Towards Augmented Reality Guiding Systems: An Engineering Design of an Immersive System for Complex 3D Printing Repair Process

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(a) (b) (c)

Figure 1: (a) A person wearing the HoloLens 2 AR headset for carrying out 3D printer nozzle replacement; (b) clotted 3D printer nozzle; and (c) visual, textual and CAD-based aids (adopted from *GrabCAD* [35,36]) for the second step of the printer repair process.

Abstract

Over the past decade, *additive manufacturing* (AM) has become widely adopted for both prototyping and, more recently, end-use products. In particular, *fused deposition modeling* (FDM) is the most widespread form of additive manufacturing due to its low cost, ease of use, and versatility. While additive processes are relatively automated, many steps in their operation and repair require trained human operators. Finding such operators can be difficult, as highlighted during the recent COVID-19 pandemic. *Augmented reality* (AR) systems could significantly help address this challenge by automating the training for 3D printer operators. Given multidimensional design choices, however, a research gap exists in the system requirements for such immersive guidance. To address this need, we explore the applicability of AR to guide users through a repair process. In that context, we report on the system design as well as the results of the AR system assessment in a qualitative study with experts.

Index Terms: Human-centered computing—Interaction design—Empirical studies in interaction design—; Human-centered computing—Visualization—Visualization design and evaluation methods——Computing methodologies—Computer graphics—Graphics systems and interfacesMixed / augmented reality

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1 Introduction

The 3D printing manufacturing process allows for fast prototyping, mass customization, and a high degree of design versatility at a relatively low-cost [4, 18]. This can play an essential role in a low-volume industrial manufacturing setting as it enables on-the-fly adjustments to production capabilities without the cost and time involved with typical re-tooling [26].

Additive manufacturing (AM) technology has also been rising to the consumer mainstream. Reports show that this steadily growing industry could reach a global market value of over $50 billion by 2027[1]. With 3D printers increasingly finding their way into the manufacturing setting and consumer market, so does the need for professional maintenance and repair services. 3D printers can malfunction like any other complex device, leading to multiple elaborate repair steps. These are usually provided in the form of paper repair manuals or through online forums and interactive websites.

Another approach to the repair process is offered by *augmented reality* (AR) technology. There are already examples of AR used to guide the user through a repair process [25, 38]. It has been shown that substituting paper manuals with digital AR instruction by overlaying them in the user's field of view (FoV) can reduce the mental and physical effort for the user [17]. Moreover, digitized AR instructions are more adaptable to changes in the product design, can be easily edited and distributed, and improve the user's safety by removing the need for operators to look at a screen or manual, which can be hazardous [15–17].

The 3D printer repair process is also interesting for AR interaction designers. It offers the unique opportunity to assess the system on a real-life problem in a controlled laboratory setting. Due to the complexity of the repair task, it will be difficult to encounter the *ceiling effect* [9].

In that context, the AR-based systems for 3D printer maintenance

[1] https://www.smithers.com/services/market-reports/printing/the-future-of-3d-printing-to-2027

inspection have been developed before [20]. Here, the authors compared the Google Glass [7], Google Cardboard [10], and tablet-based guides in the context of 3D printer inspection. However, this scenario differs from the step-by-step repair task we are investigating in this paper.

The AR-guided repair process aims to make it more accessible to inexperienced people working in the manufacturing industry and mass-market consumers (see Fig. 1). To do so, we developed an AR-based tool coupling a number of visual and audio guides using a design engineering approach. We also reasoned about the tasks such systems must support through necessary built-in functionality.

The mixture of guidance that we are using in our AR-based system consists of text, audio, imagery and dynamic 3D CAD model (see Fig. 1(c)) [23, 25, 37, 38]. However, this coupling of varying types of aids for step-by-step is still an under-explored subject [37]. Other research looked at a small subset of the guides mixed in a single system [23]. Moreover, the most similar use case presented by Perla et al. [20] focused only on textual guidance. In this context, as suggested by the literature review by Palmarini et al. [19], the AR-based maintenance guiding systems relied in 40% on dynamic CAD or video data, in 26% of cases used imagery data, 26% were text-based, and only 8% of the cases provided audio-based guiding.

In this paper, we also present the results of an "informal evaluation" [14] study with three domain experts participants tasked with repairing a 3D printer with the help of an AR system.

The analysis of experimental video and audio recordings, as well as questionnaires, allowed us to distill a list of *A–G* design suggestions for an AR-based multi-step repair guidance system.

