VIRTUAL REALITY SAFETY TRAINING FRAMEWORK IN MANUFACTURING INDUSTRY

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ABSTRACT

In recent years, virtual reality (VR) technology has gained significant traction in safety training for high-risk industries, owing to its immersive and interactive capabilities, which have been shown to substantially improve training outcomes. However, traditional safety training methods in the manufacturing industry often suffer from limited engagement, lack of interactivity, and insufficient personalization, leading to gaps between theoretical knowledge and practical application. These shortcomings no only undermine the effectiveness of training but also increase the risk of workplace accidents, highlighting the urgent need for more innovative and effective training solutions.To address these challenges, this study proposes a comprehensive VR-based safety training system framework, which integrates three core modules: safetyknowledge learning, safety experience, and online assessment. The framework emphasizes modular design and user feedback optimization to enhance adaptability and training effectiveness across diverse manufacturing environments. By conducting a thorough literature review and case analysis, this research underscores the critical importance of modular design, multi-scenario coverage, and interaction optimization in developing practical and scalable training systems. The proposed system was validated through usability testing with 20 participants, demonstrating significant improvements in user engagement, confidence, and satisfaction compared to traditional training methods. The findings reveal that VR-based training not only enhances attention retention and relevance to real-world scenarios but also fosters a deeper understanding of safety protocols through immersive simulations and real-time feedback. This research provides theoretical support and practical guidance for the design and optimization of VR-based safety training systems, offering a scalable solution that can be tailored to the specific needs of the manufacturing industry. The implications of this study extend beyond immediate training improvements,as the proposed framework has the potential to reduce workplace accidents, enhance operational efficiency, and promote a culture of safety within manufacturing organizations. By bridging the gap between theoretical research and practical application, this work contributes to the broader adoption of VR technology in industrial safety training, paving the way for safer and more efficient manufacturing environments.

Keyword: Virtual reality,Manufacturing training,, Safety training,Immersive learning

I. INTRODUCTION

As the cornerstone of the modern economy, the manufacturing industry has undergone a profound transformation from traditional handicrafts to automation and intelligent systems. This shift has significantly elevated the importance of safety training, which is now more critical than ever.

Traditional training methods, such as safety manuals, instructional videos, lectures, and exercises, often fail to engage trainees effectively, resulting in a passive learning environment. These methods, characterized by their lack of interactivity and personalization, create a substantial gap between training and real-world operations. Workplace injuries account for approximately 35% of this gap, highlighting the limitations of traditional training methods in enhancing operational competence and ultimately impacting industry competitiveness. In the context of Industry 4.0, which emphasizes integrated safety measures, collaboration, and innovation, the need for technology-assisted learning has become increasingly evident (Roldán et al. 2019). Among various emerging technologies, Virtual Reality (VR) has emerged as a crucial solution for addressing these challenges (Ulmer et al. 2020).

Virtual Reality (VR) is an immersive, three-dimensional digital environment that users can access through the internet. It allows individuals to engage, work, and learn within simulated realities, providing a platform for realistic interactions (Protopsaltis et al. 2022). In the realm of manufacturing safety training, VR enables the simulation of diverse work environments and emergency scenarios, creating a risk-free space for employees to practice and refine their skills. This immersive training method not only enhances operational competence but also significantly raises safety awareness (Li et al. 2018).

Safety training is a global imperative for reducing accidents and protecting both individuals and assets. It enhances people's ability to identify and assess risks, which is particularly critical in high-risk scenarios (Ahn et al. 2020). Research consistently demonstrates that effective safety training has a profound impact on worker behavior and disaster preparedness (Nissanka & Dissanayake 2019). Historically, safety training has relied on methods such as manuals, videos, lectures, and drills (Wang et al. 2022). However, these traditional methods often lack interactivity and meaningful feedback, limiting participants' ability to evaluate their decisions in real-time (Ajjawi et al. 2022). Moreover, they fail to simulate hazardous situations effectively (Bearman et al. 2020) and often miss key security risk identification (Yesipova & Medvid 2020; Scorgie et al. 2023).

