Virtual Reality
https://doi.org/10.1007/s10055-022-00626-6

ORIGINAL ARTICLE

An interactive extended reality-based tutorial system for fundamental manual metal arc welding training

Kalpana Shankhwar[1] · Shana Smith[1]

Received: 3 May 2021 / Accepted: 7 January 2022

Abstract
Extended reality (XR) technology has been proven an effective human–computer interaction tool to increase the perception of presence. The purpose of this study is to develop an interactive XR-based welding tutorial system to enhance the learning and hands-on skills of novice welders. This study is comprised of two parts: (1) fundamental manual metal arc welding (MMAW) science and technology tutoring in a virtual reality (VR)-based environment, and (2) hands-on welding training in a mixed reality (MR)-based environment. Using the developed tutorial system, complicated welding process and the effects of welding process parameters on weld bead geometry can be clearly observed and comprehended by using a 3D interactive user interface. Visual aids and quantitative guidance are displayed in real time to guide novice welders through the correct welding procedure and help them to maintain a proper welding position. A user study was conducted to evaluate the learnability, workload, and usability of the system. Results show that users obtained significantly better performance by using the XR-based welding tutorial system, compared to those who were trained using the conventional classroom training method.

Keywords Extended reality · Virtual reality · Mixed reality · Manual metal arc welding · Visual aids · Quantitative guidance

1 Introduction

Welding is a dangerous manufacturing process that involves high temperature and harmful ultraviolet radiation. Welding process involves various complex welding parameters (i.e., welding current, arc length, travel speed, electrode diameter, and electrode orientation) and requires high-level hands-on skills. Therefore, it is difficult to describe or understand some welding processes using the conventional classroom teaching methods. In addition, during welding training, sample disposal often causes material and energy waste. Therefore, it is necessary to find an efficient and cost-effective way to teach students about professional welding skills.

With the rapid growth of information technology, extended reality (XR) has gained a growing amount of attention in the past two decades due to its innovative human–computer interaction technique. For example, Kuo et al. (2021) used XR technology to control a remote mobile manipulator, and Matsas et al. (2018) and Hietanen et al. (2020) used XR technology to facilitate human–robot collaboration. XR is an umbrella term which refers to different reality technologies, e.g., virtual reality (VR), augmented reality (AR) and mixed reality (MR) (Doolani et al. 2020). There are many different versions of definitions for VR, AR, and MR. The Merriam-Webster dictionary defines VR as “an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment”, and defines AR as “an enhanced version of reality created by the use of technology to overlay digital information on an image of something being viewed through a device (such as a smartphone camera)”. MR is similar to AR, which also combines digital information and the real world. However, in MR, physical objects and virtual objects can interact with each other, and users can interact with and manipulate the physical and virtual objects (Doolani et al. 2020).

XR technologies have the capacity to be employed in different types of domains by facilitating immersion, presence, and interaction to enhance users' perception and performance (Kaplan et al. 2021; Pomerantz 2019). XR

✉ Shana Smith
ssmith@ntu.edu.tw

[1] Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

technologies are capable of providing safe, engaging, and effective training with reduced risk of any significant harm (Doolani et al. 2020). For example, Heirman et al. (2020) used an XR simulator to assist the Navy's firefighting training program to alleviate the issues related to danger, costs, and environmental pollution in the conventional training.

Therefore, by taking the advantages of XR technologies, it is possible to teach dangerous welding process and complex welding parameters in a harmless and intuitive way. The purpose of this study is to develop an interactive XR-based welding tutorial system to equip novice welders with basic welding knowledge and hands-on skills, in a safe and economic environment. The following of the paper is structured as follows. Section 2 provides related work. Section 3 gives an overview of the software and hardware used in the study. Section 4 introduces the VR module for fundamental welding science and technology tutoring. Section 5 describes the design and implementation of the MR module for hands-on welding training. Section 6 describes the user test. Section 7 gives the user test results. Section 8 provides a discussion. Finally, Sect. 9 offers conclusions and future work.

2 Related work

2.1 XR in education

Traditional classroom instruction is difficult for students to learn and understand critical and complex knowledge due to the lack of 3D visualization of the topics (Tang et al. 2020). Prior research has proven that the 3D visualization and immersive perception of AR could enhance teaching and learning (Wu et al. 2013). The application of AR allows learners to visualize complex spatial relationships and experience the hands-on practices of real world (Arvanitis et al. 2009). Milovanovic et al. (2017) surveyed the applications of VR and AR in architectural education, showing the multiplicity of possible uses such as immersive design, on-site simulations, and remote collaboration. Huang et al. (2018) reviewed the applications of VR and AR in dentistry. They indicated that VR and AR could help students to learn by themselves and reduce instructors' load, compared to the traditional preclinical teaching methods. Cardoso et al. (2019) presented a design-based approach using VR and AR to support the teaching and learning of technical drawing. Macariu et al. (2020) applied AR in chemistry education. The evaluation results showed that both professors and students appreciated the "overall look and feel experience" provided by the AR learning tool.

Some extensive reviews of the state-of-the-art of XR applications in K-12 and higher education have also been carried out. For example, Loureiro et al. (2020) reviewed the usage of VR and gamification in higher education. Students were found to be more focused on the tasks that were demonstrated and learned in an immersive environment. Di Natale et al. (2020) surveyed the applications of immersive VR (IVR) on K-12 and higher education. They revealed that the performance of the IVR group outperformed significantly over the control group. Maas and Hughes (2020) reviewed the use of VR, AR, and MR technologies in K-12 education. The study found that students became more competitive with their peers when using AR simulations. Middle school students also reported positive attitude towards learning by using MR systems.

2.2 XR in manufacturing

XR technologies have also been applied to workshop to enhance learners' hands-on skills in manufacturing. For example, Gonzalez-Franco et al. (2017) presented an MR setup for assisting a manufacturing procedure of an aircraft maintenance door. A knowledge retention test was conducted to evaluate the effectiveness of the training. The study indicated that the MR setup produced as effective results as the conventional face-to-face training. Matsas et al. (2018) demonstrated how VR could be used for a safe human–robot collaboration in assembly, cleaning, welding and punching. Roldán et al. (2019) presented a VR training system for industrial operators in an assembly task of building blocks. A user study revealed significant better results of the VR training system, compared to the conventional method. Hietanen et al. (2020) used an interactive AR user interface to facilitate human–robot collaboration. The AR-based systems were found superior in performance, compared to a baseline without AR interaction.

2.3 XR in welding training

XR-based welding simulators have also been drawn a lot of attention recently (Lavrentieva et al. 2019). Mavrikios et al. (2006) developed a VR-based prototype demonstrator for manual welding. Since everything was virtual in the prototype demonstrator, users lacked the realistic sensation of holding a welding gun. In addition, no user study was conducted to prove the functionality and usability of the system. Byrd et al. (2015) used a commercial VR welding simulator, VRTEX 360, to assess existing skill levels in welders. The results showed that although the VR simulator could evaluate welding skills, it could not accurately identify an individual as an experienced welder or a novice welder. Okimoto et al. (2015) used a commercial AR-based welding training tool, called Soldamatic, to conduct a user study in welding education. However, difficulties were reported in visual accommodation. In addition, no comparative study was carried out between the AR-based training system and conventional ones. Feier and Banciu (2021) conducted an ergonomics comparison between the real torches and Soldamatic torches. It was found that the weight of the Soldamatic torches was much lighter than the real ones. No educational or training aspect was mentioned in this study. In addition, Lavrentieva et al. (2019) mentioned that most commercial welding simulators were too costly.

Although prior studies have demonstrated the benefits and challenges of using XR technologies in welding training, most welding simulators are meant for assessing existing welding skills. They do not provide real-time visual aids or quantitative guidance to guide novice welders step by step through the correct welding procedure or help them to maintain a proper welding position. Therefore, they lack fundamental educational instructions for novice welders. Real-time simulation of the effects of welding process parameters on welding bead geometry is also lacking. In addition, most simulators still need an experienced welder to help novice welders to perform a quality welding simulation. For some marker-based AR welding simulators, users have to be very close to the weld plates to obtain correct tracking in the AR environment, which is contrary to the real-world practices.

Prior research has shown that 3D representation with stereoscopic visions of the topics and the simulation of the process can tremendously enhance learning and hands-on practices (Andrews et al. 2019). Learning with hands-on practices can be an efficient way to retain knowledge. The purpose of this study is to develop a realistic XR-based welding tutorial system to help novice welders to equip fundamental manual metal arc welding (MMAW) knowledge and hands-on skills in an immersive environment. The fundamentals of the welding process, including the basic terminologies and applications of various welding equipment, are elaborated using VR. In addition, the effects of welding process parameters on weld bead geometry are delivered with hands-on practices using MR. Visual aids and quantitative guidance are displayed in real time to guide novice welders through the correct welding procedure and help them to maintain a proper welding position.

3 System overview

The flowchart of the training process is shown in Fig. 1. The XR-based welding tutorial system consists of a VR module and an MR module. The purpose of the VR module is to deliver the fundamentals of welding science and technology, which is more visual related. However, the purpose of the MR module is to provide realistic welding exercises, which is more hands-on practice related.

The tutorial begins from the VR module, in which the fundamental knowledge about MMAW is presented using 3D models along with audio output for the elaboration of the contents. The contents include welding classification, applications of arc welding, MMAW, welding puddle and shielding gas, solidified metal, types of joint geometry, types of welds, nomenclature of welds, power source, welding arc, arc length, electrode angle, weld bead geometry, and types of process parameters and their effects on weld bead geometry. After receiving basic MMAW training, users can choose any welding process parameter in the VR room and enter into the MR room to acquire hands-on welding experiences and observe the effects of the chosen parameter on weld bead geometry in real time.

