Beyond Boundaries: Exploring Augmented Reality Barrier-Bypassing Display Modalities

Oliver Hein
oliver.hein@unibw.de
University of the Bundeswehr Munich
Munich, Germany

Adnan Al Qalaq
adnan.qalaq@campus.lmu.de
LMU Munich
Munich, Germany

Florian Alt
florian.alt@unibw.de
LMU Munich
Munich, Germany

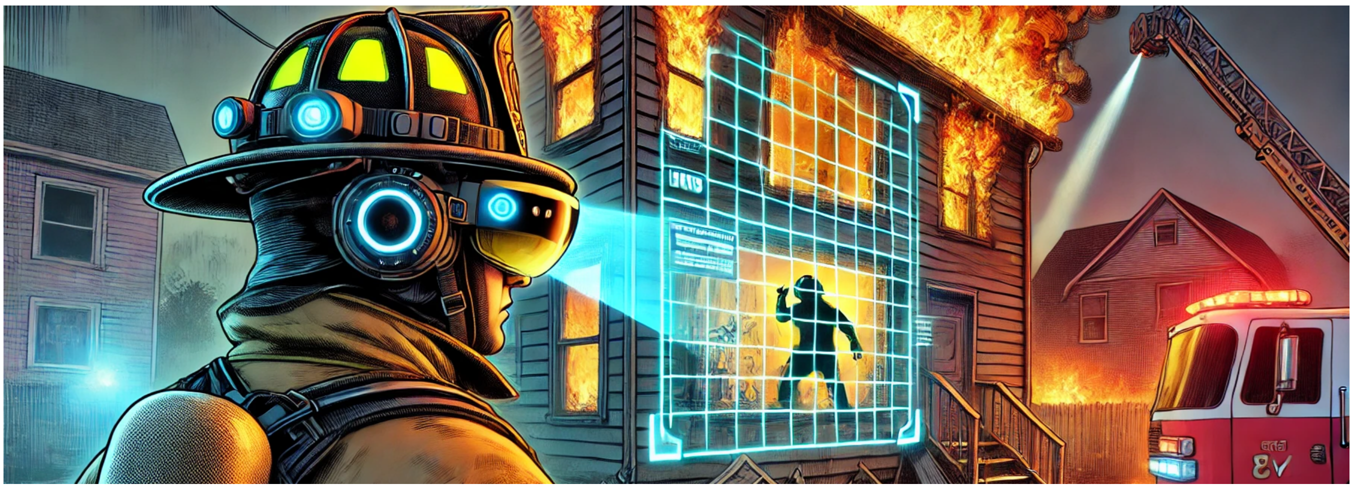


Figure 1: A firefighter in a dangerous situation: This image shows a typical use case for an augmented reality (AR) system, which can provide a visualization of occurred objects.

Abstract

This paper investigates different visualization methods in augmented reality (AR) to display obscured spaces or objects by physical barriers. Using a prototype system that combines 3D scans and AR visualization through a Meta Quest Pro, we explore the usability and effectiveness of two display modalities: point cloud and mesh visualizations. A user study with ten participants evaluates these methods across task completion time, and user experience. Results indicate a significant preference for mesh visualizations, which outperform point cloud representations in attractiveness, efficiency, and usability. These findings have relevant implications for AR applications in emergency response, construction, and other domains requiring enhanced visualization of hidden objects.

CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; *Empirical studies in visualization.*

Keywords

Augmented Reality, 3D Visualization, User Experience

ACM Reference Format:
Oliver Hein, Adnan Al Qalaq, and Florian Alt. 2025. Beyond Boundaries: Exploring Augmented Reality Barrier-Bypassing Display Modalities. In *Proceedings of ACM Augmented Humans International Conference (AHs '25).* ACM, New York, NY, USA,, 6 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Augmented Reality (AR) has evolved into robust systems that merge virtual content with physical environments. While commonly used to overlay digital information, AR also holds potential for *revealing* obstructed spaces, benefiting scenarios like firefighting, construction, and search-and-rescue [20, 24].

Advances in scanning technologies, such as LiDAR and time-of-flight cameras, alongside wireless methods like ultra-wideband radar and Wi-Fi-based tracking [16], enable real-time acquisition of occluded data. However, optimal *visualization* of this information in AR remains uncertain. Point clouds offer rapid depth representation

AHs '25, Abu Dhabi, United Arab Emirates

ACM ISBN 978-1-4503-XXXX-X/2018/06
https://doi.org/XXXXXXX.XXXXXXX

but lack clarity, while meshes provide smoother surfaces at the cost of detail and performance.

