XR-Assisted 3D Reconstruction: Improving Model Quality Through Real-Time Feedback

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Abstract: This paper explores the potential for integrating extended reality (XR) technologies into image-based 3D reconstruction workflows to better assist users in the image acquisition process. The delay between image acquisition and visualization of the final 3D model often leads to data gaps and incomplete reconstructions, requiring manual post-processing. The proposed XR-based assistance system provides real-time feedback during scanning, significantly improving the quality of the results. The system uses off-the-shelf hardware to reduce overall costs. We compare the system with a traditional method as baseline and prove its effectiveness by a user study that measures both the user experience and the quality of the resulting 3D models.

1 INTRODUCTION

Current image-based 3D reconstruction systems use multi-view-stereo (MVS) and structure-from-motion (SfM) algorithms, or harness the representational power of deep learning models that learn the reconstruction process (Wang et al., 2024) or a specific 3D representation (Gao et al., 2022) directly from the data. Either way, these methods rely on carefully captured sets of input images to reconstruct real-world scenes. With the advent of powerful smartphones, almost everyone has a capture device that can be used for manual image capture.

The challenge, however, is to avoid data gaps caused by insufficient image coverage from certain angles or difficult lighting conditions (Khilar et al., 2013). These problems not only result in incomplete surface reconstructions, but also require labor-intensive manual post-processing or additional scanning passes to fill in missing information (Dall'Asta et al., 2015). In complex scenarios, such as the digitization of complex exhibition objects or the capture of large industrial environments, these problems can ultimately reduce the reliability and quality of the results (Haleem et al., 2022). In addition, users often discover that key parts of the scene have been inadequately captured only *after* the lengthy reconstruction process has been completed, resulting in a significant delay between image capture and visualization of the final 3D model for inspection.

In recent years, extended reality (XR) systems — encompassing augmented reality (AR), virtual reality (VR), and mixed reality (MR) (Rauschnabel et al., 2022) — have advanced significantly in both hardware and software capabilities. This progress has led to new opportunities for integrating XR with 3D reconstruction workflows, where users can view and interact with digital representations of physical spaces without delay.

This work tackles the challenges of manual image-based 3D reconstruction by introducing an XR-based assistance system that simplifies image acquisition with real-time feedback on scene coverage. Combining a commercially available XR headset with a smartphone as the capture device, the system allows users to monitor progress and identify areas requiring additional scanning. This approach minimizes repeated capture-reconstruction cycles, improves 3D model quality, and helps to detect image capture errors by visualizing insufficient coverage during the scanning process.

The paper is structured as follows: Chapter 2 introduces key concepts underlying this work. Chapter 3 reviews existing user-centered 3D reconstruction approaches and highlights gaps addressed by the proposed system. Chapter 4 outlines the architecture and

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functionality of the system, while Chapter 5 presents its evaluation through a user study. Finally, Chapter 6 provides a summary and discusses future work.

2 BACKGROUND

2.1 3D Reconstruction

3D reconstruction creates a digital 3D model from physical objects or environments. This work focuses on using 2D images as input to generate 3D meshes, represented by a piecewise linear surface (triangles). Neural radiance fields (NeRFs) (Gao et al., 2022) are also compatible with the proposed system, provided the input is 2D images.

Image-based 3D reconstruction is classified by whether camera parameters (e.g., focal length, position) are known. Multi-view stereo (MVS) (Hartley and Zisserman, 2004) assumes known parameters, enabling detailed models through triangulation of common points across images. Structure-from-Motion (SfM) (Hartley and Zisserman, 2004) estimates both camera parameters and 3D structure. Recent deep learning methods, such as (Wang et al., 2024), integrate learned models to enhance these processes.

This work uses the open-source Meshroom package[1], which combines SfM and MVS to generate detailed 3D models from 2D images without requiring prior camera parameter knowledge.

2.2 Extended Reality (XR)

We follow the definition of Extended Reality (XR) as in (Rauschnabel et al., 2022), where it is defined as an umbrella term that encompasses a spectrum of immersive technologies designed to blend the real world with virtual elements. It integrates technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), all of which differ in the degree to which they immerse the user or overlay digital content onto their real-world experience. XR focuses on creating experiences that span the continuum of presence, from local presence (AR, where the user interacts with both the real and digital worlds) to telepresence (VR, where users are fully immersed in a virtual environment). Based on that definition, our proposed system is an AR system that emphasizes local presence, with a high level of integration of digital content into the real-world scene, placing it on the AR continuum closer to the MR pole.

