Immersive Authoring by Demonstration of Industrial Procedures

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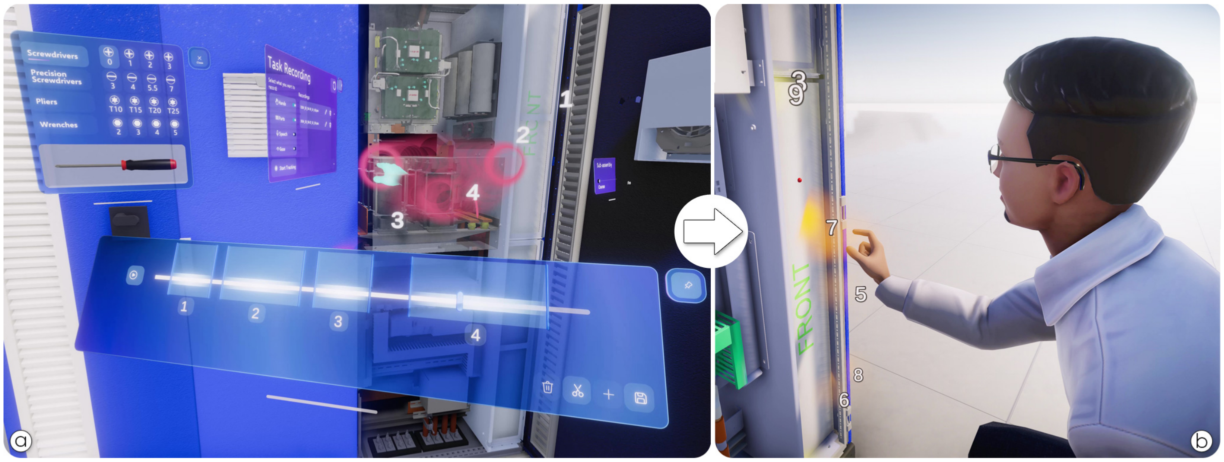

Figure 1: a) We present a system for authoring industrial maintenance instructions from 3D CAD models and interactions captured with an off-the-shelf mixed reality head-mounted display. Documentation authors demonstrate the manipulation of machine parts in virtual reality. b) Our tool automatically segments individual steps from recorded data to generate instructions in various formats, e.g. rendering highly detailed tutorial videos.

ABSTRACT

This work presents an authoring tool for supporting the creation of immersive instructions for industrial processes. Our system simplifies the creation of instructional content by providing an immersive virtual reality environment that enables expert operators to interact directly with virtual replicas of industrial devices. Hand movements, tool usage, gaze, spoken comments, and machine part movement are recorded using a head-mounted display. Editing of instructions in virtual reality is aided by automatic segmentation of recorded data into individual steps and visualizations of regions with intensive activity. A qualitative evaluation of our system by industrial experts shows that it is a viable alternative to current practices in authoring instructions for assembly and maintenance.

Index Terms: immersive technologies, computer-assisted instructions, graphical user interfaces

1 INTRODUCTION

Technical documentation is an important asset in industry. It commonly supports the setup, maintenance, and training of operating expensive machinery. Traditional approaches for creating instructional content for industrial machinery involve written manuals and training videos. In an industrial setting, creating these instructions is an iterative process that can take a long time.

Moreover, printed documents and videos are often found inferior to hands-on training on a real machine. Unfortunately, the organization of training sessions can be costly and encumbered by safety concerns and insufficient availability of equipment. Especially global companies operating in many different geographic locations need to provide remote training and support, since *expert operators* with the required qualifications are often located far from the machine on which a particular task needs to be performed. This geographical distance poses a significant challenge in providing effective guidance and support to *apprentice operators* who are available on site but lack specific knowledge and training.

A possible solution to these concerns is offered by immersive technologies, such as virtual reality (VR) and augmented reality (AR) [31], which have been shown to provide considerable advantages over traditional forms of instructional content. For example, AR enables three-dimensional presentations directly within the user's real environment [15, 24, 38, 29], free viewpoint visualization [39] and adaptive guidance based on what the user does [33, 32]. Many companies have adopted maintenance and training processes that involve a head-mounted display (HMD) or another type of immersive display. Among the most important benefits is the ability to simulate complex scenarios and provide hands-on training without the need for physical equipment. However, both traditional and immersive approaches have in common that the creation of instructional content can be tedious and time-consuming [26]. Especially the creation of immersive content typically requires suitable skills as a 3D artist and programmer, which neither the engineers nor the technical writers employed by the documentation department of an industrial enterprise commonly possess.

To address these challenges, we present an authoring tool that simplifies the creation of immersive instructional content by recording the demonstration of an expert and supporting its subsequent editing. Our tool captures the interaction of an expert with 3D replicas of industrial machines in VR – or, optionally, in AR by enabling the pass-through functionality of the HMD.

The presented system records the expert's detailed hand movements, as well as the movement of individual machine parts or subassemblies of parts. Furthermore, the system records the usage of

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physical tools, speech, and gaze data (using the eye tracking capabilities of the HMD). The expert operator can record procedures without manually indicating new steps, as step segmentation happens automatically. The step segmentation can be further refined in the immersive environment. We evaluate the usability of our tool as well as its feasibility for productive deployment in an industrial setting via a qualitative evaluation with four experts in technical writing and training. In summary, our work makes the following contributions:

- Insights gained during the evaluation of our prototype by industry professionals, which show our proposed method is an acceptable method of integrating immersive technologies into the existing instruction authoring workflow.
- An approach to capturing instructional content by recording activities performed by an expert operator in VR, which enables them to create instructional content without programming or animation skills.
- A method to automatically detect work steps from captured instructions.
- A simple and user-friendly editor interface to adjust work step segmentations directly within the VR environment.

