



Mixed reality system for nondestructive evaluation training

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Abstract

nondestructive evaluation (NDE) is an analysis technique used to evaluate the properties of a material, component, structure or system without causing damage. In this paper, we introduce a novel mixed reality system for NDE training. In particular, we model and simulate the inspected object and the inspection probe. The operator trainees with the wearable headsets are able to move and zoom the inspected object in a mixed environment, i.e., reality with virtual objects overlaid. In addition, the trainees use their gaze, gesture, and voice to control and interact with the virtual objects within the NDE training session. They can also access the help manual in order to follow the training instruction. The system is successfully operated on HoloLens, the state-of-the-art mixed reality headset. Evaluational results demonstrate that the use of mixed reality training provides significant benefit for the potential technician trainees.

Keywords Mixed reality · Nondestructive evaluation · Virtual reality · Simulation

1 Introduction

Nondestructive evaluation (NDE) is a testing and analysis technique used by industry to evaluate the properties of a material, component, object, or system for characteristic differences or welding defects and discontinuities without causing damage to the original part. The internal structure of an object can be examined for a volumetric inspection with penetrating radiation such as X-rays, neutrons or gamma radiation. Sound waves are utilized in the case of ultrasonic testing. The concept of utilizing virtual reality (VR) and augmented reality (AR) into nondestructive inspection training modules has been around since the 1990s (Kim et al. 1996). The aerospace industry has long recognized that nondestructive inspections are performed on complex components, often in unpleasant environmental conditions. These realistic conditions are not possible to simulate in a classroom setting due to the high cost and efforts. Therefore a need exists for a more effective training program that provides the trainee with an environment as close to that

experienced in the field as possible. In addition, a virtual reality training module would be much more efficiently updated to keep current with procedural changes due to new technologies and service bulletin updates for material quality inspections (Amza et al. 2018a; Eschen et al. 2018). The need for increased reliability in NDE for high value components within the aerospace and automotive industries has resulted in challenges for meeting the needs for skilled inspectors. As the instrumentation becomes more advanced, the need for more extensive operator training also increases adding to the cost of maintenance and part production. One possible method for reducing training cost while increasing reliability of the inspection is to provide operators with real-time instructions and mixed reality (MR)-based user interfaces optimized for NDE. This grants immediate access to consultation with a more experienced engineer who is better informed of the current situation while simplifying the inspector's task. Because of the complexity of technical orders, having the opportunity to display instructions within the operator's field of view during an inspection would provide significant efficiency over the current manual processes where the operator must interrupt the inspection process to refer back to written documentation (Urbasa et al. 2019; Fiorentino et al. 2014). The usage of mixed reality headsets allows for the elimination of current physical equipment that takes up space in the NDE session, i.e., inspected objects and evaluation devices.

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Fig. 1 The traditional hands-on training (left) versus mixed reality training (right) for nondestructive evaluation. The human face and the logos are blurred to protect the confidentiality



Fig. 2 The existing headsets. From left to right: **a** Oculus Rift S (4th generation), **b** HTC Vive, **c** Valve Index, **d** PlayStation VR, **e** Samsung Gear VR, **f** Epson Moverio, **g** Magic Leap One, **h** Microsoft HoloLens

It is worth noting that research needed in the area of mixed reality for integration with NDE technologies goes well beyond being able to produce virtual images that merge with the real-world surroundings on a headset display. Because nondestructive inspections are performed in precise locations on components, the position of objects in the real world (operator, instrument, probe, etc.) must be accurately represented relative to the position of the virtual object. The geometric transformation processes needed to perform these motions automatically as the operator and instruments move relative to the virtual object have not yet been developed. The justification of this need in the area of NDE is because execution of the inspection process will produce results that must be related back to an actual location on that part so that the flaw or defect can be further examined to determine safety of the component or if it needs to be replaced. In addition to the enhanced accuracy, research on methodologies for integration of NDE sensor data display with the mixed reality technology is also needed. This motivates us to combine mixed reality and NDE inspection technologies. In this paper, we conduct research on using mixed reality for NDE training. Figure 1 illustrates the setting of traditional hands-on training vs. mixed reality training in NDE. Our contributions can be summarized as follows. To the best of our knowledge, we are among the first ones who propose using mixed reality for nondestructive evaluation. We discuss the principal components of a viable method for revolutionizing inspection technologies. Further, we develop a workable prototype simulating the NDE training session. Last but not least, we conduct experiments to evaluate our proposed mixed reality system over the conventional training methods.

