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Research Paper

Training for Shielded Metal Arc Welding in Virtual Reality

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Abstract. A virtual-reality-based welding training method for workers in the industry is proposed in this paper. The structural integrity and safety of welds and welded items can only be guaranteed through technical skills. Furthermore, the work of professionally trained individuals in various industrial sectors is necessary due to workplace safety rules in the context of Industry 5.0. Although effective, the traditional welding training methods can be costly, time-consuming, and expose operators and apprentices to a range of hazards, including smoke, heat, and UV radiation. Teaching welding with Virtual Reality (VR) is an alternative tool that offers immersive, repeatable, and modular practice environments that efficiently use resources and time. The purpose of this work is to develop SMAW welding training software that can replicate realistic scenarios in a simulated environment using VR. To evaluate the effectiveness and usability of the software, a pair of reputable instruments were utilized: the NASA Task Load Index (NASA-TLX) to gauge cognitive load and the System Usability Scale (SUS) to evaluate perceived usability. Results were favorable, yielding 47.10 points for NASA-TLX and 85.38 points for SUS. Moreover, the questionnaires concerning the experience of participants with virtual reality welding were crucial to the research using 68 students. VR software can be a viable alternative to conventional training methods, as indicated by the results of tests conducted with the participants. In this regard, the software is highly usable and practical, which reinforces its potential for use in teaching students and training programs for staff in industry before traditional welding training. In this sense, the proposed method as a training tool prepares staff for SMAW operations.

Keywords: Virtual Reality, Welding Training, Industry 5.0, NASA-TLX, System Usability Scale, Cognitive Load

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1 Introduction

Multimedia, sensors, displays, human-machine interaction, ergonomics, simulation, and computer graphics work together in virtual reality (VR) to simulate physical mechanisms and provide users with multiple intuitive sensations Guo *et al.* [2020]. Through interactions with generated virtual environments, certain VR technologies allow for an immersive experience Zhu *et al.* [2019]. VR technology has been the focus of various studies in various fields in recent years and has caused significant interest in both academic and industrial fields. In this sense, VR focuses on a wide range of economic sectors such as manufacturing industries, the mining industry Borges *et al.* [2024b]; Ribeiro de Oliveira *et al.* [2020], tourism Sancho-Esper *et al.* [2023], health Ali *et al.* [2023]; Rahman *et al.* [2024], game technologies Korkut and Surer [2023], education Radianti *et al.* [2020]; Shao-Chen Chang and yung Jong [2020], inspections of airplanes Eschen *et al.* [2018] and learning Wang and Wang [2018].

Video games that are designed for problem-solving rather than entertainment are known as serious games. Using VR-based serious game applications, a new learning medium that is primarily focused on simulation can be applied for immersive and procedural simulation Corso *et al.* [2017]; Pilote and Chiniara [2019]; Luz Melo *et al.* [2025]; Malpartida and Rodrigues [2025].

Improving work safety in an industrial environment is a possible benefit of the VR-based game. We highlight that serious games can be used for training programs to teach employees about the risks and requirements of safety procedures Joshi *et al.* [2021]. In addition, digital games for industry training are of interest to industrial managers, specifically for training in risk situations Rufino Júnior *et al.* [2023].

In industries such as civil construction, shipbuilding, aerospace, and power generation, welding is a crucial process in the fabrication and maintenance of metal structures. Its relevance lies in its ability to guarantee structural integrity while providing a cost-effective and flexible option for joining metals such as steel, aluminum, and titanium. The authors in Demirel *et al.* [2023] mention that welding offers economic benefits over conventional fastening techniques like bolting and riveting. As quality and safety standards have evolved, welding technologies have advanced significantly over time.

VR-based training has proven to be increasingly feasible and effective. Despite the advancement of regulations, standards, and modern equipment, the quality of welded joints is largely determined by the technical skill of the welder. Conventional training makes it increasingly difficult and expensive to attain this high standard due to the time-consuming and demanding nature of complex techniques and higher technical levels. To ensure safe and efficient welding, it is necessary to train qualified and competent professionals, which is a major challenge.

The cost and limitations of conventional practical training are due to the requirement for large quantities of raw materials, adequate infrastructure, and monitoring by experienced professionals, which makes it costly and limited in terms of training effectiveness, corrections, and learning new techniques. Considering this, the introduction of VR-based welding software has become a promising and innovative approach. VR offers a close replica of real-world challenges through immersive and interactive experiences.

Users can improve learning outcomes by practicing welding techniques in a safe and controlled setting using VR devices such as head-mounted displays. Moreover, it decreases costs and the associated operational risks. The use of VR-based software for practical training with real materials offers many advantages, such as the ability to repeat exercises, verify performance, and adjust difficulty level based on progress of the participants.

Despite this, the potential benefits of safety instructions and procedures must be validated through user experience evaluation using the proposed VR-based welding software. This study addresses the challenge of building a VR-based serious game for Shielded Metal Arc Welding (SMAW) training for the collaborators in the industry.

While previous work Miranda *et al.* [2025] quantified the simulator's efficacy among technical students using the NASA Task Load Index (NASA-TLX) and the System Usability Scale (SUS), this study advances the literature by conducting a novel thematic analysis of qualitative feedback from both technical and undergraduate students. We categorize these insights into key educational dimensions, such as perceived learning, confidence building, and practical readiness. Furthermore, we expand the theoretical discussion by articulating how low cognitive load and high usability directly facilitate learning outcomes grounded in Cognitive Load Theory, thereby addressing a critical gap in the literature.

The main contributions reported in the paper as research highlights are as follows:

- a serious game was proposed for welding training based on virtual reality;
- the serious game was developed using various virtual reality headsets;
- the proposed game is suitable for welding training for staff before they operate in the real world;
- the serious game contributes to promoting smart industries such as Industry 4.0 and Industry 5.0;
- the findings of this paper reveal that the serious game allowed participants to acquire technical skills for operating a Shielded Metal Arc Welder.

To this end, this study aims to address the following research questions:

- **RQ1:** *What are the perceived usability and cognitive workload levels of a VR-based SMAW welding simulator among technical and undergraduate students?*
- **RQ2:** *How do participants evaluate the viability of this VR simulator as an immersive pre-training tool prior to traditional hands-on welding practice?*

This paper presents the system design and methodology employed to answer these questions.

The remainder of this paper is organized as follows. Sections 2 and 3 present the related work and the description of the software developed for welding training, respectively. Sections 4 and 5 describe the methodology and the results and discussion, respectively. Section 6 presents the conclusions of the proposed work. Finally, the last section outlines future work, with an emphasis on addressing limitations and new questions raised by participants.

2 Related Work

Both academic and industrial domains are committed to developing effective training methodologies for complex manual skills, such as welding. Traditional welding instruction can be resource-intensive, costly, and pose a risk to beginners. In this scenario, VR and serious games have come to be a promising solution, delivering safer, more engaging, and cost-effective options. This section examines the current research on the use of VR and serious games for training and skill acquisition, particularly in industrial and procedural settings. Our proposed VR welding software is built on the basis of these studies.

2.1 Virtual Reality in Training

VR is a reliable tool for training in areas where real-world practice is unsafe, expensive, or logistically challenging. In immersive VR environments, users can practice repeatedly, develop motor and spatial skills, and gain procedural knowledge in a controlled and interactive setting Borges *et al.* [2025]; de Oliveira *et al.* [2024].

Moreover, VR has been a successful tool for mining industry tasks such as equipment maintenance, inspection, and heavy machinery operation Borges *et al.* [2025]. VR systems are particularly useful for training that involves fine motor control due to their ability to simulate realistic physical mechanisms and provide intuitive sensory feedback de Oliveira *et al.* [2024]. In addition, VR training also aids in minimizing the dangers associated with high-hazard procedures by providing safe exposure to simulated danger scenarios Borges *et al.* [2025, 2024b].

The efficiency of VR-based training is significant, reducing the need for physical materials and specialized equipment, which ultimately reduces training costs and enhances safety and repeatability. In addition, these systems can provide instant feedback and performance tracking, resulting in faster and more effective learning outcomes Borges *et al.* [2024b,a].

Recent research has shown that VR can be a scalable solution for workforce training, as evidenced by the proposed modular welding training system that relies on backward design principles to improve skill transfer in realistic contexts. In this sense, visual and haptic feedback were included in the system, which demonstrated significant improvements in novice performance when compared to video-based instruction Ipsita *et al.* [2022].

Other research highlighted that VR can help reduce variability and execution errors in soldering tasks by providing consistent training experiences with real-time performance analysis, leading to a high transfer of learning to real-world tasks Alfaro-Viquez *et al.* [2025].

The work of Ribeiro de Oliveira *et al.* [2023] demonstrates the potential of VR-based applications to improve human-machine interactions by incorporating artificial intelligence methods, particularly in cases where intelligent robotic technologies are involved. Even though there are advantages, employees still need the digital skills needed to operate such technology Staffenová and Kucharčíková [2024].