The MR module consists of a real electrode holder, real welding electrodes, and real welding joints, for users to conduct hands-on welding tasks. In the MR room, users first choose a joint geometry (i.e. butt, tee, corner or lap joint) and then pick an electrode. Then, users set the value of the chosen parameter to the minimum and perform the welding. Users can increase the parameter value and observe the changes in bead geometry. The same hands-on practice is repeated until all welding process parameters are tested. In order to replicate the real welding environment, the visual effects of the MMAW process, including weld bead, sparkling particles, electrode and workpiece, are displayed in the MR environment.

The system architecture of the XR system is shown in Fig. 2. HTC Vive Pro is used to display the VR and MR scenes. The HTC Vive Pro headset includes a head-mounted display (HMD), one handheld controller, one Vive tracker, and two lighthouses. The Vive tracker is used to track the electrode, which has a distance sensor attached to it. The distance sensor readings are handled by the Arduino integrated development environment (IDE). The handheld controller is used to interact with the graphical user interface (UI). Users can press the trigger button on the handheld controller to click a virtual button or drag a virtual slider.

The VR and MR modules are developed using the C# programming language on the Unity3D game engine and ran on a 3.00 GHz Intel Core i7-9700F processor, 64 GB RAM and 6.0 GB dedicated GPU memory. The VR module includes three sub-modules: VR rendering, UI, and fundamentals of welding. The VR rendering module displays the virtual contents to the users in the VR scene with the help of Vive Input Utility (VIU). The UI module provides text and image instructions to the users and allows them to interact with the UI elements in the VR scene with the help of the handheld controller. The module of fundamentals of welding provides the basic fundamental MMAW science and technology in the VR room.

The MR module includes four sub-modules: MR rendering, interaction, UI, and welding simulation. The MR rendering module integrates the virtual objects with the real world scene with the help of SRWorks software development toolkit (SDK) and VIU. The interaction module provides an access for the users to interact with virtual objects in the MR scene. The

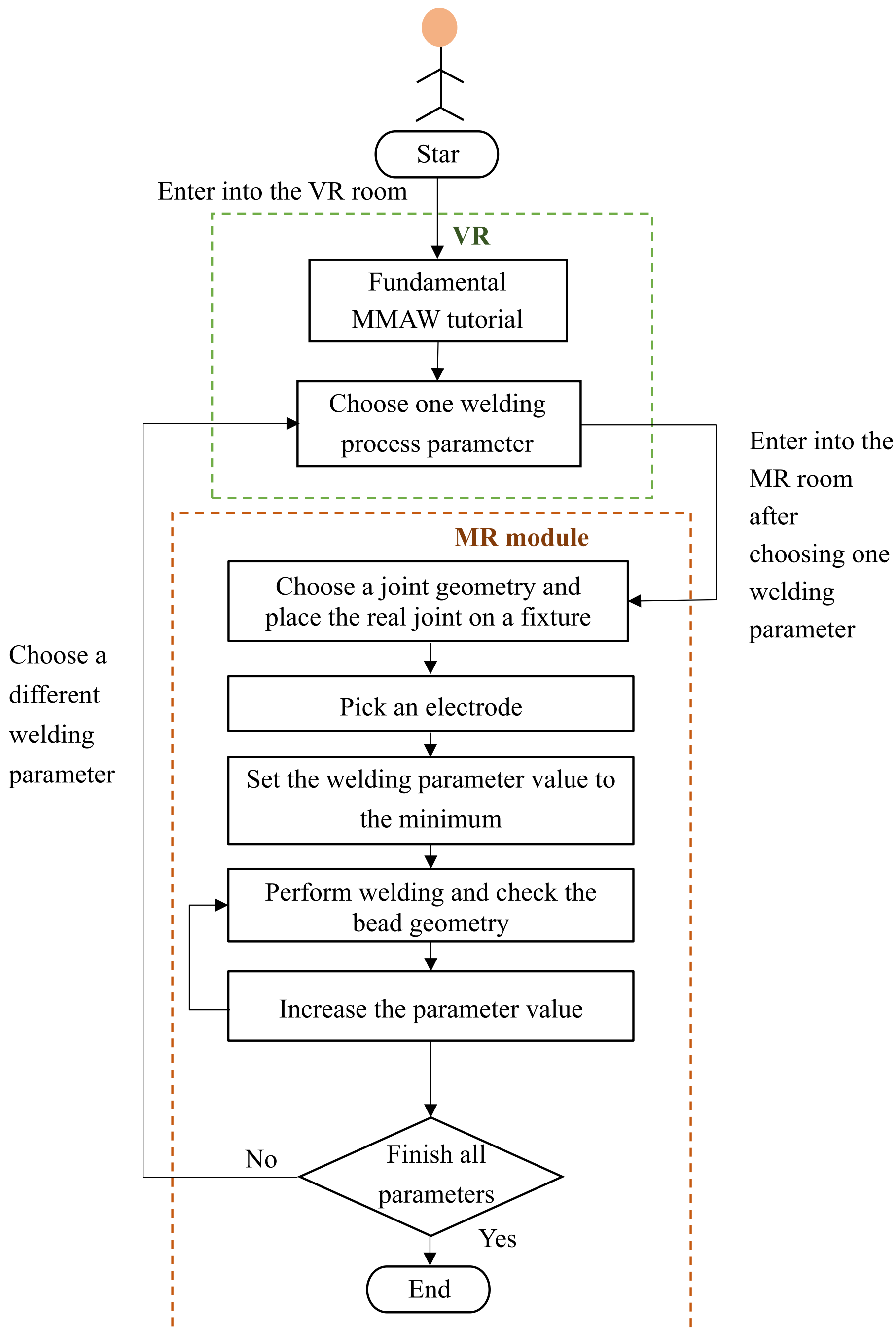


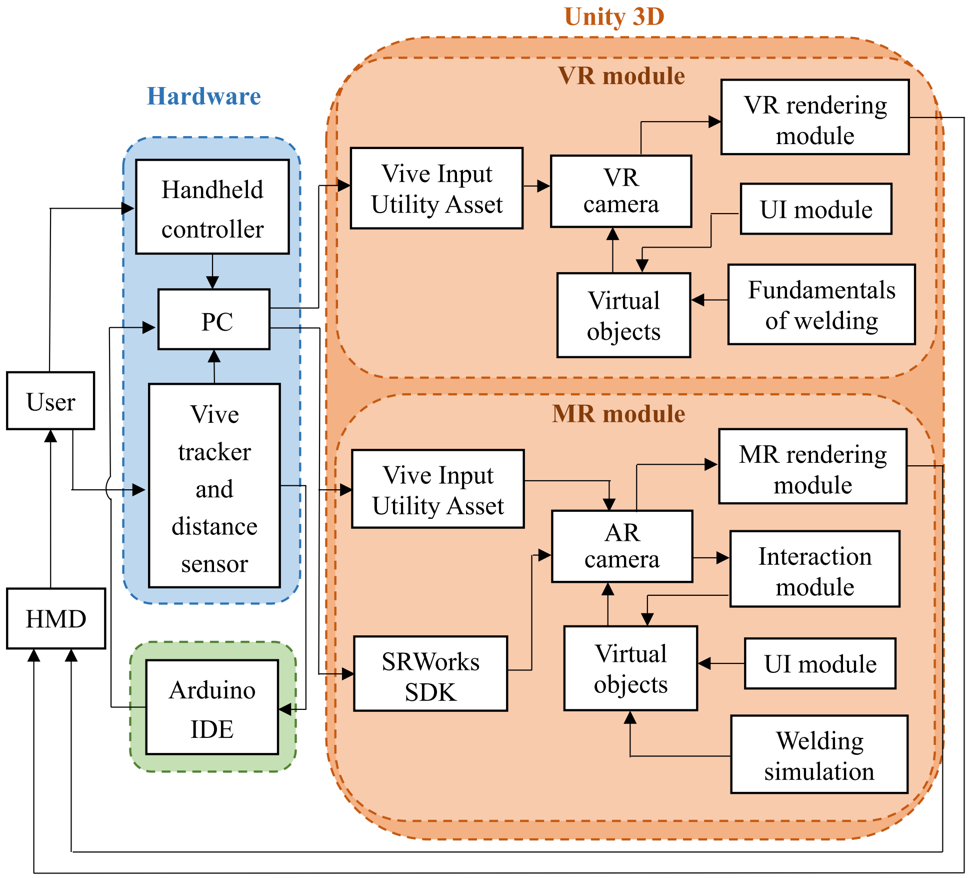
Fig. 1 Flowchart of the MMAW training process

UI module provides text and image instructions to the users and allows them to interact with the UI elements in the MR scene with the help of the handheld controller. The welding simulation module provides hands-on welding practice in the MR room.

4 VR module

The VR welding tutorial starts from an immersive virtual room with instructions to guide the users to follow the

Fig. 2 System architecture



steps. Figure 3a shows a user's first-person view from the HTC Vive Pro HMD in the beginning of the welding tutorial. Figure 3b shows the third-person view of the training. Figure 3c shows the content of the tutorial, from which users can select different MMAW topics using an interactive 3D UI. Figure 3d is an example of using 3D virtual representations to demonstrate the nomenclatures of butt weld and fillet weld.

Figure 3e shows the interface to choose a welding process parameter. When users press the trigger button on the handheld controller, a cyan light beam will be emitting from the handheld controller for users to interact with the UI elements. The explanations for each chosen process parameter will be presented. After that, in order to practically visualize the effects of each process parameter on weld beads, users can click the MR scene button, as shown in Fig. 3f, and enter into the MR room to conduct a hands-on welding practice. Users can observe the effects of welding process parameter on weld bead geometry in real time by interactively changing the value of the parameter.

5 MR module

The MR module aims to provide interactive experience and hands-on practice about the complex effects of welding process parameters on weld bead geometry. SRWorks SDK provides an access to the front facing camera of the HTC Vive Pro HMD to overlay the virtual objects on the real scene. Figure 4 shows an example of a virtual weld joint being augmented on a real weld joint, being viewed from the HTC Vive Pro HMD. Visual aids and quantitative guidance are augmented in the MR scene to guide novice welders to follow a correct welding procedure.

