

Online 3D Gaussian Splatting Modeling with Novel View Selection

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Abstract

This study addresses the challenge of generating online 3D Gaussian Splatting (3DGS) models from RGB-only frames. Previous studies have employed dense SLAM techniques to estimate 3D scenes from keyframes for 3DGS model construction. However, these methods are limited by their reliance solely on keyframes, which are insufficient to capture an entire scene, resulting in incomplete reconstructions. Moreover, building a generalizable model requires incorporating frames from diverse viewpoints to achieve broader scene coverage. However, online processing restricts the use of many frames or extensive training iterations. Therefore, we propose a novel method for high-quality 3DGS modeling that improves model completeness through adaptive view selection. By analyzing reconstruction quality online, our approach selects optimal non-keyframes for additional training. By integrating both keyframes and selected non-keyframes, the method refines incomplete regions from diverse viewpoints, significantly enhancing completeness. We also present a framework that incorporates an online multi-view stereo approach, ensuring consistency in 3D information throughout the 3DGS modeling process. Experimental results demonstrate that our method outperforms state-of-the-art methods, delivering exceptional performance in complex outdoor scenes.

1 Introduction

Online 3D modeling from an image stream is a critical challenge in robotics, virtual reality, augmented reality, and related fields. Visual *Simultaneous Localization And Mapping* (SLAM) has emerged as a key solution to this challenge. In particular, dense SLAM techniques [Newcombe *et al.*, 2011] [Teed and Deng, 2021] focus on real-time depth estimation to enable detailed 3D scene reconstruction. Recently, dense SLAM [Rosinol *et al.*, 2023] [Zhang *et al.*, 2023] [Zhu *et al.*, 2024] has been further developed to incorporate neural scene representations [Mildenhall *et al.*, 2021] [Kerbl *et al.*,

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Figure 1: The main idea of our novel view selection for online 3DGS modeling. (*upper*) Our method selects non-keyframes that observe the most uncertain Gaussians (red regions in the uncertainty map) for additional training. In the figure, blue views represent keyframes, red views represent selected non-keyframes, and white views represent the remaining non-keyframes. (*lower*) This approach enhances the completeness of 3DGS, yielding high-quality renderings.

2023] [Zhou *et al.*, 2023], enhancing high-quality rendering and realistic scene synthesis. Among these advancements, *3D Gaussian Splatting* (3DGS) [Kerbl *et al.*, 2023] has attracted significant attention for its efficient 3D scene representation and real-time rendering capabilities.

In this study, we tackle the challenge of generating online 3DGS models from RGB-only frames. Previous works [Matsuki *et al.*, 2024] [Huang *et al.*, 2024] [Sandström *et al.*, 2024] have focused mainly on dense SLAM frameworks that utilize 3DGS as a map representation. These methods achieve real-time depth estimation through techniques such as optical flow [Teed and Deng, 2020], depth prediction [Eftekhari *et al.*, 2021], or motion stereo [Song *et al.*, 2021], integrating the estimated depths directly into the 3DGS model. While these approaches have shown promising results, they still face notable limitations that require further attention.

First, many studies rely on sparse or low-resolution depths

to ensure real-time processing, which inherently limits the quality of the final model. Notably, some approaches [Zhu *et al.*, 2024] [Sandström *et al.*, 2024] employ depth prediction networks [Eftekhar *et al.*, 2021] that infer depth directly from images but often generate ambiguous estimates. Second, existing methods [Huang *et al.*, 2024] [Sandström *et al.*, 2024] [Lee *et al.*, 2024] store depth information only for keyframes, restricting 3DGS model training to these frames. This limitation can lead to incomplete reconstruction not only of unobserved areas but also of covered 3D scenes due to insufficient keyframe coverage. Lastly, online 3D modeling must operate within a constrained timeframe, which restricts the number of image frames and training iterations that can be processed. To achieve the best results within these constraints, it is essential to identify and prioritize the frames that most effectively enhance the performance of 3DGS during training.

To address these challenges, we propose a novel method that adaptively improves model completeness through novel view selection. Our approach identifies an optimal set of non-keyframes for additional training by analyzing the online reconstruction quality of the 3DGS model. Specifically, we define the uncertainty of Gaussian primitives based on their shapes and the gradients of their positions. This uncertainty metric is then used to calculate the information gain from a given viewpoint, enabling the selection of optimal views. By incorporating both keyframes and selected non-keyframes, our method refines incomplete regions from diverse viewpoints, resulting in improved completeness (see Fig. 1).

Additionally, we present an efficient framework for online 3DGS mapping that integrates an independent frontend and backend for streamlined processing. The frontend leverages a state-of-the-art *multi-view stereo* (MVS) network [Cao *et al.*, 2022] to generate accurate depths from sequential input images. Operating in parallel, the backend focuses on optimizing 3DGS models, allowing sufficient time for effective parameter refinement. To maintain consistency between the frontend and backend, the framework continuously applies *global bundle adjustment* (GBA) and Gaussian deformation. This approach achieves superior rendering accuracy compared to state-of-the-art methods, demonstrating exceptional performance in handling complex outdoor environments.

