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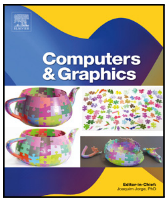

Special Section on RAIXR

Exploring the repair process of a 3D printer using augmented reality-based guidance[☆]

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ABSTRACT

In recent years, *additive manufacturing* (AM) techniques have transcended their typical rapid prototyping role and become viable methods to directly manufacture end products in a highly versatile manner. Due to its low cost and relative ease of use, *fused deposition modeling* (FDM) has become the most universally applied AM technology. Nonetheless, skilled operators are often still required to perform maintenance, diagnostic, and repair tasks. Such operators need to be adequately trained. Here, *Augmented reality* (AR) technology could be used to automate this training and help to promptly provide new operators with the necessary skills to perform specific tasks as required. However, the most effective approach to designing such AR-based assistance systems has not yet been fully explored. Consequently, we address this need by reporting on how to design such guiding systems using well-known design engineering methodologies. We then further assess the applicability of our approach through a user study with domain experts. In addition, we complete our assessment with heuristical verification of system expressiveness to reason about the influence of cognitively important components of the AR interface on the operators.

1. Introduction

The versatility offered by AM techniques enables the execution of rapid prototyping and mass customization operations at relatively low cost when compared with traditional manufacturing methods [1,2]. As such, AM is increasingly being adopted in low to medium volume industrial manufacturing environments, where the ability to switch the production area to cater for various product lines without the associated cost and time involved in traditional retooling is highly advantageous [3].

Demand for AM technologies has been steadily rising across both industrial and consumer markets, with industry forecast to generate over $50 billion in revenue worldwide by 2027.[1] In a similar vein to traditional manufacturing machines, products manufactured using 3D printers (see Fig. 1) can still be subject to build quality issues, malfunctions, and wear during extended use. At the same time, new customers may require initial set-up assistance. Therefore, as the market expands, the need for professional repair and maintenance also grows. For consumer-level machines, resources are largely found online through hobbyist forums and video-sharing websites, while industrial printers are often restricted to manufacturer-level support.

The advent of immersive technologies such as AR enables entirely new methods of supporting device maintenance in both industrial and non-industrial level scenarios [12–15]. To that end, we can already observe interest in utilizing AR to support and guide users throughout the device repair process in real-time [16,17] (see Fig. 1(c-d)).

Both discussed technologies, i.e., AM as well as AR-aided repair, are positively contributing to the “right to repair” movement, that supports the idea of users being able to maintain electronics devices instead of disposing or replacing them [18,19]. In recent years, this movement has been recognized at national-[2] and international[3] legislation. In this context, a 3D printer can easily produce missing or broken parts, which can be used to repair a given device with the help of appropriate AR guidance designed for novice, non-expert users.

[☆] This article is an extended version of the paper presented at the *2nd International Workshop on eXtended Reality for Industrial and Occupational Supports (XRIOS)*, at the 2023 IEEE Conference on Virtual Reality and 3D User Interfaces, Bozzi et al. (2023).

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

[2] https://www.legislation.gov.uk/ukdsi/2021/9780348222920

[3] https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

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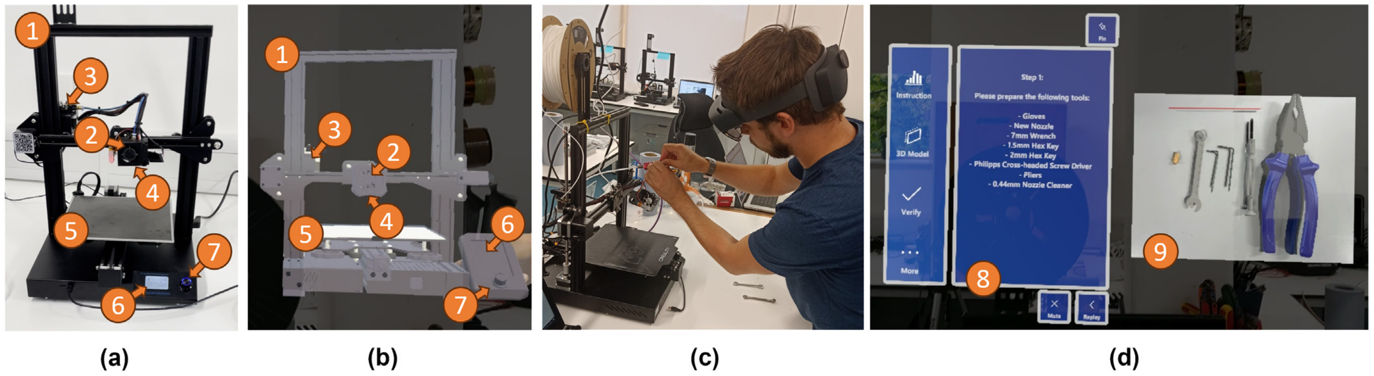

Fig. 1. (a) The *Creality CR-20 Pro* [4] 3D printer used in our study, (b) the 3D printer model utilized in the AR-based instructions (adopted from *GrabCAD* [5,6]), (c) a person repairing 3D printer aided by (d) AR-based instructions. (a-b) The main 3D printer components are (a-b)(1) frame, (a-b)(2) print head, (a-b)(3) extruder motor, (a-b)(4) hot-end/nozzle, (a-b)(5) print bed, (a-b)(6) display screen, and (a-b)(7) rotary encoder. (d) The example (d)(8) textual and (d)(9) image/model-based AR instructions (adopted from *GrabCAD* [7–11]).

Moreover, prior research reflected on the decrease in physical and mental effort required by the user when comparing instructions presented in the user's field of view (FoV) through AR interface with traditional paper-based manuals [20]. Instructions in a digital format offer further advantages over physical paper copies as they can be more easily stored, be promptly replaced, and easily edited in the case of the introduction of new products or process changes. Perhaps most critically, digital instructions can increase safety by allowing the user to focus on the desired task instead of shifting attention to paper manuals or nearby screens [20–22].

Supporting the device repair process, specifically FDM equipment, is an interesting use case scenario for AR designers and researchers due to the repair process's complexity (see Fig. 2). Furthermore, we can control the environment in which we tackle this real-world, step-by-step device repair exercise. Due to these factors, the risk of *ceiling effect* [23] decreases substantially when evaluating the AR interface with human operators.