2 RELATED WORK

2.1 Immersive training

Recent studies show that immersive training systems can lead to greater knowledge retention and therefore fewer errors and better worker performance and engagement compared to traditional training systems [8, 20]. Murcia-Lopez and Steed [25] confirm that exposure to a virtual training environment is sufficient for effective training when physical components and tools are inaccessible. Thus, such systems can even be effective in training off-site apprentice operators. Gavish et al. [10] evaluated an assembly task in which expert technicians with no prior experience with immersive technology received instructions for an assembly task with VR, AR, and video. The results showed comparable training effectiveness for all three conditions, and the AR condition performed slightly better in terms of overall errors. Zhang et al. [40] compare training systems that use a conventional screen, a projector, and an HMD to train workers. Their application enables interaction with virtual content using hand tracking. The results show that the easiest and most immersive of the three systems to use is the HMD condition.

Grabowski et al. [12] use VR training as an alternative to live training in high-risk scenarios. They implement a VR training tool to simulate detonation procedures in coal mines and evaluate their system in terms of immersion, ease of use, and functionality using a control group of industry experts. Their results showed that immersion levels were high, despite an initial difficulty in manipulating objects with their interface. Murcia-López and Steed [25] experiment with different interfaces to train the assembly of a 3D puzzle. Their results show that, even without access to the physical components of the puzzle, the participants who trained in VR performed similarly well. This exemplifies that VR training systems can be effective even when physical components and tools are unavailable, for example, when operators train off-site.

Several studies demonstrate the validity and effectiveness of virtual and mixed reality systems for industrial training. Langley et al. [20] evaluate the effectiveness of a virtual training prototype for engineers in the automotive industry. Their system displays a virtual replica of an assembly task on a projector screen and enables users to perform the task by tracking their limbs with a depth sensor. After training, participants in their study were assigned to perform real assembly tasks. All participants expressed their enjoyment using the virtual training system and showed comparable results on the real assembly task. The authors advise that interactions should be designed to minimize user mental load by ensuring that instructions are easily retrievable or self-evident. Another example of AR outperforming traditional instructions is given by Kolla et al. [19]. Their work compares paper-based assembly instructions with an AR tutorial using an HMD. In general, the participants made fewer errors and gave higher usability scores to the AR system.

Pen-based interactions in virtual reality are explored by Pan et al. [28], who asked participants in their study to follow virtual assembly instructions displayed on a 3D monitor. However, their system only demonstrates the order and orientation to use in the assembly of parts, and no further interactions are modeled. Live industrial training scenarios are explored by Wang et al. [35] in the context of remote collaboration. Their AR system provides remote experts with a real video stream from the HMD of the user on-site, as well as a virtual recreation of objects in their environment. The on-site user can see the same virtual objects augmented in their view, enabling the remote user to demonstrate assembly tasks by manipulating the virtual objects. Remote VR users preferred gesture-based interaction with virtual objects over controller-based manipulations. Ulmer et al. [34] propose an adaptive, gamified VR training system for industrial manufacturing. Their system visualizes instructions using virtual objects in a virtual workplace and adapts the level of instructional detail based on user performance.Instead of simply showing the user the end position of the machine parts, Hořejši et al. [16] introduce a tool that animates assembly instructions in 3D. Their evaluation shows that their AR and VR systems outperform paper-based solutions in terms of error reduction.

2.2 Authoring immersive content

Creating AR/VR content can be expensive and time-consuming, and has various applications outside of immersive training scenarios [21]. Nebeling and Speicher [26] state that creating immersive applications requires significant technical skills and programming experience, making them expensive in terms of time and resources and inaccessible to artists and inexperienced end-users. Ashtari et al. [1] investigate design and implementation challenges faced by AR/VR application developers. They identify various issues, including the lack of concrete design guidelines in AR/VR, difficulty in designing physical interactions such as realistic gestures, and the challenges of anticipating the user's knowledge, potentially limiting the accessibility of these applications.

Stanescu et al. [33] produce AR tutorials by capturing 3D point clouds of objects by detecting changes in the reconstructed scene, enabling automatic segmentation of work steps while authoring instructional content. Roldan et al. [30] similarly investigate VR instruction authoring by demonstration. Their system enables expert operators perform assembly tasks on virtual objects, which are automatically subdivided into discrete steps and can be later recreated in a training mode for new users. The results of their evaluation show that their system has a higher or equal training performance compared to traditional methods and significantly better evaluations in terms of mental demand and user perception. Furthermore, their experiments show that authoring by demonstration captures real behaviors of expert operators, rather than the formal procedures typically documented in paper-based instructions.

Niedermayr and Wolfartsberger [37, 27] further investigate authoring by demonstration and propose a system that enables expert users to manipulate virtual machine parts to capture assembly instructions. These instructions are limited to the location of machine parts and the expert user's hand, as tracked by the controller. Liu et al. [23] explore hand tracking for instruction authoring. Users wearing a custom hand device demonstrate fine manipulation of instructions within defined bounding boxes. These instructions are immersively replayed in AR and compared to users' inputs to generate feedback. Their evaluation shows an increase in task completion performance and user confidence.