With the advent of Industry 4.0, VR technologies have revolutionized the manufacturing sector. VR enables immersive simulations that allow workers to practice safety protocols in realistic settings. Research highlights the importance of VR for maintenance support, enabling technicians to access real-time help and simulated training (Buń, Grajewski & Górski 2021). During the COVID-19 pandemic, VR and AR provided vital remote support, eliminating the need for specialized hardware and making training more flexible and accessible (Raj et al. 2023; Ortega-Gras et al. 2023). This trend has since expanded across industries, enhancing training flexibility and efficiency.

The application of VR in manufacturing safety training offers numerous advantages. It provides realistic, risk-free simulations where employees can experience hazardous situations and learn safety protocols effectively. This immersive approach boosts engagement, retention, and overall preparedness (Holuša et al. 2023). VR-based training can be tailored to specific scenarios, ensuring that employees receive relevant, site-specific training (Joshi et al. 2020). Moreover, VR offers cost-effective and scalable solutions, eliminating the need for physical mock-ups and enabling consistent training across different locations or shifts (Lacko 2020). Ultimately, VR enhances safety knowledge retention, reduces accidents, and fosters a safer workplace environment (Abidi et al. 2019).

II. LITERATURE REVIEW

A. Virtual Reality (VR) Technology

Virtual Reality (VR) technology creates immersive three-dimensional digital environments that users can access and interact with via the internet (Protopsaltis et al., 2022). The core advantage of VR lies in its high level of immersion and interactivity, providing users with experiences that closely mimic real-world scenarios while eliminating the risks associated with actual operations (Holuša et al., 2023). In the context of manufacturing safety training, VR allows employees to simulate various workplace scenarios and emergency situations, thereby enhancing their safety awareness and emergency response capabilities (Stefan et al., 2024). For example, Lv (2023) proposed a VR-based safety training system for chemical industrial parks that significantly improved workers' safety awareness and emergency response skills through virtual scenario simulation and real-time drills.

B. Current State of Manufacturing Safety Training

Traditional manufacturing safety training methods suffer from several limitations, such as lack of interactivity, insufficient personalization, and the gap between theoretical knowledge and practical application (Joshi et al., 2020). These methods often rely on safety manuals, videos, lectures, and drills, which fail to effectively engage employees and result in suboptimal training outcomes (Scorgie et al., 2023). Research indicates that VR technology significantly outperforms traditional methods in enhancing workers' safety awareness and operational skills (Stefan et al., 2024). For instance, Joshi et al. (2020) pointed out that traditional safety training methods have limited application in real-world scenarios, while VR technology can significantly improve workers' safety knowledge and skills through immersive experiences and real-time feedback.

C. Applications of VR in Safety Training

The application of VR technology in safety training has made significant progress. For example, Lv (2023) proposed a VR-based safety training system for chemical industrial parks that significantly enhanced workers' safety awareness and emergency response capabilities through virtual scenario simulation and real-time drills. The system's modular design and user feedback optimization allow it to adapt to the training needs of enterprises of different sizes (Lv, 2023). Additionally, Zhao (2018) developed a Unity-based safety training system for the construction industry, emphasizing the importance of immersive experiences and interactive learning. The system, equipped with high-precision 3D modeling and real-time interaction capabilities, provides employees with a safe practice platform, significantly improving training effectiveness and efficiency (Zhao, 2018).

D. Advantages of VR Technology

VR technology offers significant advantages in safety training. It not only enhances interactivity and engagement but also improves workers' safety awareness and emergency response capabilities through immersive experiences (Scorgie et al., 2023). For example, Stefan et al. (2024) demonstrated that VR training significantly outperforms traditional methods in enhancing workers' safety knowledge and skills. Moreover, VR technology can further optimize training outcomes through real-time feedback and personalized learning paths (Ulmer et al., 2020). For instance, Ulmer et al. (2020) developed a gamified VR training environment for the manufacturing industry, significantly improving employee engagement and training effectiveness through game design and real-time feedback mechanisms.