Finally, according to Soori *et al.* [2024], manufacturing processes and products are designed and optimized by using virtual manufacturing, computer simulations, and models. Businesses can save time and money by testing their ideas in a virtual setting before investing in prototypes.

Sensor networks, IoT, cloud computing, advanced robotics, and artificial intelligence are among the key-enabling technologies that form the basis for a new generation of manufacturing, factories, and business processes, which is referred to as Industry 4.0 Commission [2018]; Romero-Gázquez *et al.* [2022]. The manufacturing environment is being transformed by automation and digital technology in this revolution. In Figure 1, the technological pillars of Industry 4.0 are shown.

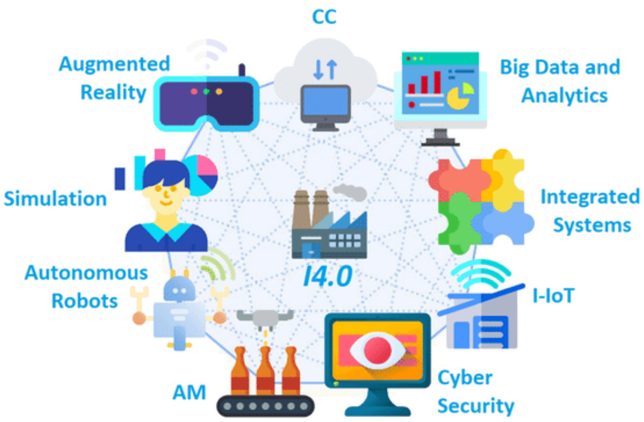

Figure 1. The pillars of Industry 4.0, adapted from Pivoto *et al.* [2021]

Through the science mapping method, the authors in Akpan and Offodile [2024] investigated the impact of VR simulations on manufacturing. The contextual structure of the literature was analyzed by them, and their analysis highlights the contexts, applications, and relevance of VR simulation in the Industry 4.0 era. The simulation is a powerful tool for digital twins, predictive maintenance, additive manufacturing, 3D printing, virtual manufacturing, and immersive simulation of virtual digital industrial units.

Thus, in the Industry 4.0 era, associating VR-based training can improve the skills of employees in the workplace, especially in the welding procedures. In this sense, Industry 5.0 aims to place human well-being, sustainability, and resilience at the center of industrial production. While Industry 4.0 was centered on using smart technology to increase efficiency and productivity, Industry 5.0 enhances these advances by developing a more human-centered and purpose-driven framework for industry Xu *et al.* [2021].

2.2 Serious Game

Industry, marketing, logistics, production, and supply chains use serious games as an intelligent process. The term "intelligent process" refers to a system that is developed using the same tools as a conventional video game, but is focused on specific objectives that transcend the playful aspect of the game.

Digital games known as serious games are primarily designed for educational or training purposes and have gained popularity as powerful tools for procedural learning. These applications can enhance practical knowledge and skill acquisition by combining with VR to create highly immersive and motivating experiences de Oliveira *et al.* [2024].

Serious games can inherit the key requirements of their recreational counterparts, such as accessibility, scalability, reach, and affordability, thanks to the similar development methods Schoneveld *et al.* [2018]. These methods are crucial for a mining company because state-of-the-art procedures involve handling heavy machinery required to accommodate long training periods, complicated logistics, and compromised productivity attributable to work being suspended because of otherwise perfectly serviceable assets.

Furthermore, the authors of work in Creutzfeldt *et al.* [2012] claimed as follows: serious games provide opportunities to simplify logistics and reduce costs by eliminating the need to allocate physical assets; and, compared to traditional methods, serious games improve worker performance and minimize mistakes.

The study by Camilo and Motta [2025] proposed a methodology for constructing a game aiming to sensitize healthcare professionals to work cooperatively in a multiprofessional and interdisciplinary manner. In this sense, the games can be a relevant way to provide integrative experiences, engaging professionals in cooperative work. Another study of Germano da Silva *et al.* [2025] developed digital simulators and games for improving the learning process in academic health training.

Users can gain benefit from VR-based serious games by being presented with realistic work scenarios that vary in complexity and risk, all without any real-world repercussions Borges *et al.* [2025]. This enhances safety awareness and user engagement while also preserving procedural knowledge. In terms of user performance and error reduction, such systems have been shown to outperform traditional methods de Oliveira *et al.* [2024].

Serious games can be helpful in welding training in terms of developing fine motor skills, spatial coordination, and adhering to safety protocols. They make it possible for learners to receive structured feedback, practice repeatedly, and progress through clearly defined learning stages, which makes them ideal for skill-based training. To support this, a multiweek study on beginning welders found that repeated VR training using systems like the VRTEX 360 led to consistent improvements in weld quality, performance scores, and learning retention, emphasizing the role of guided repetition and real-time feedback in meaningful learning Heibel *et al.* [2024]. The contribution of VR simulations to skill development has been demonstrated in previous research by offering flexible and personalized practice environments, which are particularly beneficial for novice users Yunus *et al.* [2011].

In conclusion and according to existing literature, the implementation of a serious game in a workplace can be beneficial as it can raise safety awareness and experience by simulating real work-related scenarios with varying degrees of danger in an environment where failure poses minimal risk.

Liang *et al*. [2019]. Moreover, the VR-based serious games are a tool for collaborating with companies that have a low adoption rate Liebrecht *et al*. [2021]. Another advantage is that serious games have the capacity to cover a vast array of scenarios and events, which are challenging to replicate through conventional training methods.

2.3 Virtual Reality in the Welding Training

The application of VR to welding is relatively recent but shows significant promise as demonstrated in Heibel *et al*. [2023], in which the authors present VR welding as an innovative and educational approach that supports the development of welding skills in a virtual environment. Another work of Fernandes [2016] describes the implementation of a magnetic tracking system within a Unity3D-based VR welding software. This software enables precise spatial tracking, improving realism and allowing the simulation to closely replicate the manual dexterity required in actual welding scenarios.

According to Faria *et al*. [2022], virtual and augmented reality training environments offer safe, interactive settings that lower risk exposure and material waste. Moreover, the authors note that rapid, customized feedback speeds up learning and improves long-term proficiency in processes such as Shielded Metal Arc Welding (SMAW).

Our approach draws inspiration from established industrial VR training applications Borges *et al*. [2025, 2024b]; de Oliveira *et al*. [2024], with the goal of elevating user motivation, decreasing risk, and enhancing skill transfer to real-world contexts.

The benefits of immersive environments and serious gaming elements are integrated into our proposed VR welding training software, which builds on literature findings. The objective is to enhance the learning process for SMAW by furnishing realistic, stimulating, and comprehensive experiences.

Unlike previous studies that primarily focus on hardware tracking or direct skill transfer, our proposed work fills a key gap by simultaneously evaluating usability (SUS) and cognitive workload (NASA-TLX) of a VR serious game designed specifically as a pre-training tool. Tested with 68 technical and undergraduate students, our study provides empirical evidence on how low cognitive friction facilitates procedural learning prior to physical SMAW operations.

3 Welding Software

The application emulates the experience of SMAW by enabling users to handle a virtual electrode holder and execute welding tasks on a metallic workpiece through natural hand motions captured by VR controllers. Once the training session begins, users take hold of the virtual holder and are guided to initiate and maintain a welding arc by approaching the metal surface at the correct angle and maintaining a suitable distance from the work surface.The virtual electrode behaves in a physically consistent manner, progressively decreasing in length as welding proceeds, thereby requiring continuous positional and motion adjustments similar to those demanded in real-world welding scenarios.

During the simulation, users receive visual and auditory cues to reinforce proper technique and alert them to mistakes, such as moving too fast or holding the electrode at an incorrect angle. This interactive approach closely reflects the practical challenges of manual welding, fostering skill development through iterative practice and immediate feedback within a controlled and immersive virtual environment. The overall operational framework of the application is illustrated in Figure 2, which presents a flow chart detailing the logic of the system, from the user's initial engagement with the virtual environment to the feedback mechanisms activated throughout the welding simulation.

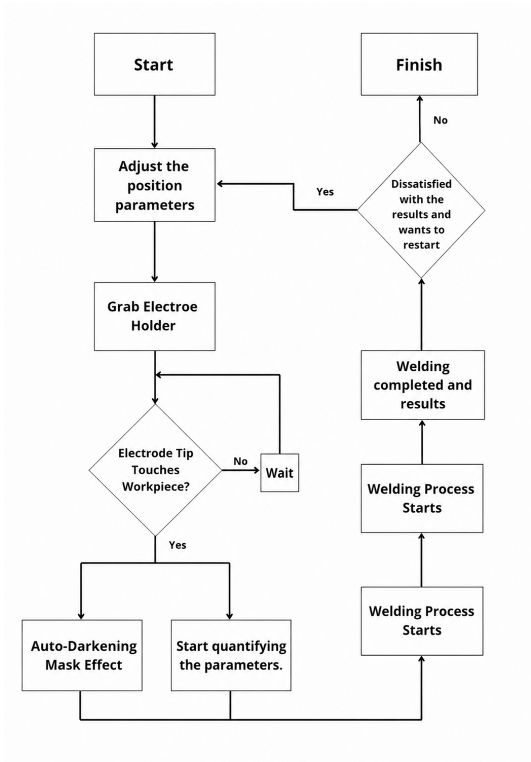

Figure 2. Welding software flowchart

3.1 System Description

The VR welding application was designed to provide a controlled and immersive training environment for people learning welding techniques. Its main objective is to facilitate the development of hands-on skills by allowing users to engage in realistic practice without exposure to physical hazards or the material expenses inherent to conventional welding activities. The simulated environment reproduces typical welding situations and incorporates interactive instructional elements that assist users in refining accuracy, motor control, and hand–eye coordination.