Huang et al. [17] present an AR tutoring system for machine

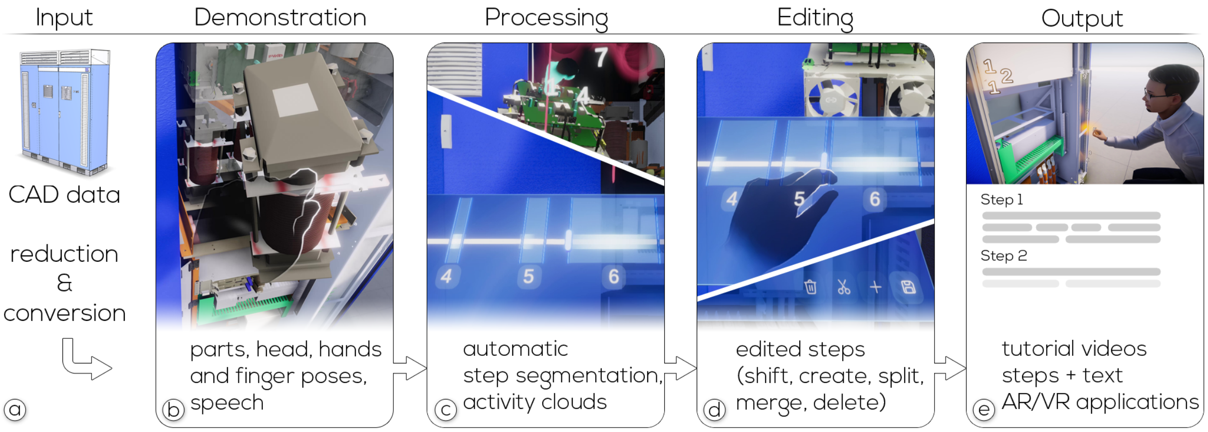

Figure 2: System Overview. a) CAD data is converted to polygonal meshes. b) The expert operator performs the task in a virtual environment using an HMD. c) Activity clouds are generated, and an automatic segmentation of steps is performed. d) The expert operator or technical author can review and edit the recording, with activity clouds and step suggestions serving as visual assistance. e) The finalized steps are then exported as .json file and can be used with a variety of different viewers.

tasks in adaptive levels of detail. Their system enables authoring by demonstration and implements multiple methods of instruction visualization.Another example of the authoring of spatial tutorials is demonstrated by Chidambaram et al. [6]. Their system features a trained YOLO object detector that instantiates virtual replicas of real tools and objects when detecting them in the user's workspace. These virtual objects can be manipulated in AR to demonstrate their intended use, an action which can then be played back in 3D.

Whitlock et al. [36] propose a system that employs OptiTrack markers in tools and materials that accurately capture their movements during an expert recording session. Stationary cameras capture a third-person perspective in addition to the camera on the user's HMD, allowing tutorial playback from multiple views.

Similarly, Chidambaram et al. [7] introduce a platform for authoring instructions in multiple media formats. Objects and tools spatially tracked with AntiLatency trackers enable users to demonstrate digitally twinned assembly tasks, which can be exported to 3D immersive instructions or 2D videos. Another system that captures object manipulations for instruction authoring is proposed by Brůža et al. [4], which enables users to author 3D model animations using VR controllers.

While some of the aforementioned systems aim to capture processes using virtual demonstrations, our work focuses on simplifying the elements of documentation that are important to industrial experts. Our design goal includes the detailed capturing of bimanual operations using hand pose tracking. We implement the functionality to automatically segment work steps and an immersive editor for refining this segmentation. Additionally, we introduce the option to manipulate hierarchical sub-assemblies, a crucial aspect of industrial processes.

3 SYSTEM OVERVIEW

The main motivation for our work was to explore how immersive authoring methods can be integrated into an actual industrial environment. To this end, observations of related work and feedback from mechanical engineering experts informed our design choices: Our application simulates working with real devices or objects and thus requires 3D models to be imported into the application. Our interactions and method of storing data during recording are generalizable for any application of manual interaction with objects, and we test it on complex, real data. In our use case, 3D models of industrial machines are generated by converting CAD data into a 3D mesh usable for real-time rendering. To ensure correct functionality, manual postprocessing of the CAD data may be necessary. For example, sub-assemblies or parts that are rigidly attached to one another require correct parenting in the hierarchy of the 3D file.

Our system visualizes content via a VR HMD, enabling bimanual operation of the application and virtual recreation of real machines on a real-world scale. This improves the user experience [40] and gives a more realistic impression of the content. The application is developed using Unity3D and incorporates the OpenXR standard, ensuring seamless integration across various platforms and VR devices. We use MRTK3 to handle user input and for building the user interface (UI), as it enables wide device compatibility.

Instructions are captured by direct manipulation of virtual objects, employing an authoring-by-demonstration approach. Our application captures the user's hands and the manipulated virtual objects to record precise operations, and, optionally, user audio and gaze data for more detailed instruction descriptions. For this reason, we require an HMD with native hand tracking. Our application offers a dedicated editing mode running in the same VR environment for further refinement of the recorded instructions. This allows experts to see the documentation in the same context as it was recorded and will be presented. An overview of our system can be found in Figure 2.

3.1 Task recording

Upon opening the application, users see a 3D representation of the machine. While recording, the expert operator demonstrates the task step by step using direct manipulation on the machine, while recording is controlled by 2D menus (MRTK "near menus" containing conventional 2D widgets).