For instance, there have been attempts to use an AR interface for 3D printer maintenance [24] where the authors explored the feasibility of using a tablet, Google Glass [25], and Google Cardboard [26] as means for printer inspection. However, a use case such as inspection is substantially less complex than the proposed scenario in this paper, where we will assess the use of AR to guide a 3D printer repair task (see Figs. 1 and 2).

Thanks to the AR-based 3D printer repair process, we aim to increase AM technology's accessibility by supporting novices in a manufacturing environment as well as aiding a growing number of untrained, non-industrial consumers (see Fig. 1). We utilized a well-established design engineering methodology [27,28] to develop a multi-modal AR-based system for guiding the device repair process in a step-by-step manner. We also captured and analyzed the key sub-tasks and functionality that such a system has to support in order to become a viable and effective support tool.

Furthermore, we present in our paper the result of a user study with three domain expert participants carried out under an "informal evaluation" [29] protocol. During the experiment, we asked the participants to undertake the 3D printer repair aided by our AR system. The whole experimental phase, as well as the immediately following semi-structured discussion, were audio and video recorded for further analysis. Consequently, utilizing this feedback, we were able to arrive at a list of *A–G* suggestions for designing and testing AR-based guiding systems of complex, multi-step repair processes.

This paper is an extended version of our prior publication [30]. This new version has been extended to include a more comprehensive literature review and further heuristic evaluation of the system expressiveness with the help of *cognitive dimensions of notation* [31,32]. The inclusion of the latter verification helped us in identifying cognitively-important elements of the guiding system and their potential influence over the user's interaction with the AR interface [33]. We also refined our *functional analysis system technique* (FAST) [27,28] to include only seven crucial functionalities (see Fig. 3). In addition, we rewrote the paper and prepared new figures to better present the complexity of the 3D printer repair process.

2. Related work

AR technology is increasingly adopted in manufacturing and other industrial environments [34–38]. Use cases span device maintenance, repairs, operations (MRO), manual assembly [15] and product design and can be found across industrial sectors [35–37,39]. Prior studies have shown that AR guidance can reduce the time required to complete the repair and lead to a more ergonomic and comfortable user position during the repair process [40].

Besides occasional attempts to use on-monitor clues [34,41], when analyzing the relevant literature, we can observe two main approaches to realize the AR interface for guiding solutions, i.e., hand-held devices (HHD) and head-mounted display (HMD).

Some examples of HHD used to provide AR-based MRO instruction include electrical transformer maintenance with tablet-PC, where the system overlaid animated *computer-aided design* (CAD) models on the object and used visual (e.g., arrows) and textual (e.g., labels) hints to guide the user [42]. The mixing of CAD models with the user's real view was also investigated by Georgel et al. [43].

An HHD-based AR system for collaborative, supervised training in the assembly and maintenance of an electro-mechanical actuator was proposed by Webel et al. [16]. The authors also relied on animated 3D models, textual clues, and vibrotactile bracelets to provide the trainee with the necessary feedback and instruction. Another example of using HHD for teleconsultation and instruction utilized computational cloud resources as the node of information exchange between the users of different mobile devices [44].

Sanna et al. investigated the feasibility of using the HHD AR interface for non-experts in the context of a notebook's hard disk replacement, remarking about the benefits of such systems to novice users [45]. Here, we could also observe the usage of CAD and textual labeling coupled with computer vision for delivering step-by-step instruction.

On the other hand, the majority of use case scenarios concern the usage of head-worn devices [14,46]. For instance, Haritos et al. proposed a system aerospace maintenance training [47]. Here, the authors used markers placed on aircraft parts to trigger the system to provide additional information. Similarly, in Tadeja et al. [15], QR codes denoted an asset's components required in a given step of manual assembly. Also, CAD models and textual information were used as additional cues.

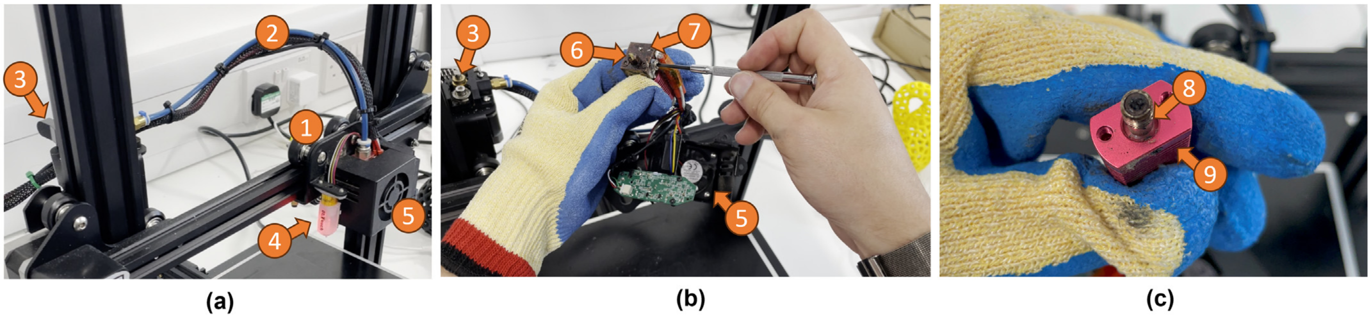

Fig. 2. (a-c) A brief overview of the level of disassembly required to reach and correct a severe obstruction of the 3D printer nozzle. (a) The 3D printer in idle state: (1) print head mounted on X-axis carriage, (2) bowden tube, (3) bowden extruder motor mounted on the frame, (4) Z-probe, (5) fan shroud. (b) The disassembled (1) print head with visible components: (5) fan shroud, (6) nozzle and (7) heat block. (c) Inspection of the (8) heat break and (9) heat sink showing an obstruction comprised of carbonized material deposits.