2 3D Printer Repair with Augmented Reality

The *fused deposition modeling* (FDM)[2] is an example of *additive manufacturing* (AM) technology which extrudes thermoplastic materials, typically in the form of continuous filaments. The material is melted, extruded through a nozzle, and selectively deposited along a predetermined tool path in a layer-by-layer manner [12]. FDM printing is the most popular AM process by the number of devices sold for personal use[3] as it is cheap, fast and easy to use, making it perfect for beginners, hobbyists and prototyping. Typically, there are seven main components of such a printer. These are: (1) frame; (2) extruder; (3) cooling fan; (4) hot-end/nozzle; (5) power supply display screen; (6) motherboard; and (7) printer bed.

For our research, we used a *Creality CR-20 Pro* [1] as it shares its design with a large body of commercially available printers. To understand the failure causes, we approached an AM expert who helped us list and rank them according to the likelihood of occurrence. Next, with the help of the same expert, we selected the "nozzle blockage/clogging" failure and its respective repair process. Such blockages prevent extrusion of material through the nozzle orifice (see Fig. 1(b)) and generally result in underextruded, or failed prints [11, 32]. These blockages can occur by a number of means, such as contamination or incorrect printer settings. Simple blockages can often be fixed with heat and nozzle cleaning rods, but more serious blockages can require complete removal of the hot-end/nozzle assembly and rectification while the part is off of the printer. We selected this process as it is one of the most common printer malfunctions that is simultaneously a complex, sixteen-step operation without including the reassembly of a fixed printer. The nozzle replacement process also requires the usage of heat-resistant gloves and hand tools. Thus, we also designed our AR system to support such operations (see Fig. 1(a-b)).

[2] https://www.hubs.com/knowledge-base

[3] https://manufactur3dmag.com

2.1 System Design

2.1.1 Functional Analysis

To capture the AR system requirements, we have used the *Functional Analysis Systems Technique* (FAST) [39]. The result of this analysis is the FAST diagram shown in Fig. 2 that allows us to reason about the required functionality of our 3D printer repair system. The diagram should be read in a top-to-bottom and left-to-right fashion. This technique was successfully employed in prior research in AR [29] and VR system design [27, 31].

2.1.2 Task Analysis

Thanks to the FAST analysis, we also identified five high-level tasks *T1-T5*. These are:

T1—Inspect printing process & results: the system must be able to inspect the printing process and its result to ascertain if repair is needed. In our case, this information is provided via a built-in screen on the printer. Moreover, as we did not connect to the printer's firmware, visual inspection alone, whether automatic or by the user, would not be satisfactory. Thus, we did not develop functionality for our initial use case scenario.

T2—Explore issue causes: the user should either allow selecting failure cause and associated repair instructions from an ordered list or support automatic selection based on T1 results. We decided to implement the former.

T3—Provide repair instructions: the system should present step-by-step repair instructions to the user.

T4—Supervise repair: the system should be able to verify the correctness of instruction step execution, prompting the repeated step if needed. Here it is also viable to offer a fallback solution to continue to the next instruction step in case the supervision falsely indicates a non-completion.

T5—Verify repair: the process must be inspected and tested to confirm the 3D printer repair.

2.1.3 Apparatus

As our AR platform, we used *Microsoft's HoloLens 2* (HL2) head-mounted display (HMD) [29] that offers state-of-the-art capabilities such as built-in hand-tracking and gesture recognition. Moreover, we developed our system using *Microsoft's Mixed Reality Toolkit* (MRTK) [2] and *OpenXR* [3] with the help of Unity [33]–a game engine widely used by the AR/VR community [27, 30, 31].

2.1.4 Repair Aides

We used a mixed guidance approach to deliver repair instructions. These were provided in the form of (see Fig. 3):

- **Textual**: A concise, descriptive text for instruction step agreed upon with a non-participant domain expert (see Fig. 1(c) and Fig. 3(a-b)).
- **Audio**: The textual instruction was provided aloud when the step started using a synthesized voice. The instruction could also be replayed or muted on demand (see Fig. 3(a)(7-8))
- **Imagery/Video**: As visual guidance, we used pictures or a video showing how to perform a given repair step. Selected photos are also complemented with arrows illustrating the required dynamic actions (see Fig. 1(c) and Fig. 3(a-b)).
- **3D Model**: As further visual guidance, the user can inspect a dynamic 3D model of the relevant parts together with their fitting or required dynamic action (see Fig. 1(c) and Fig. 3(b)).