E. *Challenges and Future Directions*

Despite the significant advantages of VR technology in safety training, several challenges remain. For example, the cost and accessibility of VR hardware may limit its widespread adoption in small enterprises (Holuša et al., 2023). Additionally, the development of VR training systems requires specialized technical knowledge and resources, which can increase development and maintenance costs (Protopsaltis et al., 2022). Future research directions include reducing the cost of VR hardware, developing more user-friendly VR training tools, and exploring the application of VR technology in other industries (Scorgie et al., 2023). Moreover, with the development of artificial intelligence and big data technologies, future VR training systems are expected to become more intelligent and personalized (Stefan et al., 2024).

F. Relevant Case Studies

Chemical Industry: Lv (2023) proposed a VR-based safety training system for chemical industrial parks that significantly improved workers' safety awareness and emergency response skills through virtual scenario simulation and real-time drills. The system's modular design and user feedback optimization allow it to adapt to the training needs of enterprises of different sizes (Lv, 2023).

Construction Industry: Zhao (2018) developed a Unity-based safety training system for the construction industry, emphasizing the importance of immersive experiences and interactive learning. The system, equipped with high-precision 3D modeling and real-time interaction capabilities, provides employees with a safe practice platform, significantly improving training effectiveness and efficiency (Zhao, 2018).

Manufacturing Industry: Ulmer et al. (2020) developed a gamified VR training environment for the manufacturing industry, significantly improving employee engagement and training effectiveness through game design and real-time feedback mechanisms (Ulmer et al., 2020).

These case studies demonstrate the broad application and significant impact of VR technology across different industries. These studies not only provide theoretical support for the application of VR in safety training but also offer valuable experience and references for future research and practice.

III. RESEARCH MODEL AND RESEARCH QUESTIONS

The system is meticulously described through a conceptual framework, with the design of a virtual reality (VR) safety training framework for manufacturing illustrated in Figure 3.2. This study offers an in-depth analysis of the classification characteristics and commonalities within the manufacturing industry, with a particular focus on the typical types of accidents that occur. Building on this foundation, a comprehensive suite of safety experience modules has been meticulously designed and developed. These modules aim to encompass a wide range of common injury scenarios within the manufacturing sector, thereby achieving the overarching goal of systematic and comprehensive safety education (Joshi et al., 2020).

To further enhance the coverage and relevance of the training content, a structured set of safety knowledge modules has been constructed. These modules cover multiple dimensions, including the identification of unsafe behaviors, comprehension of safety signage, adherence to electrical safety norms, and compliance with overall safety regulations (Huang et al., 2020). The primary objective of these modules is to enhance trainees' safety awareness and their ability to cope with potential hazards, thereby equipping them with the skills to effectively identify and mitigate risks in real-world scenarios (Moreland et al., 2019).