The remainder of this paper is organized as follows: Sect. 2 summarizes the background and related works. Next, Sects. 3 and 4 introduce the proposed system and the evaluation, respectively. Finally, Sect. 5 draws the conclusion and paves way for the future work.

2 Background and related works

In this section, we briefly review the popular headsets and mixed reality applications in the literature.

2.1 Headsets

A head-mounted display (HMD) is a display device, worn on the head, that has a small display optic in front of one (monocular HMD) or each eye (binocular HMD). A virtual reality headset is a head-mounted device that provides virtual reality for the wearer. VR headsets comprise a stereoscopic head-mounted display (providing separate images for each eye) and head motion tracking sensors. As mentioned in the review (<https://thewirecutter.com/reviews/best-desktop-virtual-reality-headset/>), some VR headsets such as Oculus Rift (<https://www.oculus.com>) and HTC Vive (<https://www.vive.com>) (Fig. 2a,b) have trackers, stereo sound, and gaming controllers. Later, more VR headsets are introduced for gaming, for example, Valve Index (<https://store.steampowered.com/valveindex>) and PlayStation VR (<https://www.playstation.com/en-us/explore/playstation-vr/>) (Fig. 2c,d). It is also worth mentioning Samsung Gear VR (<https://www.samsung.com/global/galaxy/gear-vr/specs/>). As shown in

Fig. 2e, a compatible mobile phone acts as the headset's display and processor, while the Gear VR unit itself acts as the controller. Most of VR headsets require a wired connection to a PC/laptop for the main computation. Therefore, it is really challenging to walk naturally in VR. Instead, the user has to use buttons on a gamepad or keyboard. In addition to VR headsets, binocular see-through headsets possess the transparent display. The headsets have mini-projectors to render the virtual objects in front of the user's view. Thus the users can see both the real environment with the augmented virtual objects. Two examples are the Epson Moverio (<https://epson.com/moverio-augmented-reality>) (Fig. 2f) and Magic Leap One (<https://www.magicleap.com>) (Fig. 2g). These headsets support head tracking and controller-based interaction. However, with a bulky battery, main processor, and the external controller, it is inconvenient to carry the headsets for a long time. Recently, the Microsoft HoloLens (<https://www.microsoft.com/en-us/hololens>) was introduced to resolve the problems of Epson Moverio (Fig. 2h). Its main processor and the battery are embedded onto the HoloLens headband. HoloLens is equipped with a built-in eye tracker in order to detect the user's eye gaze. Its field of view (FOV) is 34°. HoloLens also has front facing cameras and a depth sensor to perform the gesture recognition and spatial mapping. It also supports the voice recognition which provides total hands-free experience to the users.

From the list above, binocular see-through headsets such as HoloLens are the best candidate for the mixed reality application of NDE training. Therefore, we use HoloLens, particularly HoloLens 1, for the implementation in this work.

2.2 Mixed reality applications

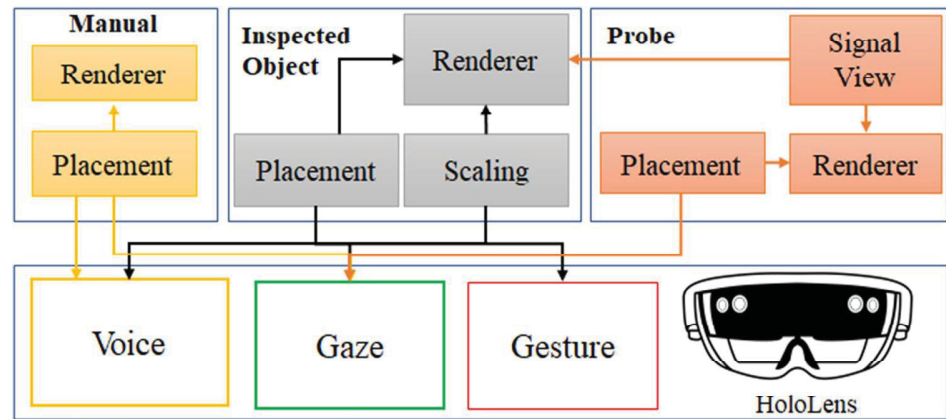
Here we briefly discuss the differences among VR, AR, and mixed reality. Virtual reality (VR) creates a sensory and psychological experience for users as an alternative to reality (Bohil et al. 2009). Virtual reality applications can range from simple desktop applications, wherein the virtual environment is presented in a window on the desktop, to immersive motion platform systems that provide users with a complete virtual experience (Burdea and Coiffet 2003). The world of systems can be divided into non-immersive and immersive approaches. The most basic non-immersive configuration is a virtual world in a window on a computer screen. This modality is, indeed, the basis for many computer games and online environments such as Second Life (<https://secondlife.com/>). Immersive virtual reality systems seek to place the user in a virtual environment. The most compelling VR systems are immersive, so termed because they immerse the senses of the user in computer controlled stimuli. In the immersive environment, the users only see the rendered virtual world. In augmented reality, the user is provided with additional computer generated information that