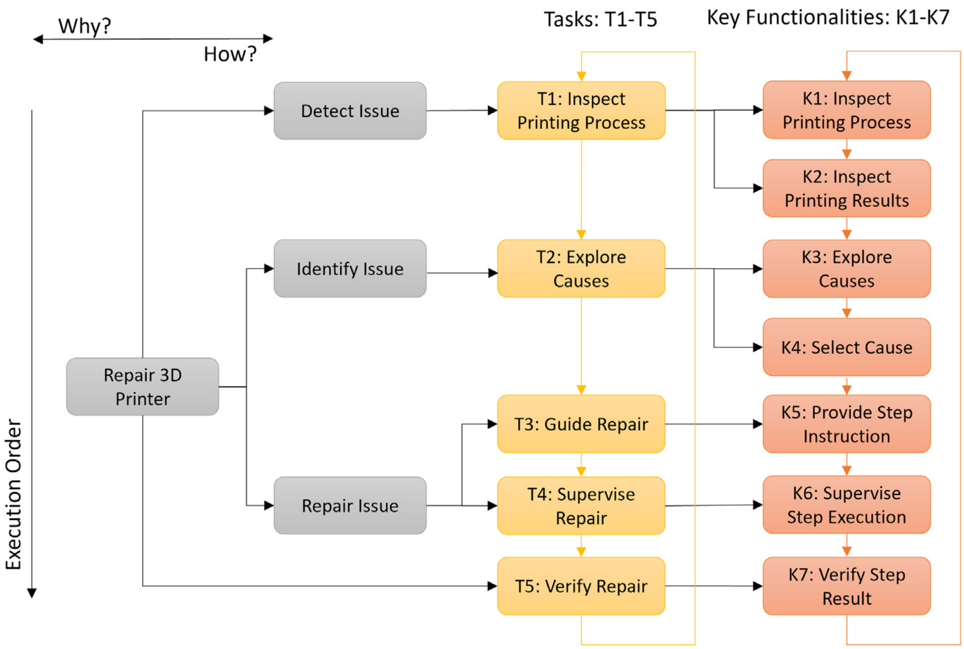

Fig. 3. The FAST diagram with the captured main tasks *T1–T5* (yellow boxes) and seven key functionalities *K1–K7* (orange boxes).

Textual cues also serve as instruction delivery means in automotive maintenance, where authors explored the possibility of using wrist trackers [17]. In addition, another automotive use case was investigated where the authors developed CAD-based tracking system to overlay 3D CAD models over the car's engine [41].

Collaboration between experts using VR HMD and trainees wearing an AR headset was investigated by Datcu et al. [48]. Other examples include military equipment maintenance [49], or autonomous ships maintenance [50].

Similarly to the above research, we decided to use HMD [49,50] as repairing 3D printers frequently requires disassembly of many small and delicate parts, in which the user needs both hands to properly carry out such tasks (see Fig. 2). However, in contrast to the presented examples, we built into our system a range of guiding modalities, including textual, audio, imagery/video and dynamic CAD models and a mixture thereof (see Fig. 1(d)) [16,17,45,49]. The coupling of these instruction modalities in the context of step-by-step guiding remains an uninvestigated research area [49]. For example, in prior work, authors looked mainly at textual information [24] or investigated a small number of these modalities mixed together [45]. Moreover, the survey of Palmarini et al. [51] remarked that dynamic CAD or video data was most frequently used in AR-based maintenance systems (40%), followed by imagery and text-based data (26% each), with audio-based information at the end of the list (8%).

3. Augmented reality for 3D printer repair

The FDM[4] is a most common example of AM, which builds objects by extruding thermoplastic materials in a spatially controlled manner. The material is typically in the form of a filament and is processed by being heated and then extruded through a nozzle with a fixed diameter orifice. The molten liquid plastic is then deposited onto a build surface that promotes adhesion and cooling below the glass transition temperature of the plastic so that it solidifies. The plastic is selectively deposited along a predetermined 2D tool path to print a layer. The Z-axis then moves to allow a new layer to be built on top of the previously printed layer, which is then repeated many times until the full object is formed [52].

FDM is the most frequently used printing process in terms of the number of devices purchased for personal use.[5] FDM offers some advantages to comparable 3D printing techniques, such as stereolithography, as FDM is cheap, relatively fast at building macroscale structures, and easy to use and maintain. These attributes make FDM perfect for beginners, hobbyists, and prototyping.

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

[5] https://manufactur3dmag.com

We used the Creality CR-20 Pro [4] (see Fig. 1(a-b) in our research, as the core design of the CR-20 pro is shared with a large body of commercially available printers. Utilizing the 3D printing expertise of two of our co-authors, who conduct active research within this specialty area, we assessed a range of breakdown or maintenance scenarios and evaluated them on their potential suitability to our AR platform. The nozzle obstruction process was chosen due to it being an extremely common printer malfunction that simultaneously offers a suitably complex, sixteen-step disassembly operation. As the process requires the use of common hand tools (see Fig. 1(d)) throughout and also heat-resistant gloves at certain stages, the AR system was designed to support such operations (see Fig. 2(b-c)).

Such obstructions prevent extrusion of material through the nozzle orifice (see Fig. 2), or potentially further up the heat brake, and generally result in underextruded, or catastrophically failed prints [53,54]. Obstructions of this nature can arise due to various conditions but are most typically because of contamination from mixed materials, poor maintenance, or incorrect printer settings. Minor obstructions can often be fixed with a mixture of heat and nozzle-cleaning rods. Still, more severe obstructions can require a greater extent of disassembly and possibly even rectification while the part is removed entirely from the printer. As such, we utilized the latter version of the scenario due to its greater complexity.

4. System design

4.1. Functional analysis

Based on FAST [27,28], we were able to capture the system requirements which are presented in the diagram in Fig. 3. When moving from left to right on the diagram, we answer the question *how?* and, when reading the diagram in the opposite direction, we answer the question *why?* The diagram also encodes the order of execution when read from top to bottom manner. The FAST analysis provides insight into the necessary functionalities (i.e. functions) of a given system without the need to provide their particular realizations (i.e. function carriers). These can be developed later for a given apparatus utilizing its particular capabilities and limitations. Such an approach was previously successfully deployed for design engineering of VR [33,55] and AR [15] systems alike.

In our case, through FAST, we identified seven critical functions denoted by orange boxes in the last column in Fig. 3. We were also able to observe, similarly to other research [15], the AR-based training system requires at least one loop in order to fulfill its main objective (e.g., device repair [30] or assembly training [15]).