To control the interfaces, we relied on the built-in HL2 gestures [29]. The user can move, rotate or scale together the virtual objects, i.e. the AR menu or 3D models. These capabilities, together with the [*Pin*] button (see Fig. 3(a)(5)), allow the user to rearrange and

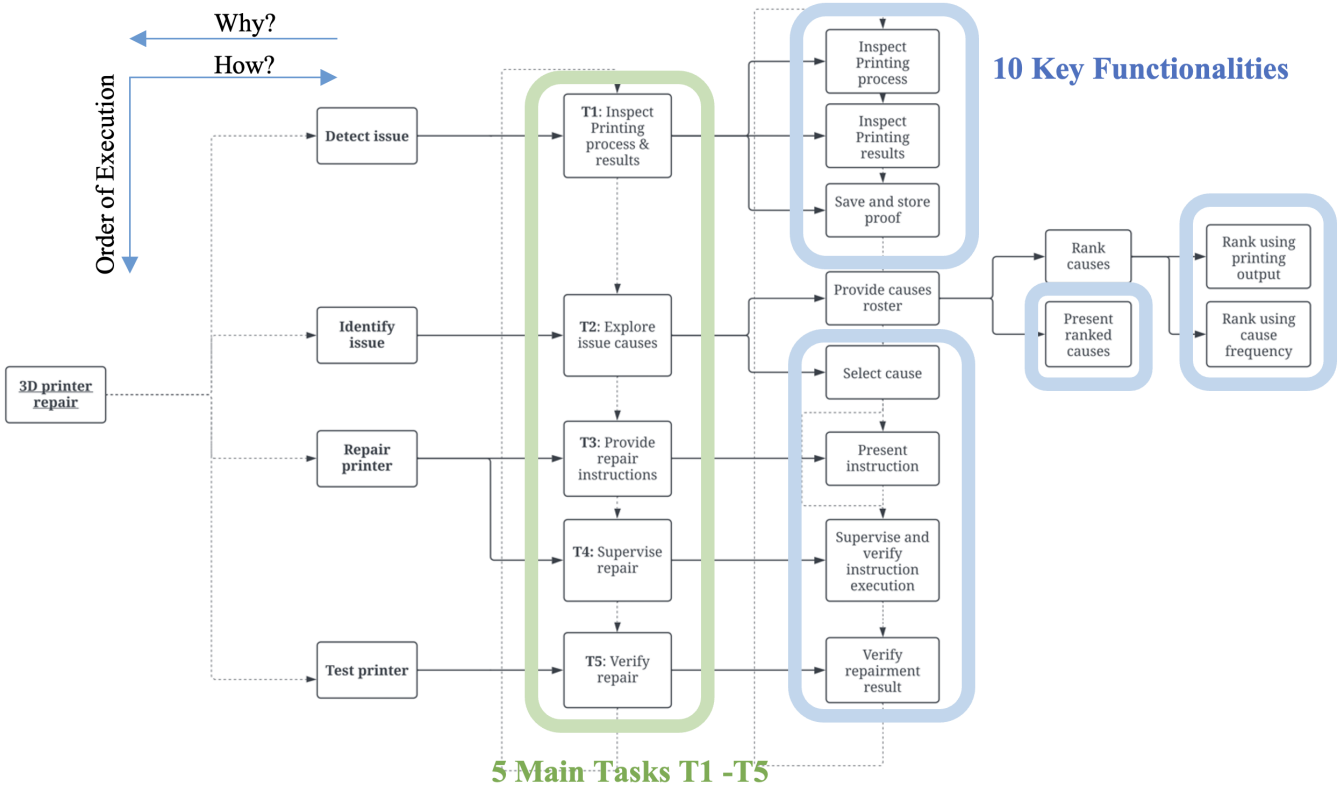


Figure 2: The FAST diagram resulting from the *Functional Analysis Systems Technique* showing the five main tasks *T1–T5* (green overlay) and five key functionalities (blue overlay).

adjust the view to remove AR guides obstructing the sight or place the whole guides in a chosen point of reference in the 3D space near the printer.

2.2 Qualitative Study

To empirically validate our system design, we carried out an observational study with domain experts [14, 30]. We decided on the qualitative rather than the quantitative approach to observe the expert's behavior once in the AR environment and use these data to rectify our initial design. To avoid conflict of interest, none of the authors of this paper were involved as experts in the qualitative study.

We started the experiment session by first collecting data on the participants' backgrounds. Next, we showed them a two-minute video clip demonstrating all the available functionality.

After the video finished, we tasked the participant with fixing the 3D printer following AR instructions step-by-step. When confused, the participants were also asked to think aloud and explain their intent and encountered difficulties.

Once the user was finished with the repair, we asked them to fill in the *NASA Task Cognition Load* (NASA TLX) [13] and the *Short Flow Scale* (SFS) [22] questionnaires. The former is a commonly used scale to measure the user's perceived workload, while the latter is designed to measure the participant's flow and anxiety levels.