The main contributions are summarized as follows:

- We propose an online 3DGS modeling method that leverages novel view selection. This approach selects optimal views from non-keyframes for additional training, significantly improving model completeness.
- We define the uncertainty of Gaussians using their shapes and positional gradients. This approach allows for more effective view selection compared to other uncertainty metrics [Jiang *et al.*, 2025] [Jin *et al.*, 2024].
- We present a 3DGS mapping framework that utilizes an online MVS approach. This framework ensures consistent 3D information throughout the entire process.
- The proposed method was evaluated using two benchmarks for indoor scenes [Sturm *et al.*, 2012] [Straub *et al.*, 2019]. To highlight its generalization capability, we also extended the evaluation to include challenging outdoor scenarios [Song *et al.*, 2021] [Knapitsch *et al.*, 2017].

2 Related Works

2.1 Monocular Dense SLAM

Monocular SLAM [Mur-Artal *et al.*, 2015] [Forster *et al.*, 2014] traditionally generates sparse feature maps from monocular images and uses them to estimate camera poses. These methods have mainly focused on achieving precise pose estimation and have achieved significant success. The focus has shifted to reconstructing detailed 3D scenes, fueling the development of dense SLAMs [Engel *et al.*, 2017].

With deep learning achieving state-of-the-art performance in optical flow [Teed and Deng, 2020] and depth estimation [Eftekhar *et al.*, 2021] [Yao *et al.*, 2018], many studies also have investigated the incorporation of deep learning modules into dense SLAM systems [Bloesch *et al.*, 2018; Koestler *et al.*, 2022; Teed and Deng, 2021]. DROID-SLAM [Teed and Deng, 2021] combines an optical flow network with GBA to achieve precise trajectory estimation and dense 3D modeling.

2.2 Differentiable Rendering SLAM

Differentiable volumetric rendering, popularized by NeRF [Mildenhall *et al.*, 2021], has recently emerged as a key technique for achieving photorealistic scenes and has been applied to dense SLAM. GO-SLAM [Zhang *et al.*, 2023] and NeRF-SLAM [Rosinol *et al.*, 2023] integrate low-resolution depth maps estimated from DROID-SLAM [Teed and Deng, 2021] into NeRFs. NICER-SLAM [Zhu *et al.*, 2024] and GLORIE-SLAM [Zhang *et al.*, 2024] leverage depth prediction networks to generate high-resolution depth maps, which are further utilized to improve NeRFs.

Recently, 3DGS [Kerbl *et al.*, 2023; Ma *et al.*, 2024] has gained attention as a promising solution for 3D modeling, offering faster rendering speeds compared to NeRF. By representing 3D space with Gaussian primitives, 3DGS achieves efficient rendering through rasterization and spatial optimization, making it highly suitable for dense SLAM. PhotoSLAM [Huang *et al.*, 2024] and MGSO [Hu *et al.*, 2024] generate Gaussian points from sparse feature points extracted using ORB-SLAM [Mur-Artal *et al.*, 2015] and Direct Sparse Odometry [Engel *et al.*, 2017], respectively. Splat-SLAM [Sandström *et al.*, 2024] further enhances 3DGS mapping by combining proxy depth maps with depth prediction results. It employs deformable Gaussians and globally optimized optical flow tracking, resulting in improved accuracy.

Existing methods [Kerbl *et al.*, 2023] [Matsuki *et al.*, 2024] [Huang *et al.*, 2024] [Hu *et al.*, 2024] [Sandström *et al.*, 2024] suffer from reduced quality due to their reliance on sparse or imprecise depth data, with depth prediction performing poorly in untrained environments like outdoor scenes. To address this limitation, MVS-GS [Lee *et al.*, 2024] leverages an online MVS approach [Song *et al.*, 2021] to estimate high-quality depth maps, enabling accurate Gaussian initialization. Building on the MVS-GS framework, our method further improves 3DGS mapping by incorporating iterative GBA with Gaussian deformation. Additionally, we propose a novel view selection strategy that prioritizes non-keyframes with high information gain, integrating them into the training process. These enhancements significantly improve the completeness and quality of the resulting 3DGS model.