4.2. Task analysis

Carrying out the FAST analysis helped us identify five high-level tasks *T1–T5* that have to be supported by our AR system. These tasks are denoted by yellow boxes in the second to last column in Fig. 3.

(T1) **Inspect printing process**: the system has to provide functionality for recognition of the device failure either through an automatic process or the inspection procedure.
(T2) **Explore issue causes**: the system should allow the user to select the device failure cause.
(T3) **Provide repair instructions**: the system must be able to provide the user with step-by-step device guidance and repair instructions.
(T4) **Supervise repair**: the system should possess the ability to oversee and track instruction execution. This is needed for the system to provide appropriate instruction for a given stage of the repair process.
(T5) **Verify repair**: the system must provide means of evaluating the repair results to conclude the correctness of the whole repair process as well as individual repair steps. This task further extends to the ability to verify individual repair steps.

In the 3D printer repair case, concerning task T1, the information about the printer failure is given by the printer itself and indicated on the operation panel (see Fig. 1(a-b)). Moreover, without connecting directly to the device's firmware, we could not reason about the exact failure cause. Hence we did not build-in this functionality into our prototype system and assumed that the operator would use our AR system after the initial recognition of the printing failure.

Such an approach to T1 dictates the approach to supporting T2, as the system does not automatically select the breakdown cause. Hence, in T2, we present the user with an order list of potential causes.

With regards to T3, the ways in which instructions can be provided to the AR user are limited to the modalities supported by a given device used to realize the AR interface. Here, we decided to couple all main modalities, such as textual, audio, and visual cues (see Fig. 4).

The next task, T4, is naturally intertwined with task T5 as it has to warrant checking the individual step completion verification as well as the whole process correctness. The latter is supported by task T1, while the former is realized thanks to task T5. Moreover, the system should also provide means to move back to the previous repair stage or repeat instructions in the current step, simultaneously allowing the user to move forward in case of false positive correctness verification.

4.3. Apparatus

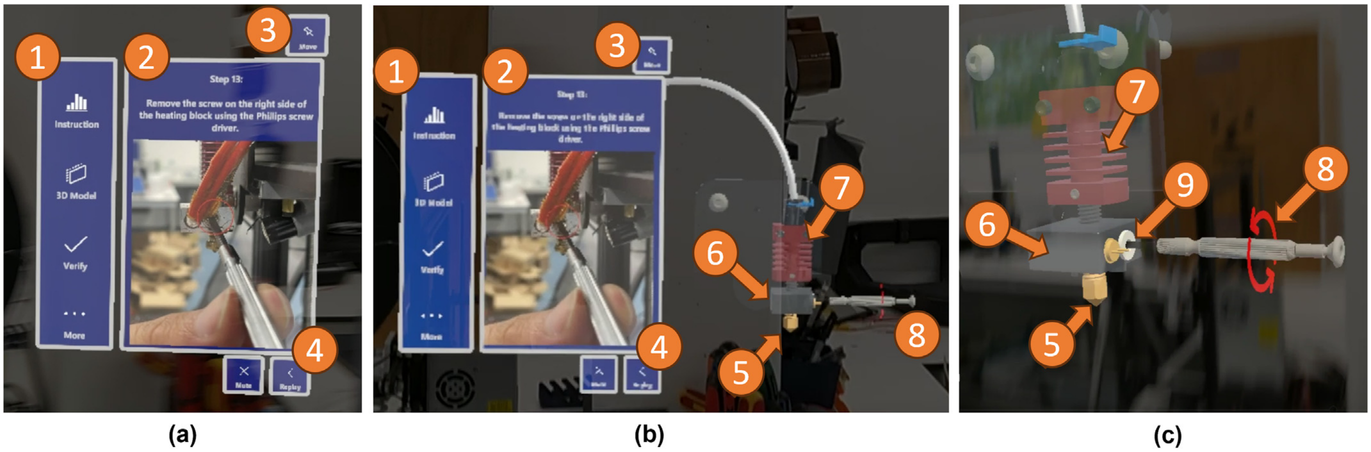
To facilitate the AR interface, we relied on the Microsoft's HoloLens 2 (HL2) state-of-the-art head-mounted display (HMD) [56]. As the software stack, we used Microsoft's Mixed Reality Toolkit (MRTK) [57], OpenXR [58] and Unity game engine [59] serving as our primary development framework. These hardware and software technologies are often used in conjunction for AR-based research [15].

4.3.1. Repair aides

We provided the operator with repair instructions using a mixed modalities approach (see Fig. 4). All these repair cues, together with the whole repair process description and step split, were prepared before the experiment in collaboration with a 3D printing expert. The four ways of delivering guidance were as follows:

- **Textual**: the AR interface provided the user with textual instructions for each step (see Fig. 1(d) and Fig. 4(a-b)).
- **Audio**: the textual instructions were automatically read on the step start and could be replayed aloud using a synthesized voice with the help of a button press (see Fig. 1(d) and Fig. 4(a-b)).
- **Imagery/Video**: the main visual cues had the form of pictures and videos depicting the given repair step (see Fig. 1(d) and Fig. 4(a-b)). When needed, we overlaid the graphical elements (e.g. pictures and videos and models) with arrows showing necessary user actions (Fig. 4(a-b)).
- **3D Model**: other visual cues consisted of animated 3D models showcasing how specific repair steps should be performed (see Fig. 1(d) and Fig. 4(b-c)).

The AR interface was controlled with bimanual gestural input offered by built-in HL2 functionality [56,60,61]. Consequently, all the interactive elements of the menu could be scaled, rotated and translated. In turn, the system allowed readjusting the position of instructions so they would not impede the user's view. Moreover, the user could anchor the instruction in a selected position in the 3D space by using the [*Pin*] button (see Fig. 4(a-b))



Step 13:

Remove the screw on the right side of the heating block using the Phillips screw driver.

Fig. 4. (a-c) The AR-based instructions show the user experience during the step where a screw must be removed from one side of the heater block. (a) The user's view within the AR interface, which features textual and imagery instructions. (b) The additional 3D model view of the task, which may help the user with spatial orientation and locating the target screw (c)(9), as well as providing guidance in (b)(8) selecting and operating an appropriate tool. This is a retaining screw (c)(9) responsible for the positioning of a delicate thermocouple which is essential for proper thermal management of the heat block (b-c)(6) and the nozzle (b-c)(5) itself. In the case of some severe obstruction, (b-c)(6) the heat block may be required to be removed, which ultimately then requires the disassembly of the other parts connected to it.