We finished the experimental phase with a semi-structured discussion. The experiment was video and audio-recorded for further analysis, and we also captured the user's view in the form of a video.

2.2.1 Participants

We invited three domain-expert participants to partake in our study hereinafter called *P1-P3*:

Participant 1 (P1) was a 26-year-old PhD student in the Engineering Department at the University of Cambridge. with no prior AR exposure. He holds undergraduate and graduate degrees in mechanical engineering. Moreover, he has five years of experience with 3D printing, including a three-year period of working with the *Creality CR-20 Pro* used in our study.

Participant 2 (P2) was a 24-year-old PhD student in the Engineering Department at the University of Cambridge. He holds an undergraduate degree in mechanical engineering and a postgraduate degree in artificial intelligence. He has over two years of experience with 3D printers, including limited experience with the *Creality CR-20 Pro*. He has some prior experience with VR games and has used the HL2 once.

Participant 3 (P3) was a 27-year-old PhD student in the Engineering Department at the University of Cambridge. He holds undergraduate and graduate degrees in mechanical engineering. He reported having four years of experience with 3D printers and two years working directly with the *Creality CR-20 Pro*. He remarked about having tried on VR goggles before.

3 Study Results

The informal study [14] with domain experts is an established interface evaluation method among immersive visual analytics researchers [30, 31]. We decided to use this approach because a 3D printer is a complex device, and repair is an often tedious and complex task requiring step-by-step instructions. For inexperienced participants, both in 3D printing and AR, such a task is likely to be an overwhelming experience. Conversely, using domain experts might overstate the ease of system usage. This is why we put particular emphasis on qualitative observations and the analysis of video and audio recordings.

First, we will report on the questionnaire results. Second, we will

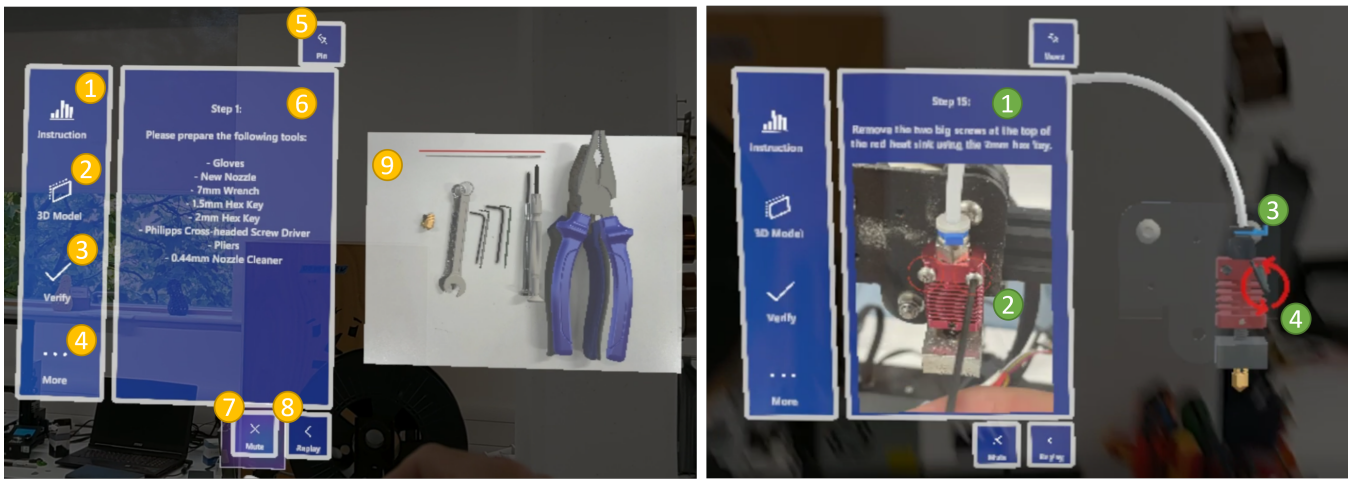


Figure 3: The AR guides consist of (a)(1-4) the menu attached to the user's hand and can be hidden or recalled on demand with the palms-up gesture. We can also anchor the menu in a given position in the 3D space by pressing (a)(5) the [*Pin*] button. The menu buttons are (a)(1) [*Instructions*] button recalling (a)(1)-(b)(1-2) the textual/imagery instructions, (a)(2) the [*3D Model*] button recalling (a)(9)-(b)(3) the 3D models (adopted from *GrabCAD* [5, 6, 21, 34, 40]), and (a)(3) the [*Verify*] button to proceed to the next task, and (a)(4) additional instructions. Moreover, selected (b)(2) images and (b)(4) models were equipped with additional visual aides such as arrows showing, for instance, the (un)screwing direction. Additionally, we gave the user possibility to mute oral instruction associated with the instructions via (a)(7) the [*Mute*] button. The user was also able to reload the voice instructions with (a)(8) the [*Replay*] button.

describe both general positive and negative participants' comments. Next, we will discuss our observations concerning users' behavior and outcomes. Finally, we will provide a list of distilled tentative guidelines for an AR-based system for a complex repair process of a 3D printer.

