technologies was carried out. Unity was chosen for its flexibility, compatibility with resources, and community support in educational environments. *Blender* complemented *Unity* through detailed three-dimensional (3D) modeling of pneumatic components. In addition, *HTC VIVE*, being a standalone headset with motion tracking, minimized the hardware requirements for the institution..

The proof of concept, that is to say, the study of the functionality of the techno-educational product, was carried out in the context of the Railway Engineering program at UPIICSA, IPN. Within this framework, a functional prototype called *Neumatic-FerroLab VR* was designed and developed, conceived as an immersive virtual laboratory for teaching pneumatic systems from a transdigital perspective. The objective of the test was to explore the technical feasibility, user experience, and perception of the educational potential of the resource. It should be noted that this type of testing is common in exploratory research on emerging educational technologies, where the analysis of the functionality of the application and the user experience are emphasized.

2.1. Participants

The proof of concept involved eight students in their final semesters of the Railway Engineering program and two from the Transportation program. These participants were selected through convenience sampling, considering their familiarity with pneumatic systems. The sample size was appropriate for the exploratory nature of the study, as it required a learning experience of almost two hours of use of the resource and did not seek to generalize.

2.2. Data collection techniques

Qualitative techniques were used to collect information, based on a questionnaire assessing perceptions after the immersive learning experience using the resource and direct observation during its use. The questions focused on immersive aspects, recognition of pneumatic components, the realism of the learning environment, and the ease of use of the devices.

2.3. Ethical considerations

Student participation was voluntary. In addition, they were informed about the purpose of this research. In this regard, the confidentiality of responses and the use of information for academic purposes were guaranteed. In no case was personal data or sensitive information collected that would allow them to be identified individually..

2.4. Justification of the sample and scope of the study

The size and composition of the sample reflected the exploratory nature of the study and its focus on proof of concept. This is because research focused on the design, development, and evaluation of the functionality of techno-educational resources does not generalize results, but rather comprises the user experience, the identification of options for improvement, and a preliminary assessment of their pedagogical potential as a digital resource.

In particular, the participation of railway engineering students with prior knowledge related to the educational content provided informed feedback on the level of realism, technical relevance, and relevance of the virtual environment with respect to traditional laboratory practices. Therefore, the selected sample was adequate for exploring educational and technological feasibility in a specific training context. Therefore, the results obtained should be interpreted as indicative and contextual, specific to a situated case study. Future research could expand the sample, incorporating mixed or longitudinal methodological designs to analyze the impact of the resource in terms of its didactic nature for the development of specific competencies.

2.5. General requirements used by the solution

- *Hardware: PC i5, 16GB RAM, GTX 1060 GPU, y Oculus Quest 2.*
- *Software: Unity, Blender, Moodle y Git.*
- *Internet: Stable connection for updates and LMS integration.*

2.6. Potential for socio-technical impact

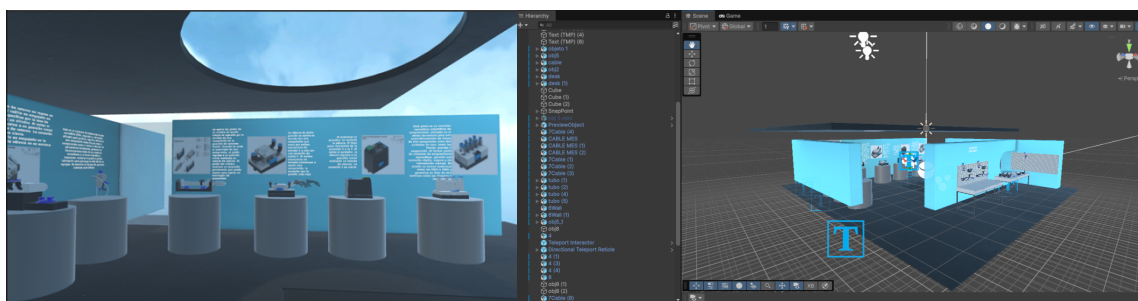
- A more equitable and competitive education is promoted for institutions that do not currently have the necessary infrastructure.
- This product can be expanded to include electrical and hydraulic modules.

- Certification criteria can be incorporated to align with the labor market.
- It has learning potential not only for specialists in the field, but also for other people who can start practicing with it.

