An Interactive Digital Twin of a Composite Manufacturing Process for Training Operators via Immersive Technology

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Abstract. Recently, there has been a growing interest in digital learning platforms and immersive technology for teaching, e.g., complex machine operators. This study investigates the use of a Mixed Reality (MR) system for operator training in a thermoforming case study, emphasizing the significance of user interface (UI), user experience (UX), and usability in MR applications. The work proposes a spatial user interface (UI) for MR applications that enables users to interact with virtual objects in the actual environment. Moreover, to enhance the UX, a real-time 3D heat transfer simulation was developed and integrated into the MR application to allow the learner to monitor and control the manufacturing process closely. The proposed framework is validated by an MR headset (Microsoft HoloLens 2). Lastly, a user study with eight participants was conducted, which showed the usability of the app using the System Usability Scale (SUS) questionnaire, scoring an overall usability rate of ~85/100.

Keywords: Mixed Reality, Immersive Training, User Study, User Interface, User Experience.

1 Introduction

Recently, a variety of applications, including training, education, and safety, have seen an upsurge in the usage of Extended Reality (XR) systems [1]. The manufacturing industry is a unique instance of this universal trend. Particularly, there is a growing interest in using immersive technologies for complicated machine operators and workforce training. Milgram et al. [2] defined a taxonomy, which is well-known today among various XR platforms, beginning with Mixed Reality (MR) as a technology that brings together 3D content and the physical world; Augmented Reality (AR) as a perspective of the physical world with additional computer-generated features; and Virtual Reality (VR) as a single virtual environment separated from the real world [3]. In recent years, the adaptation of MR applications has particularly evolved owing to the introduction of new enabling equipment.

To exemplify, Reyes et al. [4] designed and analyzed a MR guiding system for motherboard assembly with 25 participants. Their research indicated that participants with

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prior experience with AR performed much better at orienting and arranging various motherboard components than those who had merely access to the actual setup. According to the authors, the system provided reasonable dependability and may be preferable for experienced users. In another study, Rokhsaritalemi et al. [5] provided a framework for developing MR applications, including user interaction components. Their suggested approach can help researchers create more effective MR systems for industrial training in harsh situations.

1.1 User Interface (UI), User Experience (UX) and Usability in MR Applications

MR applications feature distinct UIs compared to standard digital training systems, since they use wearable technology to superimpose virtual content on the physical surroundings. MR may not only alter a user's perspective of the actual world, but it also enriches the UX in the actual world instead of replacing it [6]. A significant benefit of adopting MR headsets is that they enable users to move freely inside the MR world [7]. Moreover, vision-based wearable devices allow users to engage with the MR world utilizing hand gesture controls [8]. Since its debut, Microsoft HoloLens has been regularly evaluated by developers and academics from many perspectives [6], [7]. While the current HoloLens offers several advantageous features that distinguish it from other MR HMDs, it also has some technical limitations. For instance, the restricted field of view (FOV) of HoloLens has a negative influence on the system's usability and user experience (UX).

Thus, building a personalized UI for HoloLens applications is a potential way to improve UX [9]. When compared to its predecessor (Microsoft HoloLens 1), Pose-Dez-de-la-Lastra et al. [10] studied the use of Microsoft HoloLens 2 in orthopedic procedures and discovered that it had a nearly 25% increase in AR projection accuracy. Nguyen et al. [11] Developed a MR system for nondestructive evaluation (NDE) training that lets students interact with virtual objects and execute NDE procedures without causing them injury. Their user study favoured the MR-based NDE training method over conventional training methods.

Under the framework of Industry 4.0, Pusch et al. [12] considered the use of MR for operator training. The authors assess the efficacy of three prototypes, including a haptic tablet, a large screen, and a Microsoft HoloLens-based MR version. Feedback indicated that, despite ergonomic limitations, the MR version has the potential to replace existing training techniques and even enable novices to complete the training independently. However, further tests were recommended to generalize these findings. Wu et al. [13] proposed a visual warning system that combines digital twins, deep learning technology, and MR using HoloLens to enhance the safety of construction workers. Testing revealed that the system operates effectively, but more improvement is necessary to solve lens distortion, image-based prediction function, and manual alignment. The applicability of a MR environment for instructing construction engineering students about sensing technologies was also investigated by Ogunseiju et al. [14]. Using eye tracking, usability questionnaires, and verbal feedback, their research assessed the MR environment and discovered that the accuracy of characterized construction activities, the quality of animations, and the ease of access to information and resources are crucial for building effective MR learning environments. Unfortunately, there is still a scarcity of literature on customized UI design for mixed-reality apps employing headsets.