As shown in Figure 2, the application guides the user through a structured sequence of actions. The training session begins when the user grabs the virtual electrode holder. The system then monitors whether the electrode tip is in contact with the workpiece. If there is no contact, the application remains in a standby state. Once contact is detected, the welding arc is initiated, and the screen automatically darkens to simulate the activation of the welding helmet's filter. From that point, the welding process starts, and the electrode is gradually consumed as the user progresses. As the arc is maintained, a weld pool is formed at the point of contact, which grows in size over time depending on the user's movement and technique. This flow not only mirrors the typical behavior of SMAW equipment, but also reinforces timing, positioning, and coordination throughout the activity.

One of the strengths of the software is its ability to offer repeated practice and immediate sensory feedback, which are crucial for skill development. Although the individual components of the system are described in detail in the subsequent sections, the questionnaire employed to assess user experience is provided in the Appendices.

3.2 System Architecture

The Meta Quest 2 was chosen due to its capability to operate as a self-contained VR device, eliminating the need for an external computer to execute the application. This standalone operation streamlines deployment, lowers infrastructural requirements, and improves portability, which makes the headset particularly appropriate for adaptable and mobile training contexts. Additionally, the device provides built-in inside-out tracking and adequate onboard computational resources to deliver immersive virtual reality experiences without relying on external sensors, cables, or tracking systems.

The system architecture is structured into three core components: rendering, user interaction, and feedback delivery. To promote compatibility with a wide range of VR headsets and to accommodate future hardware advancements, the implementation incorporates OpenXR, a cross-platform and vendor-neutral API developed by the Khronos Group. By abstracting device-specific features, OpenXR enables the application to operate across multiple VR platforms with minimal code adjustments, thereby improving portability, easing long-term maintenance, and extending the longevity of the software beyond a single hardware ecosystem.

The primary advantage of the application remains its ability to function as a fully standalone solution, while supporting broader device compatibility through OpenXR.

3.2.1 *Rendering Module*

To produce realistic images, the rendering module employs physically based rendering (PBR) techniques, as illustrated in Figure 3. These techniques enable accurate simulation of metallic surface properties and dynamic lighting effects, including the intense brightness of the welding arc and the automatic darkening of the welding helmet filter when the electrode contacts the workpiece. Together, these visual elements closely approximate real welding conditions, enhancing the overall realism of the simulation.

3.2.2 *Welding Interaction Module*

The welding interaction module plays a fundamental role in reproducing the manual and perceptual demands of shielded metal arc welding within the virtual environment. Users engage with the electrode holder using VR controllers, allowing them to perform realistic welding tasks on a virtual metal workpiece. The system models essential parameters, including electrode consumption, arc length, and welding travel speed, thereby requiring users to apply proper techniques in order to produce satisfactory welds. The electrode exhibits dynamic behavior by progressively decreasing in length during operation, which enhances operational realism and obliges trainees to continuously adapt their movements. Immediate visual and auditory feedback improves the learning experience by indicating incorrect speed, improper angle or a weld linearity, supporting more accurate and consistent user performance.

Figure 3. First-person view of the virtual welding environment showing the material texture applied in-game.

3.2.3 *Multimodal approach in Virtual Welding Training*

The application incorporates a multimodal approach by combining visual and auditory stimuli to enhance realism and user immersion during welding training. Elements such as dynamic arc lighting, automatic screen darkening to simulate the welding helmet filter, and context-aware welding sounds provide synchronized audiovisual feedback that reflects the user's actions in real time. This sensory integration allows users to perceive performance through natural environmental cues, supporting intuitive learning and reinforcing essential welding skills within the virtual environment.

3.2.4 *Feedback Module*

The feedback module delivers real-time sensory responses that reinforce the realism of the welding simulation (Figure 7). Visual feedback is conveyed through the automatic dimming of the display, which emulates the activation of the welding helmet's protective filter when the arc is initiated. Auditory feedback is provided by realistic welding sounds that correspond to the behavior of the arc, assisting users in recognizing the onset of welding and sustaining a sense of immersion. Rather than relying on explicit user interface indicators, the system emphasizes environmental cues—such as sound variations and electrode consumption—to allow users to assess their performance directly through the simulated welding process.

From a multimodal perspective, the feedback module integrates multiple sensory channels to approximate real welding conditions through synchronized visual and auditory stimuli. The combination of dynamic lighting effects, screen darkening, arc visualization, and context-aware sound feedback creates a multisensory experience that supports implicit learning. By perceiving performance through natural sensory cues rather than symbolic prompts, users develop a more intuitive understanding of welding behavior, reinforcing immersion and contributing to more effective skill acquisition within the virtual environment.

3.3 Technical Implementation

The serious game was developed using the Unity engine alongside the C# programming language, selected for their capability to support interactive and immersive VR applications. The following sections outline the complementary tools employed in the creation of visual components.

To support reproducibility and align with open science practices, the system's core mechanics were designed using standardized algorithmic approaches. The physics engine evaluates electrode consumption through a linear decay algorithm tied to the active arc time. Simultaneously, collision detection between the electrode tip and the workpiece mesh utilizes a continuous raycasting method to ensure precise contact registration and prevent mesh clipping. The rendering module leverages physically based rendering (PBR) pipelines within Unity to maintain a stable 90 frames per second on the standalone hardware, a crucial threshold for preventing cybersickness. Furthermore, the integration of OpenXR guarantees that the interaction mappings—such as the spatial grab mechanics for the electrode holder—are standardized, allowing future researchers to replicate this technical setup across different VR headsets using identical logic.

3.3.1 3ds Max

The software was employed to create detailed models of the welding tools and surrounding environment, ensuring visual accuracy and coherence within the virtual space.

3.3.2 Substance Painter

Essential to the texturing workflow, this software was used to apply advanced surface details and lifelike materials to the 3D assets. Its tools allowed for the creation of nuanced textures that contributed to the overall realism and visual richness of the software.

4 Materials and Methods

4.1 Methodological Purpose of the Study

The welding software employed in this study was developed within the scope of an ongoing project aimed at applying virtual reality (VR) technologies to welding education. The software simulates real welding conditions similar to those encountered by mechanical engineering undergraduates and mechanical technician students, thereby supporting instructors in the teaching of manual welding techniques through the assessment of the visual quality of the welds produced by students within the virtual environment.

In addition, an exploratory search for the literature review was carried out using the CAPES Periodicals Portal and databases such as IEEE Xplore, Web of Science, Scopus, and SBC-OpenLib.

4.2 Training in Welding Education

Technical and vocational education institutions aim to prepare new professionals for the welding job market by providing both theoretical and practical training throughout technical programs. To support this training process and offer safe and accessible alternatives for hands-on welding practice, the use of virtual reality (VR) has been identified as a promising approach, as suggested by Yunus et al. Yunus *et al*. [2011]. For the implementation and validation of such applications, VR software must accurately replicate real welding conditions, including three-dimensional models of the equipment, the welding booth, and the procedures taught during the course, thereby ensuring a high level of fidelity to the actual training environment, as illustrated in Figure 4.

Figure 4. Welding cabin environment.

4.3 Validation with Participants

Several welding exercises were carried out by the participants and visually assessed in order to validate the welding software. Upon completion of each practice session, participants allowed their weld beads to be evaluated, as the seams remained visible in the virtual environment until the software was reset for the next user. Based on the instructor's technical criteria such as bead uniformity, excessive material deposition, bead straightness, inconsistent travel speed, irregular bead profile, and variations in bead width, the weld seams were briefly examined after each attempt. This visual inspection functioned as a formative assessment, providing participants with feedback consistent with the course objectives and professional standards in welding practice. This approach is in accordance with the methodology proposed by Heibel et al. Heibel *et al*. [2024] for the integration of VR into practical welding training. Figure 5 illustrates a weld seam generated using the welding training software developed in this study.