Effective see-through AR must support users in identifying and navigating hidden objects efficiently [22]. Prior work explores see-through AR [4, 20], but the best visualization modalities for user performance remain unclear.

In this paper, we investigate how two distinct AR visualization methods — point clouds and mesh-based renderings — impact users' ability to locate and interact with hidden objects behind a physical wall. We develop a prototype AR system that overlays a scanned room behind a wall, allowing participants to identify and ´hit' a series of virtual targets. Through a within-subjects lab study of ten participants, we measure task completion time, error rates, and user experience (UEQ) to compare the modalities. Our results show that meshes enable faster, more accurate performance and are perceived as more engaging. We discuss implications for different use cases and future research on visualization techniques, hardware optimizations, and real-time data acquisition.

Contribution Statement. Our contributions are empirical in nature [22]. Specifically, we contribute a study that explores the influence of type of visualization (point cloud and mesh visualization) on performance and user experience in an AR task.

2 Background & Related Work

2.1 3D Scanning

3D scanning has revolutionized industries by enabling precise spatial data capture for analysis and visualization. Modern advancements in techniques such as structured light [7], time-of-flight (ToF) [9], photogrammetry [15], triangulation [6], and LiDAR [18] have greatly improved accuracy, usability, and affordability. For example, devices like the Apple iPad Pro can now capture high-resolution point clouds and convert them into detailed 3D representations. Technologies like LiDAR and ToF cameras directly reconstruct 3D environments by measuring the phase delay or time of reflected light pulses.

These techniques are also used in so-called 'Simultaneous Localization and Mapping' (SLAM) procedures. These SLAM procedures help to create or update a map of an unknown environment and simultaneously track the location of an agent within it. This is mainly used by robots and autonomous systems for navigation. As Murai et al. showed in their work from 2024, these SLAM systems do not have to rely on several (different) sensors, but can work with just one monocular camera image. This system generates globally consistent poses and dense geometries at a speed of 15 FPS [13]. Therefore, this could be a good way to combine a drone with a single camera with an AR-HMD running this SLAM system to achieve a ´view through the wall' as in Figure 1.

2.2 Visualization Techniques

3D visualization techniques play a critical role in interpreting and presenting the vast datasets generated by 3D scanning technologies, enabling users to engage with and comprehend the scanned information. Point cloud visualizations represent objects as collections of 3D points, offering raw but detailed representations, while mesh visualizations connect these points into surfaces, creating clearer and more dense models [11]. Alternative methods, such as voxelization and Gaussian splatting, offer specialized representations for specific applications. For instance, voxelization depicts objects as 3D grids, providing discretized representations of scenes [11], while Gaussian splatting uses 3D Gaussian spheres to create smooth visualizations suitable for rendering pipelines [12]. Volume visualization, another technique, enables the manipulation and representation of volumetric datasets, allowing the exploration of internal structures without relying solely on surfaces [10]. Although different visualization techniques exist, the most commonly used are point cloud and mesh visualizations [8, 14].

3 Research on AR See-Through Modalities

Research on see-through modalities, such as visualizing objects behind walls, has seen substantial progress in recent years. Gaze-vergence-controlled augmented reality (AR) systems enable users to view occluded objects by tracking eye depth, proving to be efficient and well-received in experimental settings [21]. Similarly, the Wall Hack AR system utilizes LiDAR scanners (e.g., Apple iPad Pro) and Visual Positioning Systems (VPS) to create real-time 3D visualizations of environments, simulating transparency through walls [3].

A notable application, but not related to AR, is demonstrated in the work of Charvat et al. [4], where Time-of-Flight frequency-modulated continuous-wave (FMCW) technology was used to achieve depth resolution for visualizing objects through obstructions like drywall and plywood. Their system utilized point cloud data, incorporating 2D brightness, depth, and multi-spectral responses to generate 3D reconstructions on a classic display.

