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PAPER

Investigating the Efficacy of a Virtual Reality-Based Testing Station of Flexible Manufacturing System: A Usability and Heuristic Evaluation

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ABSTRACT

This study presents a comprehensive evaluation of a virtual reality-based testing station designed for flexible manufacturing systems. Given the intricate nature of flexible manufacturing systems and the demand for precision in learning, the integration of virtual reality emerges as a promising approach to enhance both student competence and engagement. By employing a combined assessment with the System Usability Scale and heuristic evaluation conducted by 36 students and 5 experts, respectively, the virtual reality-based testing station achieved an average usability score of 72.78, indicating good usability. Noteworthy heuristic challenges, particularly in the domains of 'Realistic Feedback' and 'Navigation and Orientation Support,' have been identified, providing valuable insights for potential refinements to the testing station. The outcomes of this study not only guide immediate improvements but also pave the way for future research endeavors aimed at elevating the learning outcomes in flexible manufacturing systems courses.

KEYWORDS

usability evaluation, heuristics evaluation, virtual reality, testing station, flexible manufacturing systems

1 INTRODUCTION

Virtual Reality (VR), a transformative technology, has found widespread applications, particularly in education, where it aims to captivate learners and enhance information retention [1], [2]. In the realm of electrical engineering education, VR-based learning applications have emerged to create immersive, interactive experiences, revolutionizing the understanding of complex concepts [3]–[5]. Traditional teaching methods, often grappling with the intricate nature of electrical

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engineering [4], benefit from augmentation through the engaging and interactive experiences offered by VR applications [5].

The successful integration of VR into education demands meticulous design and usability evaluation [2]. When conducting usability testing, various measurement techniques, such as the System Usability Scale (SUS) [6] and heuristic evaluation [7], are employed. These evaluations aim to identify usability potential and design issues that may impact the user experience and learning outcomes. Heuristic evaluation typically involves experts in the evaluation process, while the SUS incorporates end users. Research underscores their impact on enhancing VR-based learning applications [8], [9]. Identifying weaknesses and addressing usability concerns through these evaluations is crucial for ensuring the effectiveness and usability of VR applications in education.

A cornerstone of Industry 4.0 that holds significant importance for students in electrical engineering education to comprehend is the flexible manufacturing system (FMS). This advanced production system intricately interconnects workstations, machines, and logistics equipment, ensuring precise coordination of the entire manufacturing process through computer integration, including testing stations [10]. VR technology enhances this role by providing students with a dynamic and interactive learning environment, enabling virtual engagement with FMS intricacies. This integration not only simulates real-world scenarios but also allows students to apply theoretical knowledge in a hands-on, risk-free setting [2], [3]. Consequently, the evaluation for VR-based testing stations of FMS becomes essential for advancing the effectiveness and efficiency of electrical engineering education, underscoring the significance of evaluating the product before its integration into student learning.

While VR shows promise in electrical engineering education, the evaluation of specific applications, such as testing stations for electrical engineering students' FMS learning, remains underexplored. This study addresses this gap by focusing on the testing station of FMS. Utilizing SUS and expert heuristic evaluations, the aim is to evaluate the usability of an FMS testing station to guide refinements for optimizing student outcomes. By concentrating on the intersection of VR technology and the integral FMS testing station, this research contributes valuable knowledge to enhance the educational experience in electrical engineering. The guiding research question is: "***How do usability and heuristic evaluations enhance the learning experience of a VR-based testing station for FMS in electrical engineering education?***"

2 RELATED WORKS

VR technology has gained prominence in education as a medium for delivering engaging and immersive learning experiences [1]–[3]. VR design and development can be approached using User-Centered Design (UCD) methodology. UCD focuses on understanding the needs of the end-users to create user-friendly and effective applications. It considers factors such as user interface and user experience to enhance the interaction between users and the VR application [11]. Ensuring user-friendly and navigable VR applications is essential, and commonly employed evaluation methods include the SUS and heuristic evaluation.

SUS [6] is a standardized questionnaire widely used to assess user satisfaction across various applications, including VR-based learning. Kardong-Edgren et al. [12] applied SUS to evaluate a virtual reality learning system designed for medical students practicing sterile catheterization, resulting in a SUS score of 64.03. Notably, 75% of participants provided an overall positive rating for the system.