enhances their perception of reality (Carmigniani et al. 2011; Ma et al. 2014). The majority of AR applications relies on tracking marker. Markers are visual cues which trigger the display of the virtual information (<https://anymotion.com/en/wissensgrundlagen/augmented-reality-marker>). A piece of paper with some distinct geometries can be used. The camera recognizes the geometries by identifying specific points in the drawing. There are other AR applications not relying on markers, for example, Wikitude (<https://www.wikitude.com/geo-augmented-reality/>), Pokemon Go (<https://www.pokemongo.com/en-us/>). Mixed reality is the merging of real and virtual worlds to produce new environments and visualizations, where physical and digital objects co-exist and interact in real time. Mixed reality does not exclusively take place in either the physical or virtual world, but is a hybrid of reality and virtual reality, encompassing both augmented reality and augmented virtuality via immersive technology (Milgram and Kishino 1994). Mixed reality allows users to see the real world with the augmented virtual objects. The mixed reality headsets, HoloLens (<https://www.microsoft.com/en-us/hololens>), utilize spatial mapping which accurately detects the real-world environment, such as the locations of walls and points of intersection.

In the literature, there are many AR/VR/MR applications in different scenarios. Virtual reality is mainly used for games and simulations in different aspects, i.e., training and rehabilitation purposes (Bozgeyikli et al. 2018; Christou et al. 2018; Nguyen and Sepulveda 2016). Augmented reality can also be used for training via interactive manual scenarios (Henderson and Feiner 2009, 2011; Fiorentino et al. 2014; Crescenzo et al. 2011). Henderson and Feiner (2009, (2011) developed a prototype for military mechanics to perform maintenance tasks inside an armored vehicle turret. Fiorentino et al. (2014) conducted a research of applying AR on large monitor for interactive maintenance instructions. However, these works (Henderson and Feiner 2009, 2011; Fiorentino et al. 2014) solely use binary markers next to the objects that need the augmented reality content. It is indeed unnatural to adhere binary markers in the actual scenarios. Meanwhile, Nguyen et al. (2016) have introduced a user-friendly application creating interactive manuals from mobile devices. Given a reparation scenario, the system allows the trainer to create the interactive manuals. In the meantime, the trainee can download the manuals to repair his/her own stuff based on augmented reality instruction.

Regarding applying mixed reality for NDE training, Moro et al. (2017) showed that both VR and AR as effective teaching tools, where student learning is as successful as with tablet-based application. Avgoustinov et al. (2011) discussed both accessibility and usability of virtual reality for NDE from the aspects of technical and economical viewpoints. They also discussed the key aspects for methods and tools in order to become generally accepted and well-established.

Fig. 3 Our proposed mixed reality system for nondestructive evaluation



However, there is no practical system developed from this paper. In another work, Omer et al. (2018) performed the bridge evaluation by using virtual reality. The bridges were scanned by a Lidar scanner. The scanned bridges are later added into the virtual environment. In their work, the users cannot see the real environment and move naturally. Instead, they interact with the virtual objects via a remote controller. This really causes inconvenience to the end-users. Meanwhile, Amza et al. (2018b) applied AR for NDE by using fixed markers. However, the imperfection of tracking or detecting markers may affect the user's experience. From the literature review, the mixed reality application in NDE is worth further investigation to overcome the drawbacks of AR and VR. Therefore, in this paper, we propose a new mixed reality system which supports the operator trainees with NDE scenarios.

3 Proposed framework

In this section, we introduce our proposed framework. Our proposed system is designed under a modular design approach in order to improve re-usability, extensibility, and re-configurability in various application contexts. Figure 3 depicts the major components, namely headset input components and NDE components. The target headset is HoloLens as we discussed.

