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ORIGINAL ARTICLE

A visuo-haptic extended reality–based training system for hands-on manual metal arc welding training

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Abstract
Welding training has been an important job training process in the industry and usually demands a large amount of resources. In real practice, the strong magnetic force and intense heat during the welding processes often frighten novice welders. In order to provide safe and effective welding training, this study developed a visuo-haptic extended reality (VHXR)–based hands-on welding training system for training novice welders to perform a real welding task. Novice welders could use the VHXR-based system to perform a hands-on manual arc welding task, without exposure to high temperature and intense ultraviolet radiation. Real-time and realistic force and visual feedback are provided to help trainees to maintain a constant arc length, travel speed, and electrode angle. Compared to the traditional video training, users trained using the VHXR-based welding training system significantly demonstrated better performance in real welding tasks. Trainees were able to produce better-quality joints by performing smoother welding with less mistakes, inquiry times, and hints.

Keywords Visuo-haptic · Extended reality · Welding training · Manual metal arc welding

1 Introduction

With the advancement of information technology, in order to prepare quality professionals for Industry 4.0, traditional education or training methods should be transformed into Education 4.0, which refers to digital-based teaching and learning [1]. Augmented reality (AR) and virtual reality (VR) have been considered as the key enabling technologies for Industry 4.0 and Education 4.0 [1–4]. Prior research has demonstrated a variety of AR applications in manufacturing, such as maintenance, assembly, logistics, and quality control [5]. AR and VR technologies have also been proven to be an effective teaching and learning tool [6–9].

In the modern industry, welding can be performed by robots or automated machinery. However, in some manufacturing sectors, such as ship building, heavy equipment production, and small part fabrication, due to complex structures and inaccessibility of robots, most welding jobs are still done manually by human operators [10]. In addition to the industry, welding training is also a major program in engineering and technology education. Welding is a skill that must be taught correctly and elaborated with practice. However, it is a challenge to teach novice welders hands-on welding skills because welding usually involves high temperatures and harmful ultraviolet radiation. The global shortage of skilled welders has become an urgent issue in manufacturing industries [11]. During welding training, the high emission of welding fumes would increase environmental impacts [12]. The repetitive practice of welding often results in wastage of energy and materials [13]. In vocational training, welding is recognized as one of the most expensive training programs [14]. Therefore, it is important to transform the traditional welding training into Education 4.0 and take advantage of AR and VR to develop a hands-on, digital-based, cost-effective, eco-friendly, and risk-free welding training method to equip novice welders with sufficient welding skills.

In order to achieve high-grade welding joints, welders have to maintain a certain travel speed, arc length, and inclination angle of the electrode, under the influence of strong magnetic force and intense heat. Consequently, an effective AR and VR training tool should provide simulated, but also realistic force, thermal, and visual feedback throughout the welding training. The objective of this research is to develop a risk-free and cost-effective welding training

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system to allow novice welders to conduct a realistic hands-on welding practice and freely interact with welding components with their natural welding operation behavior as if they are performing a real welding task in the real world. The key contributions of this research are the development and verification of an extended reality (XR)–based welding training system, which provides realistic haptic feedback and real-time visual aids and quantitative guidance in assisting users to correctly perform a welding task using their natural welding behavior.

2 Related work

2.1 XR applications

XR is a universal term referring to all immersive technologies generated by computer technology and hardware, including AR, VR, and mixed reality (MR) [15]. XR technology is an integral part of Industry 4.0 concepts, as it enables operators to access digital information and combine the virtual world with the real world [2]. Prior research has provided a variety of XR applications in industries, education, medical, and healthcare [5, 16]. For example, Uva et al. [17] utilized spatial AR to develop a technical instruction manual to guide operators to perform a maintenance task on a motorbike engine and evaluated its effectiveness by comparing with a paper manual. The AR-based manual proved to be effective for complex tasks. Tang et al. [18] developed an interactive VR-based training program to facilitate procedural training for medical practitioners. Their study suggested that more emphasis should be put on the design of the content to enhance medical practioners' motivation for learning. Di Natale et al. [7] surveyed the applications of immersive VR on K-12 and higher education. They found that the performance of the immersive VR group outperformed significantly over the control group.

2.2 XR in welding training

Some prior researchers have used XR technologies to assist real welding operations. For example, Tschirner et al. [19] applied AR to help welders recognize the details of the welding environment during real manual gas metal arc welding. Aiteanu et al. [20] developed an AR welding helmet for manual welding by augmenting visual information before and during the real welding process. Users could see the real environment and correctly position the welding gun. Doshi et al. [21] used projector-based AR to improve manual spot-welding precision and accuracy for automotive manufacturing. However, their application was only restricted to specific vehicle panels with restricted projector locations.

In addition to assisting real welding operations, XR technologies have also been applied to welding training. Liu and Zhang [10] proposed a teleoperation-based AR welding training system using machine learning to calculate an optimized welding speed for unskilled workers to follow during a welding process. The actual welding task still happened at a remote welding station. The remote robot arm would follow the human's movement and perform the real welding task. Mavrikios et al. [13] developed a prototype demonstrator for simulating metal inert gas welding using VR technology. However, the proposed simulator was incapable to provide realistic sensation of holding a welding gun due to a fully virtual environment.

XR technologies have also been utilized in several commercial welding training simulators. Some of the prior studies have provided insights into the XR-based commercial simulators. For example, Okimoto et al. [22] studied user perception on a commercial AR-based welding training simulator, called Soldamatic. Although users could experience efficiency and fast learning, they needed to stand very close to the workpiece to allow the system to detect the markers. Byrd et al. [23] assessed the existing skills of welders using a VR-based welding simulator, VRTEX 360. The results showed that the experienced welders performed significantly better than the trained novice welders. Lavrentieva et al. [12] analyzed the impacts of using commercial VR and AR-based welding training simulators, such as MIMBUS, Fronius, and Soldamatic. They found that simulation-based welding training could reduce training periods, cut the cost of laboratory work, diminish CO_2 emission, save resources and materials, and avoid physical risks.

Although prior studies have shown positive outcomes of using XR technologies in welding training, most welding simulators lack realistic haptic feedback, which is an important phenomenon in real metal arc welding tasks. Therefore, in order to provide a high-fidelity simulation, it is necessary to include haptic feedback in welding training. Furthermore, prior studies also lack real-time visual aids and quantitative guidance. Since in the real world welding is performed by holding a protective helmet in front of the eyes, welding details become unclear to the welders. Thus, welders have to commence the welding with a presumed location of the workpiece. However, most existing commercial welding simulators do not provide equivalent visual effects of the real welding helmets. Moreover, most welding simulators also need the presence of an experienced welder to help the novices correctly operate the welding simulators.

2.3 Visuo-haptic applications

It is essential to acquaint novice welders with real welding challenges, e.g., strong magnetic force and intense heat, during hands-on practices in a simulated environment. Haptic feedback can increase training performance and thus plays a vital role in industrial and training applications [24]. The integration of visual effects and haptic feedback, called visuo-haptic, can enable users to see and touch digital information in a simulated environment [25].

Several studies have demonstrated the effectiveness of visuo-haptic in various manufacturing training. Chen and Yang [26] presented a VR-based machining process using a commercial haptic device, PHANTOM, to provide force feedback during virtual material removal simulation. Crison et al. [27] designed a haptic device to simulate the milling operation by applying a plastic deformation algorithm. The force feedback varied as a function of tool speed, material type, etc. Fletcher et al. [28] investigated the usage of VR and PHANTOM Omni for automatic generation of machining process plans, such as operation details and machine and tool selections. He and Chen [29] presented a haptic virtual turning operation system using PHANTOM to simulate cutting and grinding operations. The shape of the object being produced in the virtual machining process could be seen and felt by the users.

Apart from machining, some of the studies focused on using commercial haptic devices in welding training. Ni et al. [30] proposed an AR user interface for programming welding robots remotely and defining welding paths using a PHANTOM haptic device. The experimental results proved that using a haptic device could assist users to obtain an accurate welding path. Sung et al. [31] investigated human hand dexterity to learn how novices and experts operate differently in a soldering process. The manual soldering process was simulated using two PHANTOM Omni devices. By recording the force, velocity, position, and angle of the haptic pen, the skills required to perform successful soldering operations could be analyzed.