Sudarmilah & Siregar [13] demonstrated success in assessing VR-based educational games focused on waste management, achieving an SUS score indicating an average satisfaction level of 64.3. In the field of engineering education, Diwakar & Noronha [14] reported positive outcomes, with 87% of 58 engineering instructors acknowledging the usefulness of guidelines for their virtual laboratory experiment designs.

On the other hand, heuristic evaluation involves experts assessing applications based on a set of usability principles or heuristics. This method is valuable for pinpointing specific usability issues in VR-based learning applications. For example, Tham et al. [15] employed an adapted heuristic to evaluate the functionalities, attributes, and applications of VR-based applications. They not only presented the implementations but also ensured validation through triangulation by sharing findings from qualitative interviews with three users who engaged with two of the applications. This approach offers resources for practitioners, facilitating the integration of VR in interactive and relevant ways. In another study, Paliokas et al. [16] applied a heuristic evaluation to assess a proof-of-concept AR application, featuring novel elements such as an AR quiz game. The findings revealed that enhanced AR experiences in museum settings seamlessly align with user environments and 3D spatial considerations.

The literature extensively demonstrates the efficacy of combining heuristic evaluation and SUS to comprehensively assess usability and user satisfaction in various applications. Studies, including Wahyuningrum et al. [17], emphasize the combined power of heuristic evaluation and SUS in evaluating e-commerce environments. While SUS gauges overall satisfaction, heuristic evaluation delves into specific concern related to system flexibility and efficiency, particularly in the context of search engine functionality. Furthermore, in the context of VR-based learning environment, Tasfia et al. [18] proposed a set of heuristics and utilized SUS to evaluate the usability of learning applications for children. The research demonstrated the effectiveness and applicability of both evaluation methods in assessing the usability of various proposed learning applications. Heuristic evaluation was valuable in identifying usability problems, and SUS provided a reliable measure of user satisfaction with the system.

Conducting usability and heuristic evaluations is vital for ensuring the effectiveness of VR-based learning applications in electrical engineering education. This process ensures an efficient and engaging interface tailored to the specific needs of this academic context. By proactively identifying and addressing usability issues, the VR-based learning application aims to minimize frustration, maximize student engagement, and facilitate effective information retention [19]. The focus on regular usability testing emphasizes the commitment to on-going improvements, guaranteeing that the proposed application remains not only relevant and accessible but also aligned with the educational objectives of electrical engineering students [20]. Ultimately, the goal is to create a seamlessly integrated and intuitive virtual learning tool that actively supports and enhances the educational journey of students specializing in electrical engineering [21].

Overall, the literature suggests that employing heuristic evaluation and SUS methods can offer a comprehensive assessment of usability and user satisfaction in VR-based learning applications in the field of electrical engineering. Heuristic evaluation can identify specific usability issues that require attention, while SUS provides a reliable measure of overall user satisfaction with the system. Despite positive outcomes being indicated, a literature gap persists in evaluating VR-based testing stations for FMS in electrical engineering education. This highlights the necessity for usability and evaluations before integrating VR simulators into specialized technical education, motivating the current research.

3 MATERIAL AND METHOD

3.1 Development of VR-based FMS testing station

The VR-based testing station of FMS in electrical engineering education was meticulously designed using a User-Centered Design (UCD) approach [22]. This approach began with user research, the team conducted interviews to understand the needs and preferences of students and educators in the context of FMS Testing Station. This user research informed the design requirements, ensuring that the VR system would effectively support learning objectives and user engagement. Utilizing the Meta Quest 2: Immersive All-In-One VR Headset and Unity IDE, the team iteratively designed and prototyped the VR environment, incorporating feedback from users at each stage of development. The UCD approach emphasized simplicity, intuitive navigation, and clear feedback within the virtual environment.