3.1 Questionnaires

Table 1: The results of NASA TLX and SFS questionnaires.

Person	Duration [min:sec]	TLX [0-100]	SFS Flow [1-7]	SFS Anxiety [1-7]
P1	21:28	39.3	5.4	4.0
P2	15:16	57.3	5.6	3.7
P3	20:30	22.7	2.9	3.0

As can be seen in Tab. 1, the repair duration was similar for P1 and P3, and P2 was faster by roughly 25%. This could be tentatively explained by P2 being the only participant with VR/AR experience. Interestingly, P2 has the highest weighted TLX of 57.3/100. In contrast, two other participants, P1 and P3, reported substantially lower TLX scores, i.e., 39.3/100 and 22.7/100, respectively.

The results of the SFS, i.e., 5.4/7.0, 5.6/7.0 and 2.9/7.0 for P1, P2 and P3, respectively, suggest that our participants experienced acceptable levels concerning their "feel of presence".

We advise caution when interpreting the numerical scores due to the limited sample size. For these reasons, we focused on observing and interpreting experts' behavior, comments and suggestions.

3.2 Participants' Comments and Suggestions

After the repair exercises, all three participants remarked positive impressions in the informal interview phase. They all reported enjoying the experiment and our AR system. However, this is possibly amplified by a novelty effect [8] caused by no prior exposure to AR.

P1 reported liking the explicit instruction that was presented. On the other hand, P3 disagreed with P1, remarking about too many steps. However, this was expected as every expert tends to have their own habits and approach to repairing a 3D printer. Additionally, P3 may not have been aware that the guide was intended for complete novices, and therefore less complex steps delivered at a slower pace would generally be less overwhelming and more useful to a beginner. P1 also commented on liking the images visualizing the repair steps and the whole user interface. P2 and P3 noted about liking the 3D models (see Fig. 1(c) and Fig. 3(b)(4)), especially showcasing needed hand tools (see Fig. 3(a)(9)). Unfortunately, P1 accidentally turned off the 3D model through the menu and did not rely on this functionality (see Fig. 3(a)(2)).

P1 also remarked that HL2 was uncomfortable to wear due to his correcting glasses, which could also influence his FoV. P2 did not like the fact that the gloves required to grab heated parts (see Fig. 1(b)) had to be taken on and off for the hand tracking to work smoothly. He also suggested that AR guides, instead of spawning at a pre-determined place when new instructions are loaded, should be anchored by the user globally for all the following steps.

P3 mentioned that he would have wanted multiple warnings regarding the need to work with heated printed parts (see Fig. 1(b)). He also mentioned that he would like to have the possibility to rotate the 3D model separately from the other instructions to allow a more comprehensive visual inspection as suggested in prior work [29].

3.3 Observations and Discussion

All three users agreed on the application's usefulness for novice users, remarking no need for such help for trained professionals. This was to expect as the experts typically do not rely on any aides during the repair.

Moreover, the guidance type rating given by participants showed no preference within the group. However, we have to consider that P1 missed the 3D model, and P3 reported not using the imaged-based instructions. It is an interesting remark since all the different guidance types and interaction techniques are shown in the instructional video. One possible explanation is that four guidance types could be proven to be too much. However, this is not hinted in the reported respective cognitive loads shown in Tab. 1.

By pushing the button on the wrist, the user can access the HL2 built-in menu and close the application. Unfortunately, we observed that it accidentally occurred to all three participants. In such a case, the users were given the opportunity to jump ahead over the previous steps by pressing the [*Verify*] button (see Fig. 3(a)(3)). However, none of them used this functionality. In contrast, prior experiments concerning AR-guided assembly observed behavior where the [*Verify*] button was used to jump ahead without executing the given step [29]. Nevertheless, in both the prior experiment and our study the sample sizes were small (i.e. three and one participants). Thus, we have to be cautious when drawing conclusions from these results.

In the instructional video, we explained our system's complete set of gestures as well as all the functionality. However, we observed that all three participants forgot some of the gestures, with the P2 being an exception. It may be due to his previous VR experience. He was also the most capable of operating other parts of our interface, such as virtual buttons or manipulating virtual objects (see Fig. 3). Nonetheless, the knowledge retention of the instructional video is shown to diminish quite rapidly.