Although prior studies have shown promising applications of using commercial haptic devices in machining force simulation, the applications were constrained by the mechanism and degrees of freedom of the commercial haptic devices. Therefore, natural machining operation behaviors are not allowed in most manufacturing process simulators. This study develops a visuo-haptic extended reality (VHXR)–based hands-on welding training system for training novice welders to perform a manual metal arc welding (MMAW) task, using their natural welding operation behaviors. Electromagnetic force and thermal feedback are provided to simulate magnetic force and intense heat that occur in the real welding environment. The system also provides real-time visual aids and quantitative guidance to assist users to maintain a constant travel speed, arc length, and inclination angle to correctly perform a welding task.

3 Methodology

3.1 System overview

In this study, VR is used to graphically introduce basic welding knowledge and tools. However, in order to provide realistic hands-on welding practice, AR is used, so that users could see the physical welding components. The training begins with a VR module, in which welding tools are demonstrated on a worktable along with introductions and safety instructions. After the VR module, users enter into the AR module to acquire hands-on welding practices. A real electrode holder is used to help users retain muscle memory. In addition to force feedback, virtual weld beads, virtual sparkling particles, and virtual electric arc are also displayed in the AR scene.

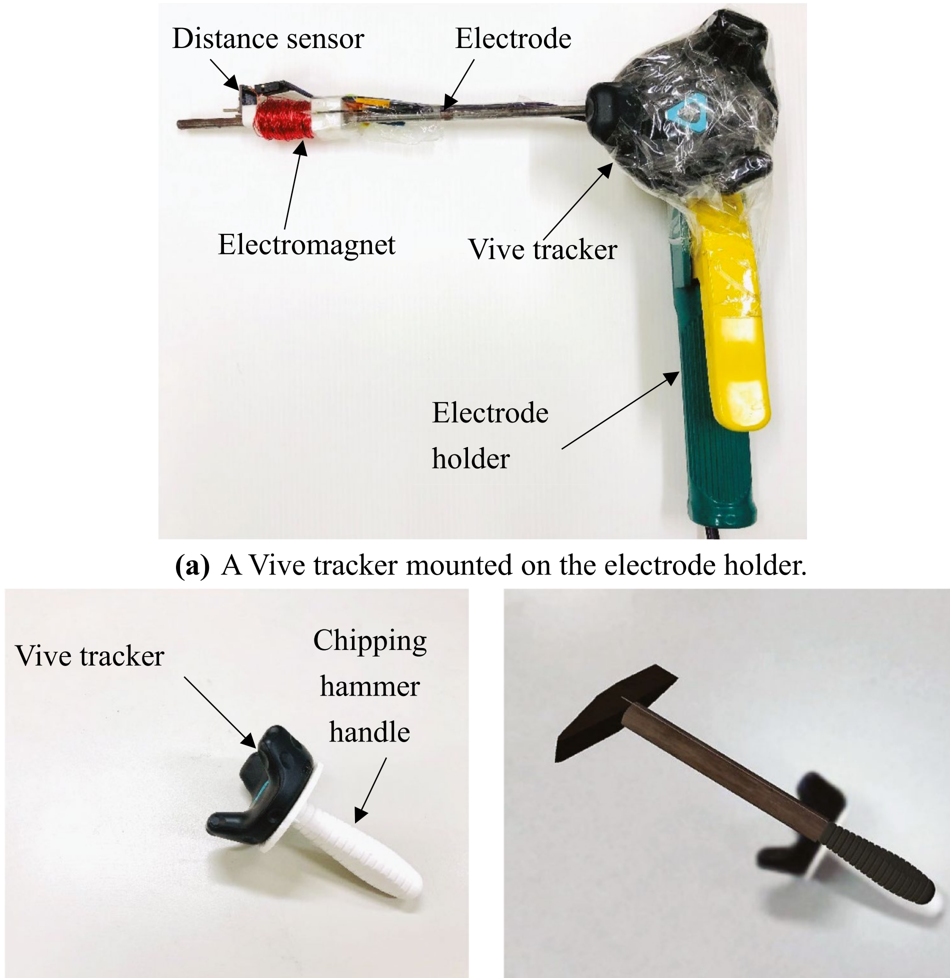
The HTC Vive Pro HMD is used as the display device. In order to build an AR environment, the Vive Input Utility (VIU) and SRWorks software development kit (SDK) are used. The VHXR-based welding training system was developed on a PC with a 3.00 GHz Intel Core i7-9700F processor, 64 GB RAM and 6.0 GB dedicated GPU memory. Scripts are written in C# using the Unity3D game engine.

3.2 Tracking

In this study, two Vive trackers and two handheld controllers are used. One Vive tracker is mounted on the electrode holder (Fig. 1(a)) to track the electrode, while the other Vive tracker is mounted on a 3D-printed chipping hammer handle (Fig. 1(b)) to track the virtual chipping hammer (Fig. 1(c)).

In the real MMAW process, welding begins when the electric arc of the desired length in the range of 2 to 8 mm is established between the weld plates and the electrode tip. In order to simulate a real MMAW process, a distance sensor, VL6180X, is mounted at the tip of the electrode to measure the distance between the weld plates and electrode tip (Fig. 1(a)). The virtual weld bead, sparkling particles, and electric arc are rendered if the arc length is maintained within the desired range. However, the best welding results are achieved when the arc length is between 2 and 3 mm.

One handheld controller is used to interact with the user interface (UI) elements, i.e., virtual buttons and sliders, while the other handheld controller is used to track the virtual helmet (Fig. 2(a) and (b)).



(a) A Vive tracker mounted on the electrode holder.

(b) A Vive tracker mounted on the chipping hammer handle.

(c) Virtual chipping hammer.

Fig. 1 Vive trackers for tracking the electrode and the virtual chipping hammer. **a** A Vive tracker mounted on the electrode holder. **b** A Vive tracker mounted on the chipping hammer handle. **c** Virtual chipping hammer

3.3 Haptic feedback

There are two challenges which might frighten novice welders during the MMAW process. One is the strong magnetic force generated between the electrode tip and the workpiece, and the other is the intense heat and hot sparks. It is essential to provide a natural user interface with realistic haptic feedback to help novice welders become more acquainted with the real welding environment.

(a) Handheld controller. **(b)** Virtual helmet.

Fig. 2 A handheld controller for tracking the virtual helmet. **a** Handheld controller. **b** Virtual helmet

In the MMAW process, when the gap between the electrode tip and the workpiece is less than 2 mm, the induction of the longitudinal magnetic field of welding current rapidly increases [32]. This leads to the electrode being stuck to the workpiece while performing welding tasks. In order to simulate the magnetic force, an electromagnet is placed at one end of the electrode, which is made of medium carbon steel, as shown in Fig. 1(a). The workpiece is made of 10 cm × 4 cm × 1 cm SS41 low-carbon steel. The electromagnet is formed by winding an insulated copper wire around the electrode rod. The magnitude of the induced magnetic force is about 7.6 N. In the real welding process, the magnetic force created in a workpiece of the same size is about 22.3 N [33], which is 2.9 times stronger than the electromagnetic force simulated in this study. Although the simulated magnetic force is smaller than the real one, due to the limitation of the size of the electromagnet, it still provides substantial obstruction in welding practice. Users can practice welding and learn to maintain a constant arc length to avoid the sticking of the electrode to the workpiece, under the influence of magnetic force.

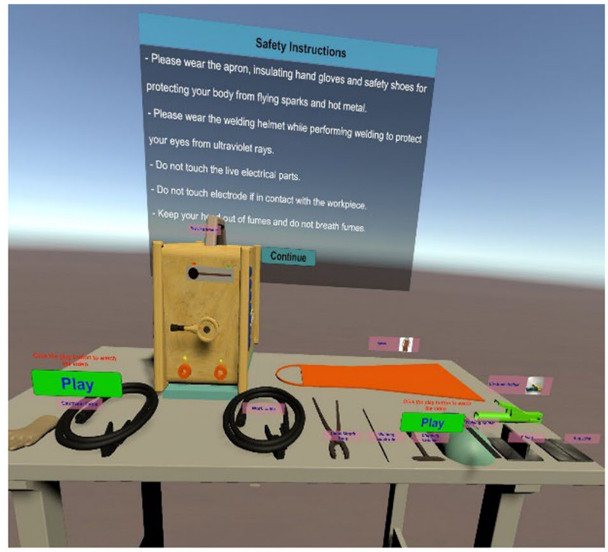
An infrared heat lamp is used to provide thermal feedback during the welding. The infrared lamp can produce heat with temperature of 65 °C at a distance of 30 cm [34]. Since the light of the infrared heat lamp might disturb users, the heat lamp is placed inside a box made of a dark blue translucent plastic foil (Fig. 3). The heat lamp is switched on when the arc length is within the range of 2–8 mm. Otherwise, the heat lamp is switched off.