5.1 Welding process parameters

There are various welding parameters such as arc voltage, welding current, travel speed, electrode orientation and

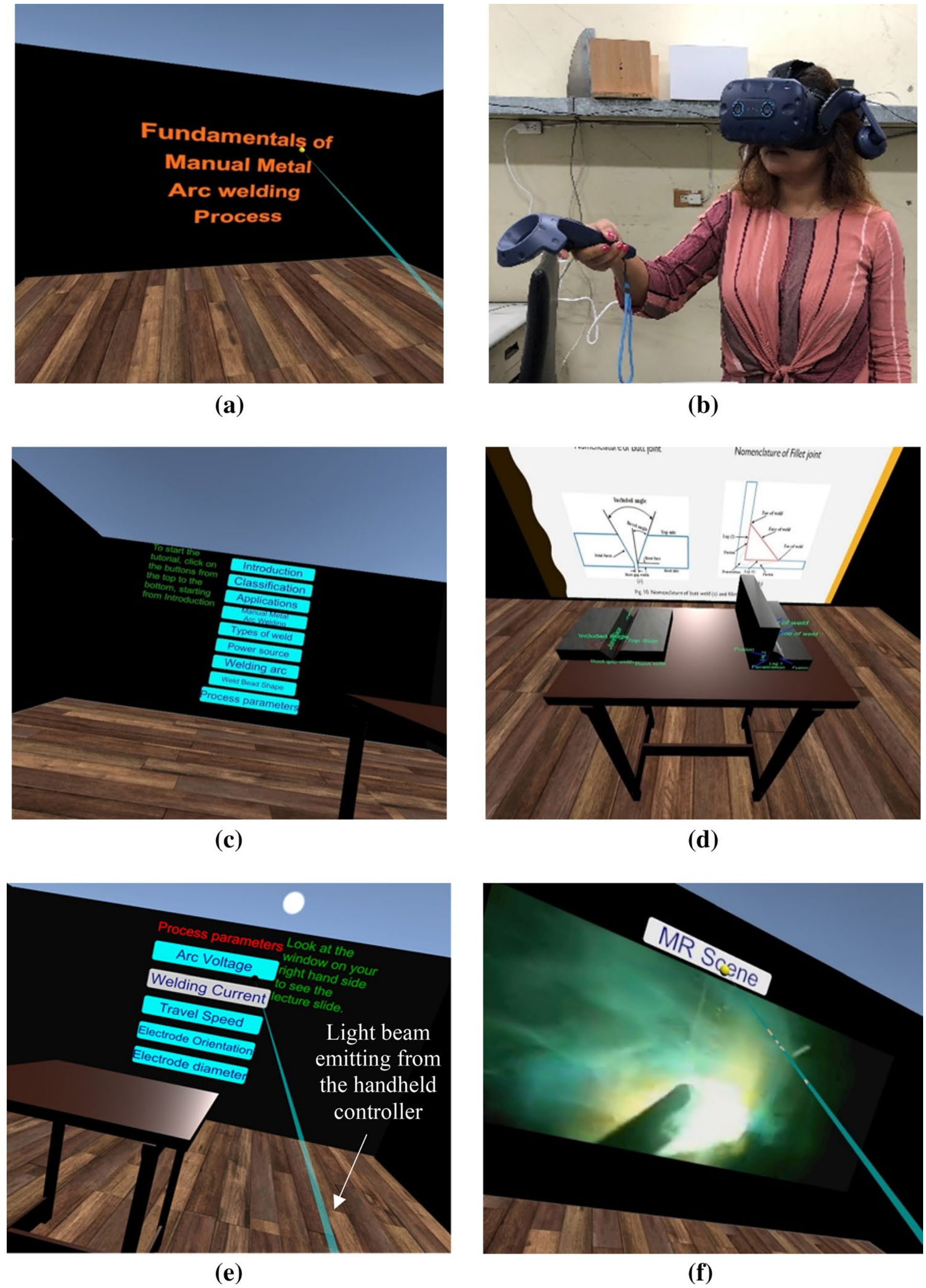


Fig. 3 Fundamental welding science and technology tutorial in the VR room

electrode diameter. Based on the prior research, in this study, the range of the welding current is set between 90 and 210 A, arc voltage is set between 27 and 45 V, travel speed is set between 0.38 m/min and 1.5 m/min and electrode diameter is set between 3.2 mm and 5.5 mm (Ahmed et al. 2018; Clark 1985; Karadeniz et al. 2007; Lenin et al. 2010; Nagesh and Datta 2002; Saha and Mondal 2017; Tewari et al. 2010). Three types of electrode orientations are considered: pulling, perpendicular and pushing, as shown in Fig. 5.

Usually, the weld bead geometry is specified by bead width, reinforcement and depth of penetration, as shown in Fig. 6. Five welding process parameters, welding current, arc voltage, travel speed, electrode diameter and electrode orientation, are considered in the MR welding training. It is necessary to study the effects of these parameters on the weld bead geometry to obtain good quality of weld (Omajene et al. 2014). Since the effects of the reinforcement are the same as the depth of penetration, the simulation is focused on the depth of penetration and the width of beads.

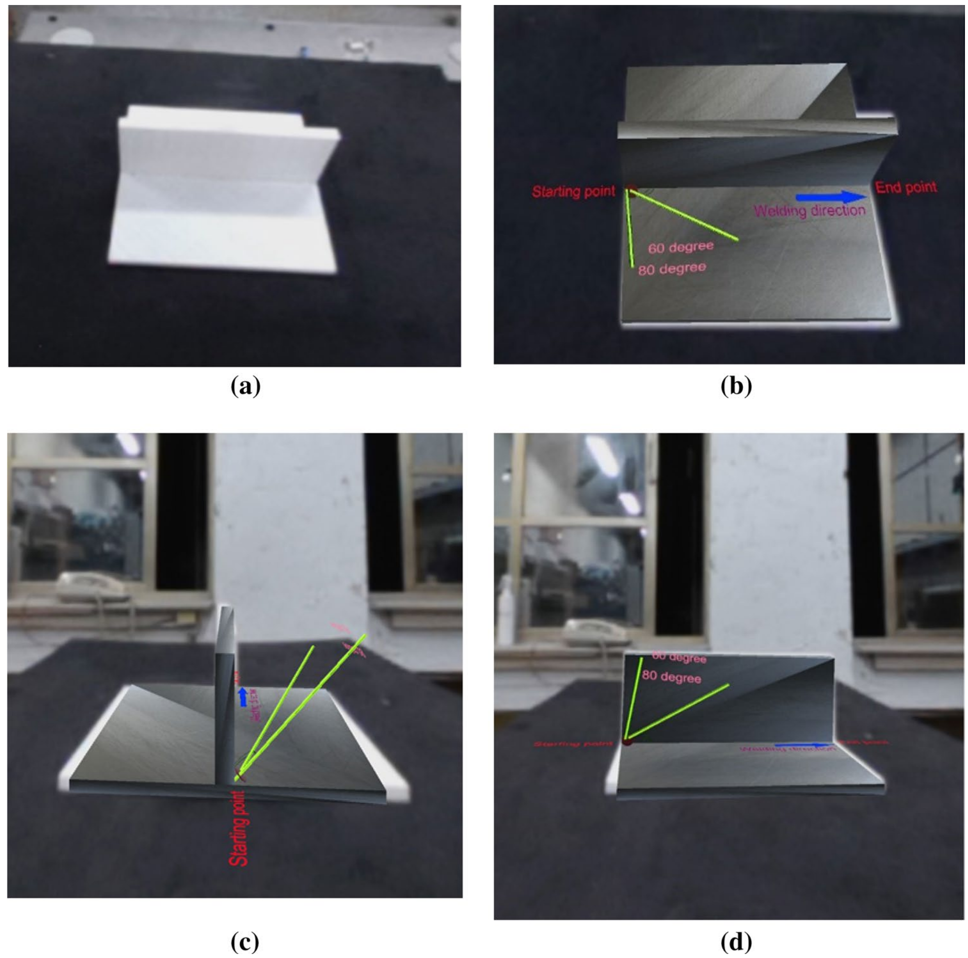


Fig. 4 MR scene being viewed from the Vive Pro HMD. **a** a real tee joint, **b** virtual tee joint augmented on the real tee joint, **c** side view of the augmented tee joint and (**d**) front view of the augmented tee joint

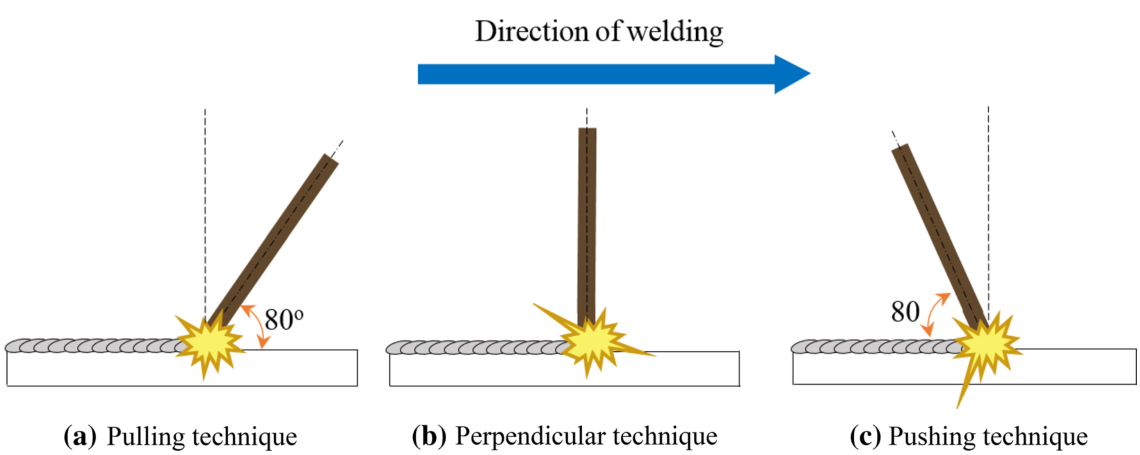


Fig. 5 Electrode orientations

In this study, four different physical welding joints, butt joint, tee joint, corner joint, and lap joint, are created using a 3D printer for the hands-on practice in the MR environment, as shown in Fig. 7.