The repair menu gives the user several possibilities to turn on and off certain features (see Fig. 3). However, we did not record the participants using those options with a clear indication of intention. We can tentatively attribute this to several causes. The users may not retain this information from the instruction video, or the domain experts relied on their own knowledge rather than on the AR aides. The second explanation is suggested by the fact that despite encouragement, P1 and P3 asked for help twice, while P1 only once and only when they accidentally closed the application. We need further studies with non-experts to pinpoint the actual causes of this behavior.

Regarding object manipulation, P1 only moved the objects twice to get them out of the way. P2, on the other hand, started by moving and scaling the AR guides. Similarly, P3 moved, rotated, and scaled the objects to get a closer look at the 3D models in detail. If some situations, this need could be potentially provoked by the textual and imagery menu obstructing the side view of the model. The behavior of P3 suggests that we should allow the user to independently manipulate the different types of guides, specifically the 3D models and the remaining guides' types [29]. Moreover, as hinted in earlier work [29], selected visual guides such as dynamic arrows showing the screwing direction (see Fig. 3(a)(2) and (b)(4)) were overlaid on an image or 3D model to provide the user with additional information.

We also noticed certain limitations imposed by the AR apparatus. From the roughly third of the repair process onward, the wearing of gloves by the users is advised since they must work with heated printer parts. However, the HL2's hand-tracking does not operate at a satisfactory level. Hence, P1 and P2 decided to remove the protective gloves when navigating the AR application to put them on afterwards to carry out the repair work. At the same time, P3 chose to keep the gloves off after removing them for the first time.

We also noticed that participants P1 and P2 frequently took multiple attempts to find the right distance at which they had to reach with their fingers to push the menu button. P1 gained more fluency during the task progress, while P3 experienced substantial difficulties when trying to press the buttons. Only P2, the most experienced with immersive interfaces, displayed almost no issues with button pressing. Due to such variance and small sample size, it is difficult to assess whether this is due to our AR equipment, menu design or individual participant traits.

Furthermore, in some cases, we observed limited application jittery. This happened, for instance, when the users tried to manipulate interface elements such as 3D models or when clicking through the steps fast. The effect correlated with the number of object manipulations the participants performed. However, the jittering seemed to have little to no effect on them as the SFS flow scores reported by them were relatively high (see Tab. 1).

4 Design Suggestions

Based on the carried out on recordings from our expert study, we distilled several tentative design guides that could be used to refine our 3D printer repair guiding system.

(A) *Validation in Industrial Setting*—In many industrial scenarios, the users must wear protective clothing and equipment, some of which may interfere with the interface functionality. Hence, we must test if and how our AR system operates under real-life conditions. In our case, the hand-tracking functionality proves to be troublesome when the users have to use heat-resistant gloves to safely carry out some printer repair steps.

(B) *Multiple Safety Warnings*—The AR guiding system should take special care of the users' safety. This, for instance, could be in the form of multiple safety warnings and pop-ups.

(C) *Mandatory Confirmations*—Similarly, as reported in previous studies utilizing an AR headset [29], we should develop the application to prevent accidental closing potentially via additional mandatory confirmation pop-ups. Earlier studies also suggest enforcing such pop-ups after each step [29].

(D) *Manipulation of Instruction Elements*—All the graphical elements of the instruction, i.e., menu, imagery and video data, as well as the 3D object, should be individually customizable, i.e. we should be able to change their position, size, and rotation independently to each other unless the user decides otherwise.

(E) *Objects' (re)Positioning*—The system should allow the user to anchor all the guide elements in selected positions in the 3D space. Furthermore, these positions should remain the same across the following steps unless the user decides to change them.

(F) *Mandatory Users Training*—The users should undergo compulsory training before using AR guides to familiarize themselves with all the functionalities of the system and extend their knowledge retention. This is especially important in industrial settings where the users' safety could be at risk.

(G) *Jittery Prevention*—We should adopt specific optimization steps and programming techniques to warrant the smoothness of the application execution. We can, for instance, reduce the number of different types of guides or use less complex graphics. On the other hand, this and similar issues should be less important with more powerful devices will be available.

5 Conclusion

In this paper, we described the design and development of an AR-based system for a 3D printer using established engineering design methodologies [24, 27–29]. This task is an example of a complex, multi-step industrial repair process in which we have to consider the user's safety. We coupled four types of different instruction modalities to arrive at an AR-based repair guiding system.