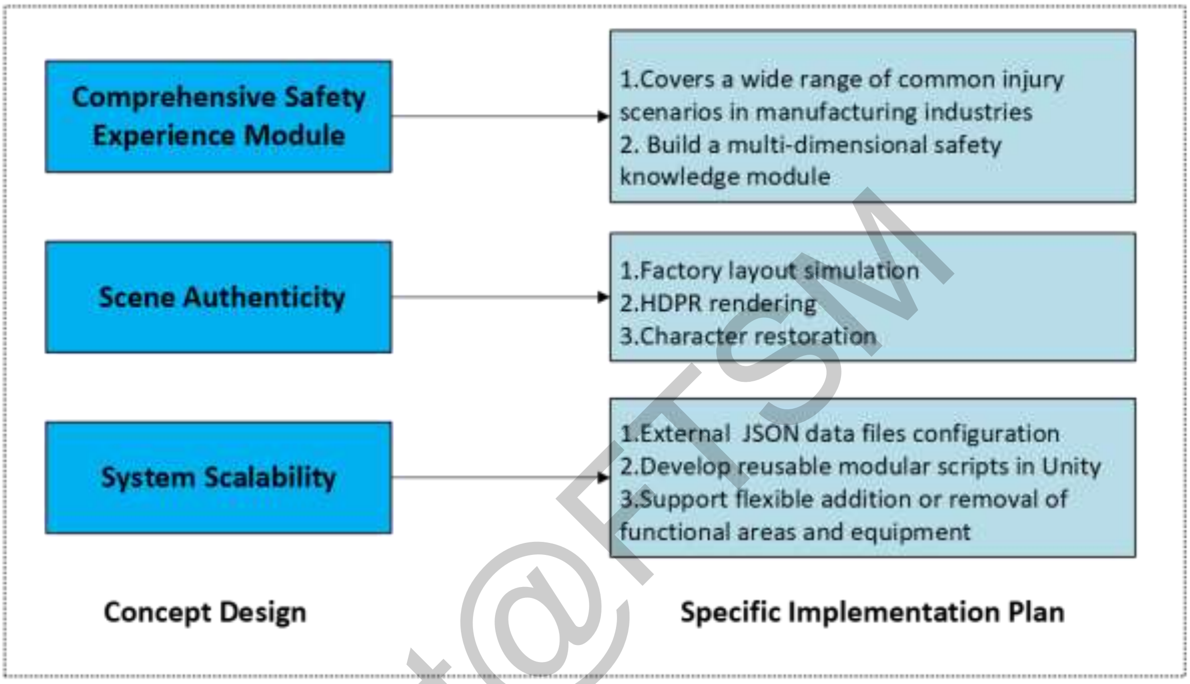


Figure 3.2 A Conceptual Design Formula for a Virtual Reality Safety Training

framework for Manufacturing

To ensure the authenticity of the VR safety training system, this study employs high-precision 3D modeling and animation techniques. These methods aim to accurately replicate the appearance and behavior of factory workers, including detailed facial features, attire, and movement patterns. By integrating VR technology with advanced 3D animation, the system achieves lifelike character expressions and fluid motions, enhancing user immersion and satisfaction (Lan, 2021).

A substantial number of non-player character (NPC) workers are integrated into the scene, modeled within a standardized small-scale factory layout using high-definition rendering technology (Xiong & Wang, 2023). Key elements such as machinery, robotic arms, and workstations are meticulously designed to boost visual and interactive realism (Zhang & Wang, 2023).

Lighting and shadow effects simulate real factory conditions, clearly delineating production lines (ABCD) and sub-lines (e.g., A1, A2, A3, A4) for easy navigation (Zhao, 2022). The layout includes distinct functional areas like production, storage, and offices, mirroring practical factory setups. Interactive equipment, such as robotic arms and conveyor belts, vividly demonstrate the manufacturing process, reflecting the efficiency and intelligence of modern industry (Shen et al., 2022). Automated robot programming and layout modeling frameworks further enhance factory system visualization and efficiency (Castro et al., 2019). Advanced VR techniques enable high-precision 3D models that heighten the realism of cooperative markers and interactive scenes (Shi et al., 2021).

To ensure scalability, the system utilizes external JSON data files for configuration, avoiding hard-coding and enhancing flexibility for future updates (Vinagrero Gutiérrez et al., 2023). Detailed documentation and code comments facilitate understanding for subsequent developers (Ergüt & Sirma, 2020). Reusable modular scripts developed in Unity's C# scripting system reduce repetitive work and improve efficiency (Wofford, 2021). The modular design allows flexible addition or removal of functional areas and equipment, supported by Unity's robust interaction capabilities for new logic and extensions (Banús et al., 2022; Zulberti et al., 2022).