In order to realistically simulate a weld bead geometry, the physics relationship between the welding process parameters and the weld bead geometry needs to be considered. The amount of molten metal, deposition rate and depth of

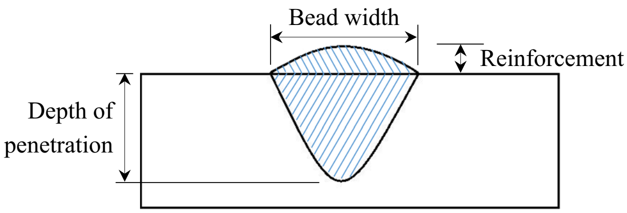


Fig. 6 Geometry of weld bead

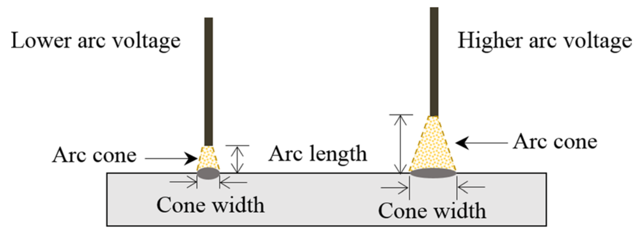


Fig. 8 Effect of arc length on the weld bead width

penetration are proportional to the heat input rate when the arc voltage keeps constant. Heat input rate is a relative measure of energy transfer per unit length of the weld plates (Boob and Gattani 2013). The relationship between the heat input rate and the welding process parameters is as follows.

$$\text{Heat input rate } Q = \frac{IV \times 60}{v} \text{ J/mm} \tag{1}$$

where V is the arc voltage in volts, I is the welding current in ampere, v is the welding speed in m/sec. Therefore, if the current increases by keeping the arc voltage constant, the penetration depth will increase, but the bead width will increase only a little.

The arc voltage is a voltage drop at the arc, which is directly proportional to the arc length (distance between the weld plates and the tip of the electrode). The relationship of the arc voltage and the welding process parameters can be described as follows.

$$\text{Arc voltage } V = \text{IR} \tag{2}$$

where arc resistance $R = \frac{\rho l}{A}$, ρ = resistivity; l = arc length; A = arc cone cross-sectional area. If the arc length increases by keeping the welding current constant, the arc cone cross-sectional area will increase, which causes wider bead width, as shown in Fig. 8, but the penetration will reduce a little.

When the electrode moves, the heat source also moves. If the moving speed reduces, the heat dissipation rate will increase, which leads to a deeper penetration and larger bead width (Omajene et al. 2014). When the electrode diameter increases, the current density will decrease,

Fig. 7 Welding joints used in the MR room

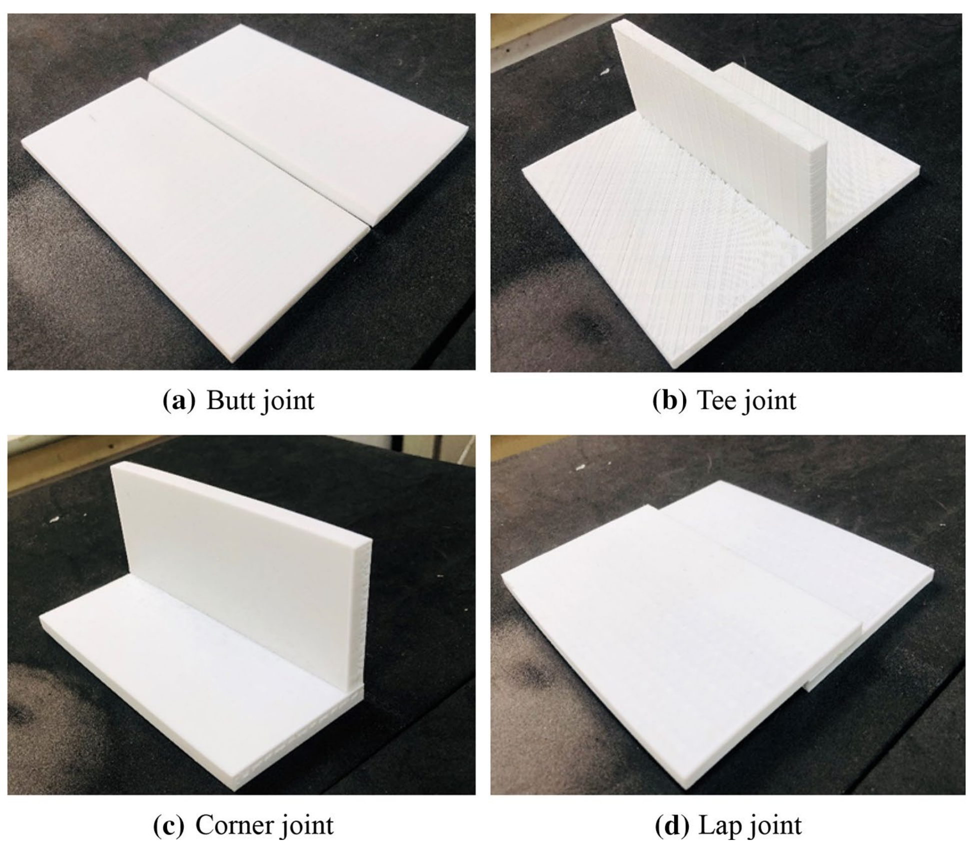
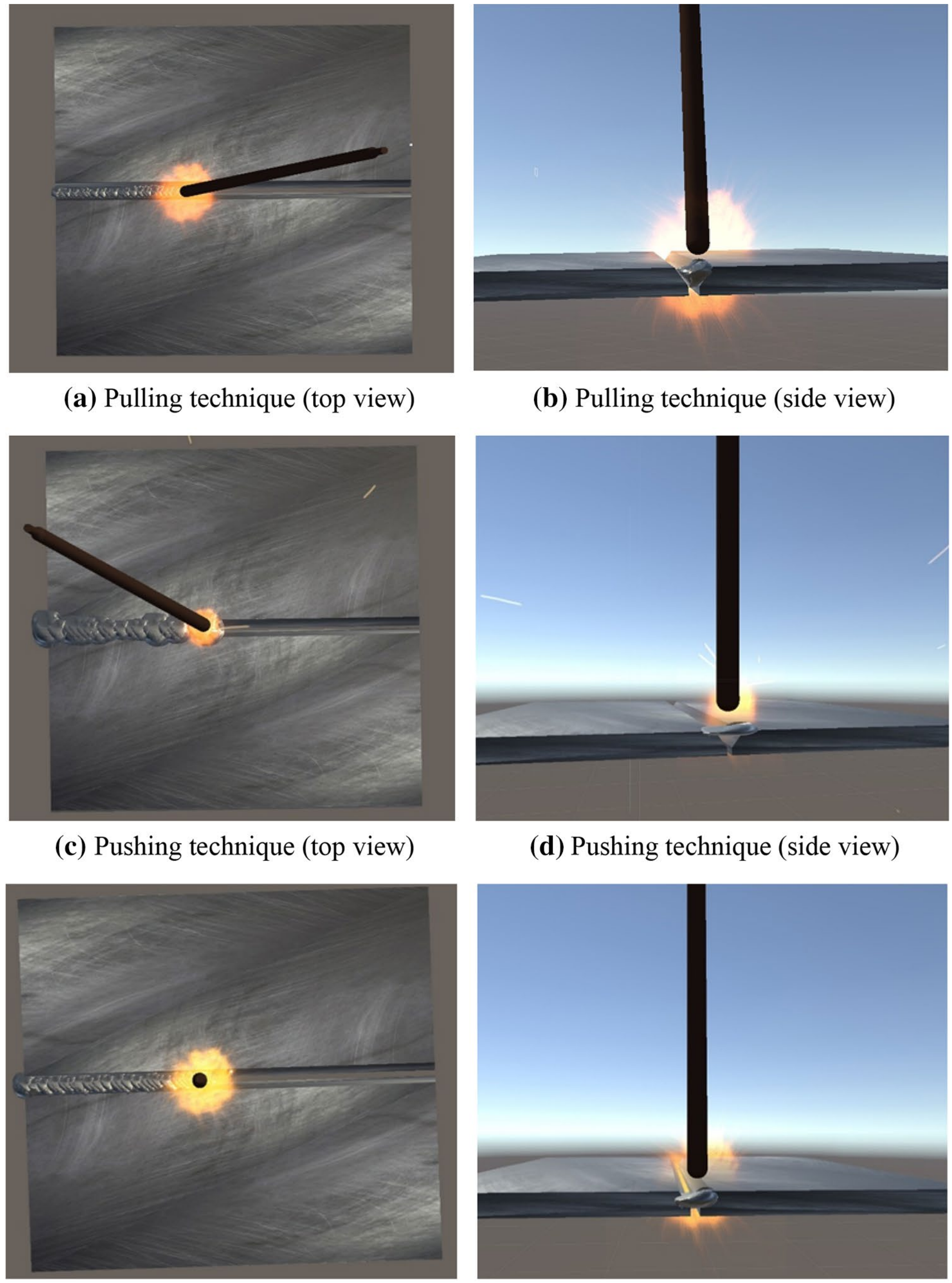


Fig. 9 **a** and **b** Pulling technique causes deeper penetration but narrower bead width; **c** and **d** Pushing technique causes smaller penetration but wider bead width; **e** and **f** Perpendicular technique causes moderate penetration and moderate bead width



(a) Pulling technique (top view) **(b)** Pulling technique (side view)

(c) Pushing technique (top view) **(d)** Pushing technique (side view)

(e) Perpendicular technique (top view) **(f)** Perpendicular technique (side view)

which reduces the penetration but increases the bead width, and vice versa.