3.4 Hands-on welding training in AR

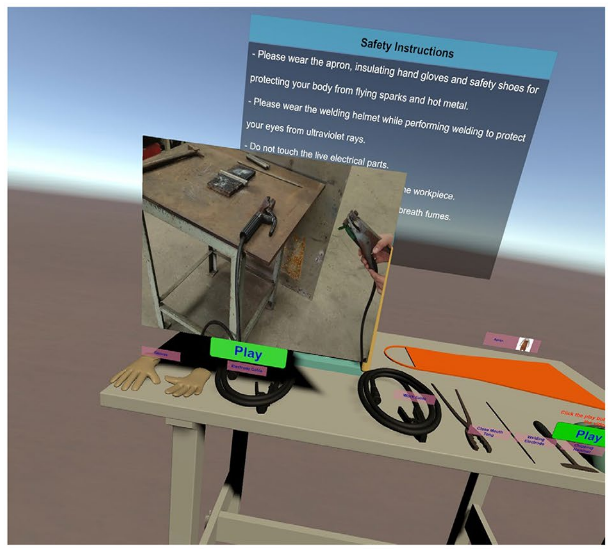
It is essential for an effective simulation to replicate the experience of a real application [35]. Therefore, each required welding step in a real welding process, from the beginning to the end, is considered in the VHXR-based welding training system. The practical hands-on welding training is provided to the users in the following steps:

Step (1): Wearing the safety shoes, hand gloves, and apron
The welding training starts from the VR module, which contains safety instructions and welding equipment introductions. The welding components and tools are demonstrated on a worktable (Fig. 4(a)). In addition, videos are provided to show the usage of the welding tools (Fig. 4(b)). After that, users enter into the AR module for hands-on welding practice.
Step (2): Checking the welding parameters
In this step, users are directed to the parameter page to make sure the values of the welding parameters are correct (Fig. 5).

Fig. 3 Infrared heat lamp inside a box made of translucent plastic foil



(a) Demonstration of welding components and tools.



(b) Video showing the usage of the welding tools.

Fig. 4 Introduction scene in the VR module. **a** Demonstration of welding components and tools. **b** Video showing the usage of the welding tools

Step (3): Mounting the electrode in the electrode holder
A video is played to show the correct way to mount the electrode in the electrode holder and the correct way to weld a butt joint and a tee joint (Fig. 6).
Step (4): Placing the butt joint on the worktable
The butt joint icon is selected using a cyan ray emitted from the handheld controller, as shown in Fig. 7(a). A yellow sphere appears when the ray hits the UI element. When the UI button is selected, a blue arrow appears and points towards the worktable to guide users to place a real butt joint in a fixture (Fig. 7(b)). After that, a virtual joint and a virtual dummy plate are overlaid on the real ones

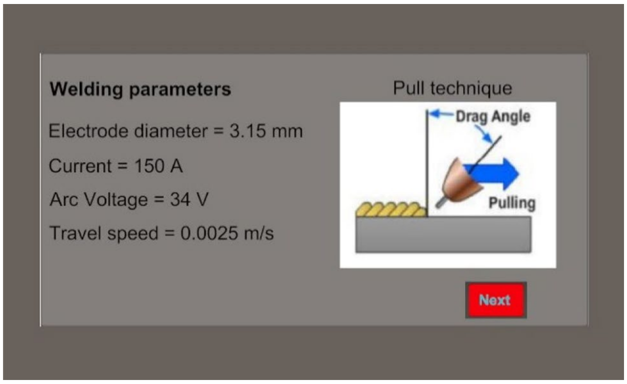


Fig. 5 Checking welding parameter values

(Fig. 7(c)). Visual aids and quantitative guidance, such as the speed indicator, arc length, and electrode angle guide, are displayed to assist users in performing the welding.

Step (5): Holding the electrode holder in the right hand

Because a Vive tracker is mounted on the electrode holder, the spatial location of the electrode holder can be acquired. After placing the butt joint, a flickering red arrow appears and points towards the electrode holder, along with text instructions to guide users to hold the electrode holder in the right hand, as shown in Fig. 8.

Step (6): Switching on the power source

In this step, users are guided to switch on the power source by dragging the UI slider from left to right using the cyan ray emitted from the handheld controller, as shown in Fig. 9.

Step (7): Holding the helmet in the left hand and placing it in front of the face

Due to the extreme brightness conditions in arc welding, a protective helmet is needed. However, even an experi-

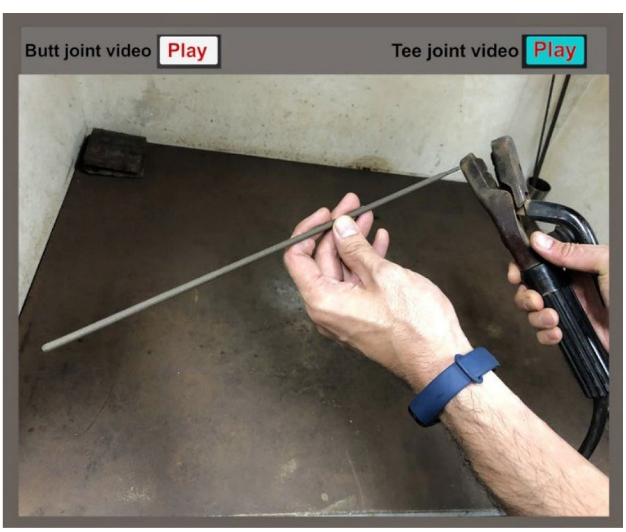
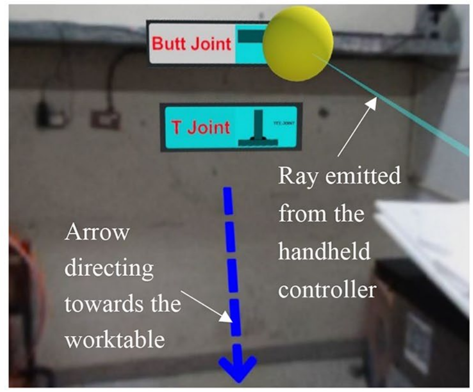
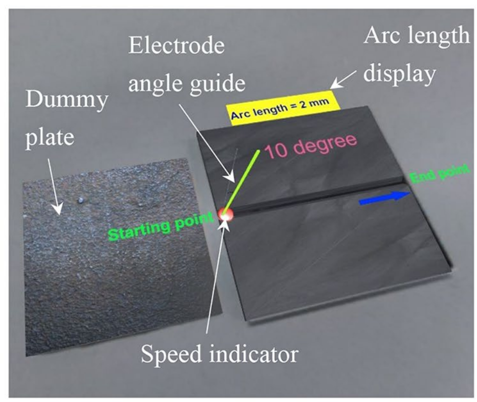


Fig. 6 Instructions for mounting the electrode in the electrode holder



(a) Joint selection using the handheld controller.

(b) Real dummy plate (left) and workpiece in a fixture (right).



(c) A virtual butt joint augmented on a real workpiece.

Fig. 7 Joint selection. **a** Joint selection using the handheld controller. **b** Real dummy plate (left) and workpiece in a fixture (right). **c** A virtual butt joint augmented on a real workpiece

enced welder can hardly recognize the details of the welding components and the surrounding environment while using the protective helmet. Therefore, users are trained to hold a helmet in their left hand during the welding training, as shown in Fig. 10.

Step (8): Scratching the dummy plate to initiate the electric arc

In order to initiate an electric arc, users have to scratch the dummy plate next to the workpiece, as shown in Fig. 11. After the arc is initiated, users need to maintain the arc

Fig. 8 Holding the electrode holder

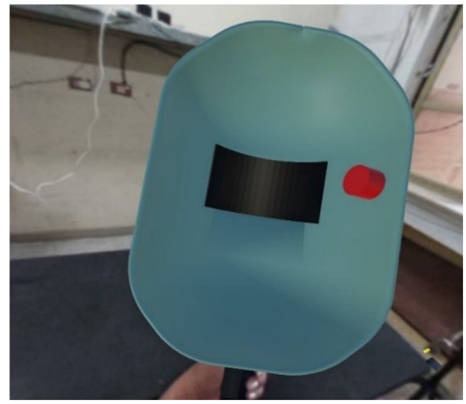


Fig. 10 Holding a helmet in the left hand

length within the range of 2–8 mm during the welding. In general, users are advised to maintain an arc length of 2–3 mm for a good quality weld.