2.7. Resource functionality

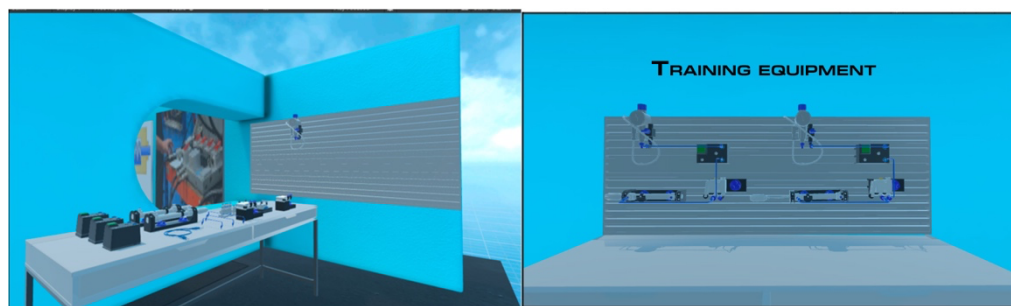
Neumatic-Ferrolab VR displays a gallery of models identical to those found in the physical laboratory at UPIICSA (Figure 1). This feature enables users to visualize the components and their roles within hydraulic systems in great detail. Additionally, it offers a comprehensive explanation of each component, which can be interacted with during the immersive experience.

Figure 1
Setting and components



A work table was also available for assembling illustrative diagrams, and a basic functional preloaded model was provided (Figure 2). This playground area allows users to freely assemble diagrams, creating project-based learning situations that enable them to visualize the functioning of fully customized pieces from scratch.

Figure 2
Prefabrication practice



3. Results

The findings from the *Neumatic-Ferrolab VR* resource test were organized based on user experience, perception of the immersive environment, and the correspondence between the virtual laboratory and practices in the physical laboratory (Figure 3).

Figure 3

Proof-of-concept results

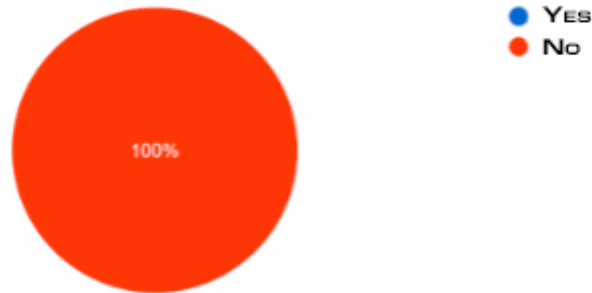


3.1. User experience and comfort during practice

None of the respondents reported experiencing discomfort, dizziness, or unease while using the VR glasses (Figure 4). Open-ended responses indicated a positive perception of the level of immersion, with descriptions such as "very immersive," "very enjoyable," "very good," and "feels very real." The result suggests that the design and interaction with the devices were adequate for continuous use sessions in a railway engineer training context such as this one.

Figure 4

Results regarding the presence of any discomfort, dizziness, or unease while using VR lenses



With regard to the level of immersion, the responses reflected a positive perception of the virtual scenario. In general, participants described the experience as *highly immersive* and *visually adequate* for learning the topics (Figure 5). The graphic quality of both the scenario and the three-dimensional models was rated favorably by all respondents. This indicated that the environment achieved allowed for a consistent immersive experience, a necessary condition for learning in technical contexts such as railways (Figure 6).

Figure 5

Results on the visual quality of the immersion

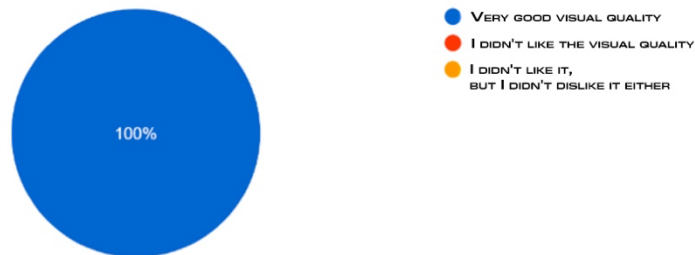


Figure 6

Results on how immersive the experience was

IT FEELS VERY REAL
VERY PLEASANT
VERY GOOD
IT'S IMPRESSIVE, IT'S MY FIRST VIRTUAL REALITY EXPERIENCE AND I FOUND IT VERY INTERESTING.
VERY SURPRISING
A LOT
I THOUGHT IT WAS PRETTY GOOD. I FEEL LIKE INTERACTING WITH IT IS PRETTY COOL. THE ATMOSPHERE WAS WELL DONE.
VERY IMMERSIVE

3.2. Component recognition and correspondence with the physical laboratory

Seven of the participants recognized parts or concepts from the physical laboratory (Figure 5). This suggested that the VR environment successfully represented familiar elements. This recognition was related to the level of detail of the 3D models and their manipulation within the immersive environment. In addition, the presence of functional diagrams and interactive parts facilitated the understanding of relationships between the different elements of the pneumatic system (Figure 7). Regarding the comparison with the physical laboratory, which was the basis for virtualization into an immersive resource, six of the participants considered it to be *partially* similar, and only two perceived it to be *equivalent* in its entirety (Figure 8).