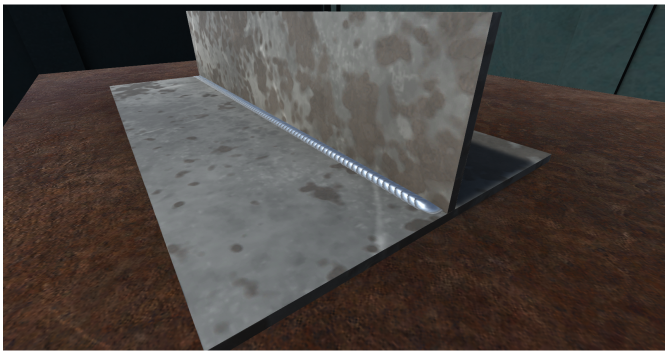

Figure 5. Close-up view of a software-generated weld seam

4.3.1 Welding performance metrics displayed in the VR environment

Certain welding factors were added to the virtual environment as part of the validation process with participants to allow for a more impartial evaluation of user performance. Travel linearity, welding speed, and electrode angle, all crucial markers of weld quality in actual welding operations, were among the important features of manual welding practice that the program tracked. As seen in Figure 6, these parameters were continually captured during task execution and visually provided to the user through performance graphs and numerical scores displayed within the virtual welding booth. Travel linearity was used to evaluate the consistency of the electrode movement along the weld seam, while welding speed assessed the stability of the user's motion throughout the welding process. The electrode angle parameter verified whether the user maintained the recommended inclination relative to the workpiece. Figure 6 illustrates the real-time visualization of these parameters, allowing both users and instructors to analyze deviations from ideal welding conditions. Although participants receive rapid feedback on crucial operational characteristics that directly affect weld quality, the inclusion of these validation aspects enriches the formative evaluation process and increases the realism of the training environment. This method helps close the gap between online instruction and actual welding practice.

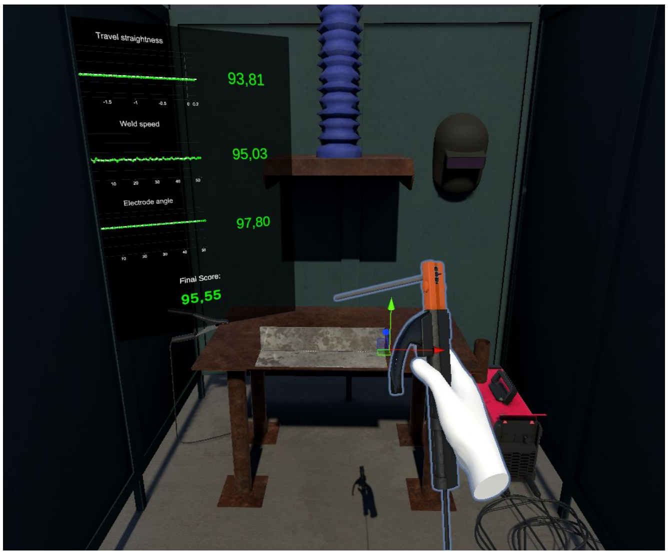

Figure 6. Real-time visualization of welding performance parameters in the virtual environment.

The visual feedback mechanism was operationalized as a continuous, real-time interface overlaid within the virtual environment. Specifically, the system continuously tracks the electrode's angle, travel speed, and trajectory linearity. When the user's execution falls outside the predefined acceptable thresholds established by standard SMAW technical guidelines the system projects dynamic visual indicators directly onto the user's field of view. This immediate visual correction loop isolates the variables of speed and angle, allowing users to instantly perceive the impact of their motor adjustments without relying on post-action verbal corrections from an instructor. The data suggests that this specific visual variable was instrumental in achieving the high effectiveness scores observed in the SUS evaluation, as it actively guided user behavior and mitigated the cognitive load required to master spatial coordination.

4.4 Students and Professors

After interacting with the software, students completed questionnaires, see the appendices, to report their perceptions of the Welding Training Environment, addressing aspects such as usability and the perceived realism of the training experience within the virtual setting. In addition, participants also completed a questionnaire (Q1) and they were encouraged to propose suggestions for future improvements where these recommendations were taken note of. The feedback collected was essential for identifying the strengths of the project that should be further developed, as well as for highlighting aspects that currently limit the user experience when compared to welding with real equipment. Similar approaches have been reported in related studies, in which participant feedback contributed to enhancing system accuracy, as noted by Michalak et al. Michalak *et al.* [2024].

As experts in the field, the professors completed another questionnaire (Q2) regarding the evaluation and validation of the simulator in the transfer of learning (see Appendix A.4).

Although students and professors responded to structured questions regarding their experience, no personal or identifiable data were collected during the study. Information such as gender, name, address, or income level was not requested.

The user evaluation was conducted in accordance with the Declaration of Helsinki and ethical guidelines for educational research. Participation was entirely voluntary, with students informed of the study's scope prior to interaction. No personally identifiable information was recorded, ensuring 100% data anonymization. The study posed no physical or psychological risk to participants and was integrated into their routine educational activities.

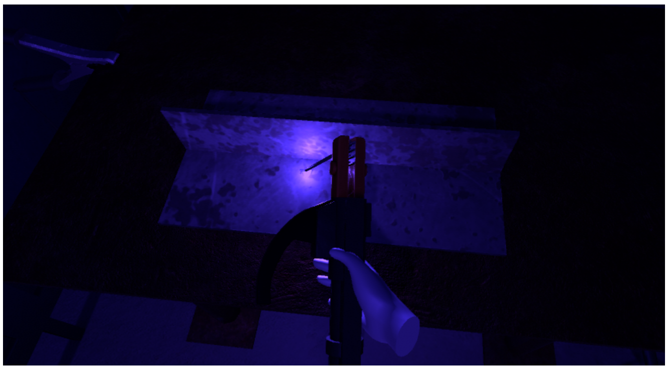

Figure 7. Welding process with visual effects. The mask automatically darkens when the arc ignites, simulating the activation of the welding helmet filter.

4.5 NASA Task Load Index

Participants completed a questionnaire based on the NASA Task Load Index (TLX) methodology Hart [1986], which is designed to measure workload by assessing physical, mental, and temporal demands, as well as the user's perceived performance, effort, and frustration levels while interacting with the welding software. Feedback was collected from participants enrolled in mechanical engineering–related programs at both technical and undergraduate levels. Overall, the participants rated the software positively across the evaluated dimensions and suggested directions for future improvements to the project. This feedback contributed to ensuring the quality of the research procedures and their favorable outcomes, while supporting subsequent updates to the 3D models. The questionnaire is presented in the Appendices section.

4.6 System Usability Scale (SUS)

During the validation stage, students completed the System Usability Scale (SUS) questionnaire Brooke [1996] to assess the usability of the welding software. Based on user experience, the SUS evaluates key criteria such as effectiveness measured by the successful completion of tasks within the software; efficiency assessed through the effort required to accomplish these tasks; and satisfaction reflecting the overall user experience. Feedback for this evaluation was collected from participants enrolled in mechanical-related courses. The questionnaire is presented in the Appendices section.

As part of the validation process, students completed the System Usability Scale (SUS) questionnaire Brooke [1996] to assess the usability of the welding software. Based on user experience, the SUS evaluates criteria such as effectiveness by examining success in accomplishing tasks within the software, efficiency by assessing the effort required to achieve these tasks, and overall satisfaction by capturing the general user experience. Feedback for this evaluation was collected from participants enrolled in mechanical-related courses. The questionnaire is presented in the Appendices section.

5 Results and Discussion

The head-mounted display application was first evaluated with a group of 41 students enrolled in a mechanical technician program and 27 students from a mechanical engineering program, resulting in a total of 68 participants involved in assessing its effectiveness as a support tool for welding procedure training. After the experimental sessions, data were gathered using the NASA TLX (Task Load Index) and the SUS (System Usability Scale), aiming to evaluate both the usefulness of the software and the users' overall perception.

Although the participant pool encompasses both students enrolled in a mechanical technician program and undergraduates in a mechanical engineering program, the data gathered from these cohorts were aggregated for analysis rather than comparatively cross-referenced. This methodological decision is based on the fact that both groups share an equivalent baseline of theoretical knowledge and introductory practical exposure to the Shielded Metal Arc Welding (SMAW) process within their respective academic curricula. Consequently, the expansion of the sample size to 68 participants serves to significantly enhance the statistical robustness and reliability of the study. By aggregating the data, the findings demonstrate that the VR simulator maintains consistent efficacy, high usability, and a manageable cognitive workload across different mechanical-related academic programs, validating its broad applicability as a universal pre-training tool for novice welders.