3 RELATED WORK

This section examines popular mobile 3D scanning applications and related academic studies, highlighting their strengths and limitations in offering real-time feedback during image capture.

Polycam (Polycam, 2024) creates 3D models using 2D images and LiDAR, with a focus on room scans. It lacks real-time guidance, providing only an image count during scanning. Kiri Engine (KIRI Innovations, 2024) emphasizes high-quality reconstructions by allowing adjustments to settings like resolution and image count. It includes a tutorial and a video mode for capturing images but lacks real-time capture monitoring. RealityScan (Epic Games, Inc, 2024) simplifies scanning for non-technical users with visual indicators of captured positions and intermediate results to reduce errors. Unlike Polycam and Kiri Engine, it offers interactive feedback, though limited to a 2D device screen. The proposed system addresses these limitations by leveraging XR headsets for immersive 3D feedback.

Dietz and Grubert (Dietz and Grubert, 2022) present an open-source 3D reconstruction pipeline hosted in a scalable cloud environment with a user-friendly interface for non-professionals. Their solution leverages cloud computing to handle intensive tasks, enabling users to use common devices like smartphones without facing local processing limits. While their approach simplifies 3D reconstruction for a broader audience, our method goes further by integrating immersive XR technologies that offer real-time guidance and feedback, reducing rescanning needs and enhancing efficiency.

In (Danhof et al., 2015), a VR-based 3D laser scanning simulation environment is proposed for generating synthetic scans of computer-aided design (CAD) models. It uses the Oculus Rift headset together with a Razer Hydra controller to mimic handheld 3D laser scanners. The system supports 3D meshes and B-spline surfaces, producing realistic 3D point clouds that mimic real-world scanning scenarios. Our system, on the contrary, captures real-world data and reconstructs based on images.

Overall, existing mobile apps and academic approaches provide useful 3D reconstruction tools but lack real-time feedback or 3D visualization for better scene understanding. The proposed XR-based system combines these features for a more effective and supportive scanning solution.

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[1] https://alicevision.org/#meshroom

4 CONCEPT

4.1 System Requirements

We identified the following system requirements:

1. The system should visually indicate the progress of the image capture process through various feedback mechanisms.
2. The system must avoid delays in visualization to prevent nausea and disorientation when using the XR headset.
3. The system must capture timestamped images for later 3D reconstruction, ensuring high quality data for accurate 3D models.
4. The system must support multiple cross-platform devices (mobile devices, XR headsets and workstations) to ensure broad deployment.

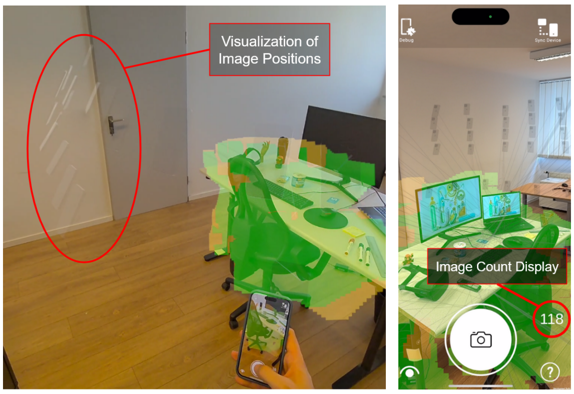
These requirements stem from the research questions and insights from related work analysis. We address them in the following system description.