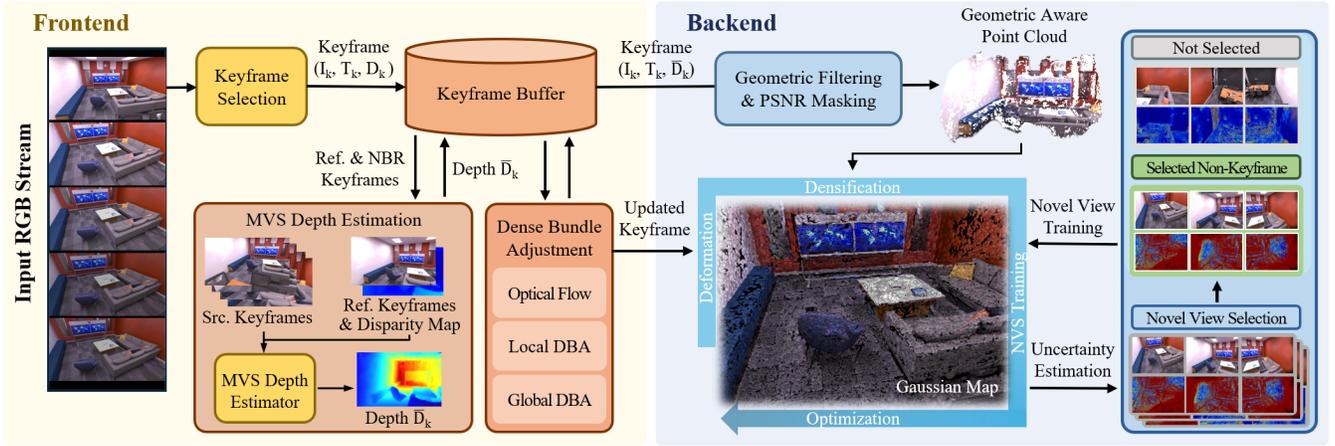


Figure 2: System overview. The frontend tracks camera poses and estimates depth maps for keyframes using MVS networks, with the disparity map derived from tracking module used to initialize the network. The backend generates new Gaussians from keyframes and continuously optimizes the 3DGS model. To further improve performance, our system periodically performs GBA and conducts additional training on non-keyframes selected through NVS.

2.3 Next-Best-View Planning

The next-best-view (NBV) problem [Scott *et al.*, 2003] focuses on identifying optimal viewpoints to gather specific information. This process aims to maximize information gain, typically defined based on uncertainty, which varies depending on the type of 3D modeling.

With advancements in NeRF, many NBV-related studies have emerged. These approaches estimate uncertainty by analyzing factors such as occupancy probability [Yan *et al.*, 2023], color similarity [Ran *et al.*, 2023], or implicit neural representations [Feng *et al.*, 2024] derived from NeRF models. However, NBV research specifically tailored to 3DGS remains limited. FisherRF [Jiang *et al.*, 2025] quantifies information gain using Fisher information in Gaussian parameters, but it relies on computationally intensive gradient calculations. GS-Planner [Jin *et al.*, 2024] evaluates completeness by comparing rendered color and depth values with their captured ones, using this measure to estimate information gain.

These methods [Jiang *et al.*, 2025; Jin *et al.*, 2024] measure uncertainty using rendered images; however, they provide inaccurate results when the original image contains noise and are heavily affected by less significant areas, such as the sky. In contrast, the proposed method effectively represents the quality of each Gaussian by leveraging its shape and gradients, allowing for efficient and precise uncertainty estimation.

3 Proposed Method

We present a system for online 3DGS modeling using RGB images, designed for high-quality rendering. This system is built on the MVS-GS framework [Lee *et al.*, 2024], featuring parallel operation of frontend and backend modules. For the frontend module, we directly adopt the tracking method of [Teed and Deng, 2021] and the MVS networks from [Cao *et al.*, 2022] to simultaneously estimate camera poses and depth maps from an image stream. Based on the outputs of the frontend, we propose novel techniques to learn a high-fidelity 3DGS scene representation in the backend module.

3.1 System Overview

Fig. 2 depicts an overview of the proposed system. Given an input image stream, the frontend dynamically constructs a frame-graph G , where each node I_k represents a selected keyframe, and each edge (I_k, I_l) denotes a co-visibility connection between two keyframes. During the construction of the graph G , the frontend tracks the camera pose and estimates the depth map for each inserted keyframe. To mitigate the effects of pose and scale drift and enhance global geometric consistency, we perform GBA online on the entire graph G every 30 keyframes. The original tracking system [Teed and Deng, 2021] performs GBA only at the end of the mapping process. In contrast, we continuously perform GBA to consistently optimize the global consistency of 3D model.

Next, the frontend estimates accurate and reliable depth maps based on the MVS network, MVSFormer [Cao *et al.*, 2022]. Depth prediction methods commonly employed in dense SLAM [Ranftl *et al.*, 2021] [Bhat *et al.*, 2023] suffer from scale ambiguity issues due to the inherent limitations of single-image-based estimation, which can result in reduced accuracy and consistency in depth estimation. In contrast, MVS leverages information from surrounding frames, effectively overcoming the scale ambiguity inherent in single-frame estimation and generating more accurate and consistent depth maps. We compute the coarse depths based on the dense optical flow results estimated during the tracking step and use it to initialize the depth map in the first layer of MVSFormer. This approach improves consistency between the tracking and MVS stages, enhancing the robustness of depth estimation while reducing computational costs.