Figure 3 (left) displays the *Task Recording* menu to manage which input channels to record. For the recording of "hands", all visible hand joints and the head pose are captured. In addition, the pose of any virtual tool chosen from the tool menu (Figure 3 (right)) is recorded while it is wielded. If selected, the pose and orientation of the machine parts are recorded while they are being manipulated. Selecting "Speech" lets users comment on their actions or provide more detailed verbal explanations, such as hazard warnings. Finally, "Gaze" captures the user's focus point in space, which can be used for hotspot display or further analysis. Once the recording is stopped, the collected data is saved in JSON format and added to the list in the recording menu. This file stores the initial transformations for every part in the scene, and for each frame of the recording saves the timestamp, the 3D transformations of parts that have been manipulated, and the head and hand joint transformations. For every frame the user is holding a virtual tool, its identifier is stored.

Figure 3: The *Task Recording* menu (left) allows the user to select what information to record and provides a button to start and stop recording. Saved recordings can be accessed from the list on the right. While recording a task, the expert operator can select a tool from the tool menu (right) and demonstrate its usage.

For machines with hierarchical structures of sub-assemblies, users can select any level of the hierarchy using the sub-assembly menu seen in Figure 4 (top). This enables the manipulation of *coarse* or *fine* sub-assemblies more efficiently than sequentially selecting multiple individual parts in the 3D representation. We let the user probe the levels of the hierarchy interactively with a slider, selecting coarser sub-assemblies to the left, and finer sub-assemblies to the right. To help users identify which parts belong to which sub-assembly, every hierarchy layer is assigned a unique color, and each part in that group is highlighted in the corresponding color while adjusting the slider, or as an optional alternative material for every part. The coloring can be seen in Figure 4 (bottom). The highlight color was chosen from the *viridis* color palette [9] to improve visibility for users with color vision deficiencies.

To help with the reassembling of parts, we store each part's or sub-assembly's original position and rotation and snap the element back into place if the user moves it to the proximity of the original position. This makes reassembly of the virtual machine easier, specifically for small parts that may be difficult to precisely manipulate.

3.2 Segmentation and editing of steps

Our system automatically segments the work steps after completing the recording. For that purpose, the recorded data is analyzed to determine periods of significant activity. As we support any kind of industrial procedure, we need to capture events other than just virtual part manipulations[30]. Every frame of the recording is inspected and flagged as potentially significant if the user's hand is closer than a threshold to a machine part. We selected a threshold value of eight centimeters as this is approximately the mean adult hand breadth[11], a distance that indicates the author is demonstrating a part manipulation. Clusters of flagged frames are greedily combined into steps. This segmentation divides instructional content into semantic units, which are essential for training and analysis. Automating step segmentation allows experts to focus on task execution without having to interrupt the demonstration to manually delimit individual steps during recording. We found that our heuristic segmentation reliably identifies most of the steps, leaving only minor corrections for manual post-processing.

For these corrections, a *timeline menu* can be invoked, which contains a timeline corresponding to the entire recorded demonstration (Figure 5, left). In timeline mode, the recorded elements are shown at their recorded locations as the user plays back the recording or scrubs through the timeline. On the timeline, segments that have previously been classified as significant appear as bright areas labeled with consecutive numbers indicating the "steps". Pressing a label plays back the associated frames, and the bounds of each step can be resized by dragging the edges of the highlighted area. As the automatic segmentation process relies on user proximity to the 3D model, our system does not support automatic detection of alternative kinds of interactions. However, our system does allow manually adding work steps to recorded data to include other kinds of operations. Steps can be manually added to segments that were not flagged automatically; existing steps can be trimmed, deleted, merged, or split, and finally, the edited data can be saved.

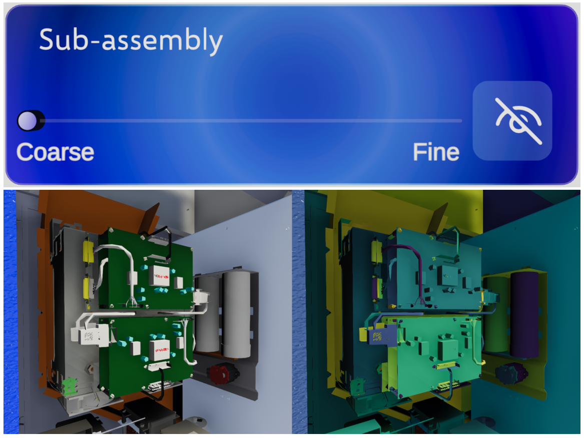

Figure 4: Using the sub-assembly slider (top), users can manipulate different levels of the parts hierarchy. Parts can be highlighted to increase contrast and to identify other parts in the same sub-assembly. (bottom)

3.3 Visual assistance

We implement several visual cues to assist users during editing and guide them to relevant areas. For every step, 3D activity is visualized as a cloud of spherical particles that indicate the spatial distribution and intensity of the work steps around the machine. Clouds are color-coded to indicate which hand was used (Figure 5, right). To limit overdrawing and occlusion, the particles are rendered as halos with a transparent center whose opacity decreases with the distance of the visualized activity to the currently selected frame.

For a better overview and to enable fast searching, each activity cloud is labeled according to its corresponding step. Touching the label on the timeline highlights the corresponding cloud. Additionally, each step in the timeline is visually linked to its corresponding region of activity by a 3D line, as can be seen in Figure 5. This makes room-scale localization of the activities easier and is especially useful if the working area spans a larger setup containing multiple large machines.

3.4 Applications of the recorded data

After the editing of the recordings is complete, the data can be used directly in a wide range of applications. One potential application is to analyze the recording to identify time-consuming steps and evaluate potential optimization strategies. Virtual manipulation of real-scale machines can provide realistic expectations concerning the duration of activities or help identify unexpected difficulties.