1.2 Objective and Practical Motivation

Here we first designed a spatial UI for the HoloLens application as part of a digital learning prototype enabling user interaction with a combination of virtual content and a real thermoforming set-up. Adhering to UX design principles, the prototype was evaluated via a user study to verify its usability. Thermoforming requires strict adherence to unique sequences of steps to avoid nonuniform thickness distribution (defect) in the final product. Therefore, the present case study is critical to explore MR's potential in such advanced and high-risk manufacturing settings. To simulate the process, the system's 3D heat transfer behaviour amongst digital assets such as heaters and sheets has been simulated (via numerical finite difference method; more details can be found in [15]) and integrated into the MR headset (Microsoft HoloLens 2).

2 Methodology

The proposed XR design workflow is demonstrated in Fig. 1. In the first step, 3D asset and UI elements are designed using the Mixed Reality Toolkit (MRTK), SolidWorks, and ProBuilder feature in Unity. In step 2, objects are imported to Unity 3D scene, and additional visual and audio effects are added. Next, in step 3, the XR development process is accrued out, where all the scenes are designed, and all the virtual elements are added. In steps 4 and 5, objects interactive behaviour, animations, user input systems, and real-time 3D heat transfer simulation among certain elements (heaters and sheet) are developed in C# and deployed to the scene using Visual Studio and Unity.

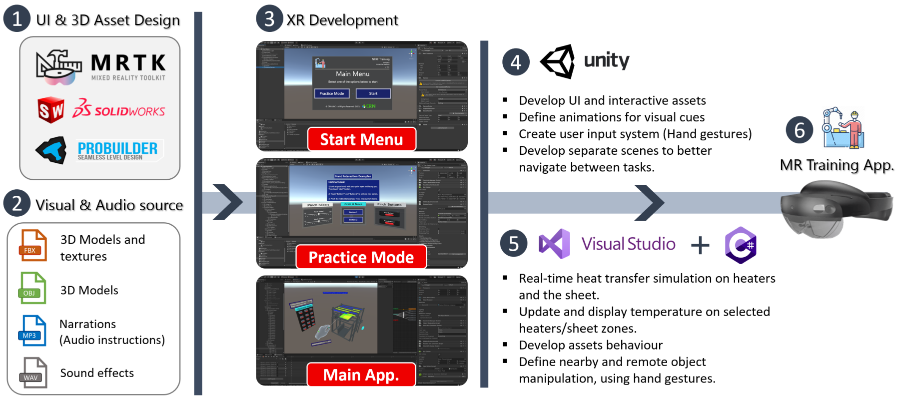


Fig. 1. – The present MR application design framework

2.1 UI and UX Design

The methodology for the UI design for HoloLens 2 encompassed a range of UX principles. These included cognitive metrics, physical characteristics, the design of ambient elements, and the provision of visual and auditory instructions. To avoid strain on the user's neck, the spatial UI environment was designed such that the user can grab and move the virtual object to best fit in their comfortable range of height. Since the training procedure involved direct object manipulation, a critical design factor included the size of the object that needed to be manipulated as well as the distance from the viewer's eyes. In terms of system characteristics (hardware and software) of the HoloLens, scenes that are heavily populated with 3D objects or overloaded with scripts that constantly update the objects render may cause lagging and a frame rate drop from 300-320 to 20 frames per second (FPS). Higher frame rates produce more detailed visualizations when observing single virtual objects. Therefore, to avoid a low frame rate in the development stage, some modifications were made to reduce the resolution of the heat transfer simulation to compensate for hardware limitations, which resulted in higher frame rates (up to 85 FPS) even in densely populated scenes.

Visual and audible instructions are crucial for maintaining user engagement and attention in the application. To ensure that the operator clearly understands the virtual environment and its interactive elements, a 'tag-along' methodology [16] was employed to provide the user with visual prompts to complete specific tasks. Audio prompts and instructions were also used to compensate for the lack of visual information within certain unpopulated areas of the virtual space, which led to a higher quality of the UX.

The main features of the UI/UX design in the MR developed app are as follows:

- Practice mode in a separate scene to allow the users to get used to HoloLens 2 input system.
- Voice and visual text instructions (cues) for each training step.
- UI menus constantly follow the user to avoid limited FOV in HoloLens 2 and loss of content in the interface.
- Remote object manipulation (resizing, moving, rotating) designed to help the user better access and interact with objects.
- Spatial Audio (360) to help the user better navigate and find objects (with sound effects) which might not be visible in the user's FOV.
- Hand menu options allow the user to restart a training step, go to the main menu, or change scenes between practice mode and training.
- Various sound/visual behaviours on interactable objects (pinch, touch, grab, hover) for a better immersion experience.