Next, we invited three domain expert users to observe and analyze how they approach printer repair with the help of AR. The results of our qualitative study suggest that AR technology could help guide a complex process such as the FDM printer repair. Furthermore, we distill several design guides *A–G* for developing similar AR systems.

6 Future Work

In the future, we plan to refine our system design and evaluate it in a series of user experiments. We will also recruit non-expert participants to ascertain if and to what degree our system is able to provide sufficient aid for 3D printer repair to inexperienced users.

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REFERENCES

[1] Creality, Creality CR-20 Pro 3D Printer, Creality CR-Series, https://www.creality3dofficial.com/collections/cr-series.

[2] Microsoft, Microsoft's Mixed Reality Toolkit (MRTK), source:, https://github.com/microsoft/mixedrealitytoolkit-unity.

[3] The Khronos Group, OpenXR Software Development Kit (SDK), source:, https://github.com/khronosgroup/openxr-sdk-source.

[4] L. F. Arenas, F. C. Walsh, and C. P. de León. 3D-Printing of Redox Flow Batteries for Energy Storage: A Rapid Prototype Laboratory Cell. *ECS Journal of Solid State Science and Technology*, 4:P3080–P3085, 2015. doi: 10.1149/2.0141504jss

[5] T. Barvik. CAD model: Wera hex-plus 1,5 - 10, https://grabcad.com/library/wera-hex-plus-1-5-10-1, source: GrabCAD: https://grabcad.com/, 2022.

[6] I. Blanchet. CAD model: Ender 3 Pro Hot End Model 1:1, https://grabcad.com/library/ender-3-pro-hot-end-model-1-1-1, source: GrabCAD: https://grabcad.com/, 2022.

[7] O. Campesato. *Google Glass Development: Pocket Primer*. Mercury Learning & Information, Dulles, VA, USA, 2014.

[8] D. M. Elston. The novelty effect. *Journal of the American Academy of Dermatology*, 85(3):565–566, 2021. doi: 10.1016/j.jaad.2021.06.846

[9] O. Garin. *Ceiling Effect*, pp. 631–633. Springer Netherlands, Dordrecht, 2014. doi: 10.1007/978-94-007-0753-5_296

[10] Google. Google Cardboard, https://arvr.google.com/cardboard.

[11] K. Günaydın and H. S. Türkmen. Common FDM 3D printing defects. In *International Congress on 3D Printing (Additive Manufacturing) Technologies and Digital Industry*, 2018.

[12] H. H. Hamzah, S. A. Shafiee, A. Abdalla, and B. A. Patel. 3D printable conductive materials for the fabrication of electrochemical sensors: A mini review. *Electrochemistry Communications*, 96:27–31, 11 2018. doi: 10.1016/j.elecom.2018.09.006

[13] S. Hart and L. Staveland. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, pp. 139–183, 1988. doi: 10.1016/s0166-4115(08)62386-9

[14] H. Lam, E. Bertini, P. Isenberg, C. Plaisant, and S. Carpendale. Empirical studies in information visualization: Seven scenarios. *IEEE Transactions on Visualization and Computer Graphics*, 18:1520–1536, 09 2012. doi: 10.1109/tvcg.2011.279

[15] G. Michalos, N. Kousi, P. Karagiannis, C. Gkournelos, K. Dimoulas, S. Koukas, K. Mparis, A. Papavasileiou, and S. Makris. Seamless human robot collaborative assembly–an automotive case study. *Mechatronics*, 55:194–211, 2018. doi: 10.1016/j.mechatronics.2018.08.006

[16] D. Mourtzis, V. Zogopoulos, I. Katagis, and P. Lagios. Augmented reality based visualization of cam instructions towards industry 4.0 paradigm: a cnc bending machine case study. *Procedia CIRP*, 70:368–373, 2018. doi: 10.1016/j.procir.2018.02.045

[17] D. Mourtzis, V. Zogopoulos, and F. Xanthi. Augmented reality application to support the assembly of highly customized products and to adapt to production re-scheduling. *The International Journal of Advanced Manufacturing Technology*, 105:3899–3910, 06 2019. doi: 10.1007/s00170-019-03941-6

[18] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Nguyen, and D. Hui. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143:172–196, 2018. doi: 10.1016/j.compositesb.2018.02.012

[19] R. Palmarini, J. A. Erkoyuncu, R. Roy, and H. Torabmostaedi. A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing*, 49:215–228, 02 2018. doi: 10.1016/j.rcim.2017.06.002

[20] R. Perla, G. Gupta, R. Hebbalaguppe, and E. Hassan. Inspectar: An augmented reality inspection framework for industry. *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, 09 2016. doi: 10.1109/ismar-adjunct.2016.0119

[21] A. R. Pérez. CAD model: PC Precision screwdriver 1.4 mm, https://grabcad.com/library/pc-precision-screwdriver-1-4-mm-1, source: GrabCAD: https://grabcad.com/, 2022.