5. Observational user study

We evaluated our system design in an observational study involving domain experts, which, in our experiments, were three Ph.D. students with at least two or more years of experience with 3D printing. None of these participants, hereinafter called P1, P2 and P3, co-authored this paper to prevent any potential conflict of interest.

We decided to adopt a qualitative approach instead of a more quantitative study design as our goal was to trim the vast and under-explored design space concerning multi-modal task guidance. Hence, we relied on participants' comments and suggestions, as well as our own observations and analysis of audio and video recordings. Such an informal evaluation methodology was recognized as a frequently used method among the visualization community to help identify design flows [29].

5.1. Participants

Three participants (P1, P2, and P3) experienced with 3D printing volunteered to take part in our study. All of them were Ph.D. students within the Department of Engineering, University of Cambridge.

Participant 1 (P1) was 26 years of age and reported no prior experience with AR interfaces. He holds mechanical engineering degrees at the undergraduate and graduate levels. He disclosed having three-year-long experience working specifically with Creality CR-20 Pro and five years in total of working with 3D printing.

Participant 2 (P2) holds a postgraduate degree in artificial intelligence as well as an undergraduate degree in mechanical engineering. At the time of the study, he was a 24-year-old and had more than two years prior experience with 3D printers. He also reported a limited exposure to the Creality CR-20 Pro. In addition, he was the only participant to disclose having been playing VR games and having used the HL2 headset once before.

Participant 3 (P3) undertook his undergraduate and graduate degrees in mechanical engineering and was 27-year-old. He mentioned four years of working with 3D printing to date, including a two-year-long period dealing specifically with the Creality CR-20 Pro. He also disclosed having used VR headset before.

5.2. Experimental design

The study began with the collection of information on participants' backgrounds, after which they were presented with a two-minute-long instructional video showcasing our AR system and its capabilities.

Table 1
The results of NASA TLX and SFS questionnaires.

Participant	Duration [min:sec]	NASA 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

Next, we tasked the participants P1, P2 and P3 with preparing the Creality CR-20 Pro 3D printer with the help of our AR guiding system and provided instructions. The device failure cause was the clogged printer nozzle, which had to be replaced. Completing this task requires a multi-step procedure involving substantial disassembly of the printer, as shown in Fig. 2.

After the task was completed, we asked the participants to fill in two questionnaires and take part in a semi-structured discussion. These questionnaires were Short Flow Scale (SFS) [62] and NASA Task Cognition Load (NASA TLX) [63].

The SFS measures the anxiety and flow levels of the system users [62, 64]. This variable is often associated with skillfully conducting a given task while being deeply immersed in this activity [65]. The NASA TLX is used to ascertain the levels of cognitive load experienced by the users in a given task [64,66]. We decided to measure participants' perceived cognitive load as human cognition plays a crucial role in instruction perception and processing [67]. Hence, the combination of participants' perceived cognitive load and flow levels can provide a measure of how well the instructions supported the execution of the 3D printer repair task.

The whole experiment, as well as the following discussion, was audio and video recorded for further analysis. We also captured the streamed FoV from the HL2 and instructed the participants to think aloud during the study and inform us about any issues they experienced.

6. Task description: Replacing 3D printer nozzle

Reaching and correcting a severe obstruction of the 3D printer nozzle requires high level of disassembly, as presented in Fig. 2.

Firstly, any plastic filament remaining in the machine must be removed. This is achieved by heating the heat block and nozzle beyond the melting point of the plastic being utilized. Once at the suitable temperature, the lever on the extruder motor should be depressed, and the filament should be manually pulled out of the machine. Access

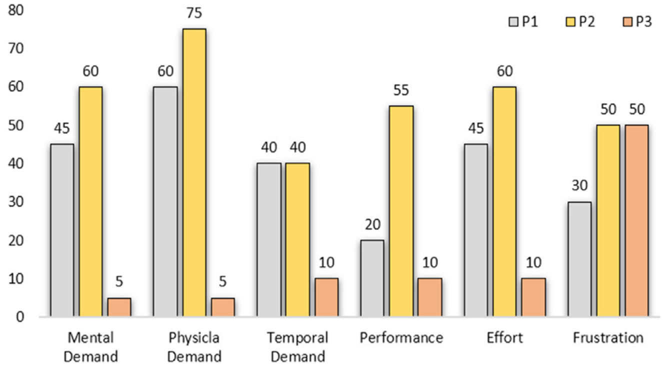


Fig. 5. The NASA TLX raw scores broken down for each participant and sub-scale showing the large variability between the users [63].

to the heat block and nozzle requires disassembly of the print head, namely removal of the bowden tube, Z-probe, and fan shroud. Following this, the removal of the last attached components (heater element, thermocouple) can be performed. The remaining assembly of the heat sink, heat brake, heat block, and nozzle can be dismounted from the printer to allow fixing within a vice or easier manipulation with other tools.

In the case presented in Fig. 2(c), the nozzle and heat block was removed to enable inspection of the heat brake. An obstruction comprised of carbonized material deposits can be seen within the heat brake.

7. Study results

We decided to implement an informal study protocol with domain experts [29] as it is often used in evaluating complex and interactive immersive interfaces [55,68]. Furthermore, novice users could be overwhelmed when simultaneously dealing with the complex repair task as well as the head-worn AR interface. On the other hand, relying just on domain experts could lead to overestimating the system's usability. To counterbalance these potential effects, we decided to use a think-aloud protocol and capture the participants' behavior through video and audio recordings for further analysis.

We will start by reporting and analyzing the questionnaires' results. Next, we will reflect on participants' comments and suggestions concerning the AR-based instruction system and discuss our own observations of users' behavior.

In addition, to strengthen our findings, we carried out heuristic verification of the expressiveness of our system. We have chosen this approach as the used cognitive dimensions of notations [31,32] were specifically designed for analyzing interactive notational systems and were previously deployed to ascertain the usability of an immersive interface [33].

Finally, we collated all these results to prepare a list of design suggestions to inform the future development of similar AR systems for complex repair.