In addition, electrode orientations also affect the width of the bead and the depth of penetration. When the electrode is dragged in the direction of welding, the penetration is deeper, but the bead width is narrower, as shown in Fig. 9a and b. It is because the pulling technique will cause more heat flow along the thickness of the weld plates but less heat at the top surface of the weld plates, which results in deeper penetration but narrower bead width. On the other hand, if the electrode is pushed in the direction of welding, the penetration is smaller, but the bead width is wider, as shown in Fig. 9c and d. The perpendicular orientation of the electrode provides moderate penetration depth and bead width, as shown in Fig. 9e and f (Eyres and Bruce 2012; Mandal 2001, 2009; Taggart et al. 1980).

5.2 Tracking

There are two tracking devices, one is the HTC Vive tracker for tracking the electrode, and the other one is the handheld controller for interacting with the UI elements. The HTC

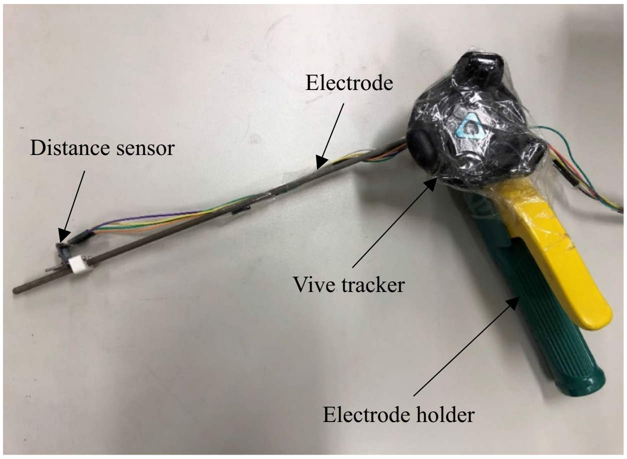


Fig. 10 Electrode with distance sensor

Vive tracker is attached to the electrode holder to track the electrode position, as shown in Fig. 10. In the real world, the MMAW process begins when the electrical arc of the desired length (2 mm to 8 mm) is established between the electrode tip and the weld plates. To simulate this process, a proximity sensor, VL6180X, is mounted at the tip of the electrode to measure the distance between the electrode tip and the weld plates. Based on the measured distance, virtual weld beads and sparkling particles will be simulated in the MR environment.

VIU is used to deal with the tracking of the handheld controller. Similar to the VR module, when users press the trigger button on the handheld controller, a cyan light beam will be emitting from the handheld controller for users to interact with the UI elements, as shown in Fig. 11a.

5.3 User interface

The usability principles suggested by Regazzoni et al. (2018) and the ergonomics guidelines suggested by Ejaz et al. (2019) are considered in the UI design. In this study, users are free to move around and interact with the virtual and real objects in a space of 1.4 m × 1.4 m.

Figure 11a shows a translucent text screen augmented in the real scene with welding process parameters and required welding instructions displayed. A fixture is used to place the 3D printed plates (Fig. 11b). Next, a virtual welding joint is overlaid on the plates (Fig. 11c). Users can set the welding speed by dragging the travel speed slider UI using the handheld controller. A red dot starts moving with the specified speed to guide users to perform the welding. Visual aids and quantitative guidance, such as speed guidance, welding direction, electrode angle range, and arc length, are displayed in the MR scene to help novice welders to perform a quality welding. Users have to maintain the arc length in the desired range by holding the electrode holder in the right hand. Figure 11d shows a user's first-person view from the HTC Vive Pro HMD while performing welding. Figure 11e shows a third-person view of the training environment. When users set the travel speed to the minimum value, wider and deeper weld beads are observed (Fig. 11f and g). When the travel speed is set to the maximum, narrower and smaller penetration are observed (Fig. 11h and i).

Users can use the similar way to vary the current parameter by dragging the current slider UI. The arc length can be changed by changing the distance between the electrode tip and the workpiece. The electrode can be chosen from three different diameters by clicking the electrode button UI.

6 User test

A user test was conducted to evaluate the XR-based welding tutorial system in terms of learnability, workload, and usability. Two groups of participants were recruited. The experimental group was trained using the XR-based method and the control group was trained using the conventional classroom method with the power point presentation. The training performance was evaluated using a written test (for learnability evaluation), the NASA task load index (NASA-TLX) (for workload assessment), the system usability scale (SUS) (for usability evaluation), and a subjective questionnaire (for general user experience assessment).

For determining an effective sample size (the number of participants) for the experiment to compare their performance, the G*Power tool was used. The sample size of the two groups was calculated with independent mean by considering one tail test. The effect size d was obtain from the following formula (Cohen 1988):

$$d = \frac{|M_1 - M_2|}{\sigma} \tag{3}$$

where M_1 is the expected mean score of the written test of the experimental group, M_2 is the expected mean score of the written test of the control group, and σ is the standard deviation of the population. The effect size d obtained from Eq. (3) is 1 by assuming the mean percentage score of 60 for the control group and 70 for the XR group with standard deviation of 10. The statistical power P is usually in the range of 0.8 to 0.95 (Cohen 1988). Here, $P = 0.8$, Type I error $\alpha = 0.05$ and sample size ratio $N_2/N_1 = 1$ are used. The obtained sample size is $N_1 = N_2 = 15$. Therefore, thirty college students were recruited randomly from different engineering and science backgrounds, except mechanical engineering. The people with the mechanical engineering background were not considered because their previous knowledge about welding might affect the results of the user

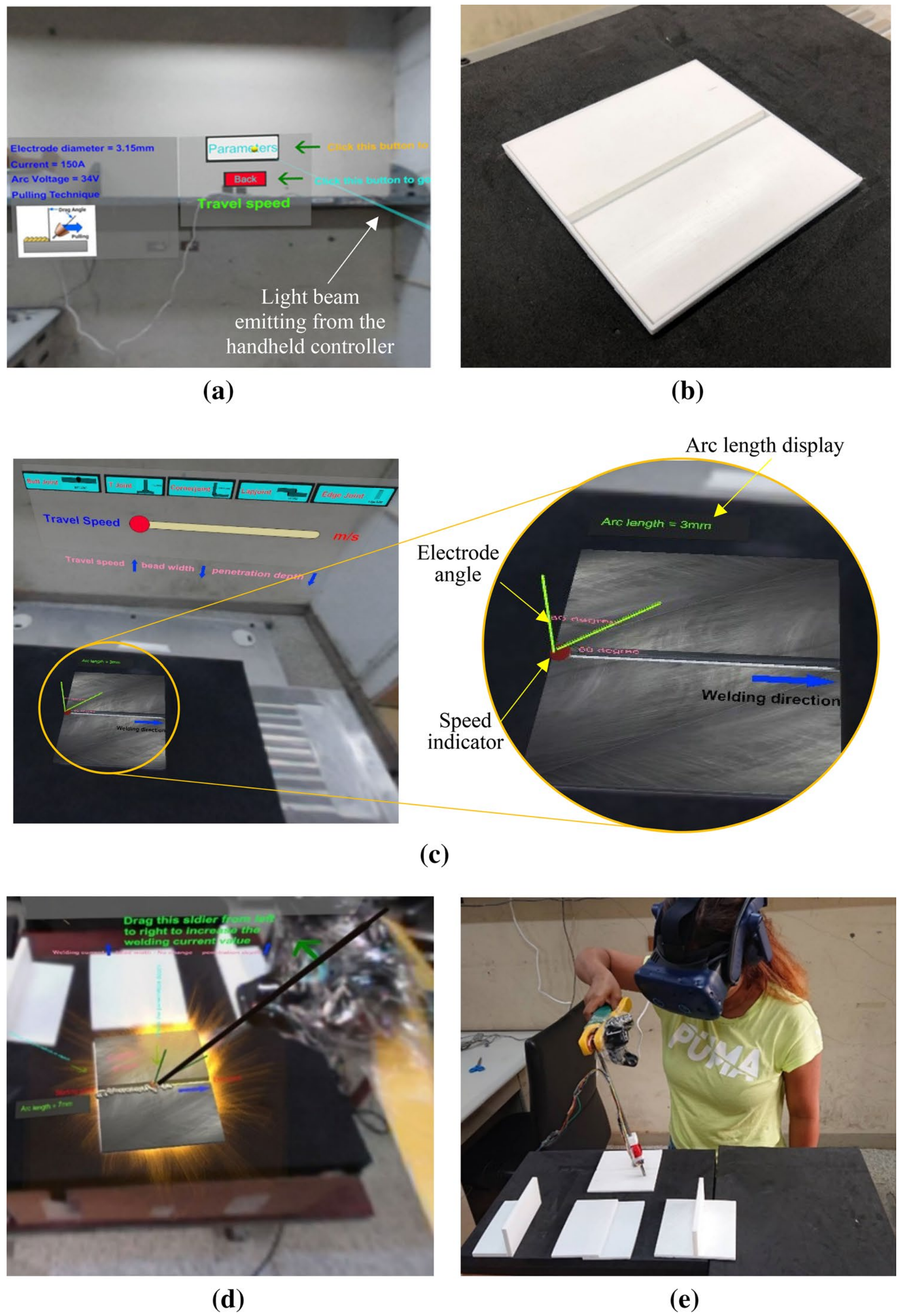
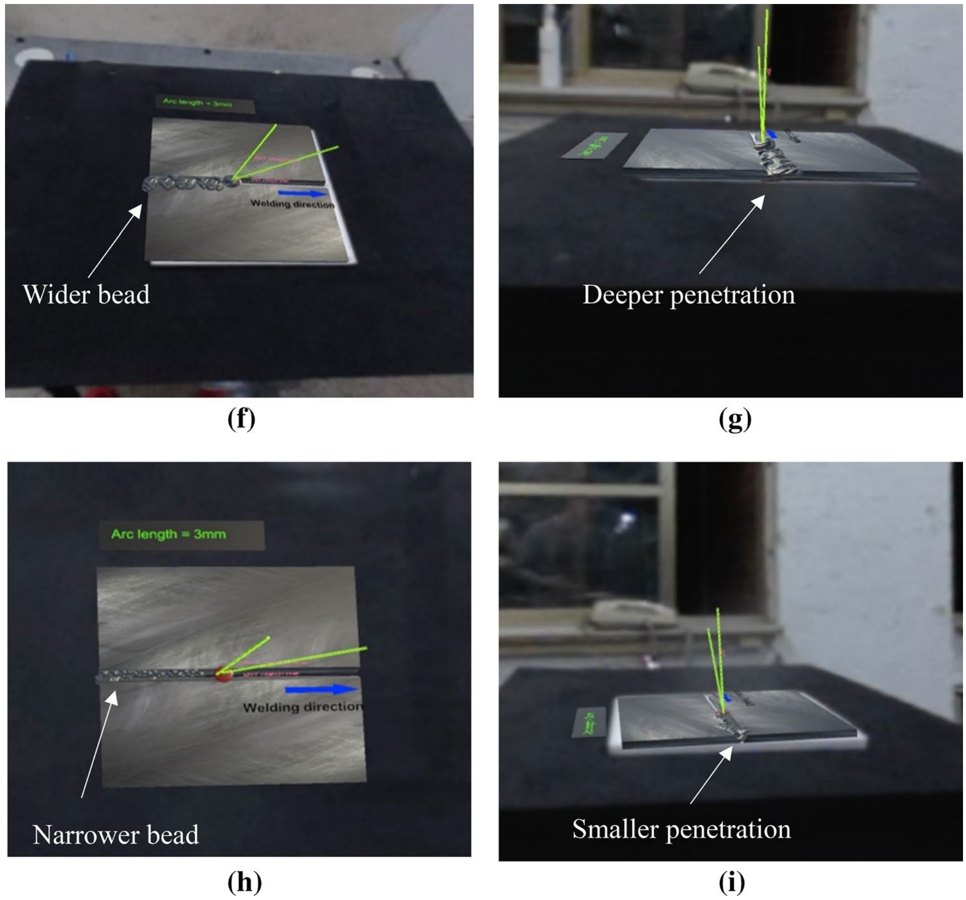