Step (9): Welding the joint with a specified arc length, travel speed, and inclination angle

In this step, users are instructed to perform welding by maintaining a constant arc length, travel speed, and electrode angle with the helmet in the left hand and the electrode holder in the right hand. Three cases are applied based on the arc length maintained by the users, as shown in Table 1. If the arc length is less than 2 mm, the simulated magnetic force will be enabled and the electrode will be stuck to the workpiece. In the meantime, thermal feedback and other visual and auditory feedback will be disabled to show the obstruction of the welding process. If the arc length is larger than 8 mm, all feedback will be disabled to show the stop of welding.

If the arc length is kept within 2 mm and 8 mm, the electric arc will be properly generated. Users are guided to perform welding with a constant travel speed of 2.5 mm s^{-1} and a constant electrode angle of 20°. In this case, magnetic force feedback is disabled, while thermal feedback, auditory feedback, the virtual arc, and speed indicator are enabled to show the continuation of the welding process, as shown in Fig. 12. The angle guidance will move along with the speed indicator to guide users to correctly align the electrode throughout the welding.

Step (10): Removing solidified slag from the welded plates using a chipping hammer

After each pass of welding, users have to remove slag from the welded plates. Figure 13(a) and (b) shows a first-person view and a third-person view of removing slag in the AR environment. An arrow with green color is shown on the edge of the chipping hammer to guide users to remove slag in the correct orientation. This step helps users remember to remove slag after each welding pass.

Step (11): Repeating the same welding procedure three times for the butt joint

For a butt joint, in order to fill the gap between the two welding plates, at least three welding passes are required.

Fig. 9 Switching on the welding power source

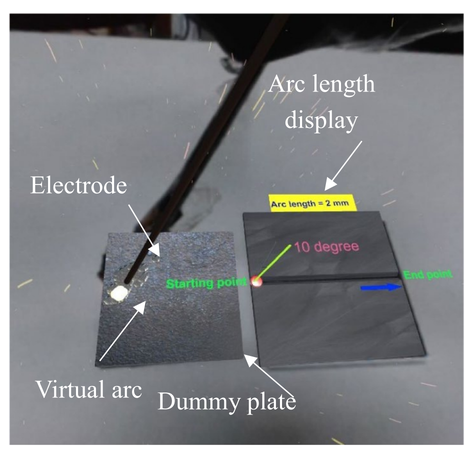
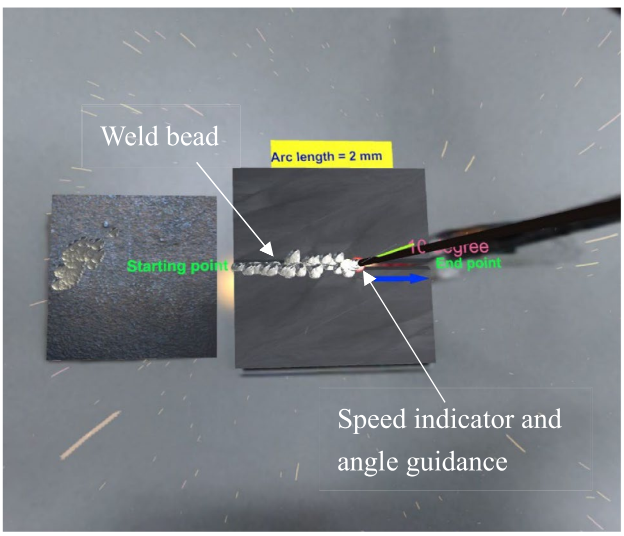


Fig. 11 Initiation of the electric arc by scratching the dummy plate

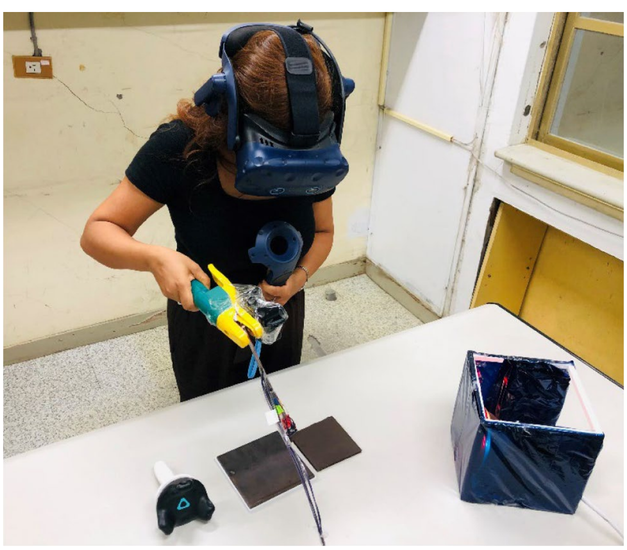
Table 1 Three different welding conditions

	Case I (arc length < 2 mm)	Case II (2 mm ≤ arc length ≤ 8 mm)	Case III (arc length > 8 mm)
Magnetic force feedback	Enabled	Disabled	Disabled
Thermal feedback	Disabled	Enabled	Disabled
Virtual arc generation	No	Yes	No
Auditory feedback	Disabled	Enabled	Disabled
Speed indicator	Stop	Move	Stop

Step (12): Repeating the same welding procedure two times for the tee joint
For a tee joint, in order to fill the gap between the two welding plates, at least two welding passes are required



(a) First-person view of case II.



(b) Third-person view of case II.

Fig. 12 Practical welding training in the AR environment. **a** First-person view of case II. **b** Third-person view of case II

4 User test

A user test was conducted to evaluate the VHXR-based welding training system. Two groups of participants were recruited. The experimental group was trained using the VHXR-based welding training system as per the steps described in Sect. 3.4, and the control group was trained using an educational video. The following general-purpose questionnaires were used to evaluate the training performance: the NASA Task Load Index (NASA-TLX) was used for *assessing the workload*, system usability scale (SUS) for *evaluating system usability*, and presence questionnaire (PQ) for measuring *the sense of presence. In addition, a subjective questionnaire was designed and used to evaluate the system performance.*

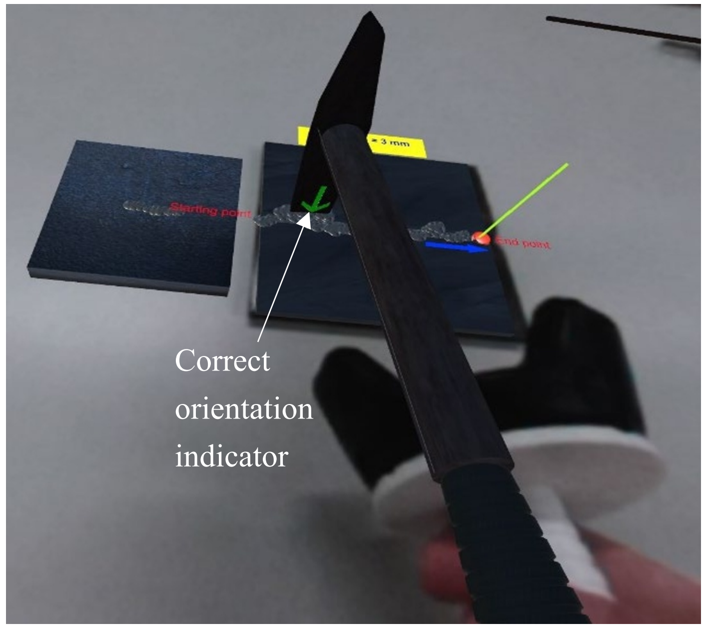
The sample size was calculated by using G*Power software, version 3.1.9.4. At least 30 participants were needed (effect size $d = 0.25$, $\alpha = 0.05$, power $P = 0.8$, correlation among repeated measures = 0.5) [36]. Twenty male and 10 female participants between the ages of 20 and 40 (average = 27, $SD = 4.23$) were recruited from different engineering and science backgrounds without prior experience in MMAW. Participants were randomly divided into the VHXR group and the control group.

Figure 14 is the flowchart of the user test. The VHXR group took about 40 min to finish the training session. However, the control group took about 15 min. The VHXR group took longer training time due to the hands-on practice in the AR environment. Participants of the both groups were asked to perform the real welding task in a workshop after 24 h from completing the training sessions.

