Motion Parallax Reproduction in Indirect Augmented Reality Using 3D Gaussian Splatting for Mobile Devices

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Figure 1: Reproduction of motion parallax in indirect augmented reality.

ABSTRACT

Augmented reality (AR) using real-time video often suffers from geometric errors and reduced visual clarity due to occlusions. Indirect AR (IAR) avoids these issues but lacks motion parallax. We propose a novel IAR system that enables motion parallax by combining 3D Gaussian Splatting (3DGS) with visual SLAM. To ensure safety and reduce memory consumption, we introduce a movement constraint, making the system scalable for mobile deployment.

Index Terms: Augmented reality, indirect AR, 3D gaussian splatting, SLAM, motion parallax.

1 INTRODUCTION

Augmented reality (AR) is widely used in tourism and education. However, real-time camera-based AR systems often suffer from geometric errors and reduced visual clarity due to occlusions. Indirect AR (IAR) [8] addresses these issues by overlaying virtual content on pre-captured omnidirectional images, ensuring stable alignment between real and virtual elements. Practical applications of IAR include museum exhibits and ruins tourism [2, 7]. To enhance immersion in IAR, a previous study [5] attempted motion parallax using a 3D scene reconstructed by SfM and MVS, with pose estimation via optical flow. However, the visual fidelity was limited.

We propose a novel IAR system that reproduces motion parallax by combining 3D Gaussian Splatting (3DGS) [4] for high-fidelity spatial reconstruction with visual SLAM. Furthermore, we introduce a movement constraint mechanism to ensure user safety and reduce memory usage, enabling scalable deployment on mobile devices. We conducted a user study comparing three AR methods: marker-based AR, omnidirectional image-based IAR, and the proposed 3DGS-based IAR, to evaluate differences in user experience.

2 PROPOSED METHOD

This section describes the proposed IAR system, which integrates 3DGS with visual SLAM to reproduce motion parallax. The system consists of offline and online processes.

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2.1 Offline Process

We capture images of the target environment from various viewpoints, and apply Structure-from-Motion (SfM) using COLMAP [6] to estimate camera poses and reconstruct a sparse point cloud. Next, these images and poses are used to train a 3DGS model. If the virtual object to be overlaid is an actual physical object, it is also reconstructed using 3DGS and composited into the reconstructed scene during the offline stage. The resulting 3DGS representation enables photorealistic rendering from arbitrary viewpoints.

2.2 Online Process

The user's camera pose is estimated in real time using visual SLAM. A virtual camera is then placed at the estimated pose in the reconstructed 3DGS environment to render the scene using the 3DGS renderer, reproducing motion parallax as the user moves.

To ensure safety and mobile scalability, user movement is restricted to within a certain range (e.g., 1-meter radius). When this threshold is exceeded, feedback such as device vibration is provided and the virtual camera stops. This restriction prevents unsafe usage (e.g., walking while viewing) and reduces the memory footprint required for high-resolution 3DGS rendering on mobile devices.

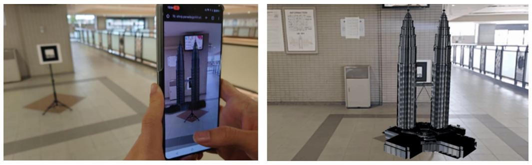
3 EXPERIMENTS

3.1 Experimental Settings

We designed two scenarios: a lobby scene with a virtual object 4 meters away for distant viewing, and a lounge scene with a 1 meter viewing distance for close-up observation, as shown in Fig. 1. Users started from a fixed position and direction, and were allowed to take one step forward. The system constrained movement within a 1-meter radius.

We conducted a user study comparing three methods: (A) Marker-based AR (Marker-AR) using real-time camera images, (B) omnidirectional image-based IAR (360-IAR), and (C) the proposed method (3DGS-IAR), as shown in Fig. 2, implemented with A-Frame [1] for A/B, and GaussianSplats3D [3] for C.