The backend module consistently trains a 3DGS model for scene representation using the estimated camera pose T_k and depth map \bar{D}_k of each keyframe I_k . The module begins by using the depths of some initial keyframes to initialize a 3DGS model. Subsequently, it incrementally integrates new 3D Gaussians from incoming keyframes into the existing model (Section 3.2). Additionally, we perform a *novel view*

selection (NVS) strategy to identify a set of non-keyframes that significantly enhance 3DGS quality, using them for further training of the 3DGS model (Section 3.3). The NVS quantifies the uncertainty of Gaussians and determines the non-keyframes that cover the largest number of uncertain Gaussians. Our method uses the selected frames for additional training, significantly improving the completeness of the 3DGS model and the generalizability of its rendering.

3.2 Online 3DGS Modeling

Map Construction. For each keyframe, we first transform the depth map \bar{D}_k into a point cloud based on the camera pose T_k . We remove noisy points and outliers from the point cloud to obtain reliable and consistent 3D points. This step was implemented using geometric and photometric consistency criteria commonly employed in MVS [Cao *et al.*, 2022].

The initial point cloud, generated from the first few keyframes, is used to create a set of Gaussian primitives for the 3DGS model. As new keyframes are extracted, the 3DGS model is incrementally updated by incorporating additional Gaussians. Following the approach of [Lee *et al.*, 2024], we generate new Gaussians exclusively from unexplored regions with low rendering quality to improve computational efficiency. The unexplored regions are identified by comparing the rendered image \hat{I}_k with the original images I_k using the peak signal-to-noise ratio (PSNR), marking those below a threshold as such regions. Throughout the map construction process, we regularly perform GBA and Gaussian optimization to refine camera poses and update the model parameters.

Gaussian Representation. We utilize the generalized exponential splatting (GES) [Hamdi *et al.*, 2024] to parameterize each Gaussian in a 3DGS model. Specifically, a Gaussian point g_i is defined by several attributes: a covariance matrix $\Sigma_i \in R^{3 \times 3}$, a mean $\mu_i \in R^3$, opacity $o_i \in [0, 1]$, color $c_i \in R^3$, and a shape parameter $\beta_i \in (0, \infty)$. The shape parameter β_i , which is learnable, controls the sharpness of the Gaussian. The GES framework efficiently captures high-frequency details of the scene using fewer primitives, making it well-suited for real-time mapping and rendering. The Gaussian density function in GES is defined as follows:

$$g_i(x) = \exp \left\{ -\frac{1}{2}(x - \mu_i)^T \Sigma_i^{-1} (x - \mu_i) \right\}^2 \beta_i \quad (1)$$

To render an image \hat{I}_k from an input pose T_k , the 3D Gaussians are projected onto the image plane. The color $\hat{c}(p)$ of each pixel p is determined by sorting the Gaussian points by depth and performing alpha blending from front to back:

$$\hat{c}(p) = \sum_{i \in N} c_i \alpha_i \prod_{j=1}^{i-1} (1 - \alpha_j) \quad (2)$$

where $\alpha_i = o_i g_i(x)$ ensures that closer Gaussian points contribute more to the color of the pixels. Similarly, the depth \hat{D}_k can be rendered using the same projection approach:

$$\hat{D}(p) = \sum_{i \in N} z_i \alpha_i \prod_{j=1}^{i-1} (1 - \alpha_j) \quad (3)$$

where z_i is the distance to the Gaussian mean along the ray.

Map Deformation. During incrementally building the 3D Gaussian map, the GBA module updates camera poses and disparity map of keyframes in entire history. Therefore, the 3D Gaussian map should be updated accordingly after each GBA update. However, our map is only rigidly deformed based on the updated camera poses instead of using non-rigid deformation as in [Sandström *et al.*, 2024]. The 3D data generated by MVS is highly accurate, allowing for the generation of a consistent model with rigid deformation. This approach helps improve the efficiency of the deformation process. The map deformation process is executed after the GBA and before the Gaussian optimization step. This helps refine the entire Gaussian map to adapt to the updated camera poses.

3.3 3DGS Optimization with Novel View Selection

Existing online methods [Sandström *et al.*, 2024; Huang *et al.*, 2024; Lee *et al.*, 2024] learn Gaussian parameters using only tracked keyframes. The keyframes are usually selected by thresholding mean of optical flow between image frames [Teed and Deng, 2020]. Those keyframes sometimes cannot fully cover the entire scene due to fast motion changes or occlusions. Additionally, it is infeasible to use all frames, including both keyframes and non-keyframes, for optimization. To address this, our NVS selects top-k non-keyframes that cover poorly reconstructed regions, based on estimated information gain.