3.1 Headset input components

The HoloLens allows users to use their voice, hand gestures and gaze to interact with virtual objects and applications (<https://docs.microsoft.com/en-us/windows/mixed-reality/>).

3.1.1 Gaze input

Gaze is the basic form of input and is a primary form of targeting within mixed reality environment. Gaze determines the location where the user is looking in the real

world. First, HoloLens continuously scans the real environment in order to map the real-world surfaces with the virtual world. This process is called *spatial mapping*. Then, HoloLens detects the gaze information including the position $g(x_g, y_g, z_g)$ and the direction $f(x_f, y_f, z_f)$ of the user's head. This gaze direction vector f can be considered as a laser pointer straight forward from the gaze position g . The detected gaze information is later mapped to the virtual environment via the spatial mapping process. As the user looks around the room, the system intersects the ray starting from g with the direction vector f to determine what virtual object the user is looking at.

3.1.2 Gesture input

The users can also interact with virtual objects and applications using hand gestures. Once an interaction has started, relative motions of the hand may be used to control the gesture, as with the manipulation or navigation gesture. Hand gestures do not provide a precise location in space, but the simplicity of putting on a HoloLens and immediately interacting with content allows users to get to work without any other accessories. Figure 4 shows the sequence of the "air tap," a recognizable gesture by HoloLens.

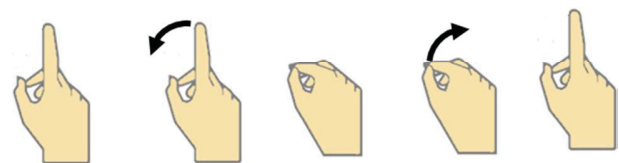
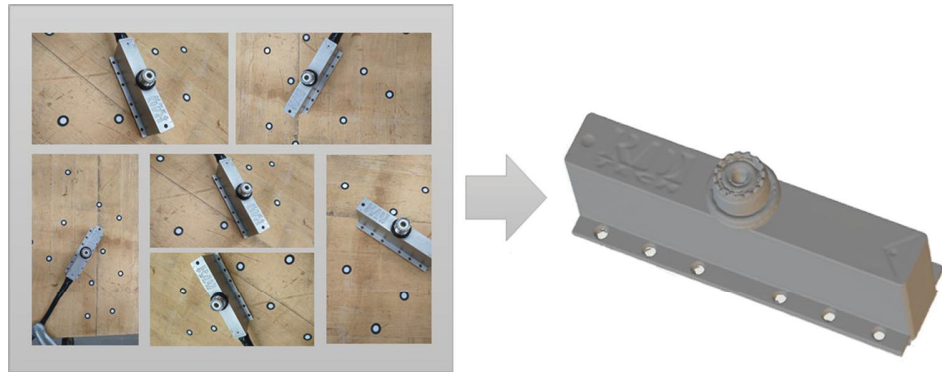


Fig. 4 The sequence of the recognizable "air tap" gesture by HoloLens (<https://docs.microsoft.com/en-us/windows/mixed-reality/>)

Fig. 5 The exemplary creation of a 3D model of the inspection probe, an ultrasound transducer, in our system



3.1.3 Voice input

Voice input is another natural way to communicate the user's intent. This allows the user to directly command a virtual object without having to use gestures. The user simply focuses on the virtual object and speak out his/her command. Using voice is especially good at traversing complex manual guidance because it lets users cut through nested menus with one command. We utilize some simple voice commands such as "larger size," "smaller size" to change the inspected object's size; and "probe one," "probe two" to change the inspected object.

3.2 Proposed NDE components

3.2.1 Object renderer

There exist two sets of objects in an NDE application, namely the inspected objects (parts) and the probe. The first challenge is to obtain the 3D models simulating these objects and render them onto the virtual environment scene. The creation of 3D models may require some 3D professional designers. In our project, we obtain 3D models via structure from motion (SfM) software. In particular, we used a Creaform HandySCAN 700.¹ This uses stereo optical views of a deformed laser grid pattern to generate a point cloud from the captured photos, which is then later meshed, all within Creaform's vxElements software.² The tracking dots are used for registration and are required to track the position of the scanner (and therefore the location of the scanned point cloud at each location) in space. There may exist some holes or some unused meshes in the scanned model. However, these can be fixed via simple mesh manipulation on available software (<http://www.meshlab.net/>). Figure 5 shows an

exemplary creation of the probe model which is an ultrasound transducer in our system. Note that these scanned 3D models are lightweight and then can be used to be placed into the virtual environment scene. As a result, these models are able to be rendered in a real-time manner.