[22] F. Rheinberg, R. Vollmeyer, and S. Engeser. Die erfassung des flow-erlebens, 2006.

[23] A. Sanna, F. Manuri, F. Lamberti, G. Paravati, and P. Pezzolla. Using handheld devices to sup port augmented reality-based maintenance and assembly tasks. *2015 IEEE International Conference on Consumer Electronics (ICCE)*, 01 2015. doi: 10.1109/icce.2015.7066370

[24] S. Shefelbine, J. Clarkson, R. Farmer, and S. Eason. Good design practice for medical devices and equipment-requirements capture, 2002.

[25] C. Siew, S. Ong, and A. Nee. A practical augmented reality-assisted maintenance system framework for adaptive user support. *Robotics and Computer-Integrated Manufacturing*, 59:115–129, 10 2019. doi: 10.1016/j.rcim.2019.03.010

[26] R. Singh and H. K. Garg. Fused Deposition Modeling – A State of Art Review and Future Applications. In A.-G. Olabi, ed., *Encyclopedia of Smart Materials*, pp. 270–288. Elsevier, Oxford, 2016. doi: 10.1016/B978-0-12-803581-8.04037-6

[27] S. Tadeja, P. Seshadri, and P. Kristensson. AeroVR: An immersive visualisation system for aerospace design and digital twinning in virtual reality. *The Aeronautical Journal*, 124(1280):1615–1635, 2020. doi: 10.1017/aer.2020.49

[28] S. K. Tadeja. *Exploring Engineering Applications of Visual Analytics in Virtual Reality*. PhD thesis, University of Cambridge, 2020.

[29] S. K. Tadeja, D. Janik, P. Stachura, M. Tomecki, and K. Walas. Design of ARQ: An Augmented Reality System for Assembly Training Enhanced with QR-Tagging and 3D Engineering Asset Model. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 466–471, 2022. doi: 10.1109/VRW55335.2022.00103

[30] S. K. Tadeja, Y. Lu, M. Rydlewicz, W. Rydlewicz, T. Bubas, and P. O. Kristensson. Exploring gestural input for engineering surveys of real-life structures in virtual reality using photogrammetric 3D models. *Multimedia Tools and Applications*, 80:31039–31058, 01 2021. doi: 10.1007/s11042-021-10520-z

[31] S. K. Tadeja, W. Rydlewicz, Y. Lu, T. Bubas, M. Rydlewicz, and P. O. Kristensson. Measurement and Inspection of Photo-Realistic 3-D VR Models. *IEEE Computer Graphics and Applications*, 41(6):143–151, 2021. doi: 10.1109/MCG.2021.3114955

[32] Y. Tlegenov, Y. San Wong, and G. S. Hong. A dynamic model for nozzle clog monitoring in fused deposition modelling. *Rapid Prototyping Journal*, 2017.

[33] Unity Technologies. Unity Game Engine, 2022.

[34] User:Eren. CAD model: Cırcır Anahtar (Ratchet Wrench), https://grabcad.com/library/circir-anahtar-ratchet-wrench-1, source: GrabCAD: https://grabcad.com/, 2022.

[35] User:IpoyPunk. CAD model: HAND-001 Right Hand VR, source: https://www.cgtrader.com/3d-models/character/man/ipoypunk-hand-0001, 2022.

[36] User:Ubermeisters. CAD model: Creality Ender 3 V2, https://grabcad.com/library/creality-ender-3-v2-2, source: GrabCAD: https://grabcad.com/, 2022.

[37] W. Wang, S. Lei, H. Liu, T. Li, J. Qu, and A. Qiu. Augmented reality in maintenance training for military equipment. *Journal of Physics: Conference Series*, 1626(1):012184, 2020. doi: 10.1088/1742-6596/1626/1/012184

[38] S. Webel, U. Bockholt, T. Engelke, N. Gavish, M. Olbrich, and C. Preusche. An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, 61:398–403, 04 2013. doi: 10.1016/j.robot.2012.09.013

[39] J. R. Wixson. 2 Function Analysis and Decomposistion using Function Analysis Systems Technique. *INCOSE International Symposium*, 9(1):800–805, 1999. doi: 10.1002/j.2334-5837.1999.tb00241.x

[40] K. Yalçın. CAD model: Pense, Pliers, Zange, https://grabcad.com/library/pense-pliers-zange-1, source: GrabCAD: https://grabcad.com/, 2022.