Figure 7

Component recognition

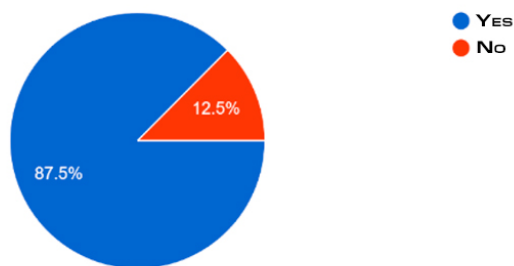
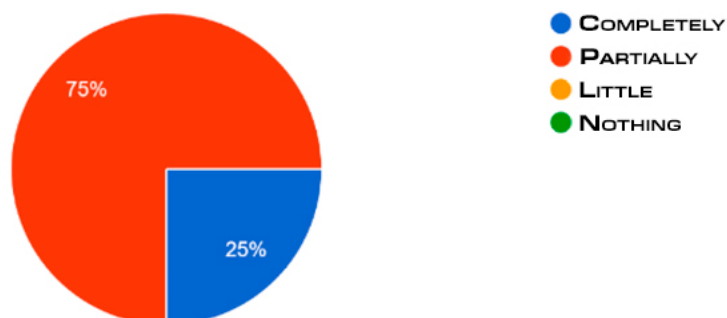


Figure 8

Similarity of the experience to a physical laboratory



This divergence of opinions, from the perception that the virtual environment was a valuable complement to face-to-face practice, as it is more than an absolute substitute for it. In fact, it is worth noting that the teacher who participated in the trial provided valuable pedagogical recommendations. In addition, she highlighted the potential of VR as a support tool for preparation prior to physical practice and for understanding the essential topics of pneumatic systems before coming into contact with the actual equipment.

4. DISCUSSION

The results obtained from the application of *Neumatic-Ferrolab VR* confirmed the statements made by the authors consulted regarding the potential of VR as an educational technology for training engineers in its technical nature. In particular, the absence of physical discomfort and the speed of adaptation to the immersive environment were situations that resonated with the studies by Šičanin et al. (2020) and Lampropoulos et al. (2025). These authors highlighted the importance of ergonomic design and visual quality as conditions that favor the use and acceptance of this type of environment.

In this regard, the positive perception of the level of immersion and graphic quality reinforced the findings of Soliman et al. (2021) and Damaševičius and Sidekerskienė (2024), who pointed out that this type of environment facilitates the understanding of complex systems by allowing active exploration and interaction with simulations that are close to reality. In the case of *Neumatic-Ferrolab VR*, this interaction facilitated the manipulation and visualization of pneumatic components, which are fundamental topics in the training of railway engineers for whom experiential learning is key.

Similarly, respondents' recognition of components and concepts suggests an adequate correspondence with the curriculum of pneumatic systems. This finding coincided with researchers such as Gittinger and Wiesche, 2023, who emphasized that the functional fidelity of models is crucial for effective learning and goes beyond visual realism. This correspondence favored hybrid pedagogies between the physical and the digital, allowing a virtual laboratory such as this to function as a space for mediation between theory and practice.

Finally, the perception of *Neumatic-Ferrolab VR* as a complement to face-to-face teaching practice, rather than a total substitute, was aligned with approaches such as those of Marks and Thomas (2021) and Williams et al. (2021), who conceived virtualization as an extension of traditional methods in the case of essentially hybrid educational ecosystems. Thus, although the study was exploratory in nature with a small sample size, the findings provided preliminary evidence on the techno-pedagogical viability of the resource and its transformative potential in the teaching of railway engineering, in line with the thinking of Qolamani and Mohammed (2023).

5. CONCLUSIONS

This article presented the design and implementation of the immersive resource *Neumatic-Ferrolab VR*, aimed at supporting the learning of pneumatic systems in Railway Engineering. It was shown that the virtualization of the IPN's UPIICSA physical laboratory was effective when combined with pedagogical principles and teacher mediation, making it a resource with viable potential for strengthening training in contexts with infrastructure, cost, and safety limitations. The test results showed that the environment favored experiences consistent with traditional practices and facilitated understanding of the subject through active exploration and manipulation of components.

In the opinion of the authors and developers, the main contribution of this work lies in the conceptualization of *Neumatic-Ferrolab VR* as a techno-pedagogical resource that extends the educational ecosystem, as it integrates physical, digital, and immersive environments into a training process. Although the exploratory nature of the study and the size of the sample were limiting factors in generating results, the findings provided preliminary evidence of the educational and technological relevance of the artifact, opening up lines of research for the future. These may be oriented toward its longitudinal evaluation, curricular integration, and transfer process, as well as its possible application in other disciplines in the field of engineering education.

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