5.1 NASA Task Load Index Results

The results obtained from the NASA Task Load Index (TLX) indicate a low to moderate overall workload, as depicted in Figure 8, even though most individual dimensions (mental demand, physical demand, performance, effort, and frustration) presented favorable evaluations. This relatively reduced workload is expected, since the system is currently in an early development stage and has not yet undergone refinements based on systematic user feedback. The mean scores for each NASA TLX dimension are shown in Figure 8. These findings indicate that participants generally perceived themselves as successful in performing the task, while the comparatively low frustration levels suggest engagement without excessive

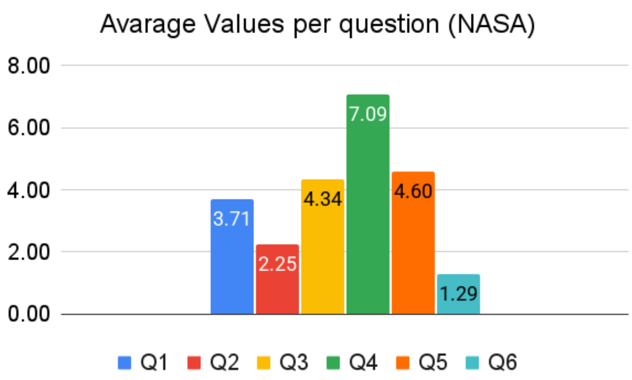

Figure 8. Average values for each question NASA TLX.

cognitive burden. Such results are encouraging for the ongoing adoption of the software in welding education. In addition, users reported that the task required minimal physical effort (Q2), whereas mental demand (Q1) emerged as the most relevant workload factor for most participants between Q1 and Q2.

5.2 System Usability Scale Results

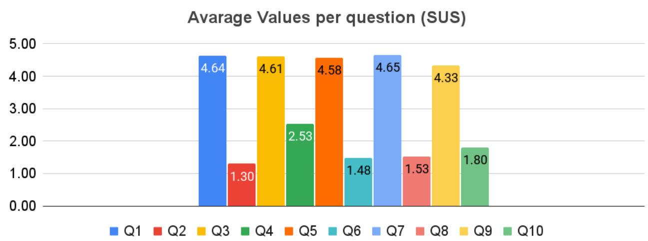

Figure 9. Average values per question SUS.

The mean values for each System Usability Scale (SUS) item are presented in Figure 9. Notably, the high average score observed in Q3 indicates that the system can be effectively operated even by users with little previous experience in virtual reality environments. The analysis of responses to Q7 and Q2 suggests that the application is intuitive and easy to comprehend, which may contribute to maintaining user engagement and facilitating the acquisition of welding skills. Furthermore, strong ratings in Q8 and Q10, combined with an overall SUS score of 85.38 (with values above 68 classified as above-average usability), as illustrated in Figure 11, reinforce the conclusion that the system demonstrates a high level of usability.

5.3 User Experience and Educational Impact Assessment

The evaluation results in questionnaire (Q1) about user experience (students) demonstrate a highly positive reception regarding the use of the application in welding training, see Figure 10. With all averages exceeding the 4.40 mark on a scale of up to 5, it is evident that the software achieved its educational goals with excellence. Below is a detailed analysis of the results, divided by areas of impact:

- Learning and Practical Preparation: The direct impact on user comprehension was the major highlight of the survey. The assessment that the application contributed to overall learning about the welding process (Q1-1) achieved an excellent average of 4.64. This high score indicates that the tool was extremely effective in transmitting knowledge. As a direct reflection of this learning, students reported a significant gain in confidence: with an average of 4.45 on Q1-2, the data shows that users feel considerably more prepared to perform welding in the real world after the virtual training.

- Effectiveness of Visual Resources: One of the core factors in the tool's success was its guidance interface. Q1-4, which evaluated the usefulness of visual feedback in understanding the correct angle and speed, tied for the highest score in the survey, also recording an average of 4.64. This proves that the visual translation of complex technical parameters was fundamental in smoothing the students' learning curve.
- Acceptance and Curriculum Integration: Given the impressive results in both theoretical effectiveness and the perception of practical readiness, the tool's acceptance was strongly endorsed by the students themselves. Q1-3, with an average of 4.55, demonstrates strong agreement that the application's use should not be just an isolated test, but rather definitively incorporated as part of regular welding instruction.

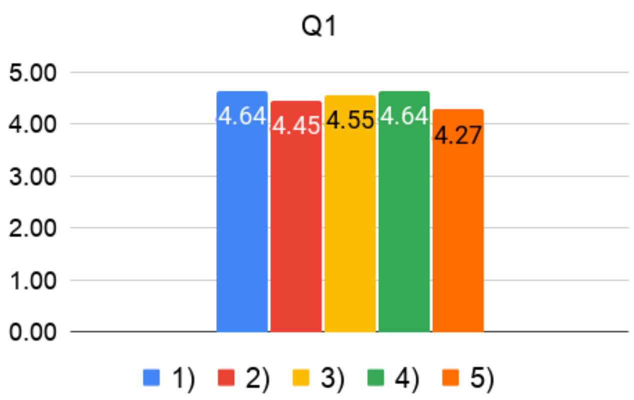

Figure 10. Average values per question about user experience (Q1).

Yunus *et al*. [2011] reported that 78.01% of participants agreed that weld skills could be developed through a VR simulator, while 72.73% of the participants in the present study rated the simulator's contribution to their learning about the welding process (Q1-1) with the maximum score. Similarly, Michalak *et al*. [2024] reported that participants recognized the great potential of the VR welding simulator as a tool for training welders. In their opinion, it could significantly reduce training costs, particularly for novice welders.

The results from Q1-5 (A = 4.27) demonstrate that training with the VR-based simulator effectively mitigated students' apprehension regarding real-world welding equipment. In summary, the software has proven to be a highly valuable educational resource. By combining the clarity of visual feedback with the increase in users' practical confidence, the application fully justified the strong recommendation to become a permanent fixture in the welders' training curriculum.

5.4 Qualitative Evaluation

Throughout and following the student testing sessions, qualitative feedback and subjective impressions were collected from the instructors involved in the evaluation process. The collected feedback indicated a highly positive reception of the technology, particularly highlighting the teachers' enthusiasm regarding the potential of VR as a complementary tool for welding education. The NASA TLX and SUS findings suggest that the software presents high usability, even when involving tasks of low to moderate complexity, which is characteristic of operational training scenarios.

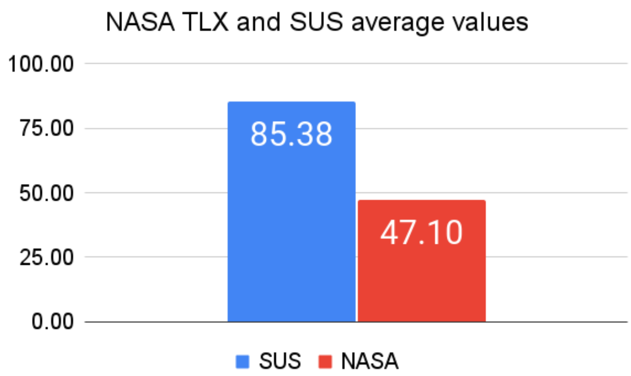

Figure 11. NASA TLX and SUS Average Result.

5.5 Qualitative Insights on Educational Value

To complement the quantitative findings obtained through the SUS and NASA-TLX instruments, qualitative feedback was gathered to gain a deeper understanding of the participants' subjective experiences and the perceived pedagogical value of the VR simulator. Analyzing student perceptions provides crucial context regarding how the virtual environment influences learning dynamics, user confidence, and practical skill acquisition. The main qualitative insights that emerged from the participant responses are structured around five primary themes:

- Perceived Skill Acquisition: participants reported that visual feedback helped them understand the correct angle and speed. The responses are as follows: a) The simulator is very good. It especially helps beginners better understand the ideal electrode angle and travel speed; b) The experience with the simulator was excellent. It provides essential knowledge for welding and greatly supports teaching by reducing material waste during initial practical training.
- Educational Value and Course Alignment, the responses are as follows: a) I found the simulator to be very good and well aligned with the welding course at Ifes; b) The simulator integrates virtual reality into higher education in a creative and innovative way. In addition, it helps students who have never had contact with welding by providing a new approach to teaching; c) Excellent simulator; d) The simulator is a valuable addition to the laboratory-based course content.
- Confidence and Anxiety Reduction: Although the participants did not explicitly mention anxiety reduction,

responses a), b), and c), as follows, highlight the simulator's value for beginners. By providing a safe space to practice without wasting real materials, the tool creates a low-risk environment, which is known in the literature to reduce student anxiety before practical laboratory sessions. The responses are as follows: a) The simulator is very good. It especially helps beginners better understand the ideal electrode angle and travel speed; b) The experience with the simulator was excellent. It provides essential knowledge for welding and greatly supports teaching by reducing material waste during initial practical training; c) The simulator integrates virtual reality into higher education in a creative and innovative way. In addition, it helps students who have never had contact with welding by providing a new approach to teaching.

- Perceived Transferability: participants highlighted that the muscle memory and procedural steps acquired in the simulator transfer directly to physical welding tasks.
- Suggestions for Enhanced Realism and Immersion, the responses are as follows: a) The simulator could support different welding processes and include an internal library of consumables, providing information about the characteristics of each consumable; b) It would be ideal to improve the simulator so that it reflects real welding conditions more accurately. For example, starting the weld on an unclean surface should make the task more difficult, and the electrode should stick under certain conditions, as it does in real-world welding; c) I believe it is important to add real welding components, such as an electrode holder, to the simulator. This would give users a better perception of the grip and weight of the equipment, facilitating learning within the simulated environment.