3.2.2 Inspected object component

The scanned inspected object is inserted as a virtual object later shown in the application. In particular, we use a model of a metal ring, a reference used for standardization of NDE probes. The ring contains embedded targets of varying sizes and depths, resulting in varying sensor responses at those locations. The inspected object has a transform's information which can be modified by using a transformation matrix. Note that the transformation matrix can be used to perform linear transformations such as translation, rotation, scaling, or shearing in 3D.

The detected gaze information can be used to place the inspected object in the virtual environment. First, the user can do an "air tap" to summon the inspected object appearing in front of the gaze position. Then, the inspected object is moved along with the transition of the user's gaze. Once the object is placed at the appropriate position, the user can do another "air tap" to release object. In addition, the user can use voice command to control the object, i.e., changing the size of the object. As shown in Fig. 6, the inspected object appears in front of the user upon an "air tap." The object's size is gradually changed from a *small* size to a *very large* size. It can also be placed down to the floor, and on top of a table. This shows the flexibility of the mixed reality system.

3.2.3 Manual component

For a first-time user, the manual is very important to show the guidance of using the mixed reality application. In our system, the user can use voice to show/hide the manual panel. To display text, we use a quad object (quadrilateral mesh) placed in front of the user's gaze and display the text on top of the quad object. By default the text may appear blurry and large. Therefore, we need to tweak a few variables

¹ <https://www.creaform3d.com>.

² Alternatively, the captured photographs can be fed into a free off-the-shelf SfM software/service like Autodesk Recap 360 (<https://www.autodesk.com/products/recap/overview>) to turn the photos into a 3D model.

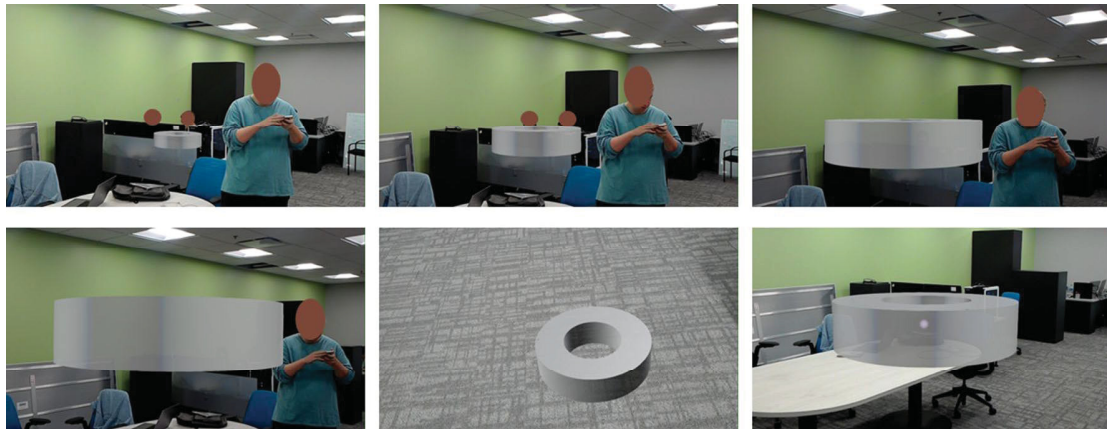


Fig. 6 The control via voice, gesture, and gaze in our system. From left to right, top to bottom: the inspected object in the small size, the medium size, the large size, the very large size, the floor placement, and the table placement

Fig. 7 The computation of the angle formed by the HoloLens raycast and the object anchor points (in yellow) (color figure online)

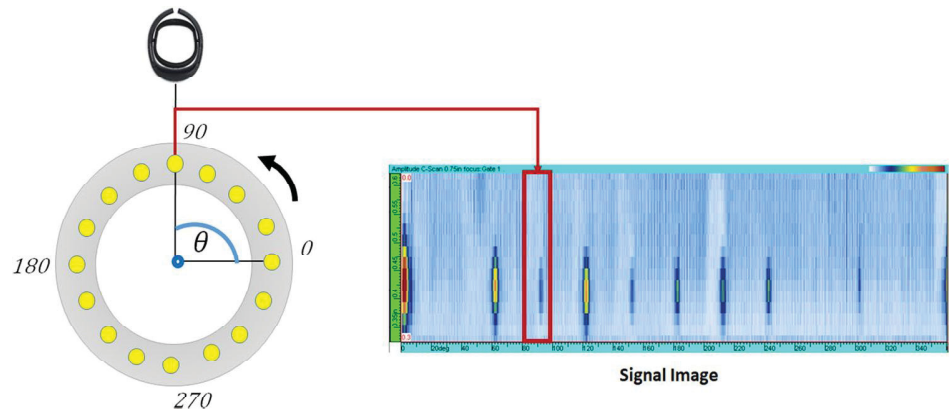


Fig. 8 The demonstration of our system: **a** the manual view panel in our system, **b** the probe with the inactivated signal view due to no inspected object, **c** the probe with the inactivated signal view due to