The Meta Quest 2 headset, known for its immersive experiences, was selected to power the VR system, providing students with an unparalleled virtual learning encounter. Developed within the Unity IDE, the system aimed to offer a seamless and captivating educational journey. Following the initial development phase, a pilot test comprising five participants, including both students and educators, was conducted to evaluate the functionality of the VR-based testing station. This pilot test was conducted to ensure that all interactive elements within the VR environment may run smoothly without encountering any technical issues.

Fig. 1. Testing station visualization

Figure 1 illustrates the visualization of the VR-based FMS testing station. Students not only read the learning materials but could also interact with virtual objects, simulating the FMS testing station process. These dynamic features elevated the learning experience, providing a hands-on dimension to theoretical knowledge.

Fig. 2. Main menu

Within the main menu (see Figure 2), students could navigate through a virtual submenu featuring five categories: *Objective*, *Learning Materials*, *Developer*, *Help*, and *Exit*. The intuitive interface allowed students to access each menu by simply clicking on the corresponding virtual buttons, facilitating effortless exploration.

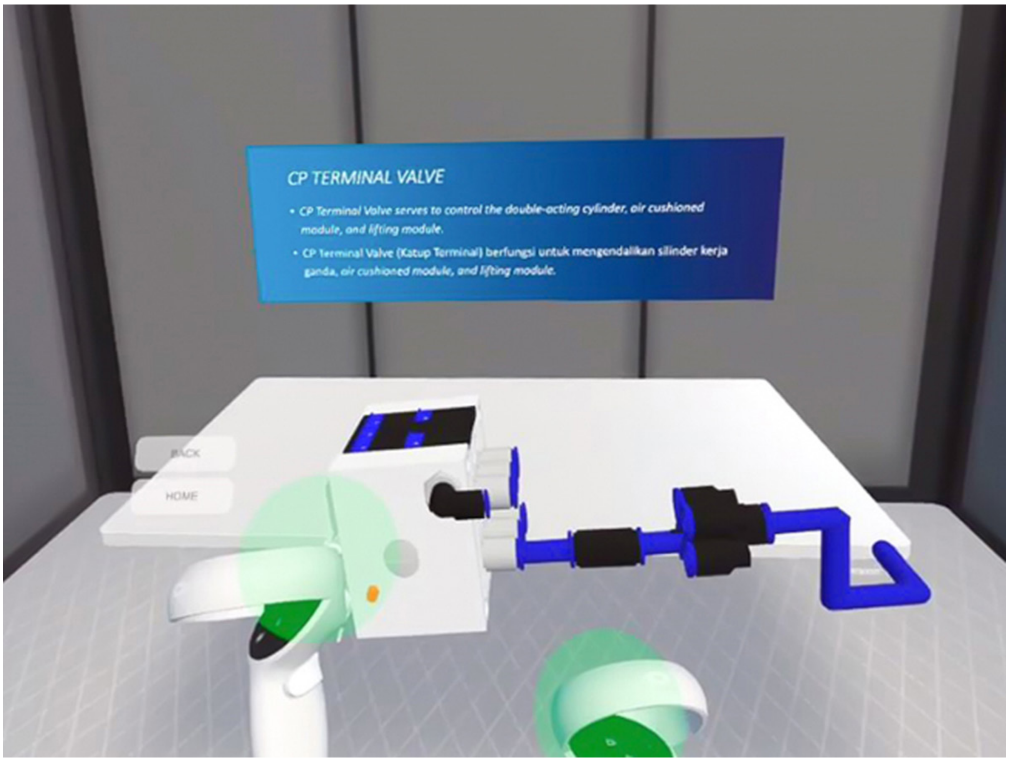

Fig. 3. Interacted with FMS's components

The "Objective" menu outlined the learning goals, immersing students in a hands-on understanding of the FMS testing station. It introduced the components of the testing station builder, elucidating their functions and underscoring their significance in the realm of electrical engineering education.

The "Learning Materials" menu offered a curated selection of 21 sub-materials, featuring components such as the Lifting Module, Air Service Unit, PLC, Trolley, etc. A detailed explanation accompanied each component, fostering a profound understanding through engaging narratives and real-world applications (see Figure 3). This interactive experience enabled students to delve into practical exercises, fostering a deeper connection with the virtual objects and real-world counterparts found in FMS testing stations.