Fig. 11 Hands-on welding practice in the MR scene

test. Finally, 16 males and 14 females at the age between 21 and 40 (average age = 26.2, *SD* = 4.1) were recruited.

Figure 12 shows the flowchart of the user test. Thirty participants were randomly divided into the XR group and control group. The welding tutorial was delivered to the XR group in the XR-based environment, and to the control group in a traditional classroom. Although the content of the welding tutorial was the same, the participants in the XR group finished the tutorial in 40 min, and the participants in the control group finished the tutorial in 25 min. The XR group took longer because of the hands-on practice in the MR environment. Immediately after the tutorial, both groups were given 20 min to take a written test about the tutorial contents. After the written test, participants in both groups were asked to fill out the NASA-TLX form to evaluate the workload. The performance of both groups was compared through the objective written test and subjective NASA-TLX questionnaire.

Fig. 11 (continued)



In order to compare the two training methods, the participants in the XR group also attended the tutorial in the traditional classroom. After that, the participants in the XR group filled out the SUS form and a subjective questionnaire to compare their experiences of using the two training methods.

7 Results

7.1 Written test

The written test is used to measure how much knowledge is retained by the participants after the tutorial, and it is used to evaluate the learnability of the system. The written test questions are designed based on the topics in the prior welding books and literature (Clark 1985; Jeffus 2020; Mandal 2001, 2009), and they also have been covered in both tutorial sessions. The written test consists of 12 questions with a total score of 32, as shown in Table 1.

The final scores are normalized between 0 and 100. The average scores obtained by the XR group and the control group are $M_1 = 76.25$ ($SD = 8.84$) and $M_2 = 44.2$ ($SD = 10.63$), respectively. The scores are normally distributed for both groups. Figure 13 shows that most participants in the XR group scored in the range of 71–80, whereas most participants in the control group scored in the range of 41–50. The *t*-test results reveal that the score in the XR group is significantly higher than the control group ($p < 0.001$) with $\alpha = 0.05$.

Table 2 represents the percentage score of each question by both groups. The XR group scored significantly higher than the control group for most questions, except for questions 4, 5, 6 and 12.

7.2 NASA-TLX

After the written test, participants in both groups filled out the NASA-TLX form. The NASA-TLX is an assessment tool for the workload of a task or system. The NASA-TLX is divided into six subjective subscales, mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart 2006). A higher score represents higher loads. The lower score implies better results. However, in this study, the performance factor is transposed to higher score with higher performance. The NASA-TLX results are shown in Fig. 14.

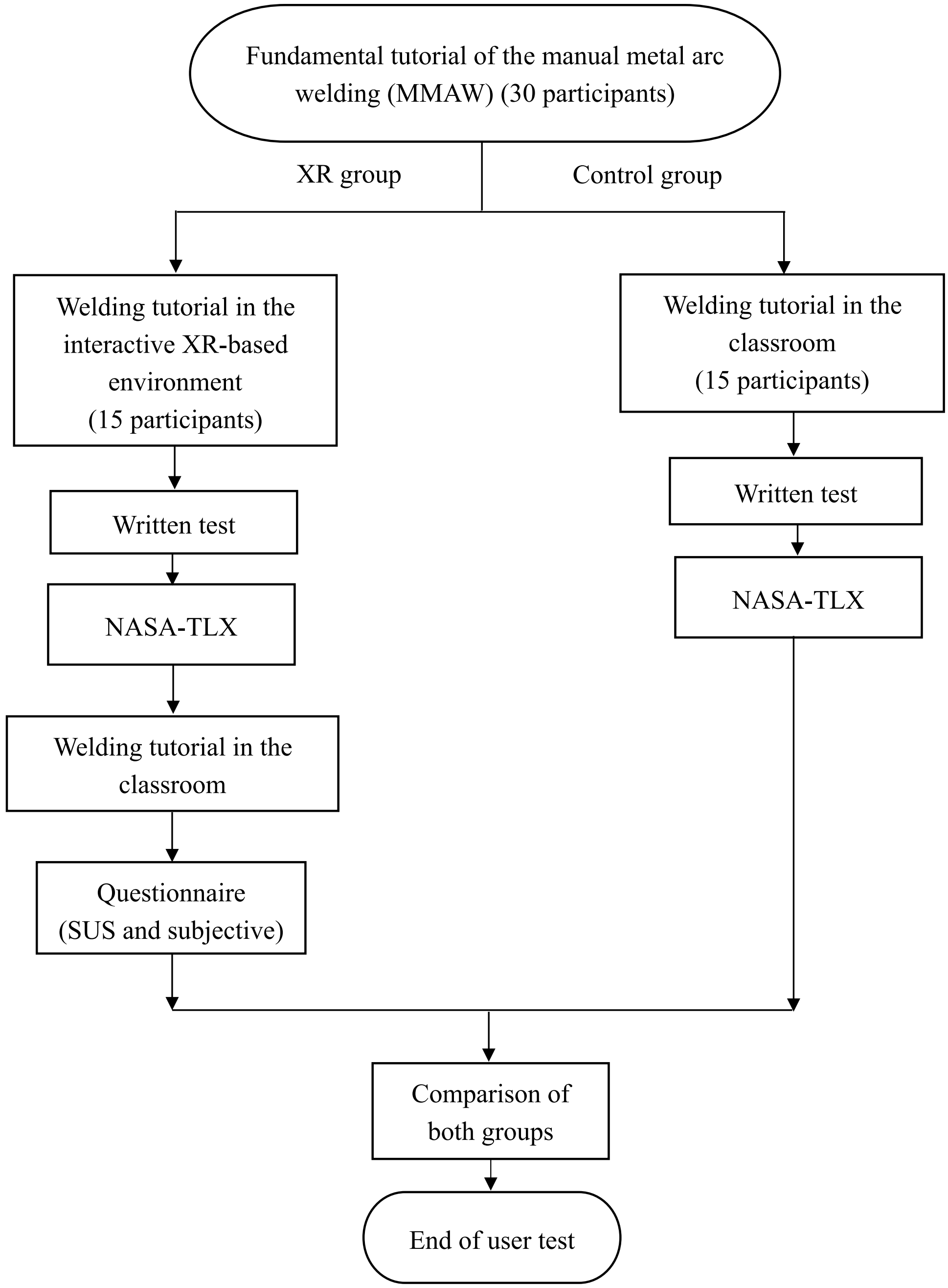


Fig. 12 Flowchart of the user test

The Kolmogorov–Smirnov test reveals that all six scale ratings are normally distributed. The *t*-test results show that the performance of the XR group is significantly higher than the control group, and the mental and temporal demands of the XR group are significantly lower than the control group. However, the physical demand, effort, and frustration of the XR group are significantly higher than the control group.

7.3 System usability scale

SUS is a reliable tool for measuring the usability of a system. It consists of 10 statements to evaluate the usability of the system (Brooke 1996). Scoring is based on a 5-point Likert scale (1: strongly disagree; 2: disagree; 3: neutral; 4: agree; 5: strongly agree). Lewis and Sauro (2009) used factor analysis to reveal that SUS actually included two factors: usability and learnability. The overall SUS score can also reveal users' satisfaction towards the system. Table 3 shows that in this study, the overall SUS mean score is 72, which is higher than the average score of 70 (Brooke 1996; Derisma 2020).