Radar technologies, including ultra-wideband (UWB) radar and self-injection-locked (SIL) radar, have demonstrated effectiveness in detecting concealed individuals and objects through frequency-modulated continuous waves and dynamic spectral subtraction [19, 25]. Wireless technologies, such as Wi-Fi and RFID systems, provide a cost-effective approach to through-wall tracking. For instance, the Tadar system uses RFID readers and tags to accurately detect movement through walls [23]. Reviews emphasize the transformative role of wireless technologies in military, gaming, and medical applications [17].

Synthetic Aperture Radar (SAR)-based systems leverage ultrawideband signals for high-resolution imaging of objects behind walls, with techniques like compressive sensing improving image quality and mitigating interference [1, 5]. Additionally, innovative systems combining drones and AR technologies (e.g., Microsoft HoloLens) provide dynamic visualizations of hidden environments by capturing and processing live video feeds, simulating X-ray vision. These drone-based systems are particularly valuable for surveillance and rescue operations [2].

Summary. 3D scanning technologies have been significantly advanced, enabling accurate and affordable spatial data capture. Wireless technologies like Wi-Fi and RFID, along with drone-based solutions, offer promising approaches for achieving this. These advancements are crucial for 3D visualization techniques, which are essential for interpreting and presenting complex data. Research on see-through modalities aims to realize this on AR devices. However, open research questions remain. In addition to the question of how exactly to obtain the recordings from the desired area and what quality they correspond to, there is also the question of which type of visualization is best suited. While various visualization techniques are available, point cloud and mesh visualizations are the most commonly used [8, 14].

4 User Study

Our overarching goal is to understand how different AR visualization methods (point clouds vs. mesh) impact users' ability to perceive and interact with hidden objects, thereby informing the design of barrier-bypassing AR systems. We chose point could and mesh visualizations, since these are the most commonly used techniques [8, 14].

We conducted a within-subjects laboratory study comparing two visualization modalities—point cloud and mesh—to answer the following questions:

(1) Does a particular visualization modality yield more efficient task performance (e.g., faster task completion and fewer errors)?
(2) How do users perceive each modality, and which do they prefer in terms of user experience?

This study design allows us to isolate the influence of visualization style on user performance and satisfaction, providing actionable insights for future AR see-through applications.

4.1 Study Design

We implemented a 2×1 *within-subjects* design, manipulating a single independent variable—*visualization modality*—with two levels: point cloud and mesh. We tried to ensure that both visualization modalities have the same level of detail and fidelity. All participants completed tasks in both conditions, enabling us to compare performance and perceptions. To ensure the task was both concrete and measurable, we asked participants to locate a virtual ´can' that repeatedly appeared in one of ten predefined locations and changed color with each move.

To create a scenario resembling ´see-through' AR, participants wore a Meta Quest Pro in pass-through mode, enabling them to view a scanned room *behind* a real physical wall. The can is already placed in the room when the application is started. The participants used two handheld controllers, each emitting a virtual ray. By pointing at the on-screen can and pulling the trigger, they could ´hit' the target and prompt it to move to another location (and potentially change color). This happens immediately and without any particular effect when the can is hit. After ten successful hits in one visualization condition, participants filled out the User Experience Questionnaire (UEQ) before switching to the other condition. We counterbalanced the order of the point cloud and mesh conditions to mitigate learning or fatigue effects.

4.2 Apparatus

We developed the experimental prototype in the Unity Game Engine, leveraging the Oculus Integration Package for the Meta Quest Pro. A LiDAR-enabled iPad Pro was used to capture the 3D environment and generate both point cloud and mesh data. In Unity, custom C# scripts handled raycasting for user interactions, scan manipulation (e.g., loading or repositioning 3D data), and logging relevant metrics.

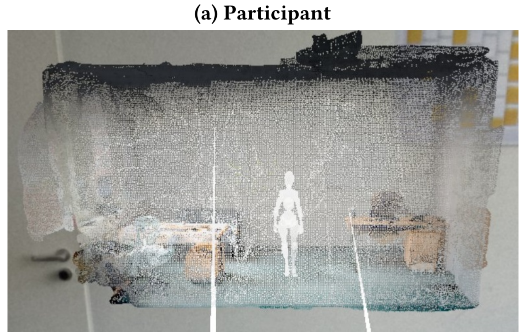
Technical challenges arose from rendering large LiDAR datasets in real time. We reduced point cloud density to balance performance and clarity, ensuring both representations remained detailed with the same fidelity and minimized frame-rate drops.