The "Help" submenu provided insightful guidance on utilizing the VR controller and navigating the user interface (see Figure 4). This not only simplified the learning process but also enhanced the overall educational journey, making it an accessible and enjoyable experience for students.

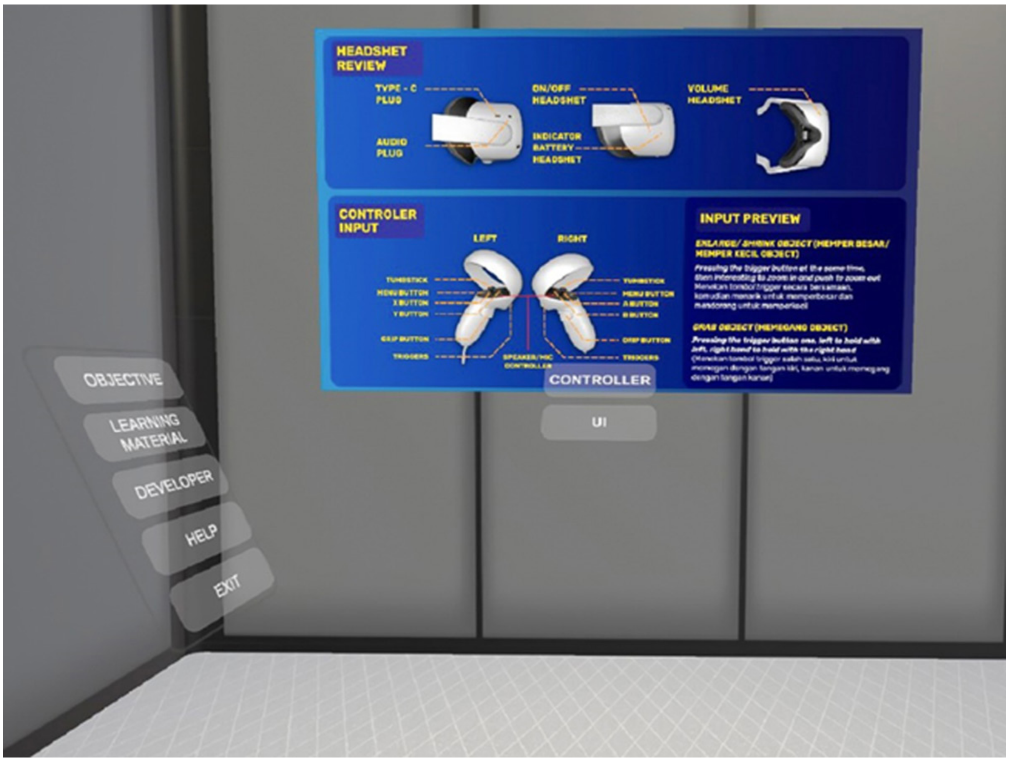

Fig. 4. Help submenu

In summary, the VR-based FMS testing station harnessed cutting-edge technology and an intuitive interface to transport students into an educational realm filled with practical skills and knowledge in electrical engineering. The immersive journey aimed not only to educate but to captivate, ensuring a memorable and enriching learning experience.

3.2 Research context and sample

The study involved a total of 36 university learners enrolled in the *Practice of Flexible Manufacturing Systems* course in Indonesia, all of whom were approximately

20 years old. The primary focus of this research revolved around testing stations, with students expected to identify and explain the functionalities of the components comprising the testing station. Additionally, five experts were invited to conduct heuristic evaluations of usability issues in the VR-based testing station of FMS.

3.3 Research procedure

This study aims to evaluate the usability and heuristics of the VR product for the testing station in FMS. The evaluation process consists of the following steps, as illustrated in Figure 5.