4.2 Feedback Mechanisms

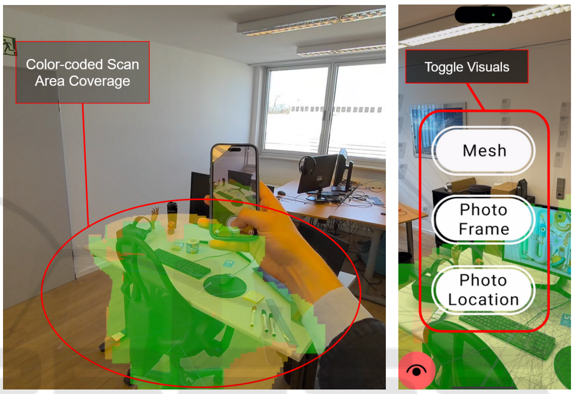
To satisfy requirement 1, the system incorporates feedback mechanisms to guide users effectively:
Visualization of Image Positions (Figure 1a): The system tracks and visualizes the position and orientation of the smartphone in 3D space for all captured images and provides real-time feedback via the XR headset (similar to (Epic Games, Inc, 2024)). This allows users to see the complete history of previous image captures directly in their physical environment, ensuring efficient coverage and preventing areas from being missed or scanned twice.
Color-coded Scan Area Coverage (Figure 1c): The system initially overlays a red 3D mesh over the scan area using the data from the LiDAR sensor of the used smartphone. As the user captures images, scanned areas are color-coded: yellow for newly scanned areas and green for areas scanned multiple times, offering immediate feedback on scan completeness.
Image Count Display (Figure 1d): The system shows the number of images already taken, helping the user tracking their progress throughout the scanning process (like in (Polycam, 2024)).

4.3 Hardware

To meet requirements 2 and 3, the proposed system integrates an iPhone 14 Pro as the sensor device and a Meta Quest 3 as the XR headset. The Meta Quest 3 provides real-time, immersive feedback through color passthrough and precise tracking. The iPhone 14 Pro, equipped with a LiDAR scanner and high-resolution camera, enables online 3D reconstructions by generating a rough 3D model for immediate feedback. It also captures high-quality images for later use in producing a detailed 3D model.



(a) Visualization of image positions. (b) Image count.



(c) Color-coded scan area coverage. (d) Main UI.

Figure 1: Feedback mechanisms shown from the Meta Quest 3 and the iPhone 14 Pro during scan process.

4.4 Software Architecture

To meet the system requirements, we use Unity3D, a platform-independent 3D visualization and interaction framework[2] in combination with its ARFoundation and Netcode for GameObjects (NfG) extensions. ARFoundation provides a unified API for developing cross-platform XR applications on iOS and Android. NfG offers a networking library for efficient wireless communication between devices. The software architecture, shown in Figure 2, consists of two main devices: the **Host** (iPhone 14 Pro) and the **Client** (Meta Quest 3), each with distinct responsibilities.

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[2] Unity Technologies, https://unity.com

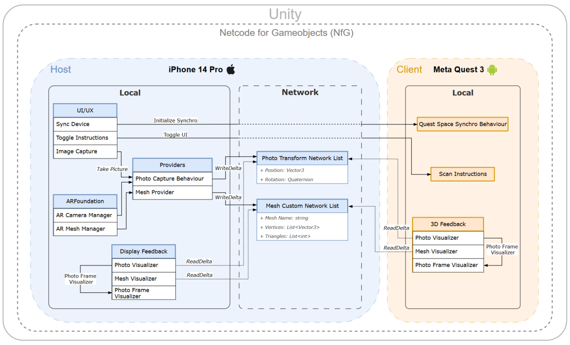

Figure 2: Software architecture of the proposed system.