Our framework can generate a variety of tutorial formats from the rich set of recorded channels, including user pose, hand motion, finger joint positions, gaze, and speech. From the recorded hand and head poses, an upper-body or even full-body 3D avatar can be animated instead of just visualizing floating hands, as seen in Figure 1. The avatar animation can be used to render non-interactive, but high-quality videos or still images for printed handbooks.

We can also segment the audio according to the steps in the timeline and parse the recordings into text that can be exported to printed handbooks or converted back to high-quality spoken instructions that can be displayed along with the step visualizations in generated videos. The extracted text has the further advantage that it can be translated into other languages for localization.

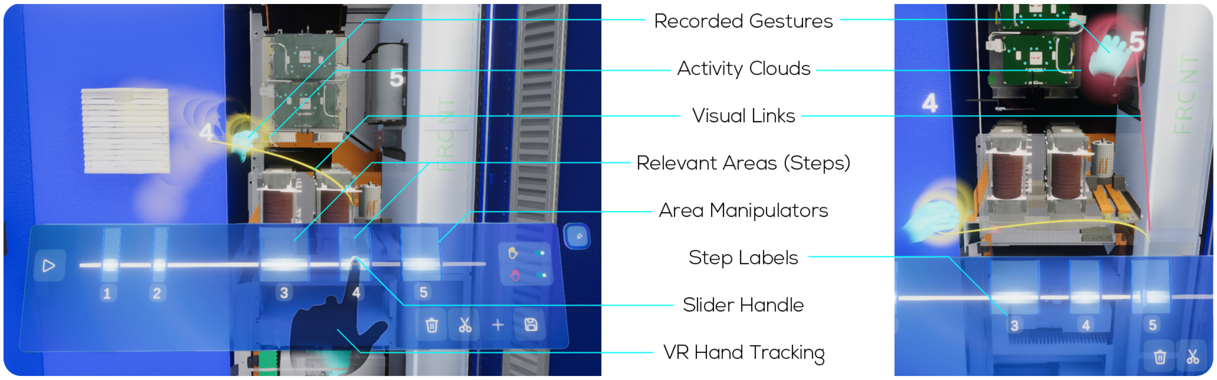

Figure 5: During playback, machine parts are animated according to the handle position on the timeline slider. Glowing hands represent the gestures captured during recording and convey detailed instructions. Automatically segmented steps are indicated by highlighted areas on the timeline slider, while activity clouds within the scene highlight relevant areas in space during each step. Pressing the step labels plays back the relevant frames of that step. Users can edit steps to divide or adjust automatically selected regions of activity.

The primary use case of the recorded data lies in the generation of interactive tutorials. Animated tutorials can be shown as a 3D view in a web browser (e.g., using WebGL), so users can freely adjust the viewpoint while watching animated instructions. If an HMD is available, the tutorial can be delivered at 1:1 scale in an immersive environment. For off-site training, a VR headset provides a realistic virtual training environment, running our application in playback rather than recording mode. If access to the real machine is available and the virtual models are representative of the real assemblies, an AR headset can be used.

4 EXPERT EVALUATION

Following the implementation, we decided to evaluate the usability of our system and in particular its feasibility for industrial applications. A qualitative evaluation was conducted in which industry professionals were asked to use our system and compare it with their current methods of authoring and using instructional material. This evaluation included an exploratory interview, a think-aloud protocol, and a reflective interview.

4.1 Study design

As a first step, we conducted an *exploratory interview* following a semi-structured approach. Participants were asked open-ended questions that allowed them to explain and reflect on their current workflows. The questions were selected to collect experiences and information about currently accepted procedures and to identify potential pain points in the current authoring and training processes.

In the second step, users tested the VR authoring system presented in this paper and asked to comment on their experience using the program using a *think-aloud protocol*. During application usage, users could ask questions and experiment with the available functions. Our demonstration was carried out using a “Meta Quest 3” headset, connected via a link cable to a *Razer Blade 15* laptop computer running the program. We believe that the low weight of the Quest 3 had a positive influence on the feasibility as perceived by the experts, who had seen heavier headsets before. The interviews and live application demonstration were held in a closed room at the experts’ workplace. We recorded audio during the interviews and the evaluation of the VR system for further analysis of comments and actions taken while using our system. After experiencing the VR system, experts filled out three questionnaires, which measured the users’ perceived simulation sickness (SSQ) [18], system usability (SUS) [3], and task load (NASA-TLX) [14].

Finally, a second *reflective interview* was conducted. Having experienced a new authoring solution, participants provided their impressions of the immersive authoring system and the potential of integrating such a system into their current workflows. Once again, open questions guided the conversation and allowed participants to freely discuss their experience using the system and any challenges they encountered. Our study did not require approval from the institutional review board of the submitting institution.

4.2 Participants

We interviewed four employees of a global engineering company; all identified as male. The participants, hereafter referred to as experts, had between 7 and 25 years of experience in their industry and were between 33 and 53 years old (mean=43.3, standard deviation (SD)=7.3) at the time of the interview. As we intended to evaluate the acceptance and integration of our solution into established workflows, we chose to interview a small group of experienced industrial documentation authors. Three of the participants are employed as technical writers, hereafter referred to as *TW1-TW3*. Their duties involve the authoring of documentation and product guides, and they are involved in the content creation, collaboration, and iteration phases of the instruction creation cycle, as presented in Table 1. The fourth participant, hereafter referred to as *TR1*, works in technical training and uses documentation to create teaching material and train engineers, as well as collaborate with technical writers, as outlined in Table 1.