In this study, the Cattell's scree plot indicates that there are three significant factors in the SUS questionnaire, as shown in Fig. 15. Table 4 presents the varimax rotation

Table 1 Written test questions

<table>
<tr><th>No.</th><th>Questions</th><th>Points</th></tr>
<tr><td>1</td><td>What is the name of the welding process discussed in the tutorial?</td><td>1</td></tr>
<tr><td>2</td><td>What are the different types of weld joints? Please draw them.</td><td>2</td></tr>
<tr><td>3</td><td>What are the names of the two types of welds (Weld 1 and Weld 2) shown in Figs. 1 and 2? Please write the nomenclature on the correct locations in the figures.

Fig. 1: Weld 1

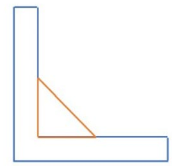



Fig. 2: Weld 2
<table>
<tr><td>Weld 1</td><td>Weld 2</td></tr>
<tr><td>Included angle</td><td>Leg (1)</td></tr>
<tr><td>Root gap width</td><td>Leg (2)</td></tr>
<tr><td>Joint faces</td><td>Toe of weld</td></tr>
<tr><td>Root face</td><td>Face of weld</td></tr>
<tr><td>Top side</td><td></td></tr>
<tr><td>Root side</td><td></td></tr>
</table></td><td>2</td></tr>
<tr><td>4</td><td>Define the arc length and draw it.</td><td>2</td></tr>
<tr><td>5</td><td>What should be the range of the electrode angle with the normal of the butt weld and fillet weld when it is seen from the side view?</td><td>2</td></tr>
<tr><td>6</td><td>What should be the range of the electrode angle with the normal of</td><td>2</td></tr>
<tr><td></td><td>the butt weld and fillet weld when it is seen from the front view?</td><td></td></tr>
<tr><td>7</td><td>What are the welding process parameters and their effects on the weld bead width and depth of penetration?</td><td>10</td></tr>
<tr><td>8</td><td>What is the difference between the push and pull techniques in terms of electrode orientation? Please draw the diagram.</td><td>4</td></tr>
<tr><td>9</td><td>What is the minimum value of the arc length required to establish an arc and start a welding process?</td><td>1</td></tr>
<tr><td>10</td><td>What is the considered range of welding current used in the tutorial?
a. 210 A – 300 A
b. 90 A – 210 A
c. 300 A – 450 A
d. None of above</td><td>2</td></tr>
<tr><td>11</td><td>What are the diameters of the electrodes used in the tutorial?
a. 3 mm, 4.5 mm, 6 mm
b. 3.15 mm, 4 mm, 5.5 mm
c. 2.5 mm, 4.2 mm, 5 mm
d. None</td><td>2</td></tr>
<tr><td>12</td><td>Is it possible to maintain a constant voltage during the welding process? Why?</td><td>2</td></tr>
</table>

Fig. 13 Frequency distribution chart for XR and control groups

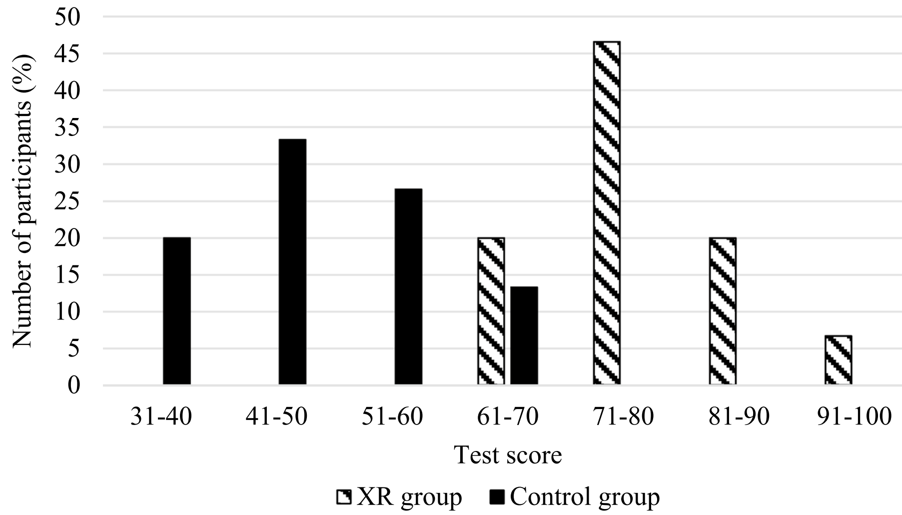


Table 2 Written test score results

No	XR group		Control group		p value
	Mean	SD	Mean	SD	
1	88	21.7	58.3	32.3	(**)
2	89	14.2	43.8	27.2	(***)
3	81	31.1	39.6	25.4	(***)
4	86.6	35.1	72	33.2	(n.s.)
5	68.3	44.7	76	31.2	(n.s.)
6	70	41.4	66.6	40.8	(n.s.)
7	71.2	16.2	29.3	14.9	(***)
8	76.6	38.3	44.1	38.6	(*)
9	85.3	35	40.6	40	(**)
10	80	41.4	43.3	49.5	(*)
11	93.3	25.8	6.6	25.8	(***)
12	53.3	38.8	56.6	40.6	(n.s.)

***$p \leq 0.001$, **$p \leq 0.01$, *$p \leq 0.05$, *n.s.* $p > 0.05$

matrix of the factor loadings of the 10 SUS statements. The factor loadings indicate that statements 4, 6, 9, and 10 are aligned with the first factor, statements 1, 2, 3, and 5 with the second factor, and statements 7 and 8 with the third factor. A reliability test is also performed to evaluate the consistency of the SUS scale. The Cronbach alpha coefficient of the overall SUS is 0.7, which confirms sufficient reliability of the SUS scale (Lewis and Sauro 2009).

7.4 Subjective questionnaire

The subjective questionnaire is used to evaluate the general experiences of using the XR-based tutorial system. A 5-point Likert scale is used (1: strongly disagree; 2: disagree; 3: neutral; 4: agree; 5: strongly agree). Table 5 shows the mean and standard deviation of each question. The Cattell's scree plot indicates that there are six significant factors in the subjective questionnaire, as shown in Fig. 16. However, in order to better categorize the statements in a more condense way, only 4 factors are extracted in this study. Table 6 presents the varimax rotation matrix of the factor loadings of the 20 statements. Statements 1, 2, 9, 15, 16, 17, and 18 are aligned with the first factor, statements 3, 5, 10, 11 and 14 with the second factor, statements 4, 6, 7, 8, 19 and 20 with the third factor, and statements 12 and 13 with the fourth factor. The reliability of the subjective questionnaire is confirmed with the Cronbach alpha coefficient of 0.73.

8 Discussion

The learnability of the system is validated by the written test. The score obtained by the XR group are significantly higher than the control group in questions from 1 to 3 and 7 to 11. It shows that the 3D representations of the joints and hands-on practices in the XR-based training system help users to remember the effects of process parameters, types of weld joints, welding current range, and electrode diameters. However, 2D texts of the arc length and range of electrode angle in the XR scene do not show any significant difference. It is because the 2D text information in the XR scene is similar to the classroom tutorial, which justifies the results.

The workload of the participants is evaluated using NASA-TLX. Since the XR-based tutorial system simulates the real welding environment, trainees need to stand up to

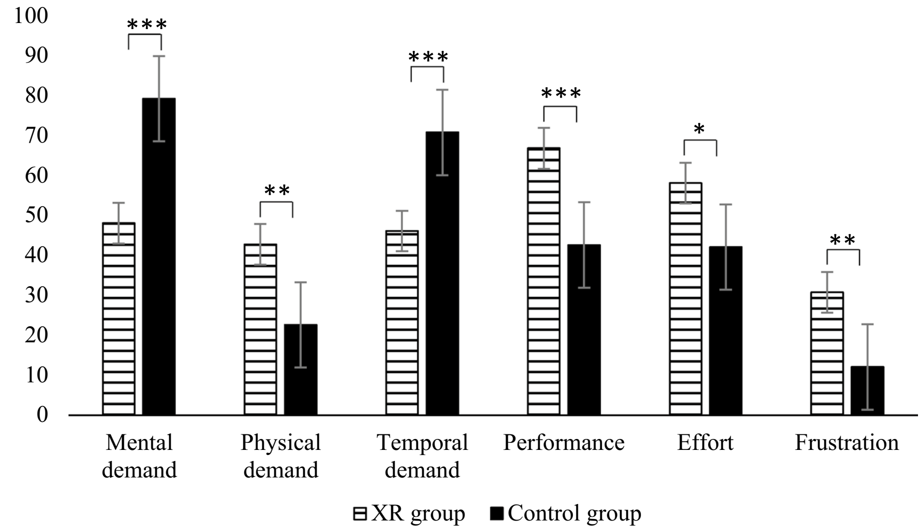


Fig. 14 NASA-TLX results for XR group and control group (***$p \le 0.001$, **$p \le 0.01$, *$p \le 0.05$)

Table 3 Questionnaire results for SUS

	SUS	Mean	SD
1	I think that I would like to use this system frequently	3.4	1.0
2	I found the system unnecessarily complex	2.1	1.0
3	I thought the system was easy to use	4.0	0.7
4	I think that I would need the support of a technical person to be able to use this system	2.9	1.0
5	I found the various functions in this system were well integrated	4.4	0.6
6	I thought there was too much inconsistency in this system	2.5	1.0
7	I would imagine that most people would learn to use this system very quickly	4.1	0.6
8	I found the system very cumbersome to use	1.8	0.7
9	I felt very confident using the system	3.4	0.9
10	I needed to learn a lot of things before I could get going with this system	1.3	0.4