the lack of focus to the inspected object, **d** the probe with the activated signal view (the scanned angle is highlighted)

to get sharp, high-quality text that has a manageable size in HoloLens. For example, by applying scaling factor to get proper dimensions, we can achieve better rendering quality. Regarding the *placement*, the manual is placed virtually 0.45 meters in front of the user gaze position g . This distance is shown to be comfortable³ to the viewers. Figure 8a demonstrates the manual view panel in our system.

³ <https://docs.microsoft.com/en-us/windows/mixed-reality/text-infinity>.

3.2.4 Probe component

As mentioned earlier, we model the probe which is an ultrasound transducer. There are two configurations of the probe for horizontal and vertical orientations for different inspection tasks. Each of them is activated via the voice command, i.e., “probe one” or “probe two.” And it is placed at the position p , virtually 0.2 meters in front of the user gaze position g .

The first challenge is how to map the user viewpoint with the signal view. The signal view here is actually a quad object whose texture is obtained from captured signal image. Since we model an ultrasound transducer as the probe, we use the ultrasound signal obtained from a real ring object as the signal image. We first compute the hit point $h(x_h, y_h, z_h)$ which is the intersection between the aforementioned gaze vector g with the direction f and the object's mesh. Mathematically, the hit point h can be defined as:

$$h = g + t \times f, \quad (1)$$

where t is the distance from the gaze to the object hit point. Here, t is positive since the hit point h is in front of the ray's gaze. ∞ is returned if no hit point h is found. In practice, there are some anchor points for the NDE operator to operate the NDE session (the yellow dot at 0° position in Fig. 7 is considered as the starting point). Therefore, we also simulate the anchor points in the NDE virtual environment. In particular, each inspected object o is embedded with n_o anchor points a_i . We set the inspected object's transform as the parent transformation of the anchor points. In other words, every transformation change with the parent object (the inspected object) will affect the anchor points. Note that the anchor points are set invisible so that they do not interfere with the simulated training environment. If the hit point h is found, we identify the active anchor point a_{i^*} which is the nearest anchor point to h as follows:

$$i^* = \arg \min_i \|h - a_i\|_2, \forall i \in \{1, \dots, n_o\}, \quad (2)$$

where $\|\cdot\|_2$ is the ℓ_2 distance between the hit point h and the anchor point a_i . Then the corresponding region in the signal view is highlighted. Figure 7 illustrates the angle computed from the user's viewpoint and the object anchor points.

The second challenge is where to place the signal view. In fact, there are many conventional options to locate the signal view, i.e., at the corner (top left, top right, bottom left, or bottom right) or at the screen center. In this sense, the signal view occludes the virtual objects like the inspected object or the probe. In order to overcome this issue, we align the signal view with the probe. In particular, we attach the signal view next to the probe handle (as seen in Fig. 8b,d). We set the probe as the parent of the transform of the signal view. Changing the parent will modify the parent-relative position, scale and rotation but keep the world space position, rotation and scale the same. We only enable and update the signal view if the probe is close to the object center. To do this, we activate the signal view once the following condition is satisfied:

$$\frac{d_{hp}}{d_{hc}} < \tau, \quad (3)$$

where d_{hp} is the distance of the hit point h to the probe, and d_{hc} the distance of h to the inspected object center c . The

Table 1 The functionality comparison of the existing and proposed methods

	Paper-based training	Hands-on training	Mixed reality training
Lightweight setting	✓		✓
Easy accessibility	✓		✓
Pervasive portability	✓		✓
Immersive experience		✓	✓
Scalability			✓
Technology dependence		✓	✓
Low cost	✓		✓

threshold τ is empirically set as 0.1. Figure 8 demonstrates the probe along with the signal view in different scenarios.