1. Initially, define the objective of the evaluation, which is to assess the usability and heuristics of a VR-based FMS testing station.
2. Assemble a group of users representing the target audience for the VR-based learning application. Additionally, gather evaluators for the purpose of heuristic evaluation.
3. On one side, users are asked to complete tasks or a series of tasks using the VR-based learning application. Their behavior is observed, and any usability issues that arise are noted. After users complete their tasks, they are requested to fill out the SUS questionnaire to assess their overall satisfaction with the system. On the other side, heuristic evaluations of the VR-based learning application are conducted using a set of heuristics instruments.
4. Analyze the results of the SUS questionnaire and heuristic evaluation to gain a comprehensive understanding of the system's usability and user satisfaction. Identify usability issues within the system for each heuristic. Prioritize the identified usability issues based on severity, frequency, and their impact on the user experience.
5. Compile a list of recommended design changes to address the identified usability issues from the heuristic evaluation. Implement the recommended design changes if feasible.

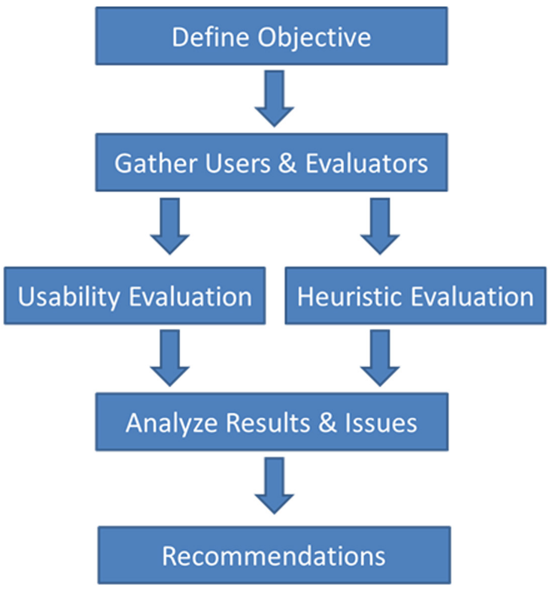

Fig. 5. Steps in usability and heuristic evaluation

3.4 Measuring tools

To evaluate the efficacy of a proposed VR-based testing station of the FMS system, multiple assessment tools were employed. These included a five-point Likert scale questionnaire to measure system usability, as well as heuristic evaluation. The SUS questionnaire was based on Brooke [6], modified to suit the context of the study, and comprised 10 questions. The SUS, with its simple administration, is suitable for small sample sizes, yielding reliable results, and has undergone validation to distinguish between usable and unusable systems [23]. To counteract potential response bias and acquiescent bias among respondents, five questions were phrased in a negative manner. This inclusion of both positive and negative items aimed to prompt respondents to carefully consider each question, thereby increasing the likelihood of obtaining accurate responses [24], [25].

Heuristic evaluation for evaluating virtual environment, as developed by Sutcliffe & Gault [26] based on Nielsen [27], was also adopted to identify specific usability issues in VR-based learning applications. It consisted of 12 statements to rate various aspects of the system on a scale from 0 to 4, where 0 indicates no usability issues, and 4 signifies severe usability problems. Moreover, experts can provide open-ended comments and suggestions to further elaborate on identified issues and propose improvements.

3.5 Data analysis

The SUS questionnaire data were analyzed using a cumulative system, aggregating participants' responses to individual items on the SUS to provide an overall usability score for the virtual reality-based testing station. The cumulative scores were then normalized to obtain a final SUS score out of 100, following the standard practice. To evaluate the usability of the system, the obtained SUS scores were classified into categories based on the thresholds proposed by Bangor et al. [28]. These categories included scores ranging from "Worst Imaginable" to "Best Imaginable". The classification offered a clear understanding of the perceived usability by participants, allowing for targeted insights into areas of improvement.

Heuristic evaluation data were analyzed by examining feedback from experts on specific usability heuristics. Each heuristic was assessed individually, and identified issues were categorized based on severity and priority for corrective actions. Issues identified through heuristic evaluation were classified based on severity and priority levels. Severity levels ranged from minor to critical, indicating the impact of the issue on user experience. This classification system aided a crucial role in prioritizing improvements for an effective and efficient refinement process.

The results from both the SUS questionnaire and heuristic evaluation analyses were integrated to provide a comprehensive understanding of the virtual reality-based testing station's usability. By triangulating the quantitative and qualitative data, the study aimed to uncover nuanced insights that guided potential revisions and enhancements for optimal user experience and learning outcomes.