5.6 Simulator Validation: Perspective of Professors

To complement the analysis, four professors, acting as experts in the field, completed an evaluation questionnaire focused on simulator validation and the transfer of learning (Expert Evaluation Questionnaire, see Appendix A.4). The objective of this step was to gather the educators' technical perspectives regarding their confidence in the practical results, the identification of students' errors and difficulties, and the real-world performance improvements observed after using the simulator. see Figure 12.

The quantitative responses for items (Q2-1) through (Q2-5) are illustrated in Figure 12. Overall, the expert professors reported highly positive perceptions regarding the simulator's validity and its impact on the transfer of learning. The highest-rated aspect was the experts' confidence in the evaluation results obtained during the real-world weld inspection (Q2-1), which achieved an average score of 4.75 out of 5. Furthermore, the simulator was strongly validated as a diagnostic and resource-saving tool; the experts gave an average score of 4.5 for its ability to identify participants facing the greatest difficulties (Q2-2), its capacity to highlight procedural errors and weld defects (Q2-3), and its contribution to reducing material waste and execution time during real welding tasks (Q2-5). Finally, regarding the direct observation of participants' real-world performance improvement after simulator

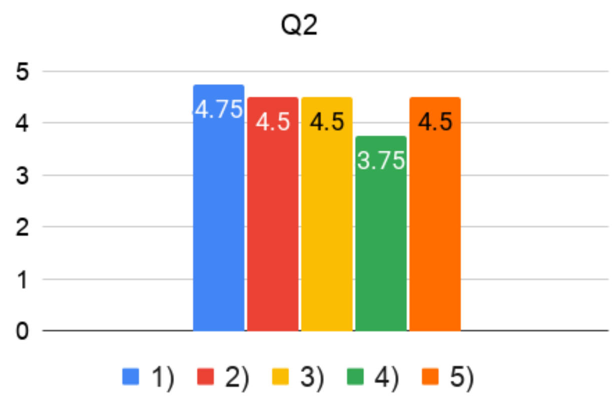

Figure 12. Average values per question about perspective of professors (Q2).

training (Q2-4), the experts indicated a positive average score of 3.75, confirming a visible transfer of practical skills to the real-world environment.

Regarding the open-ended question (Q2-6), which asked for suggestions to better align the simulator with real-world practice, the experts provided diverse feedback. The recommendations for improvement included implementing a slag removal feature, diversifying the available welding processes, and simulating additional welding defects while incorporating more variables for different processes. Notably, one of the evaluating professors stated that they would not make any modifications at this time.

Beyond demonstrating that the system is accessible and non-fatiguing, the usability (SUS) and workload (NASA-TLX) outcomes directly reinforce its pedagogical effectiveness. In line with Cognitive Load Theory, mitigating extraneous mental load enables learners to dedicate essential cognitive capacity to skill acquisition. Qualitative data corroborates this relationship, indicating that the seamless interface interaction facilitated an accelerated comprehension of welding parameters and bolstered student confidence ahead of practical application.

6 Conclusion

This study described the development and validation stages of the VR welding software, emphasizing the design of an immersive, secure, and accessible environment aimed at the training and qualification of students enrolled in technical welding programs.

The adoption of realistic scenarios simulated through VR devices enabled a hands-on learning experience while avoiding the costs and hazards commonly associated with traditional welding instruction, which requires the direct handling of welding equipment. This is in conformity with Industry 5.0.

According to the workload evaluation conducted using the NASA TLX methodology, an average score of 47.10 was obtained, characterizing a moderate to low level of workload.

This result indicates an appropriate balance between task challenge and system usability, making it compatible with welding education and training activities, even for users with limited familiarity with immersive technologies.

Concerning the usability analysis, performed through the System Usability Scale (SUS), an average score of 85.38 was achieved, indicating an excellent degree of acceptance, comprehension, and ease of use of the system among students.

The obtained results demonstrate that the simulation environment provides an intuitive, efficient, satisfactory, and advantageous experience for learners, contributing positively to the teaching and learning process in technical education, as well as in undergraduate programs related to welding.

From the students' perspective, the user experience evaluation confirmed the VR simulator's efficacy as a highly engaging and impact-driven educational tool. High scores across all metrics (exceeding 4.40/5.0) demonstrated that the software successfully accelerated knowledge acquisition, particularly through real-time visual feedback on welding parameters. Importantly, the virtual training significantly built practical confidence and reduced anxiety toward real-world machinery, leading to a strong consensus among participants in favor of permanently incorporating the simulator into the standard welding curriculum.

Overall, the expert evaluation strongly validated the simulator as a reliable tool for both training and diagnostic assessment in welding education. The expert professors reported high confidence in the practical assessment outcomes, emphasizing the simulator's capability to identify student difficulties, highlight procedural errors, and optimize time and material resources. Furthermore, the qualitative feedback provided actionable directions for future work, emphasizing the integration of slag removal mechanics, expanded welding processes, and more complex defect modeling.

Both the quantitative findings and the qualitative feedback confirm the potential of employing head-mounted display technology as an effective, innovative, and motivating alternative for professional training, fostering increased engagement, facilitating repeated practice, and strengthening the consolidation of technical knowledge acquired in classroom settings.

The limitations of this work are related to the participants' prior knowledge in the mechanical area courses, the subjective nature of the questionnaires, and other functionalities observed from feedback of participants. This aspect may affect the internal, external and construct validity of the study. Thus, in the next section we propose some future work.

7 Future Work

For future work, new opportunities have emerged from student feedback, covering several areas such as:

1. To increase the precision of the software: Adjusting the proportions of the welding equipment and the straight weld bead to allow greater freedom and manual dexterity for the student welder, as discussed in Chan *et al*. [2022] and Isham *et al*. [2022].
2. To expand the software to different welding processes: Based on feedback, it was suggested to add more welding processes beyond Shielded Metal Arc Welding, such as Tungsten Inert Gas (TIG) and Metal Inert/Active Gas (MIG/MAG), providing students with greater versatility in different welding techniques. This is in line with studies that emphasize the need to simulate a wide range of welding scenarios to reflect real industrial conditions Wang *et al*. [2023].
3. To develop software for different welding positions: In addition to the current welding position (fillet weld in the flat position), it is important to prepare the student to weld in various positions such as vertical, horizontal, overhead, among others, which can be implemented in the software to improve the student's technical learning throughout the course.
4. To increase the number of participants from other courses to evaluate the software for welding training. In this sense, it is possible to evaluate the use of the system, complexity, functionality, difficulty, and complacency during the task, and so on, with other participants from a new perspective.

Finally, considering the characteristics and the feedback received, the software can continue to evolve and better prepare students for the demands of the job market from Industry 4.0. With these refinements, the VR training environment will be further improved, allowing technical education to be applied more efficiently in various educational institutions, as also suggested by the growing interest in immersive welding training technologies Heibel *et al*. [2023].

Declarations

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Authors' Contributions

All authors contributed to the conception and investigation of this work. ASM, JVLF, TPL, ADAN, and MGN performed the experiments, data curation, and carried out the formal analysis. RVA, MQS, and MM established the methodological bases and the validation of paper. ASM, JVLF, TPL, ADAN, and MGN wrote the original draft work and developed the software. RVA has been responsible for project administration. RVA, MQS, and MM obtained the funding acquisition and the resources. MM was a supervisor of the research project. All authors worked on reviewing, editing and approved the final paper.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

Supplementary materials consisting of two datasets (Dataset 1 and Dataset 2) are openly available via Zenodo. Dataset 1 (https://doi.org/10.5281/zenodo.22115452) contains the data generated during this study, specifically the responses to the SUS and NASA-TLX surveys. Dataset 2 (https://doi.org/10.5281/zenodo.22115748) contains presentation materials related to this study, presented at Ifes, SVR 2025, and LabTef (Future Technology Laboratory, Ifes Vitória Campus), under the research project titled: Plano de Pesquisa e Capacitação em Operação e Manutenção Logística.

Further relevant information

During the preparation of this work the authors used AI tools to assist with text polishing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. Subsequently, the manuscript was submitted to Editage (www.editage.com) for English language editing.

To address potential imbalances in academic visibility and foster a more inclusive scholarly environment, we have quantified the demographic distribution of the references cited in this work. In alignment with emerging best practices in equity, diversity, and inclusion within academic publishing, we recognize that historical systemic biases can disproportionately affect the representation of researchers from diverse geographic, institutional, and demographic backgrounds. By making this commitment transparent, we aim to encourage a more equitable attribution of scholarly contributions and prompt critical reflection on our own reference selection process.

References

Akpan, I. J. and Offodile, O. F. (2024). The role of virtual reality simulation in manufacturing in industry 4.0. *Systems*, 12(1). DOI: https://doi.org/10.3390/systems12010026.