Participants were asked to follow the correct welding steps to conduct the real welding task. They were allowed to ask for help if they encountered any problems. Each participant was given SS41 low-carbon steel workpieces to weld the butt joint and tee joint, as shown in Fig. 15(a) and (b). An E6013 electrode with 300 mm in length and 3.15 mm in diameter was used. Figure 16(a) and (b) shows the participants from the VHXR group performing the real welding task and removing the slag from the welded joint using a chipping hammer, respectively.

After the real task, the welding performance of the two groups was compared. Both groups were asked to fill out the

Fig. 13 Removing slag from the welded joint using a chipping hammer. **a** First-person view of removing slag using a chipping hammer. **b** Third-person view of removing slag using a chipping hammer



(a) First-person view of removing slag using a chipping hammer.

(b) Third-person view of removing slag using a chipping hammer.

NASA-TLX questionnaire to assess the welding workload. After that, participants in the VHXR group also took the video training, and they were asked to fill out the SUS, PQ, and subjective questionnaires to compare their experiences in both training environments.

5 Results

The training effectiveness was evaluated based on the welding performance and users' responses in the questionnaires.

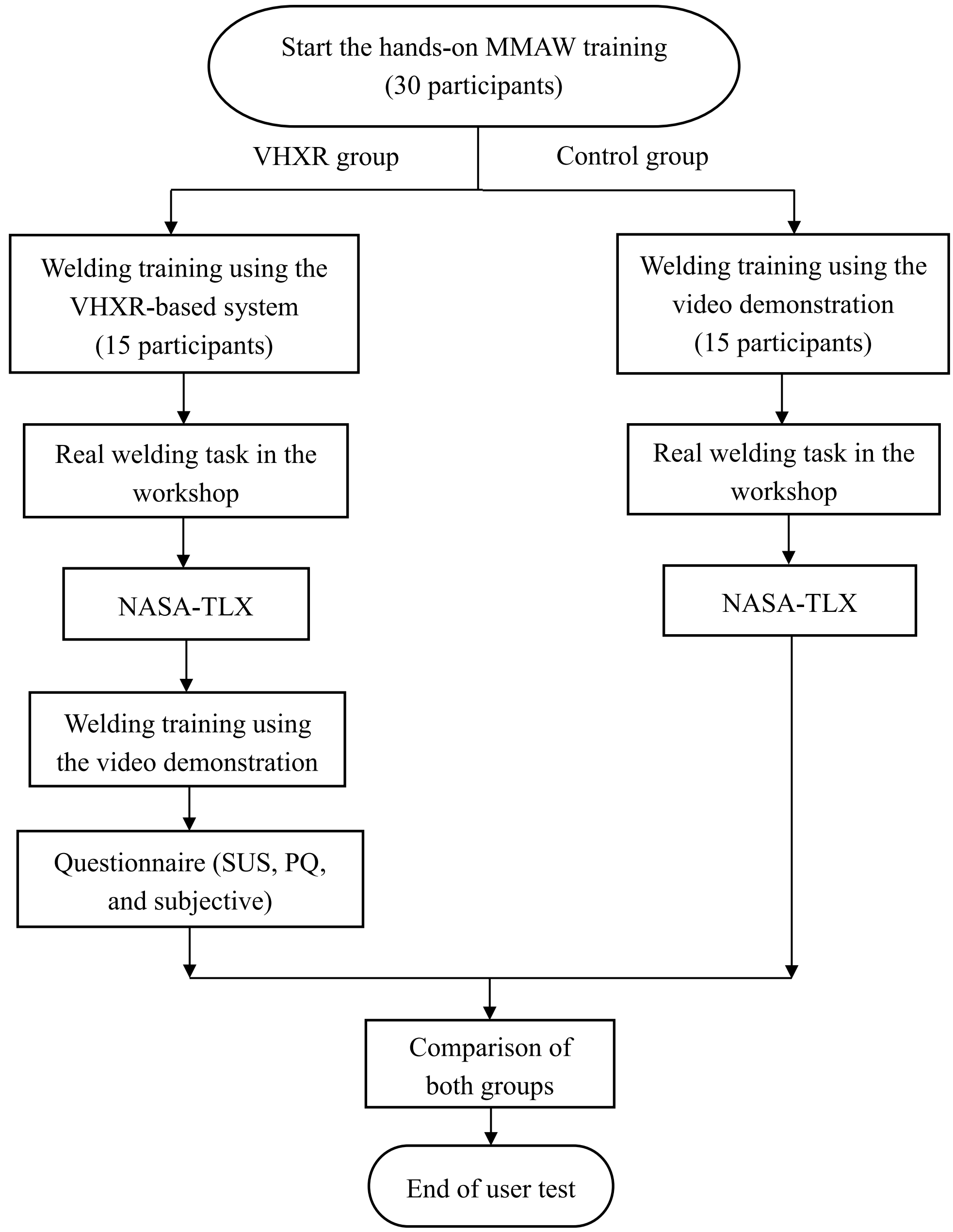


Fig. 14 Flowchart of the user test

5.1 Real welding task

The welding quality was evaluated by a skilled welder. The appearance of a welded joint was given a score between 0 and 100, based on the straightness of the weld, uniformness of the filler material, uniformness of the bead width, and spatter around the weld [37]. The welding quality was also evaluated based on the appearance of the weld joints, number of hints, number of mistakes, number of arc extinctions, number of excess welding passes, and total welding time. Table 2 shows the best and worst butt joints and tee joints in both groups.

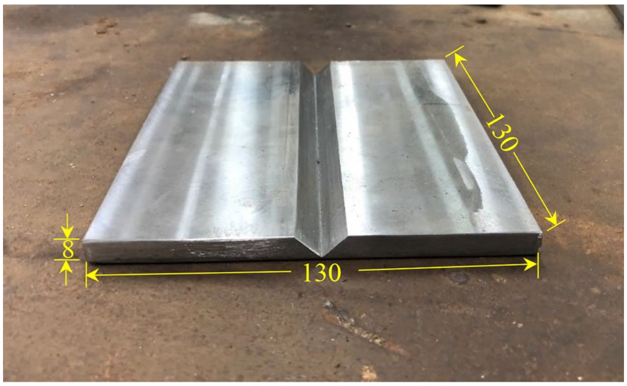
An overall score $S_{overall}$ was computed to evaluate the performance of each participant using the appearance score (A), number of hints (H), number of mistakes (M), time spent on the welding task (T), number of arc extinctions (E), and excess number of passes (P), as shown in Eq. (1).

$$S_{overall} = \mathrm{A} - (H + M + T + E + P) \tag{1}$$

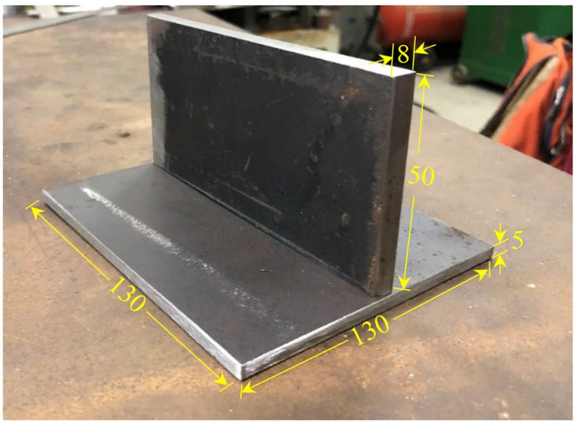
To avoid a negative score, the overall score was normalized between 0 and 1 by applying Eq. (2).

$$S_{norm} = (S_{overall} - S_{min})/(S_{max} - S_{min}) \tag{2}$$

S_{min} and S_{max} are the minimum and maximum scores among the participants, respectively. The results are shown in Table 3. The normality of the evaluation factors was checked



(a) Workpiece for butt joint



(b) Workpiece for tee joint

Fig. 15 Workpieces for the real welding task (all dimensions are in mm). **a** Workpiece for butt joint. **b** Workpiece for tee joint

by the Kolmogorov–Smirnov (KS) test using SPSS statistics software. It revealed that the number of mistakes (M), time spent on welding task (T), number of arc extinctions (E), and excess number of passes (P) were not normally distributed, and thus the Wilcoxon Rank Sum non-parametric tests were performed. In contrast, the appearance score A and normalized score S_{norm} were normally distributed, and thus the t-tests were performed. The results revealed that the performance of the VHXR group was significantly better than the control group for most evaluation factors, except for the excess number of passes and the time spent to perform the welding tasks.