TW1, *TW2*, and *TW3* self-reported that they are only “slightly” or “moderately familiar” with working with industrial machines, while *TR1* reports to be “very familiar”. This rating indicates that hands-on experience with real machines is uncommon for documentation teams, an interesting finding given that their materials are used for training. *TR1* also claims to be “very familiar” with virtual and augmented reality, while the three technical writers we interviewed reported being only “slightly” or “moderately familiar”.

4.3 Research questions

The study goal was to answer the following research questions (RQ):

RQ1 How does our application address current challenges in authoring effective manuals focused on the assembly and maintenance of technically complex machines?

RQ2 What are experts’ perceptions about integrating immersive authoring into their existing workflows, and what adjustments are necessary to support this transition?

RQ3 What features or enhancements would experts suggest so that the VR authoring system better meets the needs of creating complex instructions?

	Preparation	**Content Creation**	**Collaboration / Feedback**	**Iteration / Revision**	**Distribution**	**Maintenance**
Personnel requirements	engineers, developers	***technical writers***, developers	***technical trainers & writers***	***technical trainers & writers***, developers	***technical trainers***, sales team	support team
Tools and resources	CAD software, previous guides	CAD software + renderer, word processor	email, presentation software	email, presentation software	online portal, physical release	
Data requirements	client demands	CAD model	guides, diagrams	presentation, notes, feedback		updated client demands, updates to machine
Most time spent	development, 3D modeling	image generation from 3D models	communication between teams	long-term feedback		change management
Accuracy safeguards	expert exchange	four-eyes principle, system designer feedback	developer input		long-term iteration	
Data refinement		exchange with engineers, project developers				long-term productive use

Table 1: The journey map of each phase of the instruction creation cycle. During exploratory interviews with technical writers and trainers, we collected information to categorize and organize the requirements and processes of each phase.

The experts were interviewed individually. To answer *RQ1*, the interviewer collected answers and comments made during the semi-structured interview and used a journey map approach to allow a structured reflection of the current process of creating a manual. Using the created maps, experts reflected on the phases of creating such instructions. Furthermore, they were asked about pain points and their subjective impression of the effectiveness of each step in the process. Subsequently, to answer *RQ2*, experts were tasked with using the presented VR system to manipulate a model of an industrial machine to simulate the creation of an interactive manual. During the interaction, a think-aloud protocol was used to collect qualitative feedback from experts. Finally, in the second semi-structured interview, the experts discussed their impressions of the system and the potential of using it to improve their existing workflow. *RQ3* was addressed by gathering comments made by experts during both the authoring task and the following semi-structured interview.

4.4 Results

The first interview provided insight into the current procedure of authoring and using industrial machine assembly and maintenance instructions. During the interviews, the process of creating instructional content was investigated collaboratively with the participants. In each interview, we created a journey map, which informed us of each expert's part of the instruction creation process. The data from the four interviews was consolidated into a single journey map, seen in Table 1. Each column is labeled according to a phase of instruction development. These labels are based on the life cycle processes of industrial products [22], which follow similar development phases. The exploratory interviews informed the row labels, which helped us to more clearly categorize and arrange the requirements during each step of the instruction creation process.

Exploratory interview In their current workflow, technical writers author product and maintenance guides in close collaboration with the product development team, while often reusing material from previously created guides. Technical writers work on the creation of texts, drawing diagrams, and generating renderings from CAD models. According to *TW1*, the latter takes the longest time. Hands-on experience with the real machine can also help set realistic expectations for the writing team, as the scope of actions becomes clearer from hands-on experience compared to just seeing 3D models on a screen.

TW2 described the difficulty in gathering information, as research into technical processes can take a long time due to communication delays between various teams. Their documentation process includes incorporating screenshots of 3D models into the manuals, the final deliverable typically being a printable PDF or an interactive document accessible through an online platform. *TW2* also discussed the iterative nature of the documentation process, as adjustments may be needed after the products are distributed to clients, where changes are often made during installation or operation.

TW3 confirmed that the generation of images from CAD data is among the most time-consuming processes, citing the tedious process of positioning virtual cameras and models to create proper screenshots. They also emphasized the difficulty of maintaining correctness, as machine models often change during the planning or development phase.

TR1 provided alternative insights into the practical use of technical documentation. They typically create presentations for training sessions, which involve writing text and creating custom pictographs or diagrams explaining concepts, as well as real and rendered images of the target machine. This expert trainer commented on the cyclical iteration process of instructions, during which they provide feedback to the authoring team to add or edit instructional information when necessary. This knowledge transfer poses the greatest challenge and often introduces significant delays in the creation of accurate instructions, which can take months or years to complete. They further emphasized the importance of demonstrating complicated processes on real devices.

Think-aloud protocol The reactions and comments made by experts using the VR system were overwhelmingly positive. Despite noting some initial difficulty with interactions based on hand tracking and manipulating UI widgets in VR, all four experts found the system to be self-explanatory and user-friendly.

TW1 expressed surprise at how natural the VR environment appeared and commented on how easy the interaction with the virtual machine parts felt. They found the system intuitive to control and easy to understand, but commented that they prefer some kind of haptic feedback while manipulating machine parts.

TW2 found the VR system fun to use and would rather create screenshots to illustrate documentation using our tool. They stated that an engineer with sufficient knowledge of the details of maintenance processes would find it very easy to create instructions using our system. They commented that they could imagine adding animations created using this system to their current web-based instruction delivery. They suggested inserting hazard symbols while capturing instructions, which are essential in comprehensive instructions.