4.3 Metrics

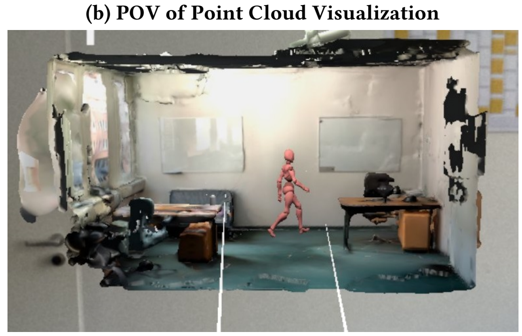
We focused on three primary metrics:

- **Task Completion Time:** Total time required for each participant to hit the moving can ten times per condition.
- **Accuracy:** Operationalized through the number of "missed hits" (i.e., unsuccessful trigger pulls before locating the correct target).
- **User Experience:** Assessed through the UEQ, capturing subjective ratings of attractiveness, efficiency, and other experiential factors.

(a) Participant



(b) POV of Point Cloud Visualization



(c) POV of Mesh Visualization

Figure 2: Testing the augmented environment

All metrics were captured automatically or self-reported. Additional interaction logs documented user actions and notable events (e.g., scan manipulations).

4.4 Procedure

Upon arrival, each participant provided informed consent and then received a brief tutorial on the Meta Quest Pro and the two visualization approaches. A short training phase allowed them to familiarize themselves with the virtual rays and the task of "hitting" the can.

Next, participants completed the main task in one randomly assigned visualization condition (point cloud or mesh). During each run (ten can hits), the system recorded time stamps, missed hits, and any scan manipulation events. On finishing the set of ten hits, participants filled out the UEQ for that condition, then repeated the entire procedure with the alternate visualization modality. Finally, we concluded with a brief debriefing to gather open-ended feedback. Sessions lasted approximately 30 minutes per participant, including training, task execution, and questionnaires.

By comparing task performance and subjective ratings across point cloud and mesh visualizations, this study aims to elucidate which display modality offers a clearer and more intuitive user experience when visualizing occluded objects in AR. These findings directly inform future AR system design for scenarios ranging from emergency response to industrial maintenance.

5 Results

5.1 Participants

Participants were invited through the university's mailing list. Ten participants took part in this study. Four identified as females and six as males. Participants age ranged from 22 to 30, with a mean age of 25.8 years and a standard deviation of 2.315. Three participants wear glasses. Five out of ten participants were current students, while the remaining five were recent graduates. The participants had diverse academic backgrounds. Participants indicated, that they had minimal experience with AR, with a mean experience score of 1.3 and a standard deviation of 0.458 on a scale of 1-10.

5.2 Quantitative Findings

The results in Table 1 show that, on average, participants completed tasks faster and with fewer errors using mesh visualization (Mean: 2:30 minutes, 58.6 missed hits) compared to point cloud (Mean: 6:17 minutes, 218.1 missed hits).

To determine whether these differences are significant, we used a Wilcoxon Signed-Rank test. The Wilcoxon test is suitable here because we cannot assume that the differences between the groups are normally distributed. The Wilcoxon signed-rank test shows a significant difference in time needed between point cloud and mesh conditions (p-value = 0.019, effect size r = 0.73). The median time for Point Cloud (302.5 seconds) is considerably higher than for Mesh (118.5 seconds). The Wilcoxon signed-rank test also shows a significant difference in missed hits between point cloud and mesh conditions (p-value = 0.049, effect size r = 0.63). The median number of missed hits for point cloud (139.5) is much higher than for mesh (16).

Table 1: Results for participants in both scenarios

ID	Gender	Time Needed for Point Cloud	Missed hits in Point Cloud	Time Needed for Mesh	Missed hits in Mesh	Order
1	Male	17:24 min	173	1:55 min	27	Point Cloud, Mesh
2	Male	4:00 min	39	1:30 min	5	Mesh, Point Cloud
3	Male	2:00 min	25	2:06 min	24	Point Cloud, Mesh
4	Male	2:51 min	184	2:12 min	16	Mesh, Point Cloud
5	Female	7:48 min	250	8:30 min	456	Point Cloud, Mesh
6	Female	5:50 min	513	1:35 min	2	Mesh, Point Cloud
7	Male	4:15 min	31	1:34 min	5	Point Cloud, Mesh
8	Female	9:12 min	795	1:35 min	29	Mesh, Point Cloud
9	Male	7:03 min	65	2:04 min	6	Point Cloud, Mesh
10	Female	2:36 min	106	2:02 min	16	Mesh, Point Cloud

These results suggest that participants generally took significantly longer to complete tasks in the point cloud condition compared to the mesh condition. Also, participants missed significantly more hits in the point cloud condition compared to the mesh condition. The box plots (see Figure 3) visually illustrate these findings, showing clear differences between the two conditions for both time needed and missed hits.