This study constructs a safety training system that integrates professionalism, education, and immersion. It provides comprehensive safety knowledge and supports safe production through realistic simulations. Developed in Unity, the virtual factory excels in visual effects, educational value, and technological integration, enhancing user experience and offering innovative solutions for industrial efficiency and training (Lan, 2021; Xiong & Wang, 2023; Zhang & Wang, 2023; Zhao, 2022; Shen et al., 2022; Castro et al., 2019; Shi et al., 2021; Vinagrero Gutiérrez et al., 2023; Ergüt & Sirma, 2020; Wofford, 2021; Banús et al., 2022; Zulberti et al., 2022).

This research aims to propose and validate a comprehensive, realistic, and scalable VR safety training framework for the manufacturing industry. The specific research questions are:

1.Current Challenges and Limitations: What are the existing challenges and limitations of applying VR technology in manufacturing safety training?

2.Framework Proposal: How can we design a VR-based framework for manufacturing safety training?

3.Feasibility Validation: Is the proposed VR safety training framework feasible and effective?

IV. METHODS: PARTICIPANTS AND DATA COLLECTION

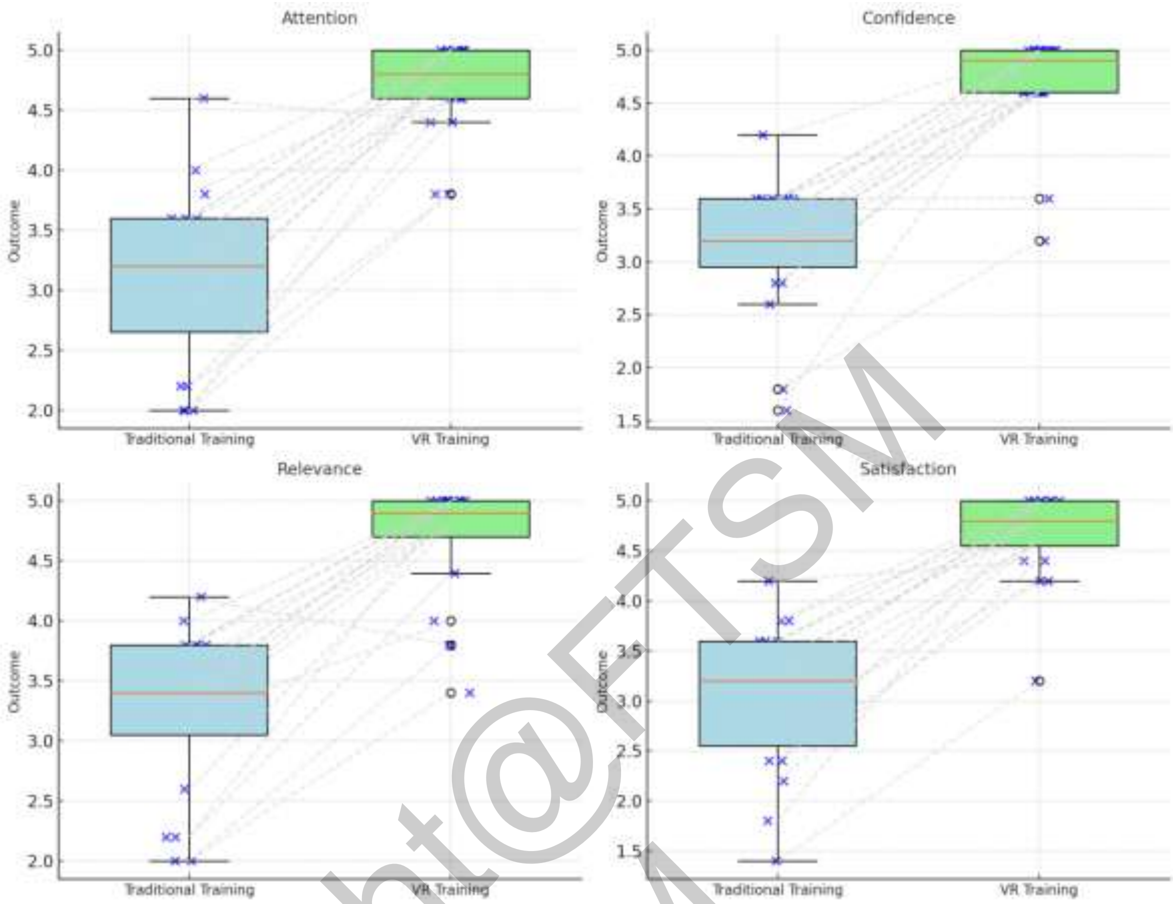
This study proposes a framework for a VR-based safety training system that includes three core modules: safety knowledge learning, safety experience, and online assessment. The framework emphasizes modular design and user feedback optimization to improve system adaptability and training effectiveness