Uncertainty Estimation. For each non-keyframe I_n , we extract visible Gaussians and compute an uncertainty score based on their shapes and positional gradients. For each Gaussian $g_{n,i}$ visible in I_n , we extract the largest eigenvalue of its covariance $\Sigma_{n,i}$. Here, $\Sigma_{n,i} = R_{n,i} S_{n,i} S_{n,i}^T R_{n,i}^T$, where $R_{n,i}$ and $S_{n,i}$ represent the orientation and scale components of Gaussian $g_{n,i}$, respectively. Since $S_{n,i} = \text{diag}(s_{n,i})$ where $s_{n,i} \in R^3$, it follows that $S_{n,i} S_{n,i}^T = \text{diag}(s_{n,i}^2)$. The largest eigenvalue $\lambda_{n,i}$ is then calculated as:

$$\lambda_{n,i} = \max(s_{n,i}^2) \quad (6)$$

This eigenvalue $\lambda_{n,i}$ represents the largest size of $g_{n,i}$ in the direction corresponding to the rotation $R_{n,i}$. Incorporating the eigenvalue into the uncertainty formulation helps address the over-reconstruction indicated by large Gaussians [Hu *et al.*, 2025; Matsuki *et al.*, 2024].

The second component of uncertainty is derived from the adaptive density control mechanism in existing 3DGS models [Matsuki *et al.*, 2024][Sandström *et al.*, 2024]. A large positional gradient indicates that the 3DGS model is still undergoing optimization. Therefore, high gradients suggest that the parameters have not yet been fully optimized [Rota Bulò *et al.*, 2024] [Kerbl *et al.*, 2023]. Therefore, we adopted the gradient as a factor for measuring the uncertainty of Gaussians. Let $d\mu_{n,i} \in R^3$ be the positional gradient of Gaussian $g_{n,i}$. We calculate the magnitude of the gradient $A_{n,i} = \|d\mu_{n,i}\|$ as a measure of uncertainty estimation. This approach helps prioritize regions requiring further optimization.

Using these two components, an uncertainty score $U_{n,i}$ is computed for each Gaussian $g_{n,i}$ as follows:

$$U_{n,i} = \alpha_1 \lambda_{n,i} + \alpha_2 A_{n,i} \quad (7)$$

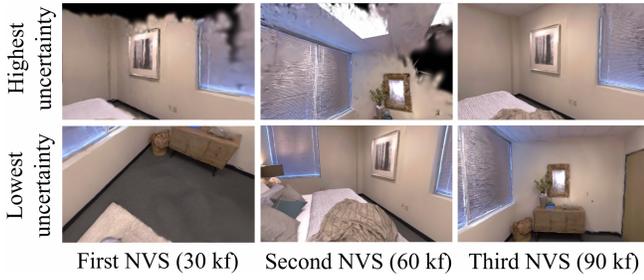


Figure 3: Rendered images from views with the highest and lowest information gain in the candidate set at every 30th keyframe.

where $\alpha_1 = 0.7$, $\alpha_2 = 0.3$ are weighted hyperparameters.

Finally, the information gain of the view I_n is defined as the total uncertainty of all Gaussians visible from I_n .

$$U_n = \sum_{i=1}^{|\{g_{n,i}\}|} \frac{1}{z_{n,i}^2} U_{n,i} \quad (8)$$

where $z_{n,i}$ represents the depth of the Gaussian $g_{n,i}$ in the view I_n . This equation highlights that Gaussians closer to the view I_n have a greater impact on the uncertainty.

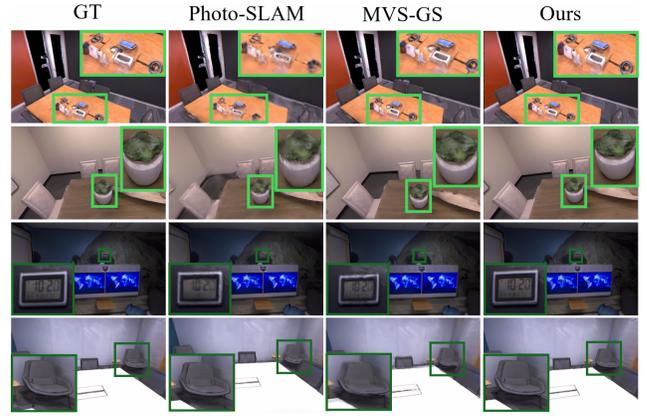
After calculating an information gain for each non-keyframe, we sort all candidate frames in descending order based on their scores. Since consecutive frames often have similar scores, we apply non-maximum suppression (NMS) [Redmon, 2016] within a local window to the sorted list. This process avoids selecting frames within the local window of previously chosen frames, promoting the selection of frames from diverse viewpoints. The top-k frames with the highest information gain are then selected and combined with the 30 most recently tracked keyframes to form the training frame set. The frame set is used for additional training, enabling the 3DGS model to enhance under-reconstructed areas and refine recently observed regions that require further training.