4.4.1 Host

UI/UX: The smartphone's interactive UI provides functionality for synchronizing client devices, toggling instructions, and initializing image capture. The `Sync Device` component initializes synchronization, while the `Toggle Instructions` component controls the display of user guidance.
ARFoundation: The application utilizes the `AR Camera Manager` and `AR Mesh Manager` for capturing AR data. These components are responsible for managing camera input and mesh creation. Furthermore, they contribute to accurate tracking of the device within the real environment, ensuring precise positioning and movement tracking.
Providers: Consists of the components `Photo Capture Behaviour` and `Mesh Provider`. The `Photo Capture Behaviour` handles the image capture process, saving high quality timestamped images to the device disk (requirement 3) and writing to the photo transform network list which holds the image position and rotation. The `Mesh Provider` uses the mesh data provided by ARFoundation's `AR Mesh Manager` and optimizes it for network traffic before writing it to the custom-implemented mesh network list (requirement 2).
Display Feedback (requirement 1): The `Photo Visualizer` reads data from the network list and instantiates a smartphone model at the corresponding position and rotation to mark the photo location. The `Mesh Visualizer` reads data from the network list to visualize mesh information and creates real-time collider objects for the `Photo Frame Visualizer`. The `Photo Frame Visualizer` does not read from the network list; instead it takes the photo positions from the `Photo Visualizer` and draws the captured frame on the generated collider objects to ensure proper visual differentiation of overlapping areas.
Photo Transform Network List: Uses an NfG network variable to manage the position and rotation data of captured images, including position and rotation. The network variables are used to ensure that updates to data (such as position and rotation) are shared efficiently across all clients, typically relying on internal messaging protocols to propagate changes and maintain synchronization.
Mesh Custom Network List: Stores the data from the optimized mesh, including mesh name, vertices and triangles. This is a complex data type that requires a custom NfG network variable implementation. Delta read and write operations need to be implemented to ensure the data can be transferred efficiently through the network, maintaining synchronization across devices. Network traffic speed plays a significant role in ensuring a fluent experience during usage, which is why the custom network variable is indispensable in regard to requirement 2.

4.4.2 Client

The architecture allows the client not to be limited to the Meta Quest 3 which means different XR devices, including mobile devices, XR headsets, and Windows PCs can be used as Client (requirement 4).
Quest Space Synchro Behavior: Synchronizes spatial information between the XR headset and the host device, aligning the positioning of the XR headset so that the origin of ARFoundation (on the smartphone) matches the origin of the headset, ensuring that both devices share a consistent representation of the scanned environment.
Scan Instructions: Provides step-by-step guidance through the scanning process in the form of a slide show, ensuring all areas are covered.
3D Feedback: Provides feedback similarly to the Display Feedback component on the smartphone but leverages the XR headset to present it in 3D, offering spatial awareness and enhancing the user's understanding of scan progress (requirement 1).

5 EVALUATION

5.1 User Study Design

The user study combines both quantitative and qualitative methods to evaluate the proposed system. The design includes an experimental approach where participants with basic familiarity with smartphones and XR technologies are given a 3D scanning task in two conditions:

- *Condition 1:* Without XR support, participants use only the native camera app installed on the smartphone. This serves as the baseline, leveraging the smartphone's high-quality imaging capability but without any guidance.

- *Condition* 2*:* With XR support, participants use the proposed system, providing real-time visual feedback on scanned areas and areas still needing coverage.

The task was to create as complete a scan as possible of the desk shown in Figure 3. Each participant completed the first condition 1, followed by the condition 2. Participants received no results or feedback on their performance on condition 1, preventing no learning effects between tasks. The comparison aims to analyze the advantages of the proposed system in terms of user experience and improved scan quality.

Figure 3: Desk that should be scanned by the participants.

User Experience Assessment. The user experience is assessed via questionnaire, which participants completed after performing the tasks. The questionnaire was distributed via Google Forms to maintain the anonymity of their responses and includes four key sections:

- *Demographics and Experience:* Collects data on age, gender, and prior experience with similar technologies. These demographic insights allow for more nuanced analysis of results by understanding sample composition.
- *Comparison of Scan Methods:* Assesses user preferences and experiences with both the traditional camera and XR-supported scan methods, focusing on usability, efficiency, coverage, clarity, and comfort. This helps to determine the system's benefits for the 3D scanning process.
- *System Usability Scale (SUS):* A standardized quantitative tool for rating the proposed system's usability, the SUS is a subjective measure of user-friendliness, allowing for comparisons with other systems (Brooke, 1996).
- *Open-Ended Feedback:* Allows participants to share personal insights, improvement suggestions, and specific experiences with the proposed system, providing valuable qualitative feedback that could highlight areas for enhancement.

These sections provide both structured insights into the performance of the proposed system and open-ended responses that reveal individual user experiences, supporting a thorough evaluation of its impact.