7.1. Questionnaires

We collected the questionnaires' results in Table 1. As can be seen, it took P1 and P3 roughly 20 min to repair the printer's nozzle, while P2 was substantially faster and finished the task in about 15 min. We could potentially associate the difference with P2 reporting on having prior exposure to immersive interfaces.

At the same time, P2 reported the highest levels of perceived cognitive load of 57.3/100. Whilst P1 and P3 experienced much lower levels of 39.3/100 and 22.7/100, respectively. The individual "raw" scores for each NASA TLX subscale can be seen in Fig. 5. When interpreting individual results [69], the raw scores across the subclasses show rather substantial variability between participants with relatively "high" *Physical Demand* scores for P1–P2, which are potentially derived from some intricate physical elements encountered during the printer repair task (see Fig. 2). Overall, P3 returned low or medium raw scores for all sub-scales except *Frustration*, which edged below the "high" bracket. The other participants generally returned higher raw subclass scores throughout. *Temporal demand* raw scores were relatively low in comparison to other subclass results across all three participants. No time limitations or expectations were indicated to the participants which may have alleviated any perceived time constraints or pressures during the task. Participants' raw scores for the *Performance* subclass were at a "medium" level on average of 28.3. This could be attributed to the participants being field experts who may have felt slowed down by the AR system's sequence of instructions that were intended for non-experts. In addition, the "somewhat high" *Frustration* scores may also reflect the above statement regarding a "medium" feeling of success. The average *Effort* score was 38.3, placing it within the "somewhat high" bracket. The basis for this scoring could be due to the low experience the group of participants had with AR/VR systems, which may be further compounded by requiring focus on performing a dexterous task.

On the other hand, the SFS measured relatively high results for P1 and P2, i.e., 5.4/7.0 and 5.6/7.0, respectively, with P3 reporting 2.9/7.0. These numbers show a high level of engagement experienced by all participants, with P1 and P2 reporting scores close to 80%, with P3 disclosing around half that result.

However, we advise caution when drawing conclusions from these quantitative data due to the relatively small sample size.

7.2. Participants' comments and suggestions

All the participants commented about having a positive impression of using the AR system for fixing the 3D printer in the experimental phase. However, these initial remarks could be polluted by a novelty that could be caused by using a new to them AR interface realized with the help of a headset [70].

Concerning the step-by-step instructions, P1 was satisfied with the instructions' clarity and conciseness. P3, however, commented that the system offered too many steps. This difference in opinion between the two participants is to be expected as experts tend to follow their own repair procedure at a chosen, individual pace. Moreover, remarks of P3 could also be associated with him not knowing that we built our system for inexperienced users. Here, incorporating a number of carefully designed, straightforward steps is a more advantageous approach in such a context.

With regards to visual aids, P1 reported liking the images depicting repair steps as well as the entire AR interface. In addition, remaining participants P2 and P3 commented on liking the supporting 3D models (see Fig. 1(b)) and Fig. 4(b-c)), including the presentation of the necessary hand tools (see Fig. 1(d) and see Fig. 2. On that note, P3 also wanted to be able to manipulate the 3D printer mode disjointedly to the instructions to warrant a more versatile visual inspection process. P1 was not able to reason about the 3D model itself as he turned off the model by accident in the very beginning and did not use it through the course of the repair process (see Fig. 1(b)).

Furthermore, P3 suggested including multiple warnings when the repair process requires working with heated printed components (see Fig. 2(b-c)). P2 also wanted the instructions to be loaded in a preselected 3D space by the user instead of in a predetermined layout by the system location at the beginning of each step.

In terms of the hardware, P1 considered HL2 uncomfortable as he was also using correcting glasses underneath the visor. Such a setup could also further limit his field of vision (FoV), thus further diminishing his comfort of use and increasing his anxiety levels which, in turn, were the highest among the participants (see Table 1). Nevertheless, he also reported a high score of over 77% with respect to flow. Additionally, P2 disliked the need to remove heat-resistance gloves used when dealing with heated printer components as the built-in HL2 hand-tracking was not working properly with gloves on (see Fig. 2).

7.3. Observations and discussion

All participants were in agreement concerning the application's potential benefits and usability in guiding novice users. As expected, they also remarked that such systems are likely not needed for professionals experienced in working and repairing 3D printers.

Concerning the guiding modalities themselves, the participants did not have any clear preference. Here, however, we have to take into consideration that P1 and P3 disclosed not using animated 3D models nor the imagery instructions, respectively. This may be caused by the instructional video not being the most efficient way of conveying information about the AR interface and interaction means built-in into it. On the other hand, having four different guiding modalities (i.e. textual, audio, model and imagery-based instruction) available to the user at the same can be too overwhelming for inexperienced AR users. This is, however, not suggested when analyzing respective cognitive load experiences by the users (see Table 1).

During the experimental phase, we observed that all three participants accidentally pressed the wrist button, recalling the HL2 built-in menu. This led to the active AR application to be closed. To help the users recover from this error, we gave them the possibility to skip the repair steps by pressing the [*Verify*] button. In regards to this, none of the participants chose to exploit this opportunity. Interestingly, some prior work remarked that including the [*Verify*] button in the AR menu could be used to jump ahead even when the given step remained fully uncompleted [15]. However, we should not infer decisive conclusions from these observations due to the small sample sizes in both experiments, i.e., one and three participants, respectively, in the prior work and this study.

In the experimental phase, we also observed a diminishing retention span with regard to the instructional video shown to participants before the commences of the printer repair task. The video showcased and described the AR interface's interaction capabilities, including all the possible hand gestures. Nevertheless, two out of three participants, namely P1 and P3, faced difficulties remembering some gestures. P2, on the other hand, showed the most skill when bimanually interacting with the AR interface and its elements (see Fig. 4). This may be explained by his prior experience with immersive interfaces, such as his one-time exposure to the AR headset or playing VR games.