We construct a candidate set consisting of non-keyframes captured within the span of the 30 most recent keyframes, and apply NVS to this set. We identify 20 high-information-gain frames selected from the current set and include them in the subsequent candidate set. This approach allows for an efficient evaluation of information gain by focusing on the latest non-keyframes while incorporating selected older non-keyframes. Fig. 3 depicts the non-keyframes with the highest and lowest gain within the set constructed at each iteration.

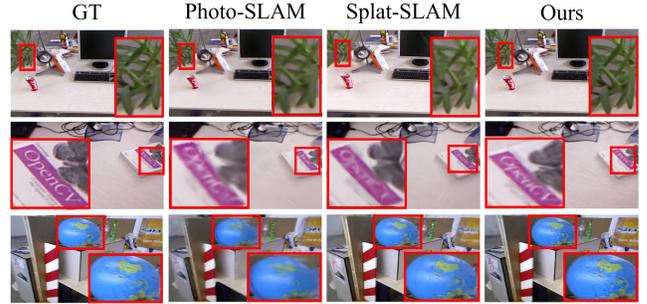
Gaussian Training This optimization step is iteratively performed to refine Gaussian parameters. These Gaussians are trained using both keyframes and selected non-keyframes. The loss function for keyframes is defined as follows:

$$L_{\text{KF}} = \lambda_{L_1} L_1 + \lambda_{\text{SSIM}} L_{\text{SSIM}} + \lambda_{\text{depth}} L_{\text{depth}} + \lambda_{\text{smooth}} L_{\text{smooth}} \quad (9)$$

where L_1 represents the L1 loss between the rendered images (Eq. 2) and the original images. L_{SSIM} is the structural similarity index measure (SSIM) loss, which preserves image quality [Wang *et al.*, 2004]. L_{depth} is calculated between the rendered depths (Eq. 3) and the MVS depths, helping to maintain the geometric structure. Lastly L_{smooth} is the



(a) Results on the Replica dataset



(b) Results on the TUM-RGBD dataset

Figure 4: Qualitative evaluation on (a) the Replica and (b) TUM-RGBD datasets. The boxes highlight areas where our method produces fine details with higher accuracy than the competing methods.

smoothness loss, designed to minimize depth differences between neighboring pixels, which is expressed as:

$$L_{\text{smooth}} = \frac{1}{N_x} \sum_{i,j} |d(i,j) - d(i,j+1)| + \frac{1}{N_y} \sum_{i,j} |d(i,j) - d(i+1,j)| \quad (10)$$

This smooths abrupt depth changes between pixels, yielding natural transitions and fewer discontinuities.

Non-keyframes contain only image information and do not include depth information. Therefore, for the non-keyframes, the loss function simplifies image rendering losses:

$$L_{\text{NKF}} = \lambda_{L_1} L_1 + \lambda_{\text{SSIM}} L_{\text{SSIM}} + \lambda_{\text{smooth}} L_{\text{smooth}} \quad (11)$$

This approach ensures that both keyframes and non-keyframes contribute effectively to improving the 3DGS model, balancing geometric accuracy and image quality.

4 Experiment Results

To assess the quality of our method, we compared to state-of-the-art methods on various datasets, including indoor and outdoor scenes. For indoor scenes, we conducted experiments using the Replica [Straub *et al.*, 2019] and TUM-RGBD [Sturm *et al.*, 2012] datasets, following the same experimental setups as other methods ([Matsuki *et al.*, 2024],

Method	Off0	Off1	Off2	Off3	Off4	Rm0	Rm1	Rm2	Avg.
PSNR \uparrow									
Q-SLAM	36.31	37.22	30.68	30.21	31.96	29.58	32.74	31.25	32.49
MonoGS	32.00	31.21	23.26	25.77	23.85	23.53	25.00	22.42	25.88
Splat-SLAM	40.81	40.64	<u>35.19</u>	<u>35.03</u>	<u>37.40</u>	<u>32.25</u>	<u>34.31</u>	<u>35.95</u>	<u>36.45</u>
Photo-SLAM	36.99	37.52	31.79	31.62	34.17	29.77	31.30	33.18	33.29
MGS-SLAM	35.51	34.25	30.83	31.86	34.38	29.91	31.06	31.49	32.41
MVS-GS	<u>41.02</u>	<u>42.04</u>	34.00	34.65	33.33	32.20	31.54	35.84	35.58
Ours	43.93	43.98	37.98	36.31	39.59	34.88	37.99	39.60	39.28
SSIM \uparrow									
Q-SLAM	0.94	0.94	0.90	0.88	0.89	0.83	0.91	0.87	0.89
MonoGS	0.90	0.88	0.82	0.84	0.86	0.75	0.79	0.81	0.83
Splat-SLAM	0.97	0.99	<u>0.97</u>	0.97	<u>0.97</u>	0.96	0.97	<u>0.96</u>	<u>0.97</u>
Photo-SLAM	0.96	0.95	0.93	0.92	0.94	0.87	0.91	0.93	0.93
MGS-SLAM	0.94	0.93	0.90	0.92	0.95	0.89	0.90	0.91	0.92
MVS-GS	<u>0.98</u>	<u>0.98</u>	0.95	<u>0.96</u>	0.95	<u>0.95</u>	<u>0.92</u>	<u>0.96</u>	0.96
Ours	0.99	0.99	0.98	0.97	0.98	0.96	0.97	0.98	0.98
LPIPS \downarrow									
Q-SLAM	0.13	0.15	0.20	0.19	0.18	0.18	0.16	0.15	0.17
MonoGS	0.23	0.22	0.30	0.24	0.34	0.33	0.35	0.39	0.30
Splat-SLAM	<u>0.05</u>	0.07	<u>0.06</u>	<u>0.04</u>	0.10	0.09	<u>0.06</u>	<u>0.05</u>	<u>0.06</u>
Photo-SLAM	0.06	0.06	0.09	0.09	<u>0.07</u>	0.10	0.08	0.07	0.08
MGS-SLAM	0.07	0.11	0.12	0.07	0.08	<u>0.08</u>	0.09	0.09	0.09
MVS-GS	<u>0.05</u>	<u>0.05</u>	0.09	0.07	0.10	0.10	0.13	0.07	0.08
Ours	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.03	0.03