TW3 suggested adding a list of parts to the machine visualization, which would allow the authors to describe processes more accurately during recording or highlight specific parts by name. They also suggested extended parts or sub-assemblies with corresponding links to instructions or schematic diagrams for visualization purposes. They remarked that the system would be useful for virtual training and expected that it would be popular with their clients.

TR1 imagined recording a task explanation with our system, as it was "already usable now". When asked whether the VR system could be useful for integration with their current workflow, they stated that they "could imagine recording videos in VR", as it would be faster than their current method of creating animated content. They proposed some features to hide machine parts, such as an inventory system or a workbench where parts could be stored.

All experts praised our method of selecting and highlighting subassemblies, stating that it was self-explanatory and helpful to select and interact with groups of components, although *TR1* had some initial difficulty interacting with the slider. Some of the experts commented that the lack of real-world visibility made it difficult to gauge physical boundaries and avoid collisions, despite the HMD overlaying grid lines to assist when approaching the boundary of the virtual space. This expert suggested that placing the virtual object in an AR environment might be more comfortable.

Reflective interview The second interview focused on the general impressions of our system by the experts and the integration of immersive authoring techniques into their workflow. *TW1* praised our system for removing the need to place virtual cameras in a scene, as recording from one's current viewpoint is much easier. They stated that manipulating the virtual representation of the machine would reduce their need to communicate with engineers because processes would be easier to understand and need less clarification. They mentioned that potential challenges should be expected when manipulating small parts and suggested introducing a zoom function, which scales up machine parts for easier demonstration. *TW1* suggested that a desktop program using data recorded in VR to generate new visualizations would represent a valuable and realistic integration of our tool with existing work practices.

TW2 praised our method of capturing instructions, which can author "text and video at the same time". They rated the interactive viewpoint used in our captured data as a more modern approach to conveying information than the one they currently use, especially for complex tasks. Given the difficulty of maintaining data quality, specifically of 3D models, *TW2* sees a potential problem with relying solely on CAD data for instructional purposes. This expert's most severe concern for replacing current documentation with immersive instructions is acceptance in the market, due to the strict regulatory requirements of printed manuals.

TW3 stated that if the sub-assemblies were linked to relevant documents, the data quality of our system would supersede their current products. They suggested that immersively recording instructions would lower the cost of documentation, and that "it would take an engineer half the time to record their processes than it would take me to write them". They expressed optimism about the possibility of integrating our system into their workflow, stating that immersive instructions or videos recorded with our system would be a "qualitative upgrade" and would increase user motivation.

TR1 specifically enjoyed interacting with the parts using their own hands, rather than a controller. They also commented that, after using our system, they no longer viewed VR as a gimmick, but rather as a "real tool" with high utility for looking up information or learning about updates to existing machines or techniques. They stated that fully replacing the training workflow with a VR solution would eliminate many of the interpersonal and social aspects of their work as instructors; however, a hybrid training system combining immersive technologies with person-to-person instructions seems like a "very realistic" solution.

To determine participant satisfaction with our VR application, we aggregated the results of the system usability, workload, and simulator sickness questionnaires mentioned in subsection 4.1. Usability was rated with an average score of 86.9 (SD=3.7), equivalent to a B according to Bangor et al. [2]. This corresponds to the qualitative statements of the experts, as their impression regarding usability was generally very positive. To evaluate the workload, we individually averaged the raw NASA-TLX subscales according to Hart [13], dropping the *temporal demand*, *performance success*, and *effort* scales, as they lacked relevance for our study, which contained no specific task to accomplish. This produced the following individual results, on a scale of 0 to 100: *mental demand* averaged 18.8 points (SD=15.6), *physical demand* 21.2 (SD=9.6) points, and *frustration* 13.8 (SD=10.2) points. Overall, these results show that participants self-reported low levels of demand, despite the fact that most experts did not have significant experience using immersive technologies. The SSQ score averaged 4.5 (SD=4.2) out of a possible 48 points due to one of the participants reporting light discomfort after a short interruption in the video stream to the HMD.

5 DISCUSSION

RQ1 - From the qualitative results of our evaluation, we reflect on *RQ1* by identifying the challenges present in the current workflow. Creating visualizations and renderings from CAD data currently consumes a significant amount of time due to the difficulty in placing 3D parts and virtual cameras using a desktop interface. Working experts in technical writing consider our system a viable alternative, particularly for creating animated camera and part movements. However, one consideration is the completeness of available CAD data, especially regarding hierarchical dependencies of parts or sub-assemblies within machines. Data from designers may need more preprocessing to represent reality more accurately. Consistent placement of parts or subassemblies within larger models may also not be achieved in real scenarios. In such cases, it may be possible to correct inconsistent data using 3D registration or reconstruction methods; however, this is outside the scope of this work.

Editing or refining existing instructions is currently an asynchronous process that involves communication between departments, often introducing delays. Details of technical processes or other forms of knowledge transfer can also suffer from language or cultural barriers. The ability to present problems by authoring more descriptive explanations using our system may also help to overcome this challenge. Enabling users to record problem demonstrations or to highlight certain machine configurations may assist in overcoming these communication barriers.

Current documentation is delivered in the form of printed handbooks or web-based instructions. Using these sources can discourage the dynamic engagement of the intended audience [8, 20], and may be inflexible in conveying complex spatial information. Immersive instructions have the advantage of allowing for interactive choice of one's viewpoint, which may enable a more complete understanding of complex actions. Creating comprehensive animations or dynamically adjustable 3D content using our system could introduce these advantages to existing documentation systems.