Scan Data Quality Assessment. The image data acquired by the participants is processed in Meshroom to assess the quality of the 3D reconstruction. The analysis is performed without modifying the images or the resulting 3D model, and each participant's data is evaluated independently. The extracted key metrics are:

- *Number of Images:* Measures the extent of image capture and indicates whether the XR assistant has improved the efficiency and thoroughness of image capture.
- *Estimated Camera Positions:* Provide insight into the accuracy and consistency of image positioning, particularly in spatial orientation.
- *Feature Point Count:* Visually distinct feature correspondences in camera images. Indicates the density of detected detail and is an indicator for reconstruction quality.
- *Mesh Vertices Count:* Reflects the level of detail of the resulting 3D model.
- *Expert Rating:* Expert ratings from Usaneers GmbH qualitatively assess the completeness, visual quality, and precision of the 3D model on a scale of 1 to 5. The scores are based on subjective criteria without a quantitative baseline.

By combining quantitative metrics with expert judgements, this analysis addresses research questions about the potential benefits of the proposed system in improving 3D scan quality, integrating both objective technical measures and user perspectives for a comprehensive evaluation.

5.2 Results

5.2.1 User Experience Assessment

Demographics and Experience. The study includes a total of 16 participants, who had no or very little experience with 3D reconstruction, and were willing to test the proposed system and evaluate their experience. The age distribution ranges from 24 to 63 years, with an average age of around 34.9 years. This range allows different age groups to be considered in terms of their perception and acceptance of the new technology. The professional backgrounds of the participants are diverse and represent different specializations. The largest group comes from the IT sector (6 participants), followed by healthcare and education professionals (2 participants each). Other participants come from the fields of business administration, administration, design/creative industries, engineering, social services and sales. See figure 4 for details of the professional background of the participants.

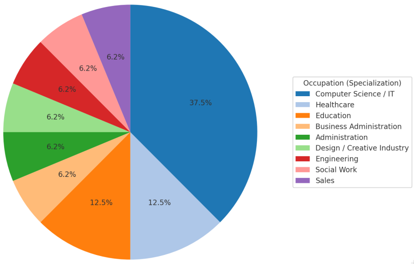

Figure 4: Professional background of the participants.

Comparison of Scan Methods. In the user study, participants rated the ease, confidence, efficiency, and tracking of the scan process for both condition 1 and condition 2 where the latter showed clear advantages, as described below (see also Figure 5):

- **Ease of the Scan Process:** condition 1 received a mean μ of 2.94 with a standard deviation σ of 1.39. condition 2 was rated significantly higher, with $\mu = 4.56$ ($\sigma = 0.73$). A t-test revealed a statistically significant difference ($t = -3.230$, $p = 0.00561$), indicating that participants generally found the XR-supported scan process much easier, likely due to additional guidance provided by the proposed system.
- **Confidence in Covering all Areas:** For condition 1, μ was 2.13 ($\sigma = 0.96$), while condition 2 scored $\mu = 4.38$ ($\sigma = 0.89$). The t-test showed a significant difference ($t = -10.593$, $p < 0.00001$), demonstrating that the proposed system provided participants with significantly greater confidence in covering the entire object, supported by the system's visual feedback.
- **Efficiency of the Scan Process:** Condition 1 scored a mean of 2.63 ($\sigma = 1.20$), compared to $\mu = 4.19$ ($\sigma = 0.98$) for condition 2. he t-test confirmed this difference as statistically significant ($t = -5.809$, $p = 0.00003$), suggesting that the XR-supported approach was perceived as more efficient, likely due to structured guidance and targeted prompts during the scan process.
- **Maintaining an Overview of Scanned Areas:** Condition 1 had a mean score of 2.00 ($\sigma = 0.93$), while condition 2 scored $\mu = 4.69$ ($\sigma = 0.48$). The difference was highly significant ($t = -9.373$, $p < 0.00001$). The high score for the proposed system indicates that the visual support and real-time feedback offered clear orientation and ease of tracking during scanning.

The descriptive analysis of means, standard deviations, and t-test results shows that the proposed system was rated higher across all examined dimensions. This suggests that the additional support provided by XR technology made the scan process more intuitive, secure, efficient, and easy to follow for users. This underscores the potential of XR technology to significantly improve the 3D scan process through simplified operation, optimized efficiency, and enhanced precision.