Table 1: Quantitative rendering performance on the Replica dataset.

[Sandström *et al.*, 2024], [Zhang *et al.*, 2024]). For outdoor scenarios, we used the Aerial [Song *et al.*, 2021] and Tanks&Temples datasets [Knapitsch *et al.*, 2017]).

Implementation Details. All experiments were carried out on a desktop equipped with an AMD Ryzen9 7900X 12-core processor and an NVIDIA GeForce RTX 4090 GPU. Training and evaluation were performed in PyTorch with CUDA to accelerate rasterization and gradient computations. While most hyperparameters follow the original 3DGS setting [Kerbl *et al.*, 2023], we empirically set λ_{L1} , λ_{SSIM} , λ_{depth} and λ_{smooth} to 0.95, 0.2, 0.2, and 0.1, respectively, for the loss function of Gaussian training. We used 100 non-keyframes for NVS, and set the NMS gap between frames to 3 to exclude neighboring frames.

Baseline Methods. We evaluated the performance of our method by comparing it with state-of-the-art monocular dense SLAM methods, including NeRF-based (Q-SLAM [Peng *et al.*, 2024] and GLORIE-SLAM [Zhang *et al.*, 2024]) and 3DGS-based (MonoGS [Matsuki *et al.*, 2024], Splat-SLAM [Sandström *et al.*, 2024], Photo-SLAM [Huang *et al.*, 2024], and MVS-GS [Lee *et al.*, 2024]) methods.

Evaluation Metrics. We assessed the modeling quality using rendered images and depth maps. For image rendering quality, we report PSNR, SSIM, and LPIPS by comparing the rendered images with the original images.

4.1 Evaluation in Indoor Scenes

Table 1 shows the rendering performance results on the Replica dataset, highlighting that our method significantly outperforms other methods. Notably, it achieves superior results in both PSNR and SSIM, with a substantial improvement compared to the second-best method, Splat-SLAM.

Fig. 4a shows a qualitative comparison between our method and the other 3DGS-based methods. Our method effectively captures intricate scene details, resulting in high-quality renderings with fewer artifacts. Our texture details are significantly better than those produced by Photo-SLAM. Notably, MVS-GS fails to handle loop closing, causing the

Method	Metrics	f1/desk	f2/xyz	f3/off	Avg.
MonoGS		19.67	16.17	20.63	18.82
Photo-SLAM		20.97	21.07	19.59	20.54
GLORIE-SLAM	PSNR \uparrow	20.26	25.62	21.21	22.36
Splat-SLAM		<u>25.61</u>	29.53	<u>26.05</u>	<u>27.06</u>
MVS-GS		20.67	24.53	22.37	22.52
Ours		26.34	<u>28.72</u>	28.10	27.72
MonoGS		0.73	0.72	0.77	0.74
Photo-SLAM		0.74	0.73	0.69	0.72
GLORIE-SLAM	SSIM \uparrow	<u>0.87</u>	0.96	<u>0.84</u>	<u>0.89</u>
Splat-SLAM		0.84	0.90	<u>0.84</u>	0.86
MVS-GS		0.77	0.86	0.80	0.81
Ours		0.89	<u>0.91</u>	0.91	0.90
MonoGS		0.33	0.31	0.34	0.33
Photo-SLAM		0.23	0.17	0.24	0.21
GLORIE-SLAM	LPIPS \downarrow	0.31	0.09	0.32	0.24
Splat-SLAM		<u>0.18</u>	<u>0.08</u>	<u>0.20</u>	<u>0.15</u>
MVS-GS		0.25	0.15	0.24	0.21
Ours		0.12	0.07	0.10	0.10

Table 2: Quantitative rendering performance on the TUM-RGBD.

chair to appear doubled. In contrast, our method accurately reconstructs a single, complete representation of the chair.