Twenty participants evaluated each method in both scenes using four 5-point Likert-scale questions on stability (Q1), visibility (Q2), consistency (Q3), and integration (Q4) (Table 1). The user study was approved by the institutional review board of Osaka Institute of Technology, and all the participants provided informed consent.



(a) Marker-AR

(b) 360-IAR

(c) 3DGS-IAR (Proposed method)

Figure 2: Three types of AR methods for experiments.

Table 1: Questionnaire items.

ID	Question
Q1	The system operated stably.
Q2	The virtual object could be clearly observed.
Q3	There was no inconsistency between the real world and the video representation.
Q4	The virtual object was well integrated with the background of the real scene in the video.

3.2 Results

Figure 3 shows the average scores and standard errors for each method across the four questionnaire items. In both scenes, Marker-AR received the lowest scores overall. 3DGS-IAR consistently outperformed 360-IAR, particularly in visibility and consistency. In the lobby scene, 360-IAR scored slightly higher in stability and integration, though the differences were not significant.

We conducted pairwise t-tests with Holm-Bonferroni correction ($\alpha = 0.05$) for each question. Significant differences were observed between Marker-AR and the other methods across many items. For Q3 (consistency) in the lounge scene, a statistically significant difference was found between 360-IAR and 3DGS-IAR ($p < 0.05$). For Q2 (visibility), while the difference did not reach statistical significance, the adjusted p-value ($p = 0.052$) suggests a possible trend that merits further exploration in future studies.

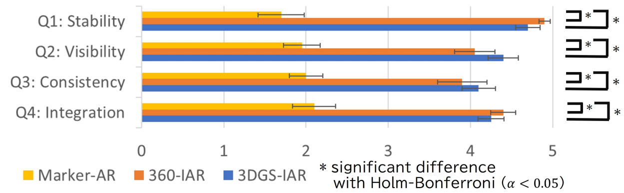
3.3 Discussion

Table 2 summarizes the average scores for each method. The proposed 3DGS-IAR method received consistently high ratings.

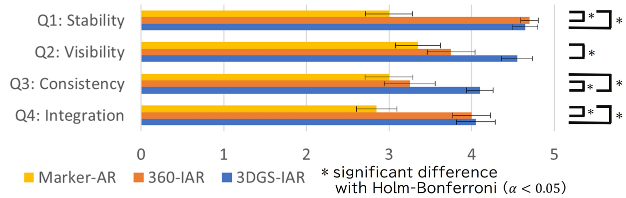
While 360-IAR achieved the highest score for stability (Q1), its lack of motion parallax may have limited user perception in close-range viewing, leading to lower visibility (Q2). This indicates a trade-off between simplicity and perceptual richness.

3DGS-IAR balanced these aspects by integrating SLAM and 3DGS. In particular, Holm-Bonferroni analysis revealed a significant difference in Q3 (consistency) between 360-IAR and 3DGS-IAR, and a marginal difference in Q2 (visibility). These results highlight the advantage of motion parallax in enhancing user experience in near-field environments.

However, the experiment was limited to two fixed viewing distances. Future studies should consider a wider range of scenarios, including closer object observation and dynamic conditions such as



(a) Lobby scene



(b) Lounge scene

Figure 3: Questionnaire results.

Table 2: Mean scores.

(n=40)	Marker-AR	360-IAR	3DGS-IAR
Stability	2.35 (D)	4.80 (A)	4.68 (A)
Visibility of virtual object	2.65 (D)	3.90 (C)	4.48 (B)
Consistency between real world and video	2.50 (D)	3.58 (C)	4.10 (B)
Integration of real bg and virtual object in video	2.48 (D)	4.20 (B)	4.15 (B)

	Mark
≥4.5	A: Excellent
≥4.0	B: Good
≥3.0	C: Fair
≥2.0	D: Poor

people walking in front of the user during interaction.

4 Conclusion

We proposed an IAR system using 3DGS and SLAM to reproduce motion parallax. A movement constraint was introduced for safe and efficient use on mobile devices. User studies showed that the proposed method outperformed Marker-AR and 360-IAR, especially in close-range scenarios such as museums and heritage sites. Future work will explore more realistic conditions.

Acknowledgments

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