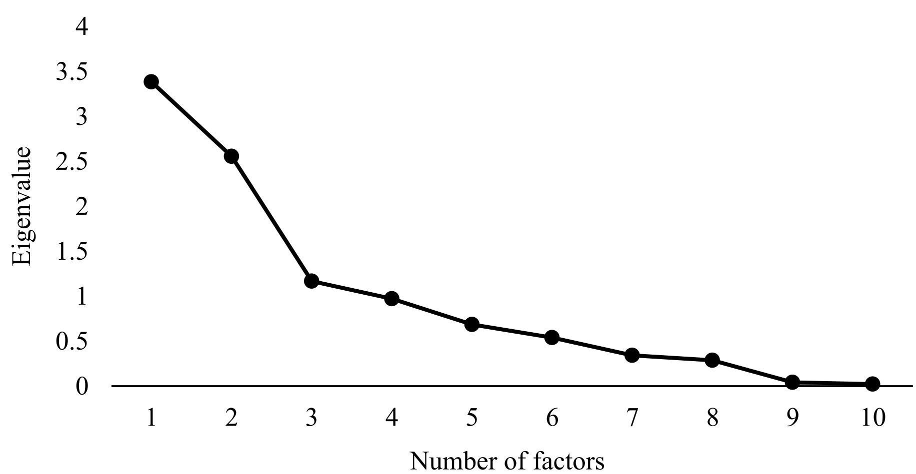


Fig. 15 Scree plot of eigenvalues for the SUS results

perform the hands-on welding task. Therefore, higher physical demand of the XR-based tutorial system is expected in the study because it reflects the high physical demand in the real welding environment. In addition, since participants in the XR group experience the system for the first time, they had to put more effort to learn the new UI. Compared to the conventional classroom tutorial, they showed higher frustration because they might accidently press the wrong button on the handheld controller or select the wrong UI. Therefore, the effort and frustration loadings of the XR group are

Table 4 Factor loading matrix for SUS

Statement	Factors		
	1 (learnability)	2 (usability)	3 (easiness)
1	−.52	**.69**	.19
2	−.10	**.75**	−.09
3	.26	**.90**	.23
4	**.62**	.14	−.10
5	.28	**.83**	.03
6	**.80**	.04	.04
7	.52	.11	**.59**
8	−.07	.09	**.88**
9	**.60**	−.02	.50
10	**.84**	−.06	.36

Bold values represent the highest correlated factor to the corresponding item (statement)

higher. However, the effort and frustration loadings can be reduced by frequent use of the XR system. The performance factor shows that the XR group perform significantly better than the control group, which justifies the learnability of the system.

The usability of the XR-based training system is evaluated using SUS. Factors analysis indicates that in this study, the SUS statements can actually be categorized into three factors: learnability, usability, and easiness, respectively. The mean score of the SUS results is above the average, and the usability of the system is categorized in rank B (Derisma 2020). It indicates that although the learnability, usability and easiness of the system is good and acceptable, some future improvements are required to enhance the usability.

Although based on the SUS responses, the system's learnability, usability, and easiness have been confirmed with mean scores either above 3.5 for most positive statements (odd-numbered) or below 2.5 for most negative statements (even-numbered), some statements received relative neutral responses (3.0). For example, statements 4 and 9 in the learnability factor received means of 2.9 and 3.4, respectively. It indicates that a more self-explanatory environment is needed to explain the training procedure more clearly to increase the confidence of the users and the learnability of the system. Statement 1 in the usability factor received a mean of 3.4. It indicates that a more intriguing UI or contents need to be designed so that users would like to use the system more frequent.

The general experiences for the XR-based training system is evaluated using a subjective questionnaire. Four factors are categorized using the factors analysis: usability, easiness, learnability, and lucidity, respectively. Users' responses show that all of the positive responses are higher than 3.5, and most of the negative responses are below 2.5, except

Table 5 Subjective questionnaire results

	Subjective	Mean	SD
1	The XR – based training system for the fundamental knowledge of the manual metal arc welding process was not very useful for learning	1.8	1.0
2	The XR – based training system was easy to operate	3.8	1.2
3	The XR tutorial is comprehensible	4.0	0.7
4	The topics in XR tutorial are poorly explained	1.8	0.6
5	The 3D representations of the objects and processes in the XR tutorial are helpful to understand the welding process	4.4	0.5
6	The tracking is correct	3.6	0.9
7	The augmented instructions were adequate and intuitive for user guidance	4.0	0.7
8	The user interface was appropriate for exploring the tutorial	4.4	0.6
9	The user interface was complex and difficult to interact	2.1	1.0
10	XR tutorial was more useful than classroom tutorial	4.1	0.9
11	XR tutorial was more interesting than the classroom tutorial	4.4	1.1
12	The graphic interface was complex and intrusive	2.5	1.1
13	The XR tutorial rapidly enhances the knowledge about the fundamentals of metal arc welding process	4.4	0.5
14	The XR tutorial is not useful for non – mechanical engineering background	1.6	0.9
15	The XR training system was helpful for practicing to keep a constant speed of welding	3.8	1.0
16	The XR training system was helpful for practicing to maintain a desired inclination angle of the electrode	4.0	1.0
17	The distance sensor is useful for practicing to maintain a desired gap to build an arc	4.0	1.1
18	The XR training system was useful to learn welding on various welding joints	4.3	0.6
19	XR tutorial is more useful to understand and remember the effects of various welding process parameters on weld bead geometry	4.4	0.5
20	I want the XR tutorial more interactive to allow me to ask questions	3.7	0.7

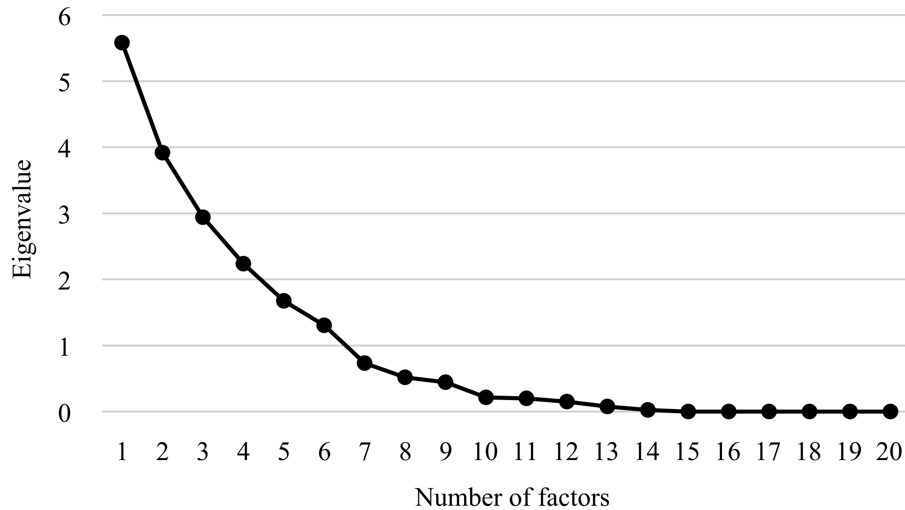


Fig. 16 Scree plot of eigenvalues for the subjective questionnaire

Table 6 Factor loading matrix for the subjective questionnaire

Statement	Factor			
	1 (usability)	2 (easiness)	3 (learnability)	4 (lucidity)
1	**0.666**	0.356	0.001	0.037
2	**0.860**	−0.365	−0.042	−0.165
3	0.405	**0.484**	0.096	−0.063
4	−0.094	0.301	**0.813**	0.070
5	−0.300	**0.315**	−0.257	0.173
6	0.043	−0.528	**0.611**	0.150
7	−0.143	−0.193	**0.744**	−0.440
8	0.446	−0.032	**0.551**	−0.098
9	**0.809**	−0.090	0.357	−0.072
10	0.000	**0.899**	0.123	0.044
11	0.036	**0.834**	−0.139	−0.262
12	0.035	−0.312	0.068	**0.843**
13	0.391	0.260	0.227	**0.730**
14	−0.084	**0.721**	−0.090	−0.128
15	**0.902**	0.282	−0.180	−0.122
16	**0.922**	−0.014	−0.145	0.220
17	**0.678**	−0.359	−0.233	0.175
18	**0.874**	0.015	−0.141	0.338
19	−0.082	0.484	**0.524**	0.352
20	−0.131	−0.063	**0.730**	0.177

Bold values represent the highest correlated factor to the corresponding item (statement)

for question 20 in the factor of learnability. It indicates that although the subjective questionnaire confirms the usability, learnability, easiness, and lucidity of the system, a more intelligent and intuitive UI needs to be created to allow users to interactively ask questions and receive relevant answers from the XR system.

Since the participants in the XR group also attended the traditional classroom training, participants in the XR group provided some comparative remarks as follows: “I feel XR tutorial was a lot better than having a classroom tutorial. It is interactive and keeps me attentive throughout the process. The best part is the hands-on experience right after in-depth exploration of the topics. We cannot ask questions to the teacher in the XR environment. Since the XR system was new to me, I felt uncomfortable while performing welding in the XR environment. The hands-on experience is very useful to understand the effect of process parameters and practice to maintain constant arc length and speed. Distance sensor performance can be improved for better accuracy of the welding. It is an easier and more interesting method to learn complex topics. The 3D representation of the models is more comprehensive and helpful to retain the knowledge. Bright colors on the UI should be avoided for the comfort of eyes.”

9 Conclusions

Welding is one of the important engineering and technology topics which need heavy hands-on practices. Welding is also a hazardous manufacturing process due to intense heat and harmful ultraviolet radiation. Most welding tutorials are delivered through the conventional classroom settings. This study developed an interactive XR-based welding tutorial system for fundamental MMAW training for novice welders. 3D interface allows users to perform a hands-on welding task with natural welding behavior, improving the effectiveness of the welding training. Novice welders can follow the visual instructions step by step and maintain a proper welding position. They can change the values of the welding process parameters to observe the effects on weld beads in real time in an immersive environment. The learnability, workload, and usability of the developed system have been validated through a user study. The results show that the

XR-based welding training system can help novice welders to retain welding knowledge and enhance hands-on welding skills. Future work can focus on improving the accuracy of the tracking and arc length measurement. In addition, a more interactive, interesting, and self-explanatory UI will be created.

Acknowledgements The authors would like to thank the Ministry of Science and Technology of Taiwan for financially supporting this research under contract MOST 108-2221-E-002-161-MY2.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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