3.3 Implementation

We developed our proposed system with Unity3D engine for Mixed Reality⁴. The main reasons are threefold. First, Unity3D engine supports drag-and-drop game design which facilitates our implementation. Second, Unity3D provides a wide range of available libraries, packages, and resources that make it simple to realize a mixed reality application. Third, the engine also supports cross-platform which helps us build and run the application to different devices including HoloLens. We insert the scanned inspected object and the scanned probe into the Unity scene. We write the script (in C# programming language) for each object instance. For example, we display the manual based on the gaze position and the gaze direction. We enable the voice recognizer to recognize the user's voice input. In addition, we attach the invisible anchor points to the inspected object. We set the probe as the parent of the transform of the signal view. In order to compute the raycast hit point h , we apply the mesh collider onto the inspected object model.

4 Evaluation

In this section, we evaluate the proposed system with the two traditional training methods, namely paper-based and hands-on training. The assessment will be conducted via a functional comparison and a user study.

4.1 Functionality comparison

Table 1 summarizes the functionality comparison of the three training methods. All the methods are compared in

⁴ <https://unity3d.com/partners/microsoft/mixed-reality>.

terms of the lightweight setting, easy accessibility, pervasive portability, immersive experience, scalability, technology dependence, and low-cost. Hands-on training obviously dominates regarding the immersive experience, the most important criterion, since the trainees directly interact with the inspected object and the probe. However, this training method is limited in terms of lightweight setting due to the bulky inspection device and the heavy inspected object. Meanwhile, the paper-based training shows its strength about lightweight setting, easy accessibility, pervasive portability, and low cost. However, the trainees totally lack the necessary hands-on experience.

Our proposed method with mixed reality training achieves all criteria. In particular, the trainees are able to undergo the training with a lightweight setting. A single headset is only required for this training manner. In addition, this way of training is able to scale up (scalability). New inspected objects can be easily added into the system. This is very important since possessing and cloning inspected objects are very challenging and unrealistic in practice.

4.2 User study

We follow (Kaur 1997) for the design methodology, namely requirements specification, gathering of reference material from real world objects, structuring the graphical, building objects and positioning them in the virtual environment, enhancing the environment with texture, lighting, sound and interaction. We updated the text accordingly. We follow the study in Suárez-Warden et al. (2015) for the sample size. There are in total 20 participants whose ages ranged from 18 to 55 years ($\mu = 28.9$) taking part in the user study. All participants are NDE trainers and trainees from the university and the research institute. Among them, seven participants are female. They are requested to try all methods in a random order. The training content is provided by the experts (https://udayton.edu/udri/capabilities/materials/nondestructive_evaluation.php). The evaluation mainly focuses on the usability. We provide the instruction about the experiment. We brief the participants about different training methods. Later we show the questions and ask for the feedback. Following (Nguyen et al. 2018; Gopalan et al. 2016), the participants were requested to indicate their satisfaction with respect to the following perspectives:

- Ease of use: Was this method easy to use?
- Convenience: Was this method convenient?
- Experience: Did the method help you experience the training?
- Preference: How do you prefer the method over the others?

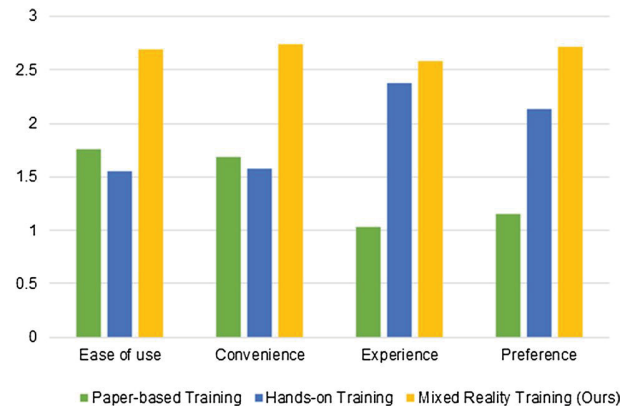


Fig. 9 The mean/average scores from the conducted user study evaluation. Our proposed method yields the best performance for all criteria, while the conventional methods perform worse

For each criterion, the participant ranks each method on a 3-point modified Likert scale as in Nguyen et al. (2012), Nguyen et al. (2018) from the best (3) to the worst (1). The modified Likert scale aims to avoid the duplicate rating scores. Figure 9 depicts the mean/average rating scores of different methods. The paper-based baseline yields the lowest score in experience due to the lack of hands-on experience in the training. However, paper-based training is highly rated in terms of the ease of use and convenience. Meanwhile, the hands-on training has a high score in terms of experience. Some participants prefer the hands-on training over the other two due to the “touch” sense. Even though the hands-on training is not highly appreciated in terms of *ease of use* and *convenience*, it is preferred than the paper-based training for the *preference*. This shows the importance of the actual experience. Generally, our proposed system outperforms others in all aspects. First, our system is easy to use. After few trials, the participants can get used to the system to perform their own tasks. Second, there is no strict requirement for space. In addition, the participants appreciate the object manipulation, i.e., *scaling*, or *placement*, enhancing their experience.