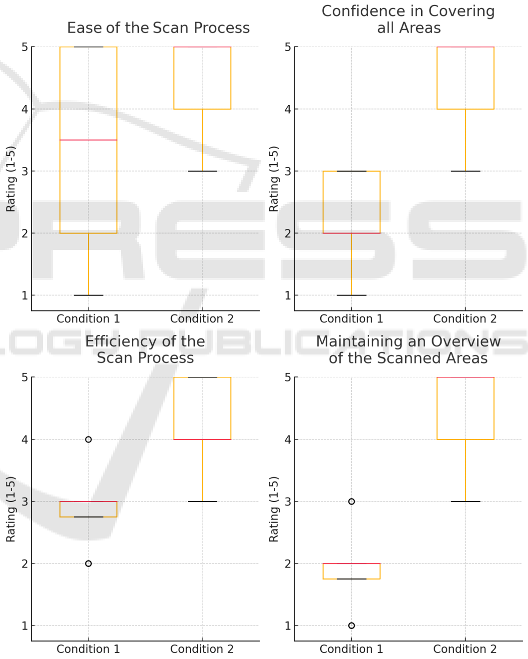

Figure 5: Comparison of scan methods.

System Usability Scale (SUS). The SUS analysis reveals that the proposed system achieved an average SUS score of 80.47, indicating a high level of perceived user-friendliness. SUS scores are generally interpreted on a scale from 0 to 100, where values above 68 are considered above average and scores of 80 or more are rated as excellent. Among the 10 SUS items, questions related to ease of use and system integration scored the highest, while those concerning initial learning effort received comparatively lower ratings. This highlights the intuitive interface of the system, though there may be room for improvement in onboarding and first-time use. Such a high score suggests strong user acceptance and satisfaction, which is a critical indicator of success for practical applications.

Several factors investigated in this study likely contributed to this high score, including the system's real-time feedback and intuitive user guidance. These features support a quick learning curve, allowing users to confidently complete the 3D scanning process without needing constant assistance. Combined with the results from comparison questions on scan quality and efficiency, the SUS findings support the assumption that the proposed system provides a user-friendly and effective enhancement for the 3D scanning process.

In conclusion, the SUS evaluation affirms the proposed system's effectiveness in terms of usability and highlights its potential applicability in practical, real-world scenarios.

Open-Ended Feedback. The qualitative feedback from open-ended questions suggests for this particular scenario that the proposed system engages users and sparks technical curiosity more than the traditional method. The real-time visualization of image capture progress adds significant value, while the traditional method is appreciated for its simplicity and familiarity. However, feedback on improvements highlights the need for adjustments in headset weight, visual clarity, and synchronization to enhance comfort and effectiveness.

5.2.2 Scan Data Quality Assessment

Overall Results. Figure 6 shows example meshes that were generated based on the images captured by a selection of participants for both conditions. From the visible detail and surface coverage it can be concluded that the mesh quality improves when using the proposed system (condition 2). A full overview of the results of the quality assessment can be found in the Appendix, which shows, for example, that the average expert rating is significantly higher for results using the proposed system (3.0625 vs. 2.1875).

Number of Images & Mesh Vertices Count. Figure 7 illustrates the linear relationship between the number of images captured and the number of vertices in the resulting reconstructed mesh for condition 1 (blue) and 2 (red). It also demonstrates the tendency for users of the proposed system to capture more images, resulting in meshes with a larger number of vertices. Furthermore, the same number of captured images typically yields more detailed meshes when the proposed system is used.