5.2 NASA-TLX

NASA-TLX assesses the overall workload based on six ratings: mental demand, physical demand, temporal demand, performance, effort, and frustration [38]. The rating is between 0 and 100. A lower score implies a lower workload. In this study, NASA-TLX was used to evaluate the subjective workload of the real welding task for the VHXR group and control group. The evaluation results are represented in Table 4. The KS test results confirmed the normality of the six ratings. The t-test was performed to check the significance of the results. The results in Table 4 revealed that the overall workload of the real welding task for the control group was significantly higher than for the VHXR group.

(a) Real welding task **(b)** Chip removal from the welded joint

Fig. 16 Participants from the VHXR group performing the real welding task. **a** Real welding task. **b** Chip removal from the welded joint

5.3 System usability scale

Only the VHXR group took the SUS questionnaire. The SUS scale is a reliable tool to evaluate the usability of a system [39]. Scoring is based on a 5-point Likert scale, with 1 as "strongly disagree" and 5 as "strongly agree." Table 5 shows the SUS results of the VHXR-based welding training system. The overall SUS mean score is 72, which is higher than the average score of 70 [40, 41].

The factor analysis with varimax rotation revealed three significant factors in the questionnaire. The factor loadings of the statements are shown in Table 6, which indicates that statements 1, 2, 3, 5, and 6 are aligned with the first factor; statements 4, 7, and 10 with the second factor; and statements 8 and 9 with the third factor. The reliability test was conducted to determine the consistency of the SUS scale. The Cronbach alpha coefficient confirms sufficient reliability with a value of 0.71 above the threshold of 0.7, recommended by Lewis and Sauro [42].

Table 2 The best and worst butt joints and tee joints in both groups

		VHXR group	Control group
Best welding quality	Butt joint		
	Tee joint		
Worst welding quality	Butt joint		
	Tee joint		

5.4 Presence questionnaire

The PQ analysis was designed to assess the sense of presence in a virtual environment [43, 44]. The scoring is based on a 7-point Likert scale, with 1 as "strongly disagree" and 7 as "strongly agree." PQ Version 3.0 was used in this study. The questionnaire was composed of four factors: involvement (items 1 to 13), sensory fidelity (items 14 to 17), adaptation/immersion (18 to 25), and interface quality (26 to 28). The PQ evaluation results are shown in Table 7. The reliability of the PQ questionnaire was confirmed with Cronbach alpha coefficient of 0.72.

Table 3 Performance results of the welding task ($\alpha = 0.05$)

Evaluation factors	VHXR group		Control group		
	Mean	SD	Mean	SD	p value
Appearance score (A)	39.8	21.3	20.3	11.8	(**)
Hints given (H)	1.2	1.4	6.6	5.1	(**)
Number of mistakes (M)	1.8	1.8	10.2	5.2	(***)
Total time (s) to finish the welding on both joints (T)	1326	600	1281	543	(n.s.)
Number of arc extinction (A)	5.3	3.9	15.5	14.4	(**)
Number of excess passes (P)	3.2	1.8	8.3	12.3	(n.s.)
Normalized score ($Score_{norm}$)	0.8	0.15	0.5	0.2	(***)

n.s. ($p > 0.05$); *($p \leq 0.05$); **($p \leq 0.01$); ***($p \leq 0.001$)

5.5 Subjective questionnaire

The subjective questionnaire was designed and used to evaluate the users' subjective experience of using the VHXR-based training system. A 5-point Likert scale was used, with 1 as "strongly disagree" and 5 as "strongly agree." Table 8 shows the results of the subjective questionnaire. Factor analysis reveals seven eigenvalues from the Cattell's scree plot. The results infer seven significant factors in the questionnaire. However, for better categorization of the statements in a concise way, only the first three dominate factors were extracted in this study. The statement categorization is represented by the varimax rotation matrix of the factor loadings as shown in Table 9. The reliability of the questionnaire was validated with the Cronbach alpha coefficient of 0.83.

Table 4 NASA-TLX results for welding user test

	VHXR group			Control group	
	Mean	SD	Mean	SD	*p* value
Mental demand	48	22.8	53.3	24.1	(n.s.)
Physical demand	48	27.9	66	22.2	(*)
Temporal demand	43.3	25.9	63.3	14.9	(**)
Performance	29.7	81.3	66.7	76.5	(***)
Effort	57	23.3	76	15.0	(**)
Frustration	28.6	19.4	54.6	37.1	(*)
Overall workload	42.4	11.2	57.7	8.4	(**)

6 Discussion

The results of the real welding task show that the overall normalized score of the VHXR group is significantly higher than that of the control group. With the help of quantitative guidance for arc length, travel speed, and electrode angle, participants in the VHXR group were able to practice how to make a uniform and straight welding joint during the training. Therefore, the VHXR group obtained a significantly higher appearance score than the control group in the real welding task. Using the natural welding operation behavior in the training also helped participants to remember the correct steps required in the real welding task. Therefore, significantly fewer hints and mistakes were recorded for the VHXR group than the control group. Moreover, hands-on welding practices under the influence of magnetic force helped participants to keep a proper arc length under a strong magnetic force in the real welding task. The retained muscle memory helped the VHXR group make significantly fewer number of arc extinctions than the control group. However, on the other hand, since the VHXR group paid more attention to controlling the arc length, travel speed, and electrode angle, they took more time in the real welding task, although the difference was not significant.

The NASA-TLX results show that the control group encountered significantly higher physical, temporal, effort, and frustration demands in the real welding task. Although no significant difference was found in the mental demand, the average metal demand of the VHXR group was still lower than the control group. Since the participants in the control group experienced the strong magnetic force and heat for the first time, some of them expressed fear during the real welding. However, since the participants in the VHXR group have already been aware of strong magnetic force and heat during the training, they showed less workload in the real welding task. The performance of the VHXR group was also significantly better than that of the control group.

The SUS results indicate that the system's usability was appropriate and acceptable. In this study, the factor analysis reveals that the SUS questionnaire can be classified into three significant categories: usability, learnability, and easiness with satisfactory results. Despite the system having satisfactory usability, learnability, and easiness, it still requires further improvements to enhance the usability. For example, because most participants used the VHXR system for the first time, they showed a neutral response to the question that they needed the support of a technical person

Table 5 SUS evaluation of welding task

	SUS	Mean	SD
1	I think that I would like to use this system frequently	3.9	1.0
2	I found the system unnecessarily complex	2	0.8
3	I thought the system was easy to use	4	0.8
4	I think that I would need the support of a technical person to be able to use this system	3	0.9
5	I found the various functions in this system were well integrated	3.8	0.7
6	I thought there was too much inconsistency in this system	2.3	1.0
7	I would imagine that most people would learn to use this system very quickly	4.2	0.8
8	I found the system very cumbersome to use	1.8	0.7
9	I felt very confident using the system	4.5	0.6
10	I needed to learn a lot of things before I could get going with this system	2	0.7

Table 6 Factor loading matrix for SUS

Statement	Factors		
	Usability	Learnability	Easiness
1	**0.71**	0.34	−0.49
2	**0.70**	0.45	0.10
3	**0.85**	−0.27	−0.04
4	−0.10	**0.83**	0.17
5	**0.62**	−0.31	0.45
6	**0.68**	−0.01	−0.47
7	0.48	**0.54**	0.33
8	−0.11	0.16	**0.84**
9	0.03	0.06	**0.85**
10	−0.01	**0.88**	−0.08

Bold values represent the highest correlation factor with the corresponding statement

to be able to use the system. Therefore, a clearer and more self-explanatory user interface will be needed in the future.