5.3 Qualitative Findings

To evaluate the user experience of the developed prototype, we utilized the UEQ. In addition to the UEQ, participants were asked two open-ended questions about their preferred scan type and the reasons for their preference.

5.3.1 User Experience Questionnaire. Figure 4 and Figure 5 present the reported user experience in the UEQ for point cloud and mesh visualization across its six dimensions (attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty).

The results indicate that the mesh scan generally achieved higher user satisfaction across all dimensions compared to the point cloud scan. This suggests that users found the mesh visualization more appealing, supportive, understandable, engaging, and was better received on average.

5.3.2 Participant Preferences. 9 out of 10 participants preferred the mesh scan over the point cloud scan. The mesh scan was favored for its faster and clearer images, user-friendliness, stability, lack of lag, and ease of locating cans, which provided greater visual comfort and reduced strain. In contrast, the point cloud scan was described as challenging, visually confusing, and straining, making it less appealing. However, one participant preferred the point cloud scan because it felt like a rewarding and fun challenge, despite the difficulty in seeing the cans. Overall, the mesh scan was preferred for its clarity, efficiency, and engaging experience.

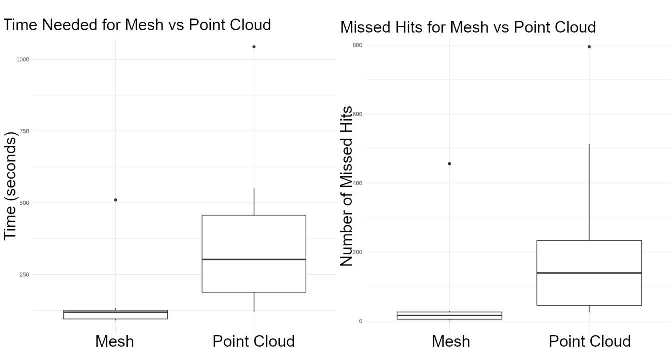
6 Discussion

Our findings highlight a pronounced user preference for mesh-based visualizations, evidenced by faster task performance, fewer missed hits, and more positive user experience ratings. In this study, mesh surfaces helped users form cohesive mental models of obscured environments, whereas point clouds often lead to user confusion or slower target acquisition.

Mesh Advantages and Performance. Participants commonly praised mesh rendering for its clarity and stability, noting that they could more easily gauge object boundaries and spatial relationships. By offering a continuous surface rather than discrete points, mesh visualizations appear to reduce the mental workload required to interpret depth and shape. However, rendering dense meshes in real-time can be computationally demanding, especially when leveraging consumer-grade headsets like the Meta Quest Pro.

Influence of Hardware Constraints. Although our results strongly favor mesh-based rendering, certain hardware factors might have shaped user impressions. The Meta Quest Pro's onboard processing capabilities and display resolution may have exacerbated the drawbacks of point-cloud displays. The performance gap might be less pronounced on a more powerful device (or with point-cloud rendering optimizations). Understanding how different hardware platforms and 3D engines handle large 3D datasets in real time remains an important question for developers.

Applications Beyond the Lab. Our study focused on a controlled indoor scenario, but potential real-world uses of see-through AR span firefighting, construction, facility management, and beyond. In high-stakes contexts such as emergency rescue, efficiency and clarity matter greatly for user safety and task success. Balancing factors such as scanning speed, rendering fidelity, and domain-specific constraints (e.g., dusty or smoke-filled environments) is key to broader adoption.