The system's menu possesses a range of features that could be used (see Fig. 4), including [*Replay*] button to replay aloud the instructions or [*Mute*] button to switch the audio help off completely. However, when analyzing the recorded data, we did not observe convincing indications that would suggest the explicit intent of the participants to use any of these features. The are two potential reasons for this behavior among the participants. Firstly, the domain-expert users rely on the AR instructions only in a small capacity. Secondly, as we observed before, the video instructions may not allow users to retain enough knowledge about the AR interface and its feature as the repair progresses and the time since watching the video clip lapses. The first explanation seems to be supported by the fact that participants asked about the help purely when they accidentally closed the AR application. Consequently, we have to carry out additional user studies with inexperienced users to address the above concerns.

Concerning manipulating the menu elements, we saw no apparent patterns in the recorded videos. For example, P1 translated the menu elements twice as they occluded his view of the printer. In opposition, P2 started the task by scaling, rotating and translating the AR guides as he pleased. Furthermore, also P3 use all three manipulation techniques to interact with the menu and inspect the 3D models in detail. This behavior could also be dictated by the menu elements obstructing his view of the model. In addition, P3 also commented on the need to allow the users to manipulate and interact with the guide types individually (e.g., the 3D models could be interacted with independently to textual or imagery-based instructions [15]).

Our study also revealed additional limitations and caveats of using current, widely considered state-of-the-art AR equipment. These involve the object detection and tracking provided through built-in HL2 capabilities. Here, the gesture recognition and tracking were not operating satisfactorily when the participants needed to work wearing gloves due to heated 3D printer parts (see Fig. 4). As a result, P1 and P2 had to put the gloves on and off multiple times when interacting with the AR interface. Furthermore, P3 decided not to use the gloves anymore after experiencing the problems for the first time. There are ongoing works towards enhancing HL2's capabilities in object detection, and tracking [71], which we plan to utilize in the future for the repair task.

Interestingly, P1 and P3 often required time and repeated trials to establish the correct distance at which they were able to press the menu buttons. P1 became more fluent in these tasks while the repair process progressed, and P3 experienced considerable challenges in properly operating the button menu. On the other hand, participant P2, with prior exposure to the immersive interface, was able to press the virtual buttons with no visible problems. This suggests the need for familiarization and training for inexperienced AR users. However, we advise caution when making decisions based on such a small sample size.

Finally, we noticed certain levels of jitter when the participants manipulated elements of the AR interface (e.g. 3D models) or when fastly moving from one step instruction to another. These jittery effects correlate directly with the amount of elements manipulated at the same time by the user. Nonetheless, this seems to have very limited influence on the participants as the reported SFS levels were relatively high (see Table 1).

8. System expressiveness

To further reason about our system design as well as on available instruction modalities, we decided to carry out heretical verification of the system expressiveness [31,32]. To achieve this, we used the cognitive dimensions of notation [31,32] that allowed us to analyze limitations and capabilities of a given notational system such as interactive, immersive interface [33].

(i) **Viscosity:** The repair instructions are provided in a similar manner utilizing the same textual, audio and, if possible also, visual guides such as 3D models or animated images. Furthermore, the whole repair process is guided via step-by-step instructions leading from the initial selection of the printer's fault to the nozzle replacement (see Fig. 2).

(ii) **Visibility**: The user is able to manipulate the instructions by translating, rotating and scaling them as desired. This can be achieved with simple gestural input when the instructions obstruct the user's view over the 3D printer or its parts.

(iii) **Premature commitment:** The system requires the repair to be carried out step-by-step in a predetermined order. Hence, we did not provide the possibility to move back from the current step once the previous step was verified. The guide the current step execution, the user can recall or close the various guiding modalities or replay the audio instructions (see Fig. 4). The user can also move and pin the instructions in the chosen place within the 3D space near the printer.

(iv) **Hidden dependencies:** Due to its nature, the AR interface shows clear and direct dependencies between the shown visual guides, i.e. 3D printer parts and tools models and their actual physical counterparts (see Figs. 1 and 4).

(v) **Role-expressiveness:** Thanks to using the different modalities of the AR interface, such as textual and visual guides utilizing models of tools and 3D printer parts (see Fig. 1(b)(d) and Fig. 4(b-c)), the user does not have to build a cognitive model of the instruction elements.

(vi) **Error-proneness:** The system allows the user to recall the various instruction elements (i.e. textual instructions and visual guides) and to replay audio instructions when needed (see Fig. 4). In addition, guiding instructions can be moved and resized when obstructing the user's view.

(vii) **Abstraction:** We minimized the abstract notations of the AR interface by utilizing visual guides consisting of 3D tool and printer models (see Fig. 1(b)(d) and Fig. 4(c-d)). We also used the metaphor of buttons to operate the system and step menus. Moreover, as the AR superimpose digital artifacts on top of the real-world user's view, such an interface further decreases the abstraction levels experienced by the headset wearer.

(viii) **Secondary notation:** The secondary notations included the animated arrows and other visual cues placed on top of supporting images and part models that are showcasing, for example, how to use a given tool for unscrewing tasks (see Fig. 4).

(ix) **Closeness of Mapping:** The closeness of mapping between our system and the real-life tasks is achieved thanks to the use of an AR interface and visual guides (e.g., images depicting step instructions as well as models of tools and 3D printer parts) (see Fig. 4).

(x) **Consistency:** The interaction modalities, system menu and instructions layouts are similar in each repair step providing consistency of usage throughout the repair task (see Fig. 1(d) and Fig. 4).

(xi) **Diffusenesss:** To mitigate the diffuseness effects, the user is able to manipulate the visualization elements, i.e. rotate, scale or move them. Thus, they can be removed when the instructions occupy too much of the user's FoV or obstruct 3D printer elements. Furthermore, with the help of the [*Pin*] functionality, the user can anchor the menu in a chosen place in space and return to it when needed.

(xii) **Hard mental operations:** Thanks to the domain-expert study, we can reason that users of our system experience relatively low to mild cognitive load scores (see Table 1), which hints no challenging mental operations are required to carry out the complex repair task with the help of our AR interface.

(xiii) **Provisionality:** The system imposes hard constraints on the order in which the repair operations have to be carried out. This is dedicated to how the 3D repair process is carried out in non-laboratory settings and the need to use safety clothing (i.e. thermal-resistant gloves) during the selected repair steps.

(xiv) **Progressive evaluation:** The system shows numbered, step-by-step instructions for the device repair process (see Fig. 4). When needed, this guidance has a form of imagery or 3D model data allowing the user to compare them with the actual physical state of the printer and evaluate the progress in each step.