In the PQ evaluation, all the questions in the involvement factor received positive responses with scores above 4. It indicates that providing natural welding user interface with haptic feedback and visual feedback enhanced the participants' attention and involvement in the welding training. For the sensory fidelity factor, the participants' responses indicate that realistic haptic, auditory, and visual feedback enabled them to sense different aspects of the VHXR environment. Participants were able to be more involved within the VHXR environment and examine the virtual objects. For the adaptation/immersion factor, participants agreed that they were able to quickly and easily adapt to the VHXR

Table 7 PQ evaluation results

	PQ	Mean	SD
	Involvement		
1	How much were you able to control events?	5.3	0.7
2	How responsive was the environment to actions that you initiated (or performed)?	5.4	0.9
3	How natural did your interactions with the environment seem?	5.6	1.3
4	How much did the visual aspects of the environment involve you?	5.7	0.9
5	How natural was the mechanism which controlled movement through the environment?	4.9	1.0
6	How compelling was your sense of objects moving through space?	5.0	1.1
7	How much did your experiences in the virtual environment seem consistent with your real-world experiences?	5.1	1.3
8	How completely were you able to actively survey or search the environment using vision?	5.4	1.1
9	How compelling was your sense of moving around inside the virtual environment?	4.8	1.5
10	How well could you move or manipulate objects in the virtual environment?	5.8	1.0
11	How involved were you in the virtual environment experience?	5.9	0.9
12	Were you involved in the experimental task to the extent that you lost track of time?	5.7	1.3
13	How easy was it to identify objects through physical interaction, like touching an object, walking over a surface, or bumping into a wall or object?	6.0	1.0
	Sensory fidelity		
14	How much did the auditory aspects of the environment involve you?	5.7	1.2
15	How well could you actively survey or search the virtual environment using touch?	5.5	1.1
16	How closely were you able to examine objects?	6	1.1
17	How well could you examine objects from multiple viewpoints?	5.6	1.1
	Adaptation/immersion		
18	Were you able to anticipate what would happen next in response to the actions that you performed?	5.4	1.5
19	How quickly did you adjust to the virtual environment experience?	5.0	0.8
20	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	5.6	1.0
21	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	5.7	1.0
22	How completely were your senses engaged in this experience?	5.7	0.9
23	Were there moments during the virtual environment experience when you felt completely focused on the task or environment?	5.9	1.1
24	How easily did you adjust to the control devices used to interact with the virtual environment?	6.1	0.9
25	Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?	6.0	1.1
	Interface quality		
26	How much delay did you experience between your actions and expected outcomes?	2.1	1.1
27	How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	3.4	1.8
28	How much did the control devices interfere with the performance of assigned tasks or with other activities?	4.4	1.6

Table 8 Subjective questionnaire for VHXR welding training

	Subjective	Mean	SD
1	The VHXR training for MMAW was not very useful for learning	2.1	1.1
2	VHXR training system was easy to operate	3.7	0.7
3	VHXR training system replicates the real welding process	3.8	0.9
4	The welding process in the VHXR system looks very artificial	3.2	1
5	The welding operation in the VHXR system was accurate	3.4	0.8
6	The magnetic force at the tip of the electrode resembles the real force of attraction during welding	3.6	1.2
7	The effect of the heat of the heat lamp makes the VHXR training more realistic	3.2	1.3
8	The augmented instructions were adequate and intuitive for guidance	4.1	0.9
9	The user interface was suitable for welding training	3.8	0.7
10	The user interface was complex and difficult to interact	2	0.8
11	The VHXR training was more useful than the video training	4.4	0.7
12	The VHXR training was more interesting than the video training	4.4	0.6
13	The graphic interface was complex and intrusive	2.4	1
14	The VHXR training system rapidly enhanced my welding skill	4	0.5
15	The VHXR training system was helpful for practicing to keep a constant speed of welding	3.6	1.1
16	The VHXR training system was helpful for practicing to maintain the desired inclination angle of the electrode	4.0	0.2
17	Incorporating the distance sensor in this training made it useful to maintain the desired gap between workpiece and electrode tip to build the arc	3.7	0.7
18	It was useful to learn welding for the Butt joint and Tee joint	4.3	0.9
19	It was difficult to understand the instructions to perform the correct welding operation	1.8	0.7

environment and perceived themselves being immersed within the VHXR environment. Participants were able to acquire a continuous stream of experiences. They could proficiently conduct the welding task using a natural welding behavior and concentrate on the assigned tasks with the help of haptic, auditory, and visual effects. Lastly, for the interface quality factor, the participants' responses revealed that the training system was quick in responding to their actions. Participants were able to focus on the assigned tasks without any distraction and practice the welding technique in a natural way. However, question 28 reveals that the control devices slightly interfered with the performance of the assigned tasks. It might be because some of the participants did not correctly use the handheld controller to interact with the UI elements.

Table 9 Factor loadings for the subjective questionnaire

Statement	Factors		
	Usability	Learnability	Realism
1	0.01	0.29	−0.01
2	**0.89**	−0.04	0.03
3	0.03	0.00	**0.86**
4	0.07	**0.59**	−0.17
5	0.55	−0.47	**0.57**
6	−0.39	−0.15	0.21
7	**0.81**	0.14	−0.36
8	**0.82**	0.30	0.13
9	**0.66**	0.44	0.27
10	**0.67**	0.01	0.13
11	0.01	**0.66**	0.31
12	−0.08	**0.78**	0.01
13	0.20	**0.84**	0.25
14	0.39	**0.72**	−0.09
15	**0.74**	0.36	−0.06
16	0.12	**0.52**	−0.06
17	**0.73**	0.01	0.16
18	0.36	**0.61**	0.32
19	0.11	0.06	**0.63**

Based on the results of the factor analysis, the subjective questionnaire was categorized into three dominate factors: usability, learnability, and realism. The factor analysis indicated the acceptable usability, learnability, and realism of the system. In addition, questions 3, 6, and 7 confirm that the electromagnetic force and heat lamp make the VHXR-based training more realistic. The natural user interface greatly enhances the users' welding skills. However, because the VHXR system was purposefully designed with several difficulties to make the users be familiar with the obstructions in the real welding environment, some users found it difficult to operate the VHXR system. Although the magnetic force and the heat generated by the heat lamp in the VHXR environment were not as strong as in the real welding, participants could still learn the welding techniques in a similar and interruptive way. The tracking of the virtual objects needs to be more accurate. The graphical representations need to be more realistic. In addition, a more precise and stable distance needs to be obtained to maintain a constant arc length.

Participants also provided some remarks as follows: “The welding training system was very useful to practice the steps required in performing real welding.” “The magnitude of the magnetic force can be increased to make it exactly the same as the real welding,” “The thermal feedback provided by the heat lamp built a natural welding environment, which helped me not to be afraid of the heat during the real welding,” and “The welding training system can be taken to the next level if the tracking accuracy can be improved.”

7 Conclusion

Welding is a manufacturing process that needs highly manual skills. It requires a large amount of resources to train novice welders. In addition, the hazardous environment often frightens the users. This study developed an interactive VHXR-based training system with realistic haptic and visual feedback to train novice welders with the correct welding steps in a safe and realistic environment. The system has been validated by a user study. The results show that the VHXR system significantly improved the performance of novice welders, and the natural user interface enabled the users to easily adapt to the real welding environment. Future work will focus on developing a more self-explanatory user interface, increasing the magnetic force and thermal feedback, as well as the accuracy of the distance detection.

Author contribution All authors contributed to the study conception and design. KS implemented the algorithm and wrote the first version of the manuscript. TJC supported the software and hardware development. YYT provided the practical workshop experiment. SS read and approved the final manuscript.

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Declarations

Ethics approval This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of National Taiwan University.

Consent to participate Not applicable.

Consent for publication All authors agree to publish this manuscript in International Journal of Advance Manufacturing Technology and confrm that this work has not been published anywhere before.

Conflict of interest The authors declare no competing interests.