(a) Box plots of time needed **(b) Box plots of missed hits**

Figure 3: Comparison of needed time and missed hits

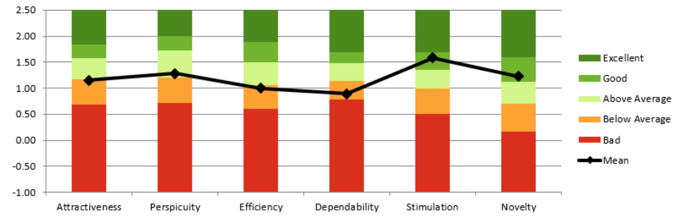


Figure 4: Bar chart of UEQ dimensions for *Point Cloud*

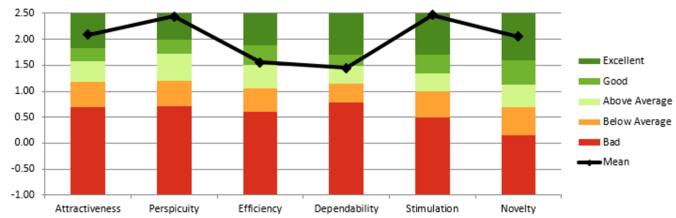


Figure 5: Bar chart of UEQ dimensions for *Mesh*

Enhanced Visualization and Real-Time Data Acquisition. Our results also invite exploration into more sophisticated rendering approaches. Techniques like Gaussian splatting or voxel-based representations may combine the benefits of both mesh and point cloud approaches, providing smoother visuals without overburdening the system. Equally important is the question of *how* to capture real-time data in the field. Drone-based scanning could rapidly build 3D models behind barriers, but ensuring low-latency updates that maintain spatial accuracy presents an ongoing challenge. As already mentioned in section 2.2, the SLAM system by Murai et al. shows great potential for this, as it generates consistent and dense 3D models at a speed of 15 FPS [13].

7 Conclusion and Future Work

This work demonstrates the promise of barrier-bypassing AR applications and provides empirical evidence favoring mesh-based visualization over point clouds for improved clarity, user satisfaction, and efficiency. By illuminating how users perceive and interact with two common rendering modalities, our study lays initial groundwork for designing ´see-through' AR systems in diverse domains.

Moving forward, we plan to (1) investigate advanced visualization strategies that could merge the fidelity of meshes with the flexibility of point clouds; (2) integrate real-time data acquisition methods (e.g., drone scans, 360° camera) to support truly dynamic AR see-through experiences; and (3) conduct field studies in more realistic, high-pressure scenarios (e.g., firefighting drills or construction site inspections) to better understand how hardware constraints, domain needs, and user stress levels influence design choices. By addressing these avenues, we hope to enable more robust, user-friendly AR systems that empower users to see — and act — beyond physical boundaries.

References

[1] Moeness Amin and Fauzia Ahmad. 2013. Compressive sensing for through-the-wall radar imaging. *Journal of Electronic Imaging* 22 (2013). doi:10.1117/1.JEI.22.3.030901

[2] Anonymous. 2022. See Straight Through Walls by Augmenting Your Eyeballs With Drones. https://spectrum.ieee.org/see-straight-through-walls-by-augmenting-your-eyeballs-with-drones

[3] Anonymous. 2022. Wall Hack AR: AR See-through system with LiDAR and VPS. https://www.researchgate.net/publication/360597918_Wall_Hack_AR_AR_See-through_system_with_LiDAR_and_VPS

[4] Gregory Charvat, Andrew Temme, Micha Feign, and Ramesh Raskar. 2015. Time-of-Flight Microwave Camera. In *MIT Camera Culture Projects*. http://cameraculture.media.mit.edu/time-of-flight-microwave-camera/ Accessed: 2024-06-04.

[5] M. Dehmollaian and K. Sarabandi. 2008. Refocusing through building walls using synthetic aperture radar. *IEEE Transactions on Geoscience and Remote Sensing* 46 (2008), 1589–1599. doi:10.1109/TGRS.2008.916212

[6] João Guilherme DM França, Mário A Gazziro, Alessandro Noriaki Ide, and José Hiroki Saito. 2005. A 3D scanning system based on laser triangulation and variable field of view. In *IEEE International Conference on Image Processing 2005*, Vol. 1. IEEE, I–425.

[7] Andreas Georgopoulos, Charalabos Ioannidis, and Artemis Valanis. 2010. Assessing the performance of a structured light scanner. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 38, Part 5 (2010), 251–255.

[8] Farook R Hamzeh, Hisham A Abou-Ibrahim, Anthony Daou, Mazen Faloughi, and Nadim Kawwa. 2019. 3D visualization techniques in the AEC industry: The possible uses of holography. (2019).