4 FINDINGS AND DISCUSSION

4.1 Usability evaluation

The dataset, derived from collected questionnaires, underwent data coding and tabulation. Table 1 summarizes the data, including individual scores for each statement and the overall average score. The "Raw Score" column displays original average scores, distinguishing odd and even items. The "SUS Score" column adjusts even statement scores into positive responses, representing the standard SUS range calculations in both 0–4 and 0–100 formats.

Table 1. Usability assessment

No	Statement	Raw Score	SUS Score	
			0–4	0–100
1	I think I will frequently use this Virtual Reality application.	3.72	2.72	68.06
2	I find this Virtual Reality application complicated to use.	1.83	3.17	79.17
3	I think this Virtual Reality application is easy to use.	4.22	3.22	80.56
4	I believe I would need assistance from a technician to use this Virtual Reality application.	2.89	2.11	52.78
5	I feel that various functions in this Virtual Reality application are well-integrated.	4.19	3.19	79.86
6	I think there are too many inconsistencies in this Virtual Reality application.	1.94	3.06	76.39
7	I imagine that most people will quickly understand how to use this Virtual Reality application.	4.28	3.28	81.94
8	I find this Virtual Reality application very inconvenient to use.	1.75	3.25	81.25
9	I feel very confident when using this Virtual Reality application.	4.06	3.06	76.39
10	I need to learn a lot before I can start using this Virtual Reality application.	2.94	2.06	51.39
Average			2.91	72.78

From Table 1, the minimum score (51.39) (Statement 10) and the maximum score (81.94) (Statement 7) were observed. Figure 6 illustrates the SUS Score distribution. The average rating of 72.78 falls within the "C" range, indicating somewhat below the "Good" of adjective ratings, surpassing the acceptable threshold set by Bangor et al. [28] and Sauro & Lewis [29].

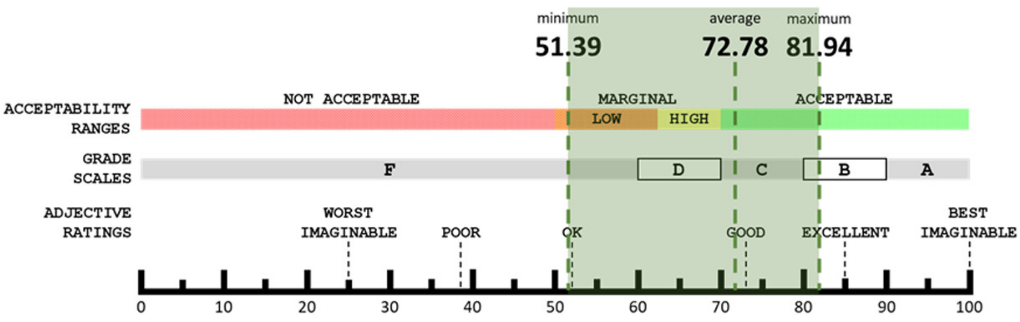

Fig. 6. SUS score

4.2 Heuristic evaluation

Heuristic evaluation assessed the performance and usability of the VR testing station application. The VR testing station was thoroughly explored and examined in detail, as implied in the evaluation tasks. Table 2 presents the identified usability problems based on heuristics. The highest issue scores were found in Statements 5 and 7 (score 1), while Statements 6 and 10 had no issues (score 0).