Based on the conceptual framework, this study developed a prototype VR safety training system. The system was developed using Unity3D, which combines high-precision 3D modeling and real-time interaction techniques. The prototype system includes a safety knowledge learning module, a safety experience module, and an online assessment module.

In order to verify the effectiveness of the system, 20 participants were invited to conduct usability tests in this study. The test results showed that the VR training system significantly outperformed traditional training methods in terms of user engagement, confidence and satisfaction.

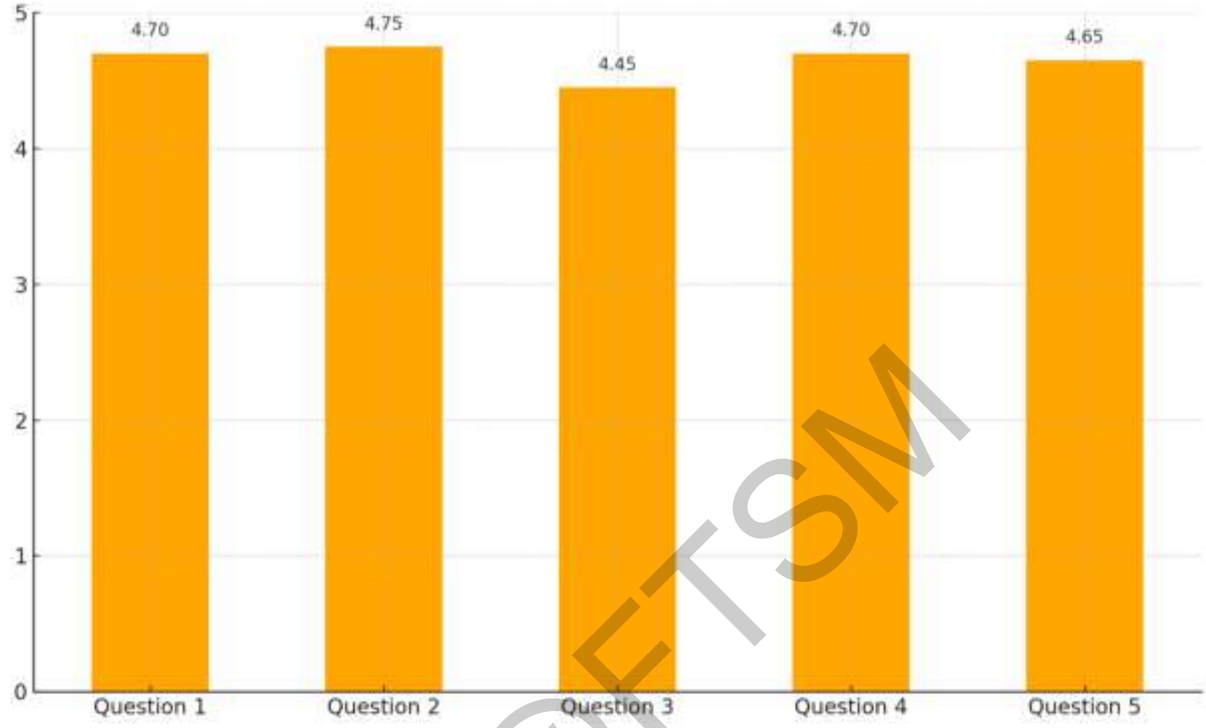
V. RESULTS & DISCUSSION

Results are presented in Figure 4.1 through box plots,the results of the data analysis are presented visually. The ratings of traditional training in the attention dimension ranged from 2.0 to 4.6, with a median of 3.0, a wide data distribution and outliers, indicating that some participants had difficulty maintaining attention; whereas the ratings of VR training were centered on a narrow distribution and high ratings of 3.8 to 5.0, with a median of 4.8, indicating greater attraction and attention maintenance. In the confidence dimension, the ratings of traditional training ranged from 1.6 to 4.2, with a median of 3.2, a dispersed distribution and low outliers, while the ratings of VR training ranged from 3.2 to 5.0, with a median of 4.8, a concentrated distribution, and no outliers, indicating that the VR training significantly increased participants' confidence. In the relevance dimension, the ratings for traditional training ranged from 2.0 to 4.2, with a median of 3.6 and low outliers; the ratings for VR training ranged from 3.4 to 5.0, with a median of 4.8, which is a high overall rating, but a few low outliers suggest the need for content optimization. In the satisfaction dimension, the ratings for traditional training range from 1.5 to 4.0, with a median of 3.0 and a wide distribution; the ratings for VR training range from 4.0 to 5.0, with a median of 4.9, and the distribution is highly concentrated and free of outliers, suggesting that VR training is more favored by users in terms of design and experience. Overall, VR training outperforms traditional training on all four dimensions and has a more concentrated distribution of ratings, showing higher user consistency and experience enhancement. However, a few low outliers in the relevance dimension suggest that course content still needs to be further optimized to meet individualized needs.



4.1 Comparative analysis of the effect of virtual reality and traditional training based on the ARCS model