RQ2 - Our evaluation confirms that working experts are already willing to adopt such a system, at least partially, for productive use in authoring instructional content. Experts envisioned using our system to create videos or animated 3D content to demonstrate complicated manipulation of machine parts. *TW1* said that immersive instructions would eliminate the need to "worry about where the camera was placed" when generating instructional content using 3D models. Using natural movements to animate a virtual camera would significantly speed up the current video creation process. Furthermore, manipulating a machine on a real-world scale may help technical writers better understand technical processes, reducing the need for extensive communication with engineers.

While experts seem to agree that fully replacing existing instructional workflows is overly ambitious, integrating our system with existing documentation practices may already be viable in certain situations. For authoring purposes, our system can help technical writers create more realistic instructions and better understand complicated processes. All four interviewed experts were optimistic about the integration of immersive technologies into their workflow.

RQ3 - Expert interviews suggest implementing some improvements and features to better meet the needs of complex instructions. While the experience of using our system was praised as self-explanatory by experts, some improvements to the interface might streamline certain aspects. Other useful extensions might include a zoom feature to better manipulate small objects, or record highly precise manipulations that would otherwise be difficult to capture. The ability to export instructions as videos or to capture screenshots while immersed would enable detailed instructions to be easily exported without the need to exit the immersive environment. In terms of usability, our system was perceived as comfortable and ergonomic. Overall, experts appreciated that they did not need to know any specific gestures before using our application and that the interactions were evident without the need for a tutorial. For future developments, this aspect should be honored to retain simplicity in the interface.

Following our exploratory interviews and the feedback from experts during and after the live demonstration and testing of our VR application, we summarize our insights:

Potential

- We find our system may reduce the time it takes to create 2D content, such as screenshots or videos, from 3D data, one of the most time-consuming steps in the current instruction creation workflow.
- Recordings made with our application can lead to more efficient communication. Realistic human movements and interactions with virtual machines can convey issues or questions more clearly, improving the common ground between groups of people.
- Interacting with real-scale devices can improve spatial understanding of processes and products for technical writers who commonly do not have access to real, room-scale machines.
- Multiple output modalities are possible using a single data source, as our system has the potential to generate immersive 3D recreations of processes, as well as screenshots, animated videos, and text from speech.

Considerations

- Our system relies heavily on high-quality, up-to-date CAD data with accurately modeled details and hierarchical subassemblies, which may not always be guaranteed.
- Participants commented that immersive environments at room scale may be socially inconvenient to use in an office and potentially impractical in small spaces. Some experts commented that seeing virtual models in AR instead of VR would help them feel more comfortable using the application.
- Small-scale manipulations and precise changes are hard to model using our system, which relies on off-the-shelf hand tracking and 3D interface elements.

6 CONCLUSION AND FUTURE WORK

This work presents a prototype of an authoring tool designed to support the creation of immersive content for industrial assembly and maintenance processes. Our primary goal was to make capturing knowledge and creating instructional content accessible to expert operators without the need for programming or animation skills. This is achieved by adopting an authoring-by-demonstration approach. The emphasis was placed on streamlining instructional content creation, simplifying the interface, and eliminating the need for tedious pre- and post-processing on desktops. We integrated a visual assistance system to improve the editing process and facilitate the automatic extraction and labeling of tutorial steps. Moreover, the system displays a 3D activity cloud directing attention to areas in which work was performed on the device. Care was taken to ensure a user-friendly interface, intuitive workflows, and visual support features. The development of our system was informed by feedback from our industrial partners, who are experts in industrial documentation.

We qualitatively examined the effectiveness and suitability of our system for industrial applications by gathering expert opinions. Based on comments made during the use of our system and observations collected from interviews, we conclude that our system has the potential to be used in practical applications. In particular, the simplified interface and natural interactions described in earlier sections enable experts unfamiliar with immersive technologies to easily author instructional content. The insights gained during the evaluation confirm that our application has the potential to address the challenges of their current documentation authoring and industrial training workflows. We conclude that tools like ours hold great promise for training applications, particularly in industries reliant on highly detailed manipulations. The benefit of our presented system over other capturing and instruction methods, such as text-based guides or videos, is that the creation is fast and straightforward and that information such as exact hand movements, gaze, and the movements of individual machine parts are recorded in detail. This enables the generation of visual supports, such as activity clouds and step segmentation, while allowing the data to be analyzed and edited in the same immersive environment in which it was captured. These features have great potential to streamline the content creation process.

In addition, we identified future expansions and improvements of our system during development, as well as during the evaluation process. We plan to develop a dedicated, immersive training mode that will demonstrate the benefits of immersive instructions. While the initial groundwork for the training mode has been laid, our future work will focus on the optimal delivery of immersive instructions. This work will include a specific exploration of the visualization of captured instructions. Furthermore, we plan to extend our framework to include AR scenarios. Instructions captured by manipulating virtual parts could be visualized either directly on spatially registered real machines or by animating an avatar to demonstrate instructions in AR. Expanding upon this concept, another future direction involves not only the delivery but also the authoring of instructions in AR.

While our prototype demonstrates numerous benefits, it is important to acknowledge its current limitations. In the current prototype state, it lacks several advanced features and functionalities that would be expected to apply the proposed authoring process broadly. One particular aspect is alternate visualizations of the trajectories of moving parts [5] instead of just the activity cloud. Furthermore, the interaction with virtual parts and VR interfaces could be improved to be more realistic.

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