Thanks to the expressiveness analysis, we can see how important it is to include 3D models in the AR system. Their usage for providing instructions can potentially decrease the cognitive load experienced by AR users when carrying out a complex repair task.

Moreover, our analysis suggests two potential improvements to our interface. First, the development of computer vision algorithms that would allow the system to directly indicate parts and tools needed to be used in a given step [72], and to provide automatic verification of both the individual repair steps and ultimately the whole process. Second, the instruction for each step could contain information about how many steps are left in the repair process instead of just having the current step number (see Fig. 4). We could provide this information as either text or a graphical progress bar.

The heuristic approach to verification also complements the findings from our domain expert study, allowing us to reason about the importance of visual guides when we did not capture a sufficient amount of information from the user experiments.

9. Design suggestions for AR guiding systems

Thanks to the conducted analysis for the experimental results as well as heuristic expressiveness verification, we were able to distill these seven design suggestions when developing an AR-based guiding system for a complex repair process.

(A) *Validation in Non-Laboratory Environment*: as the 3D printer repair process shows, the task carried out by the user with the help of the AR system may require wearing protective gear such as thermal-resistant gloves or specialized glasses. These, in turn, may cause a negative impact on some system functionalities, such as hand-tracking or limiting the user's FoV. Thus, we need to understand and consider the potential impact of the procedure impact when executed in a non-laboratory setting.

(B) *Safety Warnings and Alerts*: When working with industrial systems, we should especially consider the factors impacting users' safety. As suggested by P3, we could include multiple safety warnings and alerts requiring direct confirmation that would pop up when dealing with hot 3D printer parts (see Fig. 2).

(C) *Compulsory Confirmations*: In agreement with other research findings concerning multimodal systems [73], we should design our interface to mitigate the risk of accidental closing or to prevent unwanted step omittance as well as other mistakes and slips [74]. We can achieve this by including mandatory confirmations when providing safety warnings [75] or important step instructions [74].

(D) *Instruction and Interface Customization*: We should provide the users with means of manipulating the interface and thus allow the customization of instruction (see Fig. 4) for individual participants and particular repair steps. As observed in our study, all three participants tried to manipulate and readjust graphical components of the system by changing their relative positions, rotation or scale. In addition, the behavior of P3 hints that we should provide the possibility of disconnecting these graphical elements and allow them to be manipulated separately.

(E) *Menu Elements Repositioning*: As suggested from observed users' behavior, the user should be able to place the individual instruction components in the virtual 3D space, for example, near or on top of the repaired device and anchor them there for the other steps as well.

(F) *Compulsory Training*: Before using the system for the first time to carry out an actual task, the users should be given a period of familiarization with the system as well as undergo compulsory training. Such an approach could, to an extent, counterbalance the impact of novelty effects [76] on, among others, cognitive load experienced during the task and extend the users' retention span.

(G) *Jittery Prevention*: When developing the AR platform, we should put an emphasis on utilizing various software optimization techniques, e.g., implementing efficient algorithms, to make our system work fluently. This design suggestion, however, should reduce in significance over time with new releases of more powerful edge computing devices (e.g. AR headsets) and more robust software libraries.

10. Discussion and conclusion

We present in this paper the development process of the guiding system utilizing an AR interface to support and aid the repair process of a 3D printer. The system design was established with the help of well-known design engineering methodologies [27,28], often used in industrial use case scenarios involving immersive interfaces such as AR or VR [15,33].

Furthermore, the 3D printer repair procedure, specifically the task of fixing the obstructed printer nozzle (see Fig. 2), represents a complex process in which a series of factors have to be considered when preparing a guiding solution. This, in turn, allowed us to mix together a range of different instruction modalities (i.e., audio, textual and various types of visual clues) and ascertain their viability for the AR-supported repair task.

The system was evaluated in an informal study protocol [29] with three domain expert participants using a mixed-methods approach [68]. To further reason about the usability and expressiveness of the system design, we carried out a heuristic exercise using cognitive dimensions of notation [31,32] to capture the elements of the AR interface that have the potentially highest impact of the cognitive load perceived by the system users. The latter is especially important when dealing with novice users, even though domain experts did not report high levels of cognitive load when using our system (see Table 1). Moreover, thanks to the heuristic analysis, we were able to a highlight various improvements that we plan to incorporate into the next version of our repair software.

In summary, the heuristic usability verification, analysis of captured questionnaire results as well as audio and video recordings depicting users' behaviors suggest the potential usefulness of such a system in guiding a complex repair process. Moreover, this approach has led us to distill seven design suggestions *A–G* when building AR-based repair guiding systems. In addition, this work supports the suggestion that AR guidance systems show promise in being utilized as an enabling tool for the right to repair of complex items or parts. This would have a further impact from an environmental perspective by reducing needless waste.

10.1. Limitations

The main limitation of our work is the relatively small number of participants involved in our study. Thus, we advise caution when interpreting the quantitative results. Consequently, we grounded our results and observations on the captured qualitative data. Such informal study protocol is often deployed when assessing the visualization-based interface with domain experts [29].

11. Future work

We plan to evaluate our system and interaction design in a series of controlled user studies [29]. This will allow us to independently ascertain selected system components, such as menu and instruction layouts (e.g., button placements and respective sizes), as well as investigate suggestions made by participants (e.g., instruction spawning placement and anchoring in the 3D space). We will also test our system against users with non-expert backgrounds to see if our AR system can support the repair task when carried out by inexperienced participants.

Furthermore, we will validate our system in a non-laboratory setting, likely in industrial or home environments, to ascertain whether the surrounding conditions have a direct impact on how users behave and approach to exert the AR system and its various functionalities.

The analysis of gathered data will allow us to reason about the design of particular components as well as the entire AR system. Next, we will use the results to refine our system and interaction design.

CRediT authorship contribution statement

Sławomir K. Tadeja: Conceptualization, Methodology, Visualization, Writing – original draft. **Luca O. Solari Bozzi:** Software, Formal analysis, Investigation, Data curation, Validation. **Kerr D.G. Samson:** Methodology, Formal analysis, Data curation, Writing – review & editing. **Sebastian W. Pattinson:** Supervision, Project administration, Funding acquisition. **Thomas Bohné:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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