The study results, as shown in Figure 4.2, indicate that the average scores across all dimensions ranged from 4.45 to 4.75, reflecting high overall user satisfaction. The highest score was achieved in interface clarity and simplicity, with an average of 4.75, demonstrating strong user approval of the system design. The intuitiveness of system operation and the realism of the immersive experience also scored highly at 4.70, highlighting the system's effectiveness in user-friendly design and virtual environment simulation. However, the dimension assessing the understanding and application of safety rules within the virtual environment had a relatively lower score of 4.45, suggesting that some users faced difficulties in comprehending and applying the rules. Additionally, the interactivity dimension received an average score of 4.65, indicating that interactivity positively impacted user engagement and learning outcomes.



4.2 Statistical chart of average user experience scores for manufacturing safety training systems

VI. CONCLUSION

In this study, we explored the application of virtual reality (VR) technology in manufacturing safety training and proposed an immersive, interactive VR training system designed to enhance employees' safety awareness and emergency response capabilities through highly realistic virtual scenarios. By simulating hazardous work environments, the system allows employees to practice safety procedures in a risk-free setting, thereby improving their ability to handle real-world emergencies. Through feasibility tests, we analyzed the system's performance in terms of user satisfaction, confidence, and overall experience. All test results indicate that the VR training system significantly enhances users' safety knowledge, operational confidence, and overall training experience, offering an efficient and innovative solution for manufacturing safety training.

As future work, we will focus on enhancing the flexibility, practicality, and scalability of the VR safety training system. Specifically, we will introduce multiple viewpoint options to alleviate user discomfort, develop team-based training modules to address complex scenarios, and implement machine learning to deliver personalized training content. Additionally, we will expand the content library to cover more industry-specific scenarios and explore cloud-based solutions and more affordable hardware options to reduce deployment costs and broaden the system's applicability. These improvements will make the system more efficient, adaptable, and accessible, providing a more innovative and sustainable solution for manufacturing safety training.

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