[9] Miles Hansard, Seungkyu Lee, Ouk Choi, and Radu Patrice Horaud. 2012. *Time-of-flight cameras: principles, methods and applications.* Springer Science & Business Media.

[10] Arie E Kaufman. 1996. Volume visualization. *ACM Computing Surveys (CSUR)* 28, 1 (1996), 165–167.

[11] Muhammad Saif Ullah Khan, Alain Pagani, Marcus Liwicki, Didier Stricker, and Muhammad Zeshan Afzal. 2022. Three-Dimensional Reconstruction from a Single RGB Image Using Deep Learning: A Review. *Journal of Imaging* 8, 9 (2022), 225.

[12] Xinhai Li, Huaibin Wang, and Kuo-Kun Tseng. 2023. GaussianDiffusion: 3D Gaussian Splatting for Denoising Diffusion Probabilistic Models with Structured Noise. *ArXiv* abs/2311.11221 (2023). https://api.semanticscholar.org/CorpusID:265294507

[13] Riku Murai, Eric Dexheimer, and Andrew J Davison. 2024. MASt3R-SLAM: Real-Time Dense SLAM with 3D Reconstruction Priors. *arXiv preprint arXiv:2412.12392* (2024).

[14] Gianpaolo Palma, Manuele Sabbadin, Massimiliano Corsini, and Paolo Cignoni. 2018. Enhanced visualization of detected 3d geometric differences. In *Computer Graphics Forum*, Vol. 37. Wiley Online Library, 159–171.

[15] Torcuato Pulido Mantas, Camilla Roveta, Barbara Calcinai, Cristina Gioia di Camillo, Chiara Gambardella, Chiara Gregorin, Martina Coppari, Teo Marrocco, Stefania Puce, Agnese Riccardi, et al. 2023. Photogrammetry, from the land to the sea and beyond: A unifying approach to study terrestrial and marine environments. *Journal of Marine Science and Engineering* 11, 4 (2023), 759.

[16] Gautam Verma and D. Sharma. 2022. Seeing through the walls with wireless technology: A review. *International Journal of Sensors, Wireless Communications and Control* (2022). doi:10.2174/2210327912666220325161625

[17] Gautam Verma and D Sharma. 2022. Seeing through the walls with wireless technology: A review. *International Journal of Sensors, Wireless Communications and Control* (2022). doi:10.2174/2210327912666220325161625

[18] Maximilian Vogt, Adrian Rips, and Claus Emmelmann. 2021. Comparison of iPad Pro®'s LiDAR and TrueDepth capabilities with an industrial 3D scanning solution. *Technologies* 9, 2 (2021), 25.

[19] Fu-Kang Wang et al. 2013. Detection of concealed individuals based on their vital signs by using a see-through-wall imaging system with a self-injection-locked radar. *IEEE Transactions on Microwave Theory and Techniques* 61 (2013), 696–704. doi:10.1109/TMTT.2012.2228223

[20] Zhimin Wang, Yuxin Zhao, and Feng Lu. 2022. Gaze-vergence-controlled see-through vision in augmented reality. *IEEE Transactions on Visualization and Computer Graphics* 28 (2022), 3843–3853. doi:10.1109/TVCG.2022.3203110

[21] Zhimin Wang, Yuxin Zhao, and Feng Lu. 2022. Gaze-vergence-controlled see-through vision in augmented reality. *IEEE Transactions on Visualization and Computer Graphics* 28 (2022), 3843–3853. doi:10.1109/TVCG.2022.3203110

[22] Jacob O Wobbrock and Julie A Kientz. 2016. Research contributions in human-computer interaction. *interactions* 23, 3 (2016), 38–44.

[23] Lei Yang et al. 2015. See Through The Wall with COTS RFID System!. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*. doi:10.1145/2789168.2790100

[24] Yunqiang Yang and Aly Fathy. 2005. See-through-wall imaging using ultra wideband short-pulse radar system. In *2005 IEEE Antennas and Propagation Society International Symposium*, Vol. 3B. 334–337. doi:10.1109/APS.2005.1552508

[25] Yunqiang Yang and Aly Fathy. 2005. See-through-wall imaging using ultra wideband short-pulse radar system. In *2005 IEEE Antennas and Propagation Society International Symposium*, Vol. 3B. 334–337. doi:10.1109/APS.2005.1552508

accepted 6 March 2025