Alfaro-Viquez, D., Zamora-Hernandez, M., Fernandez-Vega, M., Garcia-Rodriguez, J., and Azorin-Lopez, J. (2025). Integrating virtual reality into welding training: An industry 5.0 approach. *Electronics*, 14(10):1964. DOI: https://doi.org/10.3390/electronics14101964.

Ali, S. G., Wang, X., Li, P., Jung, Y., Bi, L., Kim, J., Chen, Y., Feng, D. D., Magnenat Thalmann, N., Wang, J., and Sheng, B. (2023). A systematic review: Virtual-reality-based techniques for human exercises and health improvement. *Frontiers in Public Health*, 11. DOI: https://doi.org/10.3389/fpubh.2023.1143947.

Borges, L. F. M. R., Andreão, R. V., Schimidt, M. Q., Mestria, M., Dias, G. S., and Marques, C. (2024a). Introduction to gauss's law in electromagnetism through a virtual reality application. In *Proceedings of the SVR 2024 Conference*, pages 128–133. SVR. DOI: https://doi.org/10.1145/3691573.3691577.

Borges, L. F. M. R., Miranda, A. S., Ferreira, J. V. L., Lazarini, T. P., Neto, A. D. A., Novais, M. G., Schimidt, M. Q., Andreão, R. V., and Mestria, M. (2025). Virtual reality system for inspection and training: A case study in wheel-loader operations. *Journal on Interactive Systems*, 16(1). DOI: https://doi.org/10.5753/jis.2025.5171.

Borges, L. F. M. R., Viana, P. H. P., de Oliveira, T. a. R., Martins, T. d. S., Andreão, R. V. a., Schimidt, M., and Mestria, M. (2024b). Evaluating virtual reality simulations for wheel loader inspection. In *Proceedings of the 25th Symposium on Virtual and Augmented Reality*, SVR '23, page 8–16, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3625008.3625010.

Brooke, J. (1996). Sus: A quick and dirty usability scale. In Jordan, P. W., Thomas, B., Weerdmeester, B. A., and McClelland, I. L., editors, *Usability Evaluation in Industry*, pages 189–194. Taylor and Francis, London.

Camilo, M. d. S. and Motta, C. L. R. d. (2025). Methodology for building rpg games to raise awareness of interdisciplinary collaboration among healthcare professionals. *Journal on Interactive Systems*, 16(1):109–119. DOI: https://doi.org/0.5753/jis.2025.4173.

Chan, V. S., Haron, H. N. H., Isham, M. I. B. M., and Mohamed, F. B. (2022). Vr and ar virtual welding for psychomotor skills: A systematic review. *Multimedia Tools and Applications*, 81:12459–12493. DOI: https://doi.org/10.1007/s11042-022-12293-5.

Commission, E. (2018). *Re-finding industry – Defining innovation*. European Commission and Directorate-General for Research and Innovation - Publications Office.

Corso, A. D., Stets, J. D., Luongo, A., Nielsen, J. B., Frisvad, J. R., and Aanæs, H. (2017). Virtual reality inspection and painting with measured brdfs. In *SIGGRAPH Asia 2017 VR Showcase*, SA '17, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3139468.3139472.

Creutzfeldt, J., Hedman, L., and Felländer-Tsai, L. (2012). Effects of pre-training using serious game technology on cpr performance—an exploratory quasi-experimental transfer study. *Scandinavian journal of trauma, resuscitation and emergency medicine*, 20(79):79. DOI: https://doi.org/10.1186/1757-7241-20-79.

de Oliveira, T. R., Gomes, G. I. R., Martins, T. S., Borges, L. F. M. R., Ludke, G. G., Andreao, R. V., Cotini, L. G., Viana, P. H. P., Schimidt, M. Q., and Mestria, M. (2024). Virtual reality system for inspection and training in wheel loader. In *Proceedings of the 24th Symposium on Virtual and Augmented Reality*, SVR '22, page 11–20, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3604479.3604503.

Demirel, T., Bişkiner, E., and Şahin, Z. (2023). Research of metal welding: Works technical review. In *Ases International Scientific Studies Conference*, Balıkesir, Turkey.

Eschen, H., Kötter, T., Rodeck, R., Harnisch, M., and Schüppstuhl, T. (2018). Augmented and virtual reality for inspection and maintenance processes in the aviation industry. *Procedia Manufacturing*, 19:156–163. Proceedings of the 6th International Conference in Through-life Engineering Services, University of Bremen, 7th and 8th November 2017. DOI: https://doi.org/10.1016/j.promfg.2018.01.022.

Faria, I. C. S., Filleti, R. A. P., and Helleno, A. L. (2022). Evolução dos processos de automação em células de soldagem: Uma revisão da literatura. *Soldagem & Inspeção*, 27:e2704. DOI: https://doi.org/10.1590/0104-9224/SI27.04.

Fernandes, M. T. (2016). Integração de um tracking magnético a um simulador de soldagem manual com realidade virtual utilizando unity3d. `https://repositorio.ufsc.br/xmlui/handle/123456789/171292`. Accessed on 26 August 2026.

Germano da Silva, A., Gonçalves, G. S., Muller, L., Galindo, B. R., Ruiz, L. D. A., Sepulvedra, M. A. T., Lellis-Santos, C., Brandão, A. L., and Malinverni, A. C. d. M. (2025). Prototypes of digital simulators and board games for cervical cancer prevention: Insights from cytology professionals. *Journal on Interactive Systems*, 16(1):795–804. DOI: https://doi.org/10.5753/jis.2025.5633.

Guo, Z., Zhou, D., Zhou, Q., Zhang, X., Geng, J., Zeng, S., Lv, C., and Hao, A. (2020). Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review. *Journal of Manufacturing Systems*, 56:525–

538. DOI: https://doi.org/10.1016/j.jmsy.2020.07.007.

Hart, S. G. (1986). NASA task load index (TLX). In *NASA Ames Research Center Moffett Field, CA United States*, pages 1–26.

Heibel, B., Anderson, R., and Drewery, M. (2023). Virtual reality in welding training and education: A literature review. *Journal of Agricultural Education*, 64(4). DOI: https://doi.org/10.5032/jae.v64i4.38.

Heibel, B., Anderson, R., Swafford, M., and Borges, B. (2024). Integrating virtual reality technology into beginning welder training sequences. *Journal of Agricultural Education*, 65(1):210–225. DOI: https://doi.org/10.5032/jae.v65i1.2468.

Ipsita, A., Erickson, L., Dong, Y., Huang, J., Bushinski, A. K., Saradhi, S., Villanueva, A. M., Peppler, K. A., Redick, T. S., and Ramani, K. (2022). Towards modeling of virtual reality welding simulators to promote accessible and scalable training. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '22)*, New Orleans, LA, USA. ACM. DOI: https://doi.org/10.1145/3491102.3517696.

Isham, M. I. M., Haron, H. N. H., Mohamed, F. b., Siang, C. V., Mokhtar, M. K., and Albakri, I. F. (2022). A conceptual design for welding training simulation using virtual reality with multiple marker tracking method. In *AIP Conference Proceedings*, volume 2433, page 020023. DOI: https://doi.org/10.1063/5.0072931.

Joshi, S., Hamilton, M., Warren, R., Faucett, D., Tian, W., Wang, Y., and Ma, J. (2021). Implementing virtual reality technology for safety training in the precast/ prestressed concrete industry. *Applied Ergonomics*, 90:103286. DOI: https://doi.org/10.1016/j.apergo.2020.103286.

Korkut, E. H. and Surer, E. (2023). Visualization in virtual reality: a systematic review. *Virtual Reality*, 27:1447–1480. DOI: https://doi.org/10.1007/s10055-023-00753-8.

Liang, Z., Zhou, K., and Gao, K. (2019). Development of virtual reality serious game for underground rock-related hazards safety training. *IEEE Access*, 7:118639–118649. DOI: https://doi.org/10.1109/ACCESS.2019.2934990.

Liebrecht, C., Kandler, M., Lang, M., Schaumann, S., Stricker, N., Wuest, T., and Lanza, G. (2021). Decision support for the implementation of industry 4.0 methods: Toolbox, assessment and implementation sequences for industry 4.0. *Journal of Manufacturing Systems*, 58:412–430. DOI: https://doi.org/10.1016/j.jmsy.2020.12.008.

Luz Melo, R., Moreira, V. d. S., Amaral, E. M. H. d., and Domingues Júnior, J. S. (2025). Victus exergame: An approach to rehabilitation of amputees based in serious game. *Journal on Interactive Systems*, 16(1):137–147. DOI: https://doi.org/10.5753/jis.2025.4194.

Malpartida, K. F. C. and Rodrigues, K. R. d. H. (2025). Building serious games to exercise computational thinking: Initial evaluation with teachers of children on the autism spectrum. *Journal on Interactive Systems*, 16(1):148–162. DOI: https://doi.org/10.5753/jis.2025.4492.