Next, we conduct the significance test to answer the question whether the user ratings of two methods are equivalent, for example, $r(\text{EU}_{\text{MR}}) = r(\text{EU}_{\text{Paper}})$, where $r(\text{EU}_{\text{MR}})$ and $r(\text{EU}_{\text{Paper}})$ are the user ratings with regard to the ease of use from mixed reality training and paper-based training, respectively. In particular, a significance test is applied to test the null hypothesis $H_0 : r(\text{EU}_{\text{MR}}) = r(\text{EU}_{\text{Paper}})$ against the alternative one $H_1 : r(\text{EU}_{\text{MR}}) \neq r(\text{EU}_{\text{Paper}})$. To this end, we compute p-values using the Wilcoxon signed rank test (Wilcoxon 1992) for paired comparison between every two method ratings. Table 2 shows p-values of every two compared method ratings (X_A and X_B), where X is the rating in terms of ease of use (EU), convenience (CV), experience

Table 2 Wilcoxon signed rank test with p -values of every two compared method ratings

	X_{MR}, X_{Paper}	$X_{MR}, X_{Hands-on}$	$X_{Hands-on}, X_{Paper}$
Ease of use (EU)	0.00850	0.0002	0.2418
Convenience (CV)	0.00370	0.0001	0.5276
Experience (XP)	0.00001	0.5127	0.0001
Preference (PR)	0.00006	0.0276	0.0007

(XP), and preference (PR), respectively. Meanwhile, A and B are the two compared methods, for example, Mixed Reality, Hands-on, and Paper-based methods. As shown in Table 2, p -values of mixed reality training and paper-based training are < 0.05 meaning that the null hypothesis is rejected to the two methods. Thus, the differences between two methods are statistically significant. Likewise, the null hypothesis is rejected to MR and hands-on in terms of EU, CV, and PR. However, p -value of mixed reality training and paper-based training with regard to experience is > 0.05 meaning that the null hypothesis is true. In other words, mixed reality training and hands-on training share similar user experience. Regarding hands-on and paper-based training, their differences are significant in terms of XP and PR (not with EU and CV).

The results show that the mixed reality training approach is preferred by trainers and trainees alike. The trainers appreciated the ability to display technical instructions on a screen during the simulated inspection, as well as the ability to provide the student with a virtual 3-D model of the component being inspected. The trainees appreciated the ability to visualize the size and geometry of the structure to be inspected prior to actual hands-on training with the component. This really demonstrates that the use of mixed reality training provides significant benefits for potential technician trainees. The participants mention that they can simultaneously interact things along with the manual instructions from the system instead of interrupting the process by refer back and forth to the manual booklets/slide deck. The participants also suggested to apply our system to more complicated structural inspection. In addition, our proposed platform is not restricted to the NDE sector only. It can be utilized in other domains, i.e., maritime, health care, and city planning.

5 Conclusions and future work

In this paper, we have introduced a novel mixed reality system for nondestructive evaluation (NDE) training. Given an NDE scenario, the system allows operator users to interact with the virtual objects. In the meantime, the users are able to perform the NDE operations such as inspecting object and reading signal from the signal view. The proposed system

shows its prominence in terms of the lightweight setting, easy accessibility, pervasive portability, immersive experience, scalability, technology dependence, and low cost. The user study indicates that our system is preferred for the NDE training.

For future work, we are aiming to improve the current system. For example, we plan to add different kinds of inspected objects with their corresponding signal. We can also add more probes. We are also interested in future development of inspections for other components. We also look forward to an authoring system to allow trainers to design NDE training scenarios. Finally, we believe this work can inspire more research in the future on using mixed reality application for NDE training. We expect the release of modern headsets in the future with more advanced features help us improve the system. For example, the hand detection and tracking in the next generation headset can be used to place the signal view in order to make it more realistic.

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