Table 2. Heuristic evaluation

No	Heuristic	Rating	Problems Encountered
1	Natural Engagement	0.8	• The retrieval of silver and red work-pieces becomes challenging if they fall too far. • Some buttons are difficult to locate. • Fallen objects do not function correctly. • Adjustments are required in product virtualization to better align with real-world conditions. • It is already realistic, but additional identity names are needed on the PLC.
2	Compatibility with the User's Task and Domain	0.8	• The station's display matches the real world. • Certain objects, expected to slide, accumulate instead. • Sometimes, the distance between the touch object and the user appears too far.
3	Natural Expression of Action	0.2	• Interaction can be maximized within the virtual world. • Users need some time to adapt.
4	Close Coordination of Action and Representation	0.2	• Overall, responses from the virtual trainer are fast. • There is still a delay in picking up work-pieces.
5	Realistic Feedback	1	• Work-pieces can float if thrown outside the intended workflow. • After measuring the height, work-pieces should rest on the air blow, but in reality, they float. • While sound effects are appropriately integrated, there is a need for increased volume to ensure a more pronounced and engaging auditory experience. • It would be more engaging if sound effects were also used for station/object movements.
6	Faithful Viewpoints	0	–
7	Navigation and Orientation Support	1	• Users face difficulties in navigating and exiting the program during the trainer simulation, whereas the material section is relatively easy. • A tutorial is needed before use. • The navigation lacks contrast. • To enhance user visibility and interaction, consider employing striking colors like red for block/exit buttons.
8	Clear Entry and Exit Points	0.6	• Further attention is needed on how to enter and exit the virtual environment. • Contrast needs to be increased. • The strategic placement of the exit button, following the user's gaze, minimizes the need for users to search for it.
9	Consistent Departures	0.2	• Inconsistencies in object sizes, such as the small plate, undersized PLC, and oversized sensor, need attention to ensure a realistic and proportionate representation.
10	Support for Learning	0	–
11	Clear Turn-Taking	0.2	• Good.
12	Sense of Presence	0.2	• Optimization and precision in placing objects require refinement to enhance the overall sense of presence within the virtual environment.

Notes: Rating scale: 0: no problem found, 1: cosmetic, 2: minor, 3: major, 4: catastrophe.

The heuristic evaluation of the VR-based FMS testing station provided valuable insights into its usability and performance across various dimensions. *Natural engagement*, as indicated by the heuristic rating of 0.8, highlighted key issues such as the inability to retrieve fallen objects, difficulty in locating buttons, and the need for adjustments in product virtualization. These aspects play a crucial role in ensuring user immersion and should be addressed to enhance the overall user experience.

Similarly, compatibility with the *user's task and domain* scored 0.8, revealing issues related to the realism of object movements and the perceived distance between the touch object and the user. These issues, if resolved, can significantly improve user engagement and task completion.

The heuristic assessment also pointed out that while the *natural expression of action* (rating: 0.2) can be maximized within the virtual world, users may need some time to adapt. This suggests the importance of user-friendly guidance and a smoother learning curve. *The close coordination of action and representation* (rating: 0.2) raised concerns about delays in specific actions, emphasizing the need for improved system responsiveness.

Realistic feedback, with a heuristic rating of 1, highlighted issues such as floating work-pieces and the need for louder sound effects. Enhancing the authenticity of object behavior and audio cues can contribute to a more immersive experience. The evaluation also recognized the *faithful viewpoints* (rating: 0), indicating that the visual perspectives align well with user expectations.

Navigation and orientation support (rating: 1) revealed challenges in program navigation and exiting during the trainer simulation. Introducing a tutorial, improving contrast, and using striking colors for buttons were recommended to enhance user efficiency. *Clear entry and exit points* (rating: 0.6) called for attention to detail in entering and exiting the virtual environment, including increased contrast and optimized exit button placement.

Consistent departures (rating: 0.2) emphasized the importance of realistic object sizes for visual coherence. *The support for learning* (rating: 0) underscored the application's effectiveness in aligning with educational objectives. *Clear turn-taking* (rating: 0.2) indicated effective communication of task sequences to the user. *The sense of presence* (rating: 0.2) suggested that while the application succeeds in creating a sense of presence, improvements in object placement precision are necessary.

Furthermore, based on open-ended questions, several experts' comments and suggestions were also provided as follows:

1. *Navigation and Interaction Improvements*

   The expert recommends several enhancements to the VR testing station, emphasizing the importance of clearer navigation for entry and exit [7], [28]. Additionally, improvements are sought to ensure that thrown objects can seamlessly return to their original position, eliminating issues like disappearance or floating. Consistency in the performance of the virtual environment, especially during repeated attempts at the station, is identified as an area requiring attention. These suggestions underscore the significance of refining the user experience and addressing potential challenges in navigation and interaction.
2. *Educational Multimedia Appeal*

   The expert expresses a positive viewpoint on the VR implementation in the testing station, highlighting its high appeal as an educational multimedia tool [3], [30]. Acknowledging its potential to enhance enthusiasm, engagement, and attention among learners, the comment affirms the educational value and positive impact of VR technology in the context of the testing station.
3. *Quality Enhancement for VR as Educational Multimedia*

   The expert identifies minor shortcomings in the VR system and suggests their enhancement to achieve a higher quality educational multimedia experience [31]. This comment emphasizes the ongoing pursuit of refining and optimizing the VR technology to meet the standards of educational multimedia, ensuring a seamless and effective learning environment.

4. *Integration of AR Technology*
   A forward-looking suggestion is made to explore the implementation of augmented reality (AR) technology within the VR testing station. The prospect of incorporating real objects into the virtual space through AR is proposed, indicating an innovative avenue that could further enrich the user experience and contribute to the station's overall effectiveness [32].
5. *System Refinement and Error Anticipation*
   The need for a smoother refinement in the working system is highlighted, with a specific emphasis on anticipating and addressing potential work errors. This comment underscores the importance of system reliability and the proactive identification and resolution of issues to ensure a seamless and error-free user experience.
6. *Instructional Videos for User Guidance*
   Acknowledging the potential for user confusion, the expert suggests the creation of tutorial videos. These instructional materials would serve as valuable guidance [33], helping users navigate and interact with the VR testing station effectively. This recommendation aligns with the goal of enhancing the usability and accessibility of the educational tool.
7. *Suitability for Learning*
   The expert positively affirms that the VR testing station is suitable for learning. This statement supports the educational utility of the system, reinforcing its role as an effective tool for imparting knowledge and practical skills in the field of electrical engineering [3], [19], [21].
8. *Exit Button Placement and Color Clarity*
   Clarity in exit button placement and color is highlighted as an area for improvement. The expert recommends enhancing the visibility and intuitiveness of the exit button, underlining the importance of user-friendly design elements for a seamless experience [34].
9. *Method for Finding Fallen Workpieces*
   The expert suggests the addition of a method for finding fallen or thrown workpieces within the virtual environment. This recommendation aims to enhance user experience by providing a mechanism for users to locate and retrieve objects, contributing to a more realistic and engaging simulation [7], [35].

   These expert comments and suggestions collectively provide valuable insights into the strengths and areas of improvement for the VR-based testing station, guiding future enhancements and refinements.

5 CONCLUSIONS

The incorporation of the Practice of FMS course, featuring the VR-based testing station, emerges as a pivotal component in advancing students' comprehension of the subject matter. Ensuring the usability of this learning medium becomes imperative for effective educational delivery. This study was pursued to respond to the research question: *"How do usability and heuristic evaluations enhance the learning experience of a VR-based testing station for FMS in electrical engineering education?"* The study undertook an empirical usability evaluation of the VR testing station, utilizing the widely recognized SUS questionnaire and heuristic evaluation.

The study reported an average SUS score of 72.78 out of 100, providing a quantitative measure of usability. Notably, the study aligns with an acceptance table designating the achieved score within the "Good" category. Augmenting the quantitative findings, a heuristic evaluation proved instrumental in identifying nuanced performance issues within the VR testing station. The highest issue scores surfaced in statements 5 (Realistic Feedback) and 7 (Navigation and Orientation Support), warranting attention and potential refinement. Conversely, statements 6 (Faithful Viewpoints) and 10 (Support for Learning) exhibited no identified issues, offering valuable insights into the strengths of the VR learning medium. These heuristic evaluation findings serve as a foundation for targeted product revisions, focusing on the enhancement of identified issues to elevate overall usability.

Acknowledging the study's limitations is crucial. The relatively small sample size and course-specific nature of participants in the usability evaluation might constrain the generalizability of findings. Furthermore, the study's focus on the VR testing station's usability aspects excludes exploration of other potential factors influencing learning outcomes. Future research endeavors should aim for a more expansive and diverse participant pool, transcending course specificity, and consider a broader spectrum of educational aspects to enable a comprehensive evaluation, yet focused, evaluation of VR-based learning applications in the realm of electrical engineering education. These considerations will undoubtedly contribute to the continuous evolution and optimization of VR learning environments.

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