References

1. Mourtzis D (2018) Development of skills and competences in manufacturing towards Education 4.0: a teaching factory approach. In: Proceedings of 3rd International Conference on the Industry 4.0 model for Advanced Manufacturing, AMP 2018. Lecture Notes in Mechanical Engineering. Springer, Cham., Springerr, Cham, pp.194–210
2. Jamwal A, Agrawal R, Sharma M, Giallanza A (2021) Industry 4.0 technologies for manufacturing sustainability: a systematic review and future research directions. Appl Sci 11:5725
3. Masood T, Egger J (2019) Augmented reality in support of Industry 4.0—implementation challenges and success factors. Robot Comput Integr Manuf 58:181–195. https://doi.org/10.1016/j.rcim.2019.02.003
4. Van Lopik K, Sinclair M, Sharpe R, Conway P, West A (2020) Developing augmented reality capabilities for industry 4.0 small enterprises: lessons learnt from a content authoring case study. Comput Ind 117:103208. https://doi.org/10.1016/j.compind.2020.103208
5. Egger J, Masood T (2020) Augmented reality in support of intelligent manufacturing – a systematic literature review. Comput Ind Eng 140:106195. https://doi.org/10.1016/j.cie.2019.106195
6. Calvert J, Abadia R (2020) Impact of immersing university and high school students in educational linear narratives using virtual reality technology. Comput Educ 159:104005. https://doi.org/10.1016/j.compedu.2020.104005
7. Di Natale AF, Repetto C, Riva G, Villani D (2020) Immersive virtual reality in K-12 and higher education: a 10-year systematic review of empirical research. Br J Educ Technol 51:2006–2033. https://doi.org/10.1111/bjet.13030
8. Loureiro SMC, Bilro RG, de Aires AFJ (2021) Virtual reality and gamification in marketing higher education: a review and research agenda. Span J Mark - ESIC 25:179–215. https://doi.org/10.1108/SJME-01-2020-0013
9. Maas MJ, Hughes JM (2020) Virtual, augmented and mixed reality in K–12 education: a review of the literature. Technol Pedagogy Educ 29:231–249. https://doi.org/10.1080/1475939X.2020.1737210
10. Liu Y, Zhang Y (2015) Super welder in augmented reality welder training system: a predictive control approach. In: 2015 IEEE 24th International Symposium on Industrial Electronics (ISIE), Buzios, Brazil, pp.131–136
11. Rousku A (2020) Global welder shortage – viewpoints from three continents. https://weldingvalue.com/2020/11/global-welder-shortage-viewpoints-three-continents/. Accessed 28 February 2022
12. Lavrentieva O, Arkhypov I, Kuchma O, Uchitel A (2020) Use of simulators together with virtual and augmented reality in the system of welders' vocational training: past, present, and future. In: Proceedings of the 2nd International Workshop on Augmented Reality in Education, Arnold E. Kiv, Mariya P. Shyshkina, Kryvyi Rih, Ukraine, pp.201–216
13. Mavrikios D, Karabatsou V, Fragos D, Chryssolouris G (2006) A prototype virtual reality-based demonstrator for immersive and interactive simulation of welding processes. Int J Comput Integr Manuf 19:294–300. https://doi.org/10.1080/09511920500340916
14. Wu C (1992) Microcomputer-based welder training simulator. Comput Ind 20:321–325. https://doi.org/10.1016/0166-3615(92)90080-7
15. Doolani S, Wessels C, Kanal V, Sevastopoulos C, Jaiswal A, Nambiappan H, Makedon F (2020) A review of extended reality (XR) technologies for manufacturing training. Technologies 8:77. https://doi.org/10.3390/technologies8040077
16. Tang YM, Chau KY, Kwok APK, Zhu T, Ma X (2021) A systematic review of immersive technology applications for medical

practice and education-trends, application areas, recipients, teaching contents, evaluation methods, and performance. Educ Res Rev 100429. https://doi.org/10.1016/j.edurev.2021.100429
17. Uva AE, Gattullo M, Manghisi VM, Spagnulo D, Cascella GL, Fiorentino M (2018) Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations. Int J Adv Manuf Technol 94:509–521. https://doi.org/10.1007/s00170-017-0846-4
18. Tang YM, Ng GWY, Chia NH, So EHK, Wu CH, Ip WH (2021) Application of virtual reality (VR) technology for medical practitioners in type and screen (T&S) training. J Comput Assist Learn 37:359–369. https://doi.org/10.1016/j.chb.2015.12.054
19. Tschirner P, Hillers B, Graser A (2002) A concept for the application of augmented reality in manual gas metal arc welding. In: International Symposium on Mixed and Augmented Reality, IEEE, Darmstadt, Germany, pp.257–258
20. Aiteanu D, Hillers B, Graser A (2003) A step forward in manual welding: demonstration of augmented reality helmet. In: The Second IEEE and ACM International Symposium on Mixed and Augmented Reality, Tokyo, Japan, pp.309–310
21. Doshi A, Smith RT, Thomas BH, Bouras C (2017) Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing. Int J Adv Manuf Technol 89:1279–1293. https://doi.org/10.1007/s00170-016-9164-5
22. Okimoto MLL, Okimoto PC, Goldbach CE (2015) User experience in augmented reality applied to the welding education. Procedia Manuf 3:6223–6227. https://doi.org/10.1016/j.promfg.2015.07.739
23. Byrd A, Anderson R, Stone R (2015) The use of virtual welding simulators to evaluate experienced welders. Weld J 94:389. https://dr.lib.iastate.edu/handle/20.500.12876/44402
24. Cosco F, Garre C, Bruno F, Muzzupappa M, Otaduy MA (2012) Visuo-haptic mixed reality with unobstructed tool-hand integration. IEEE Trans Vis Comput Graph 19:159–172. https://doi.org/10.1109/TVCG.2012.107
25. Eck U, Pankratz F, Sandor C, Klinker G, Laga H (2015) Precise haptic device co-location for visuo-haptic augmented reality. IEEE Trans Vis Comput Graph 21:1427–1441. https://doi.org/10.1109/TVCG.2015.2480087
26. Chen Y, Yang Z (2004) Haptic rendering based on spatial run-length encoding. Robot Comput Integr Manuf 20:237–246. https://doi.org/10.1016/j.rcim.2003.09.002
27. Crison F, Lécuyer A, d'Huart DM, Burkhardt JM, Michel G, Dautin JL (2005) Virtual technical trainer: learning how to use milling machines with multi-sensory feedback in virtual reality. In: IEEE Proceedings. VR 2005. Virtual Reality, Bonn, Germany, pp.139–145
28. Fletcher C, Ritchie J, Lim T, Sung R (2013) The development of an integrated haptic VR machining environment for the automatic generation of process plans. Comput Ind 64:1045–1060. https://doi.org/10.1016/j.compind.2013.07.005
29. He X, Chen Y (2006) A haptic virtual turning operation system. In: International Conference on Mechatronics and Automation, IEEE, Luoyang, China, pp.435–440
30. Ni D, Yew A, Ong S, Nee A (2017) Haptic and visual augmented reality interface for programming welding robots. Adv Manuf 5:191–198. https://doi.org/10.1007/s40436-017-0184-7
31. Sung R, Ritchie JM, Lim T, Dewar R, Weston N (2011) Knowledge capture inside a haptic soldering environment. In: Proceedings of the 6th International Conference on Virtual Learning, CLUJ-NAPOCA, Romania, pp.38–44
32. Chigarev VV, Shchetinina VI, Shthetinin SV (2016) Magnetic field in electric arc welding. Weld Int 30:319–324. https://doi.org/10.1080/01431161.2015.1058008
33. Kumar A, DebRoy T (2003) Calculation of three-dimensional electromagnetic force field during arc welding. J Appl Phys 94:1267–1277. https://doi.org/10.1063/1.1587006
34. MacCargar B (2006) Watts, heat and light: measuring the heat output of different lamps. Accessed 05 November 2021
35. Howie S, Gilardi M (2021) Virtual observations: a software tool for contextual observation and assessment of user's actions in virtual reality. Virtual Real 25:447–460. https://doi.org/10.1007/s10055-020-00463-5
36. Cohen J (2013) Statistical power analysis for the behavioral sciences. Academic Press, New York, NY, USA
37. Kumar V, Albert S, Chandrasekhar N, Jayapandian J (2018) Evaluation of welding skill using probability density distributions and neural network analysis. Measurement 116:114–121. https://doi.org/10.1016/j.measurement.2017.11.009
38. Hart SG (2006) Nasa-task load index (NASA-TLX); 20 years later. Proc Hum Factors Ergon 50:904–908. https://doi.org/10.1177/154193120605000909
39. Jordan PW, Thomas B, McClelland IL, Weerdmeester B (1996) Usability evaluation in industry. CRC Press, London, UK
40. Borsci S, Federici S, Bacci S, Gnaldi M, Bartolucci F (2015) Assessing user satisfaction in the era of user experience: comparison of the SUS, UMUX, and UMUX-LITE as a function of product experience. Int J Hum-Comput Interact 31:484–495. https://doi.org/10.1080/10447318.2015.1064648
41. Derisma D (2020) The usability analysis online learning site for supporting computer programming course using system usability scale (SUS) in a university. Int J Interact Mob Technol 14:182–195. https://doi.org/10.3991/ijim.v14i09.13123
42. Lewis JR, Sauro J (2009) The factor structure of the system usability scale. In: International conference on human centered design, Springer, pp.94–103
43. Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence 7:225–240. https://doi.org/10.1162/105474698565686
44. Witmer BG, Jerome CJ, Singer MJ (2005) The factor structure of the presence questionnaire. Presence 14:298–312. https://doi.org/10.1162/105474605323384654

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