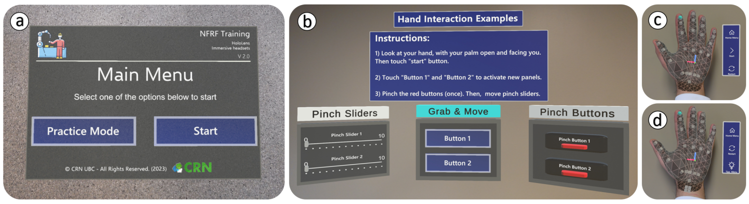
2.2 User Study and Data Analysis

For assessing the developed MR application's usability, the System Usability Scale (SUS) [17] was used as a standard evaluation method. Once the user study was conducted, the correlations between pairs of the SUS questions (using the participants' responses) were statistically analyzed via the Spearman rank-order correlation coefficients. To further analyze the reliability of the SUS and the survey, Cronbach's alpha [18], as a measure of internal (mean) consistency of the data, was also calculated (theoretically, the values can vary between 0 to 1).

3 Results and Discussion

3.1 MR Application

Figure 2 shows the start menu and practice modes of the app., each with various UI features allowing the user to explore and acquaint themselves with the input system of the HoloLens 2. Fig. 3 displays the steps of user training within the MR application. The application was simplified by displaying only important interactive features in each phase, and a control panel, which controls power adjustment and on/off switch functions. A screen also displayed the real-time temperature and power usage of each heater.



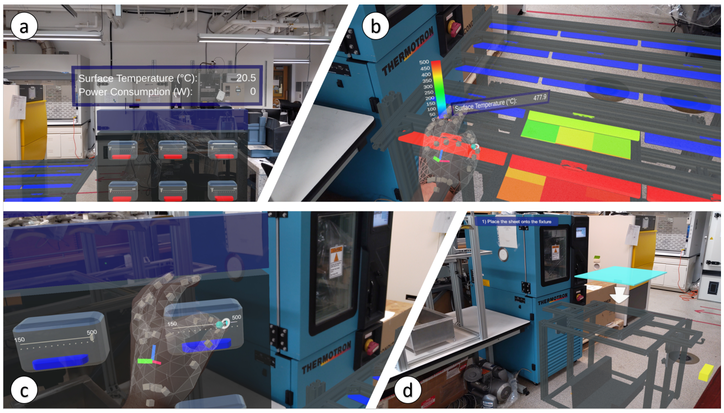
Instructions:

1) Look at your hand, with your palm open and facing you. Then touch "start" button.

2) Touch "Button 1" and "Button 2" to activate new panels.

3) Pinch the red buttons (once). Then, move pinch sliders.

Fig. 2. Screenshots from the “Main Menu” and “Practice Mode” scenes of the MR app. a) shows the available options once the application starts. b) Practice scene options, which allow the user to explore hand interactions (touch, pinch, grab, move, and scale) before testing the Training application. c) Near-Hand menu in Practice Mode. d) Near-Hand menu in Training Application.



1) Place the sheet onto the fixture

Fig. 3. – Features of the developed digital twin for training thermoforming operators. a) Control panel provides the info screen, showing the surface temperature distribution and the power consumption of heaters. b) Visualizing the heater’s surface temperature by hovering the hand over a selected heater. Once the heater is pinched, a visual heat bar guide is also shown on the side. c) Adjusting the heater's power range using the slider. d) Text instruction and the guiding arrow are facing the operator.

3.2 User Study

Eight participants with different backgrounds were recruited to test the MR application and provide feedback. Fig. 4 depicts their responses on Likert Scale (from strongly disagree to strongly agree). Table 1. also demonstrates the total score obtained from the SUS questionnaire. With the overall mean of 84.34 (out of 100) and the median of 86.25, the study suggests that the participants have indicated a high usability rate.