Michalak, D., Rozmus, M., Tokarczyk, J., and Szewerda, K. (2024). Portable vr welding simulator. *Applied Sciences*, 14(17):7687. DOI: https://doi.org/10.3390/app14177687.

Miranda, A. S., Ferreira, J. V. L., Lazarini, T. P., De Angeli Neto, A., Novais, M. G., Schimidt, M. Q., Andreão, R. V., and Mestria, M. (2025). Shielded metal arc welding training using virtual reality. In *2025 27th Symposium on Virtual and Augmented Reality (SVR)*, pages 89–97. DOI: https://doi.org/10.1109/SVR67689.2025.00023.

Pilote, B. and Chiniara, G. (2019). Chapter 2 - the many faces of simulation. In Chiniara, G., editor, *Clinical Simulation (Second Edition)*, pages 17–32. Academic Press, second edition edition. DOI: https://doi.org/10.1016/B978-0-12-815657-5.00002-4.

Pivoto, D. G., de Almeida, L. F., da Rosa Righi, R., Rodrigues, J. J., Lugli, A. B., and Alberti, A. M. (2021). Cyber-physical systems architectures for industrial internet of things applications in industry 4.0: A literature review. *Journal of Manufacturing Systems*, 58:176–192. DOI: https://doi.org/10.1016/j.jmsy.2020.11.017.

Radianti, J., Majchrzak, T. A., Fromm, J., and Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Comput. Educ.*, 147:103778. DOI: https://doi.org/10.1016/j.compedu.2019.103778.

Rahman, O. F., Kunze, K. N., Yao, K., Kwiecien, S. Y., Ranawat, A. S., Banffy, M. B., Kelly, B. T., and Galano, G. J. (2024). Hip arthroscopy simulator training with immersive virtual reality has similar effectiveness to nonimmersive virtual reality. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*. DOI: https://doi.org/10.1016/j.arthro.2024.02.042.

Ribeiro de Oliveira, T., Biancardi Rodrigues, B., Moura da Silva, M., Antonio N. Spinassé, R., Giesen Ludke, G., Ruy Soares Gaudio, M., Iglesias Rocha Gomes, G., Guio Cotini, L., da Silva Vargens, D., Queiroz Schimidt, M., Varejão Andreão, R., and Mestria, M. (2023). Virtual reality solutions employing artificial intelligence methods: A systematic literature review. *ACM Comput. Surv.*, 55(10). DOI: https://doi.org/10.1145/3565020.

Ribeiro de Oliveira, T., Martinelli, T. F., Bello, B. P., Batista, J. D., Silva, M. M. d., Rodrigues, B. B., Spinassé, R. A. N., Andreão, R. V., Mestria, M., and Schimidt, M. Q. (2020). Virtual reality system for industrial motor maintenance training. In *2020 22nd Symposium on Virtual and Augmented Reality (SVR)*, pages 119–128. DOI: https://doi.org/10.1109/SVR51698.2020.00031.

Romero-Gázquez, J. L., Cañavate-Cruzado, G., and Bueno-Delgado, M.-V. (2022). In4wood: A successful european training action of industry 4.0 for academia and business. *IEEE Transactions on Education*, 65(2):200–209. DOI: https://doi.org/10.1109/TE.2021.3111696.

Rufino Júnior, R., Classe, T. M. d., Santos, R. P. d., and Siqueira, S. W. M. (2023). Current risk situation training in industry, and games as a strategy for playful, engaging and motivating training. *Journal on Interactive Systems*, 14(1):138–156. DOI: https://doi.org/10.5753/jis.2023.3222.

Sancho-Esper, F., Ostrovskaya, L., Rodriguez-Sanchez, C., and Campayo-Sanchez, F. (2023). Virtual reality in retirement communities: Technology acceptance and tourist destination recommendation. *Journal of Vacation Marketing*, 29(2):275–290. DOI:

https://doi.org/10.1177/13567667221080567.

Schoneveld, E., Lichtwarck-Aschoff, A., and Granic, I. (2018). Preventing childhood anxiety disorders: Is an applied game as effective as a cognitive behavioral therapy-based program? *Prevention Science*, 19(2):220–232. DOI: https://doi.org/10.1007/s11121-017-0843-8.

Shao-Chen Chang, Ting-Chia Hsu, Y.-N. C. and yung Jong, M. S. (2020). The effects of spherical video-based virtual reality implementation on students' natural science learning effectiveness. *Interactive Learning Environments*, 28(7):915–929. DOI: https://doi.org/10.1080/10494820.2018.1548490.

Soori, M., Arezoo, B., and Dastres, R. (2024). Virtual manufacturing in industry 4.0: A review. *Data Science and Management*, 7(1):47–63. DOI: https://doi.org/10.1016/j.dsm.2023.10.006.

Staffenová, N. and Kucharčíková, A. (2024). Human capital management – values, competencies, and motivation – concerning industry 4.0. *Economic Research-Ekonomska Istraživanja*, 37(1):2324160. DOI: https://doi.org/10.1080/1331677X.2024.2324160.

Wang, X. and Wang, X. (2018). Virtual reality training system for surgical anatomy. In *Proceedings of the 2018 International Conference on Artificial Intelligence and Virtual Reality*, AIVR 2018, page 30–34, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3293663.3293670.

Wang, Y., Di, F., Li, J. Y., Wu, J. J., and Liu, J. Y. (2023). Research on welding process simulation training technology based on virtual manufacturing. In *Proceedings of the International Conference on Industrial Design and Intelligent Technology*, pages 499–507. DOI: https://doi.org/10.2991/978-94-6463-266-8_55.

Xu, X., Lu, Y., Vogel-Heuser, B., and Wang, L. (2021). Industry 4.0 and industry 5.0—inception, conception and perception. *Journal of Manufacturing Systems*, 61:530–535. DOI: https://doi.org/10.1016/j.jmsy.2021.10.006.

Yunus, F. A. N., Baser, J. A., Masran, S. H., Razali, N., and Rahim, B. (2011). Virtual reality simulator developed welding technology skills. *Journal of Modern Education Review*, 1(1):57–62.

Zhu, W., Fan, X., and Zhang, Y. (2019). Applications and research trends of digital human models in the manufacturing industry. *Virtual Reality & Intelligent Hardware*, 1(6):558–579. DOI: https://doi.org/10.1016/j.vrih.2019.09.005.

Appendices

A Questionnaires

The following questionnaires are shown that were used in this research. They consist of a set of questions using the SUS survey, NASA TLX and the experience of participants with the virtual reality welding software.

A.1 System Usability Scale (SUS)

1. I think I would like to use this system frequently.
2. I find the system unnecessarily complex.
3. I found the system easy to use.
4. I think I would need help from a person with technical knowledge to use the system.
5. I think the various functions of the system are very well integrated.
6. I think the system is very inconsistent.
7. I imagine that people will learn how to use this system very quickly.
8. I found the system difficult to use.
9. I felt confident using the system.
10. I had to learn a lot of new things before I could use the system.

A.2 NASA Task Load Index (TLX)

1. How mentally demanding was the task?
2. How physically demanding was the task?
3. How rushed or fast-paced was the task?
4. How successful were you in meeting the objectives of the task?
5. How hard did you have to work to achieve your level of performance?
6. How insecure, discouraged, irritated, stressed, and annoyed versus secure, satisfied, content, relaxed, and complacent did you feel during the task?

A.3 Questionnaire (Q1) about user experience

1. On a scale of 0-5, the application contributed to my learning about the welding process. (0 = Not at all, 5 = Very much)
2. I feel more prepared to perform welding after using the software. (0= Not more prepared, 5 = Much more prepared)
3. The use of the application should be incorporated as part of regular welding instruction. (0 = Strongly disagree, 5 = Strongly agree)
4. The visual feedback helped me understand the correct angle and speed. (0 = Not at all, 5 = Very much)
5. I feel more intimidated by real welding equipment after training with the proposed VR-based welding simulator. (0 = Highly intimidated, 5 = Not intimidated at all)
6. Please leave any additional comments or suggestions about the simulator:

A.4 Expert Evaluation Questionnaire (Q2) - Simulator Validation and Transfer of Learning

1. On a scale of 0–5, how confident are you in the evaluation results obtained by the participants during the real-world weld inspection? (0 = Not confident at all, 5 = Extremely confident)
2. On a scale of 0–5, to what extent does the simulator help identify participants who face the greatest difficulties in real-world welding? (0 = Not at all, 5 = To a great extent)
3. On a scale of 0–5, to what extent does the simulator help identify procedural errors or weld defects that need to be addressed in real-world practice? (0 = Not at all, 5 = To a great extent)
4. On a scale of 0–5, to what extent did you observe an improvement in the participants' real-world welding performance after using the simulator? (0 = No improvement observed, 5 = Significant improvement)

5. On a scale of 0–5, to what extent did simulator training reduce material waste or execution time during the real welding task? (0 = Not at all, 5 = Significantly reduced)

6. What modifications, if any, would you suggest for the simulator or the training workflow to better align with real-world welding? Please describe: