SkillsMalaysia Journal, Vol. 10 No. 1 (2024) p. 37-44

SkillsMalaysia Journal

Journal homepage: www.ciast.gov.my/journal/

e-ISSN : 0127-8967

Prototype Development of an Interactive Flame Cutting Process Simulation Using Virtual Reality Application

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Received October 2024; Accepted Accepted 2024; Available online December 2024

Abstract: In Technical and Vocational Education and Training (TVET), practical training in flame cutting methods incurs high costs due to the need for materials like steel, gas and equipment. Trainees need to perform practical exercises repeatedly to achieve a proficient skill level. Inadequate training or mistakes during practical sessions can lead to wasted training materials and may result in accidents and injuries. This study aims to present the development of a flame cutting prototype system using Virtual Reality (VR) interactive technology, along with cutting parameters such as cutting speed, nozzle distance and cutting angle. The system is designed to simulate the actual flame-cutting process in a realistic 3D simulation environment where trainees can practice flame cutting in a controlled manner, avoiding material wastage and eliminating physical risks and safety hazards. Key features of this system include the capability to provide real-time feedback on trainee performance, particularly on the cutting speed parameter. This allows trainees to practice repeatedly to improve their skills until proficient before engaging in actual cutting in a hazardous environment. The results of the study show that the developed system successfully simulates the flame cutting process using VR technology, incorporating cutting parameters such as cutting speed. This project demonstrates the significant potential of VR in vocational training institutions, especially for applications involving dangerous tools and processes like metal cutting.

Keywords: Virtual Reality, Flame Cutting, Cutting Speed, Technical and Vocational Education and Training (TVET)

Abstrak (Malay): *Dalam bidang Pendidikan dan Latihan Teknikal dan Vokasional (TVET), latihan amali dalam kaedah pemotongan api melibatkan kos yang tinggi disebabkan oleh keperluan bahan seperti keluli, gas dan peralatan. Pelatih perlu menjalani latihan amali berulang kali untuk mencapai tahap kemahiran yang mahir. Latihan yang tidak mencukupi atau kesilapan semasa latihan amali boleh menyebabkan pembaziran bahan latihan serta berisiko menyebabkan kemalangan dan kecederaan. Kajian ini bertujuan untuk membangunkan prototaip sistem pemotongan api menggunakan teknologi interaktif Realiti Maya (VR), bersama dengan parameter pemotongan seperti kelajuan pemotongan, jarak muncung dan sudut pemotongan. Sistem ini direka untuk mensimulasikan proses pemotongan api sebenar dalam persekitaran simulasi 3D yang realistik, di mana pelatih boleh berlatih pemotongan api secara terkawal, mengelakkan pembaziran bahan serta menghapuskan risiko fizikal dan bahaya keselamatan. Ciri utama sistem ini termasuk keupayaan untuk memberikan maklum balas masa nyata mengenai prestasi pelatih terutamanya pada parameter kelajuan pemotongan. Ini membolehkan pelatih berlatih berulang kali bagi meningkatkan kemahiran mereka sehingga mahir sebelum menjalankan pemotongan sebenar dalam persekitaran berbahaya. Hasil kajian menunjukkan bahawa sistem yang dibangunkan berjaya mensimulasikan proses pemotongan api menggunakan teknologi VR dengan menggabungkan parameter pemotongan seperti kelajuan pemotongan. Projek ini membuktikan potensi besar VR dalam institusi latihan vokasional, terutamanya untuk aplikasi yang melibatkan alat dan proses berbahaya seperti pemotongan logam.*

Kata kunci: Realiti Maya, Pemotongan Nyala, Kederasan Memotong, Pendidikan dan Latihan Teknikal dan Vokasional (TVET)

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1. Introduction

Flame cutting, also known as oxy-fuel or oxy-acetylene cutting, uses oxygen combined with a fuel gas such as acetylene, propane or natural gas to cut steel and other metals. This process involves using the gas as fuel to generate the heat needed for cutting. Flame cutting is widely used across various industries, from manufacturing to aerospace, to cut through thick metal, particularly mild steel.

Due to its extensive industrial applications, flame cutting is predominantly taught in vocational and technical training institutions, where practical, hands-on skills are emphasized. These programs are designed to align with industry demands, ensuring trainees acquire the necessary competencies for sectors such as manufacturing and construction.

The effectiveness of these programs is often greater when an on-the-job training element is included, allowing trainees to gain direct, supervised experience in real-world settings, thus bridging the gap between learning and industry requirements. Existing flame cutting training program nowadays predominantly utilize real materials and hands-on approaches to ensure practical skill development. These programs typically involve the direct use of oxy-fuel cutting tools on various metal types, particularly mild steel, allowing trainees to gain experience in real cutting conditions. The training process focuses on essential aspects, including equipment setup, safety procedures and practical cutting techniques, which are practiced on real materials to simulate industry standards.

However, this training programs face notable challenges in terms of cost and safety. The high expenses associated with procuring real materials, such as steel plates and maintaining the necessary oxy-fuel cutting equipment, including gas supplies and safety gear, represent significant financial burdens. Additionally, infrastructure requirements, such as specialized training facilities with adequate ventilation and safety systems, further contribute to operational costs. In terms of safety, the use of flammable gases, coupled with the high temperatures involved in the cutting process, creates substantial fire and explosion hazards. Trainees are also exposed to health risks, such as respiratory issues, due to fumes generated during cutting, necessitating proper ventilation and Personal Protective Equipment (PPE). Moreover, the risk of physical injuries, such as burns or eye damage, underscores the importance of stringent safety protocols and effective supervision throughout the training process (Monaghan, 2010). Thus, this study is carried out to develop a cutting process simulation using VR technology to improve the effectiveness and safety of skill in flame cutting training without material waste or exposure to physical risks and safety hazards. By offering a virtual environment for practicing flame cutting, the simulation will allow users to gain hands-on experience, reinforce procedural knowledge and build confidence before working with real equipment.

Certain studies have been conducted to develop multiple types of simulation for flame cutting training using real-time technology over the last few years to address those issues. A study on Immersive Virtual Reality (IVR) instruction in vocational schools reveals that IVR significantly enhances domain-specific knowledge acquisition among retail trainees compared to conventional methods. The findings showed a notable advantage for IVR in knowledge gain while some trainees reported moderate motion sickness, no direct correlation was found between these symptoms and learning outcomes. The research underscores the potential of IVR to improve vocational training while highlighting considerations for learner wellbeing (Kablitz et al., 2023).

VR is defined as a simulated three-dimensional (3D) environment that allows users to interact with virtual surroundings in a manner that replicates real-world sensory perceptions. VR's effectiveness is largely determined by its ability to evoke a sense of presence, or the feeling of being there within the virtual environment (Slater, 2018). These environments are constructed through sophisticated computer hardware and software systems, often necessitating the use of specialized devices such as headsets, goggles or bodysuits for immersive interaction. In educational setting, VR is used as an innovative tool for enhancing learning experiences. It can create immersive, interactive environments where students can engage in experiential learning that traditional methods may not provide. VR's capacity to simulate real-world scenarios allows learners to practice complex skills in fields such as medicine, engineering and vocational training without the associated risks or costs of real-life experimentation (Kuna et al., 2023).

VR technology has been applied in welding training programs, aiming to enhance skill development while addressing the safety, cost and resource challenges associated with traditional welding training. A study demonstrates how VR environments simulate welding processes, providing trainees with immersive, hands-on experiences that mimic real-world conditions. By integrating VR into welding education, the training system offers real-time feedback, which helps learners improve their technique, reduce errors and increase efficiency (Fast et al., 2004). The research aligns with broader trends in vocational training that explores the development and application of a VR-based training system designed to improve welding education through immersive 3D interactions (Liu et al., 2014). This system offers a multimodal experience by integrating visual, auditory and haptic feedback to closely replicate real-world welding environments. The 3D multimodal interaction allows trainees to perform welding tasks with greater precision and provides real-time feedback on performance. The study demonstrates that this VR-based simulator enhances learning by allowing users to practice various welding techniques in a controlled, safe and cost-effective environment, which minimizes the risks associated with conventional training. By leveraging advanced VR technology, the system addresses limitations in traditional methods such as high material costs, safety hazards and limited availability of real-world training scenarios. Furthermore, the inclusion of multimodal interactions deepens the trainee's engagement and accelerates skill acquisition.

VR technology is increasingly applied not only in vocational training but also in industrial training programs, offering immersive environments that replicate real-world operations. According to Zawadzki P (2020), VR technology is important in simulating complex production tasks, allowing employees to practice in a risk-free, immersive environment. By integrating VR into training programs, the research shows improved skill acquisition, operational efficiency and error reduction, aligning with the goals of Industry 4.0 (Zawadzki et al., 2020).

There is a training for metal arc welding processes which integrated with VR technology has been developed for both training and simulation purposes. The study emphasizes how

VR technology can simulate complex welding environments, providing users with interactive experiences that enhance learning without the need for physical materials, outlines a conceptual design of a virtual welding platform using 3DS Max as modeling software, offering a cost-effective and safe alternative to traditional training (Bharath et al., 2017). The VR system allows trainees to visualize weld puddles, bead deposition and cooling effects, making the simulation highly realistic. In virtual reality welding simulations, parameters such as arc length, position, work angle, travel angle and travel speed can be effectively evaluated and utilized as assessment tools to measure the performance of existing welders (Byrd et al., 2015). The study employed the VRTEX® 360 virtual reality welding simulator to assess the skills of both experienced welders and trained novices. While the simulator effectively evaluated overall welding performance, the results indicated that it was unable to distinguish between the skill levels of experienced welders and novice trainees. This suggests that while VR technology is a useful tool for performance evaluation, it may have limitations in differentiating between varying levels of expertise.

A study presented by Yang U, in 2010 proved that the development of a VR welding training system that incorporates 3D multimodal interaction, providing an immersive and interactive environment to simulate real welding conditions. The system offers real-time feedback through visual, auditory and haptic components, enhancing the practical training of welding techniques and improving trainee performance in a controlled, safe and cost-effective manner (Yang et al., 2010). Silva J in 2022 also verified that but by implementing Augmented Reality (AR) as an innovative approach to enhancing Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding processes by integration with cloud-based data analysis. AR tool that overlays real-time data during welding operations, allowing operators to visually compare their performance against optimal welding parameters (Silva et al., 2022). The system fosters more consistent welding outcomes by identifying errors in real-time and guiding the welder through corrective measures.

Research in 2023 conducted by Tran N. H. presents a VR-based simulation system designed to replicate three welding techniques: Shielded Metal Arc Welding (SMAW), Metal Inert Gas (MIG), and Tungsten Inert Gas (TIG). This system aims to enhance welding training by offering real-time feedback and interactive simulations, which allow trainees to gain hands-on experience without the risks associated with real welding. This study demonstrates the system's accuracy in replicating welding conditions, helping to improve training outcomes and minimize operational errors through immersive learning environments (Tran et al., 2023). This VR technology has shown promise in enhancing welding instruction, particularly by facilitating the development of VR-assisted welding courses. A study conducted with 34 first-year students from an electric welding practice course evaluated the effectiveness of integrating VR in experimental teaching. Most students reported a significantly positive impact on their learning experience, emphasizing the effectiveness of the VR-assisted course in improving their practical skills (Huang et al., 2020). Additionally, most participants expressed high levels of satisfaction with the VR-enhanced welding teaching, affirming its role in improving both learning outcomes and engagement. This aligns with similar findings in VR-based training, highlighting its potential in vocational education.

One of the benefits of VR in making welding training is more accessible to a wider audience, particularly in reducing material waste and improving safety by eliminating the risks associated with live welding practice (Ipsita et al., 2022). By integrating advanced modeling techniques, the VR simulators provide real-time feedback, which enhances skill acquisition and technical proficiency among trainees. A study done by Ipsita A in 2022 focuses on creating a VR-based system that allows users to practice welding in a realistic, yet safe and controlled environment, addressing issues related to cost, safety and scalability in traditional training methods. VR technology can also be used to simulate the complex and precise nature of pipe welding in a controlled, immersive environment (Postlethwaite et al., 2014). It has the capability to provide real-time feedback, which enhances the user's technical skills and reduces errors, also addresses key challenges in traditional training, such as material costs, safety concerns and limited access to expensive equipment. VR can serve as an effective complement to live welding training, offering benefits like increased accessibility and lower material costs for educational programs. VR technology significantly improved motor skills like workpiece preparation, welding process control and reading diagrams. However, it was noted that for certain skills such as weaving moldings (related to width and height), the VR simulators provided less accuracy compared to real-world welding (Wells et al., 2020). Therefore, while VR training helps develop foundational skills, it cannot fully replace the precision and experience gained through actual welding practices.

During the Covid-19 pandemic, VR proved effective in enhancing welding education, particularly when traditional hands-on training was limited or unavailable due to safety constraints (Prasetya et al., 2023). The methodology involved implementing VR-based learning modules that simulated welding processes, allowing students to engage in practical tasks virtually. Results showed that students demonstrated significant improvements in welding skills, with many reporting higher engagement and satisfaction with the VR learning experience. The VR system was effective in maintaining the continuity of technical education during the pandemic, providing an immersive and interactive alternative to traditional hands-on training.

2. Methodology

Technology, especially in interactive multimedia, advanced rapidly (Roedavan et al., 2022). The development methodology for the VR prototype application that simulated the flame cutting process used the Multimedia Development Life Cycle (MDLC) approach to ensure that each phase was systematically managed. MDLC was a structured approach for planning, developing and implementing information systems (Topan Bahari et al., 2023). It helped organize each phase systematically, ensuring that the final product met both quality standards and user requirements.

The MDLC consisted of six stages: concept, design, material collecting, assembly, testing and distribution (Sumaryana et al., 2020). The concept phase involved planning to define the project's direction; the design phase developed visual ideas and the development phase transformed these ideas into functional solutions, leading to the final implementation and evaluation. The development phase created a functional application and testing ensured

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product quality. During the implementation phase, users could try the application, while maintenance ensured that the application remained relevant and effective for long-term use. Figure 1 shows the implementation cycle of the project using the MDLC method.

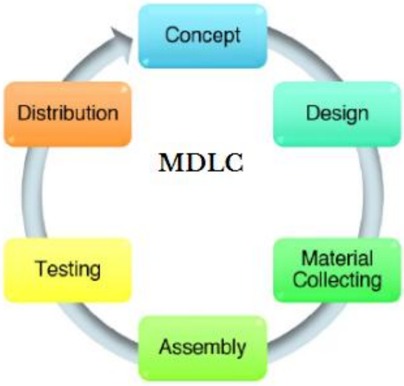

Figure 1: Multimedia Development Life Cycle (MDLC) (Samala et al., 2023).

2.1 Concept

The concept phase in developing the prototype simulation of the flame cutting process using a VR application was a crucial initial step. This phase focused on defining the overall direction and objectives of the project. It involved identifying user needs and analyzing the challenges faced by students and instructors in metal cutting processes. Early research was necessary to gather information on the latest VR technologies and existing educational applications.

A data-driven approach helped collect feedback from instructors and students, providing a clear picture of the features and functions required for the simulation. A literature review on flame cutting techniques and VR based training applications aided in identifying both the needs and potential benefits of the project.

Setting initial success criteria ensured that progress in subsequent development phases could be measured and evaluated effectively. Therefore, the concept phase was not just about planning but also about laying a solid foundation for all future stages in the MDLC. Clarity at this stage simplified the design and development processes, ensuring that the final product effectively met user needs.

2.2 Design

In the design phase, the structure and visual elements of the VR simulation application were carefully developed to ensure an interactive and user-friendly experience. The first step involved preparing a storyboard and flowchart to map the application's flow. This flow included several stages, such as the main menu, material selection, cutting process and final evaluation. Each part was designed to allow users to follow the process smoothly and understand the cutting steps clearly.

The design of the user interface (UI) was also a key focus. A user-friendly interface was created with easy navigation, a clear display of cutting parameters and access to instructions and guidance. Elements like menus, tool icons and interaction buttons were arranged systematically to enhance the user's experience within the virtual environment.

The multimedia elements included the selection of 3D models of the cutting torch and metal materials used in the simulation. These models were meticulously built using AutoCAD to replicate real equipment. Additionally, sound effects, such as the noise of metal cutting were incorporated to increase realism.

All these components were integrated into a virtual environment using Unity or Unreal Engine depending on the project's technical requirements and interactive features. Unity, also known as Unity 3D, was widely recognized and chosen for its robust support for VR development, enabling smooth interaction (Brookes et al., 2020). It also facilitated the integration of multimedia elements like graphics, audio and animation, providing a platform for intuitive interactive experiences. The design phase served as the essential foundation for the subsequent development process, ensuring that the VR application was not only functional but also engaging and easy to use.

2.3 Material Collecting

The material collection phase involved the creation of essential elements and the integration of multimedia components to develop a fully functional VR simulation application. In this project, 3D models of the cutting torch and metal materials were built using AutoCAD software. Media and material experts recommended that the Interactive 3D AutoCAD Multimedia met the "Very Good" criteria (Nurtanto et al., 2021) These models were carefully designed to closely resemble real equipment, providing users with a realistic visual experience. Figure 2 shows the gas cylinder and cutting torch modelled using AutoCAD software.

Figure 2: Gas cylinder and cutting torch model

2.4 Assembly

The interactive VR content was developed using Unity. This involved creating a virtual environment where users could interact directly with the equipment. C# programming within Unity was necessary to ensure functionalities such as moving the cutting torch, emitting cutting flames and controlling cutting speed worked smoothly. These interactive features were critical to delivering an immersive and responsive simulation experience.

The development phase also integrated multimedia elements like graphics, animations and audio. Sound effects, such as the cutting flame sound, were added to enhance

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realism. Animations were included to visually depict changes in the material during the cutting process, providing users with visual feedback that helped them understand the impact of their actions within the simulation.

All these elements were combined in the VR development environment to ensure the application ran smoothly. This process involved internal testing of each component to identify and correct any errors before moving to the next phase. At this stage, the primary goal was to ensure the application not only functioned effectively but also provided users with an engaging and meaningful learning experience. Figure 3 shows the example of development program for cutting simulator.

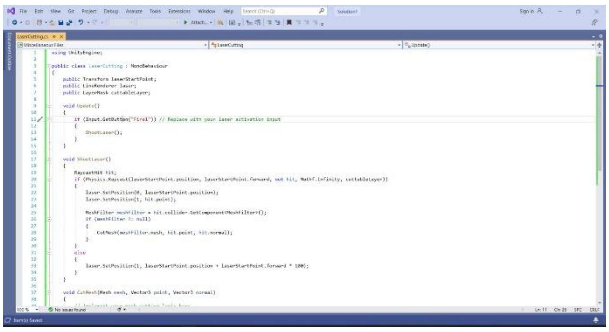

Figure 3: Example of development program.

2.5 Testing

The testing phase ensured that the VR simulation application functioned smoothly, was free of errors and met the predefined objectives. In this phase, functional testing was performed to verify that each feature of the application operated as intended. For instance, the movement controls of the cutting torch, material selection, flame ignition and cutting speed were thoroughly tested to ensure all components functioned seamlessly without interruptions.

Additionally, compatibility testing was conducted to ensure that the application ran efficiently across various VR devices, such as the Oculus Quest or other relevant platforms. This ensured users experienced a smooth simulation without technical issues, regardless of the device they used.

If any errors or issues were identified, a debugging and correction process was carried out before the application was finalized for launch. Comprehensive testing ensured the resulting application was stable, user-friendly and aligned with user needs. With rigorous testing, this project aimed to deliver an effective and high-quality simulation experience.

2.6 Distribution

The distribution phase involved launching the fully developed VR application to the target users for evaluation and initial use. At this stage, the application was installed and configured on VR headsets such as the Oculus Quest to ensure it was ready to use in practical sessions. This step ensured that all components and functions operated as intended in a real-world environment.

The process also included a formal demonstration at ILP Kuantan, where students could try the application firsthand. This session not only helped users familiarize themselves with VR technology but also allowed instructors to assess the application's effectiveness in enhancing understanding of the flame cutting process. To maximize the application’s benefits, user training was provided. Both students and instructors at ILP Kuantan were guided on how to correctly use the simulation, including selecting materials, setting the torch’s temperature and speed, and performing the cutting process virtually. This training ensured users could interact effectively with the application and understand each step of the simulation.

Through this implementation, early feedback was collected to identify any issues or shortcomings that required improvements. The launched application aimed to offer a realistic, safe and interactive learning experience, complementing or replacing existing physical training methods.

After the launch, continuous monitoring was conducted to identify any technical issues or bugs that arose during use. Any problems were promptly addressed through updates and fixes to ensure the application remained stable and functional. Additionally, feedback was gathered from users, including students and instructors, to evaluate their experience and satisfaction with the application.

3. Results and Discussion

The development of this simulation prototype underwent several critical phases, from design to implementation. This section discusses the outcomes of the development and testing processes, as well as the application’s effectiveness in achieving the defined objectives. The prototype was designed to support students’ learning process by enabling them to understand and master the technique of metal cutting using flames more effectively. Key features of the simulation include realistic visual representations, interactive controls for critical parameters such as cutting speed, and a user-friendly interface. Students can experience the cutting process in a virtual environment that replicates real-world conditions, eliminating the risk of injury or equipment damage. Figure 4 illustrates the successfully developed flame cutting simulator.

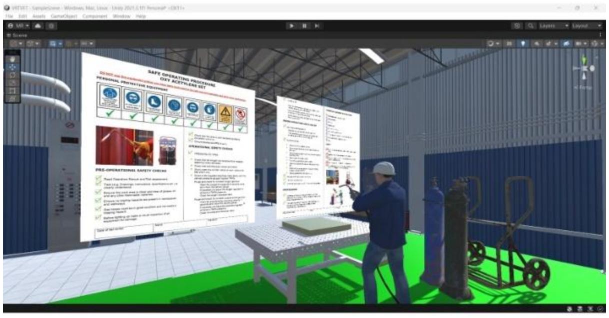

Figure 4: Front-end interface of flame cutting simulator

The developed prototype underwent a testing phase, during which all data and information gathered by the developers were analyzed. The testing conducted focused on the application’s functionality. The functionality testing process was performed on all hardware and software components to ensure that the application operates as expected and is well-documented. Developers began with a functional specification outlining the application’s features and limitations. Functionality testing was carried out by the mobile application developers after completing the application or before distributing it to users. Any errors detected during the testing phase were promptly resolved to ensure the application's functionality and usability were optimized. Table

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1 presents the results of the application functionality testing. All interface buttons and data within the application were tested to determine whether they met the expected outcomes as defined by the developers.

Table 1: The results of the functionality testing conducted on the application developed by the developers.

Testing	Expected result	Actual result
Functionality Testing for Home Page		
Start Application Button	Redirects to the learning module	Functions as expected
Exit Application Button	Allows users to exit the application	Functions as expected
Functionality Testing for Learning Module		
Reset Button	Resets users to the learning module	Functions as expected
User Movement	Users can move freely within the virtual environment	Functions as expected
Cutting Torch Movement	Torch can be moved according to user hand movements	Functions as expected
Cutting Flame Functionality	Flame activates when the cutting lever is pressed	Functions as expected
Metal Cutting Process	Metal is cut when cutting operations are performed	Functions as expected
Data Record	Cutting speed is recorded and analyzed during the operation	Functions as expected

After the application was fully developed, a user acceptance test was conducted involving 30 respondents. The respondents consisted of final semester trainees and Subject Matter Experts (SME) in the field of Structural Metal Fabrication Technology (Oil & Gas) at ILP Kuantan. This testing aimed to gather user feedback to ensure the application met the desired criteria. The System Usability Scale (SUS) was used to evaluate the application's usability. SUS calculates the percentage of user acceptance based on questions designed for respondents to answer.

The test was conducted through an online survey distributed via Google Forms. Table 2 lists the 10 questions respondents needed to answer regarding their feedback on the application's user acceptance. Subsequently, all responses were scored according to the formula provided. Users are required to evaluate each question provided based on a predetermined scale, where the guide for the scale is as follows: (1 - Poor, 2 - Fair, 3 - Satisfactory, 4 - Good, 5 - Excellent). Figure 5 presents the results of the target users' feedback on the developed application.

Table 2: List of user acceptance feedback questions.

No	Questions
S1	The application interface design is easy to understand and aligns with the theme
S2	All buttons and interaction styles in the application function properly
S3	The movement of the cutting torch is easy to control
S4	The application provides training in a safe and controlled environment
S5	The application helps increase user confidence before performing actual cutting operations
S6	The application engages users and encourages them to repeat the metal cutting process multiple times
S7	The application is easy to use
S8	The scores displayed help users improve their metal cutting skills
S9	The use of the application enhances the user's understanding of the cutting process
S10	The use of the application can reduce the cost of practical metal cutting training

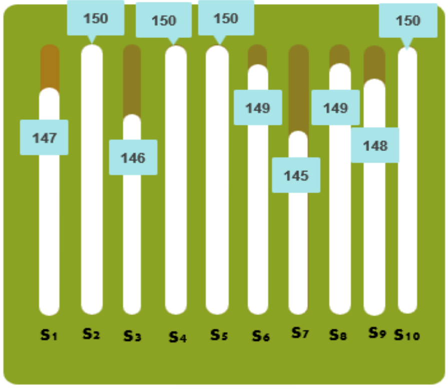

Figure 5: The results respondent scores (User Acceptance Testing)

Based on the SUS score scale shown in Figure 5, the proposed SUS score for the application is 98.93%, which indicates a very good and acceptable level of user satisfaction.

4. Conclusion and Recommendation

The results from the development and testing indicate that this VR simulation application successfully meets the project objectives by effectively replicating the real-world flame cutting process in a controlled virtual environment. The simulation not only provides users with a highly immersive and interactive practical training experience in a safe and risk-free setting but also plays a crucial role in minimizing training costs and eliminating potential hazards associated with actual hands-on training. By integrating VR technology, students can practice repeatedly without worrying about the limitations of training materials, equipment wear and tear or safety concerns. Additionally, the ability to receive real-time feedback on key cutting parameters, such as speed, nozzle distance and cutting angle, enhances the learning process by allowing trainees to refine their skills systematically. This ensures that students develop a strong understanding of the techniques and achieve a high level of competency before engaging in real-world cutting operations, ultimately improving overall training efficiency and effectiveness.

However, there are several technical challenges that need to be addressed for future improvements. For instance, further adjustments are required to support more VR devices and improve performance on lower-specification devices. Additionally, the incorporation of advanced features, such as training on gas types and other technical parameters, could make the application more comprehensive.

This application also demonstrates great potential in helping instructors monitor student performance more easily through automatic assessments in the simulation. By incorporating analytics data, instructors can evaluate student progress based on the time taken to complete the cutting task and the quality of the cut results.

Acknowledgement

The authors gratefully acknowledge to Centre for Instructor and Advanced Skill Training (CIAST) and Universiti Sultan Zainal Abidin, Kampus Gong Badak for the financial support and infrastructure.

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