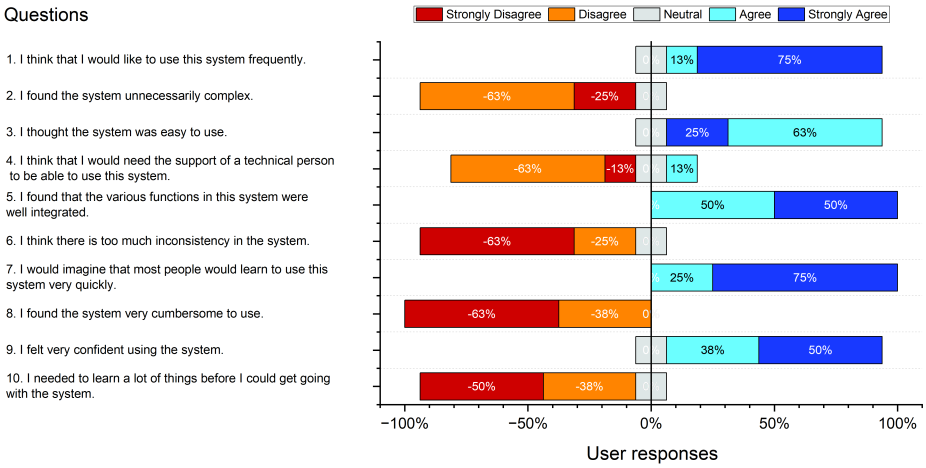


Fig. 4. Users responses distribution on the System Usability Scale (SUS), ranging from strongly disagree to strongly agree. Notice that some of the SUS questions are deliberately (by the standard) set in a negative form (i.e. in these cases 'strongly disagree' is the top rate).

Table 1. The SUS score for different users of the MR application

User ID	#1	#2	#3	#4	#5	#6	#7	#8
Survey points	40	23	33	31	35	37	37	34
SUS Score	**100**	**57.5**	**82.5**	**77.5**	**87.5**	**92.5**	**92.5**	**85**

After performing the statistical analysis of the responses, it was found that some questions within SUS were significantly correlated when using a significance (alpha) level of 0.05. Results of the Spearman analysis indicated that there were some significant positive correlations between the following pairs: questions 1 and 9 (r = 0.717), questions 3 and 9 (r = 0.737). Similar significances were found for some negative-form questions: questions 4 and 8 (r = 0.71), questions 4 and 10 (r = 0.732), and questions 8 and 10 (r = 0.802). Of course, it is possible that the observed correlations might not also be fully logical due to the small sample size. Hence, the Cronbach's alfa mean metric was next calculated to estimate an 'overall internal consistency' measure of the survey, without relying on a particular significance level. The Cronbach's alfa mean was 0.879, indicating that the SUS questions and responses have been relatively consistent.

Of particular note, among the questions, based on Fig. 4, the speed of learning via the MR app (question 7) was highly noted (all participants rated as 'agree' or 'strongly agree').

During the qualitative assessment phase of data collection, participants were also given minimal instructions to operate the HoloLens application. However, some participants required further guidance to use the HoloLens HMD independently. This suggested that developing the necessary skillset through practice is crucial for users to control the virtual environment effectively. With regard to physical aspects and variations in individuals' heights within the test group, potential safety concerns were observed when utilizing the HoloLens HMD. Another issue that emerged during the testing phase concerned the HoloLens2 direct manipulation input model. While general gestures are intuitive, the pinch gesture for grasping augmented objects has been judged non-intuitive because the fingers appear to pass through the objects themselves.

4 Concluding Remarks

This study investigated how a MR system could be developed and used to train thermoforming manufacturing operators. The user study (with 8 participants in a university lab environment) emphasized the significance of UI, UX, and usability in MR applications. A spatial user interface was developed for the MR application, enabling users to interact with virtual items in the physical surroundings. In addition, a real-time 3D simulation of the heat transfer phenomenon in the process was developed and included in the application to enhance the UX. The suggested architecture was tested using a Microsoft HoloLens 2 headset. Participants indicated that the app was usable, with an overall usability score of ~85 out of 100, based on the System Usability Scale (SUS) questionnaire. Internal consistency of the survey data was also evaluated as satisfactory, suggesting that the SUS responses have been useable despite the limited sample size.

Some limitations were observed during the development of the application, including the need for assistance from users to better utilize the HoloLens app, emphasizing the significance of prior practice with the HMD. Additionally, variations in individuals' heights raised potential safety concerns during testing. Moreover, the pinch motion was considered non-intuitive as the fingers appeared to pass through the augmented objects. However, this is directly related to the HoloLens input system and hand gestures, which cannot be modified in the current version. Future research options may also involve targeting participants with other relevant backgrounds, such as industrial technicians. Additionally, incorporating uncertainties into the thermoforming process during training may be beneficial for simulating real-world manufacturing scenarios.

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