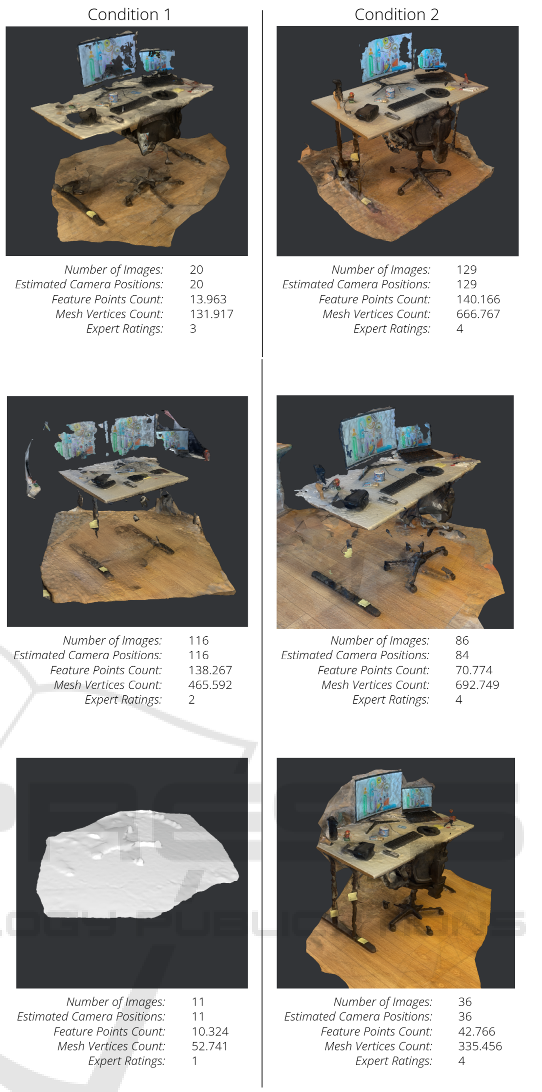

Figure 6: Comparison of scan data quality for three selected participants (one participant per row). Left column: Condition 1, Right column: Condition 2 (the proposed system).

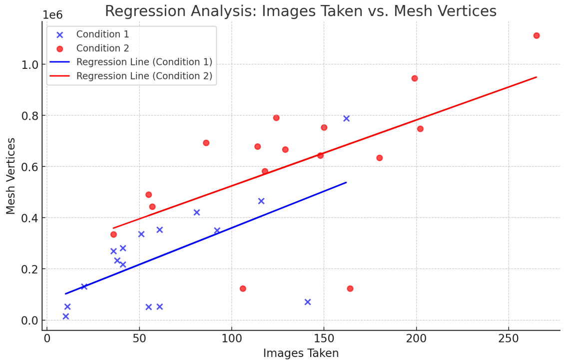

Figure 7: # images taken vs. # mesh vertices.

6 CONCLUSION

This paper demonstrates that the integration of XR technologies into image-based 3D reconstruction workflows improves both the image acquisition process and the quality of the resulting reconstructions. The proposed system, using off-the-shelf hardware, significantly improves the user experience and model quality, as confirmed by a comparative user study. While statistically significant improvements were observed with 16 participants, the small sample size limits the generalisability of the results. Larger studies are needed for more comprehensive validation. Future work could also extend this system to support collaborative scanning, allowing multiple users to capture and visualise a scene simultaneously, improving efficiency and coverage in complex environments.

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APPENDIX

Scan data quality assessment (complete results):

Table 1: Scan data quality assessment for condition 1 (without XR support).

Participant	**Images taken**	**Estimated Cameras**	**Feature points**	**Mesh vertices**	**Quality 1-5**
1	61	61	469251	53332	1
2	141	140	42618	71856	1
3	162	162	175985	789076	1
4	41	41	41169	282311	4
5	36	36	29895	269755	4
6	38	36	32046	233338	4
7	55	55	25691	52050	1
8	92	92	96594	350625	2
9	20	20	13963	131917	3
10	61	60	65246	353028	3
11	51	50	37380	336177	2
12	116	116	138267	465592	2
13	41	41	62178	217535	3
14	10	10	3694	14844	1
15	81	81	114424	421103	2
16	11	11	10324	52741	1

Table 2: Scan data quality assessment for condition 2 (with XR support, proposed system).

Participant	**Images taken**	**Estimated Cameras**	**Feature points**	**Mesh vertices**	**Quality 1-5**
1	164	160	705702	123875	2
2	106	103	41037	123584	1
3	150	135	72038	753014	2
4	124	124	115921	790881	4
5	118	118	138190	582178	4
6	199	199	238315	944914	4
7	180	180	218073	634975	3
8	114	114	98443	679456	4
9	129	129	140166	666767	4
10	265	265	315167	1112605	4
11	202	147	85930	747849	1
12	86	84	70774	692749	4
13	55	55	70582	490227	4
14	57	57	51772	444308	3
15	148	148	189464	644123	1
16	36	36	42766	335456	4