Table 2 presents the evaluation results on real-world scenes from the TUM-RGBD dataset. Despite the inherent challenges of real-world datasets, including noisy images and complex scene variations, our approach maintains stable and reliable rendering quality. The qualitative results are shown in Fig. 4b. This demonstrates the robustness of our method in handling real-world data, ensuring consistent performance across diverse indoor scenes.

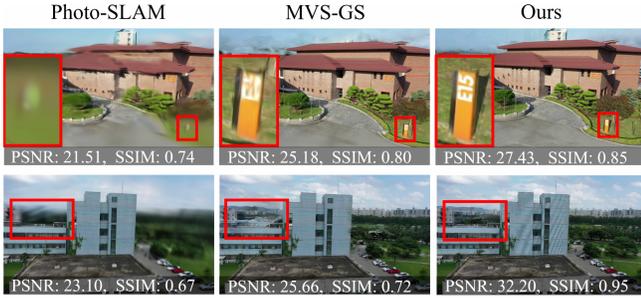
4.2 Evaluation in Outdoor Scenes

In this section, we validated the generalization capability of our method by evaluating its performance on outdoor scenes. Depth prediction-based methods, including Splat-SLAM and GLORIE-SLAM, failed to generate 3DGS models in these environments. Fig. 5a presents a performance evaluation of aerial scenes, demonstrating that our method outperforms both Photo-SLAM and MVS-GS, particularly in capturing small structural details. Leveraging the strengths of MVS in accurately reconstructing large-scale scenes, our method significantly outperformed Photo-SLAM in aerial scenes.

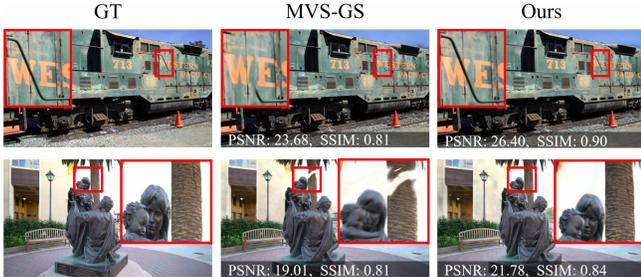
On the Tanks and Temples dataset, Splat-SLAM, MonoGS, and even Photo-SLAM failed to generate 3DGS models due to the lack of sufficient continuous motion in the image frames. Fig. 5b presents the rendering results for this dataset. While MVS-GS successfully produced a 3DGS model, its quality was compromised by limited training views and the absence of loop closure. In contrast, our method delivered high-quality rendering results that closely resembled real photographs. These findings highlight the effectiveness of the proposed NVS method and consistent geometric alignment, even in challenging outdoor scenes.

4.3 Ablation Study

To evaluate the impact of each key component in our method, we performed an ablation study on the ‘‘Office0’’ scene from the Replica dataset. Each component was progressively assessed as follows:



(a) Results on the Aerial dataset



(b) Results on the Tanks and Temples dataset

Figure 5: Qualitative evaluation on (a) the aerial scenes and (b) Tanks and Temples datasets. The red boxes highlight areas where our method achieves better accuracy in capturing fine details.

Method	PSNR \uparrow	SSIM \uparrow	LPIPS \downarrow	Depth L1 \downarrow	FPS \uparrow	#Gaussians (K) \downarrow	Map Size [GiB] \downarrow
A	40.92	0.979	0.023	0.042	19.39	1365	0.305
B	42.37	0.984	0.019	0.046	15.66	1253	0.280
C	42.71	0.985	0.018	0.044	15.28	1357	0.303
D	42.73	0.985	0.019	0.038	15.11	1377	0.308
E	43.93	0.988	0.016	0.034	9.18	1078	0.241

Table 3: Comparison results of our method with different model variants on the Replica “office 0” scene.

- **Method-A:** The baseline method, MVS-GS.
- **Method-B:** Incorporates the global GBA module.
- **Method-C:** Builds on Method-B by applying depth initialization using the disparity map from DROID-SLAM.
- **Method-D:** Extends Method-C by introducing a smoothness loss for training Gaussians.
- **Method-E:** Represents our full model, including the NVS.

We evaluated both image and depth rendering performance using metrics such as PSNR, SSIM, and LPIPS for images, and L1 error for depths. We also reported the number of Gaussians, map size, and computational speed (measured in frames per second, FPS) for each method. Table 3 summarizes the results for the variant methods.

Compared to Method-A, both Method-B and Method-C showed progressive improvements in rendering performance. This indicates that the application of the GBA and the depth initialization approach enhances the completeness of 3DGS modeling. Furthermore, Method-D incorporated the smooth depth loss, which showed no noticeable improvement in rendering quality but led to substantial enhancements in reconstruction performance. Fig. 6 shows the comparison results

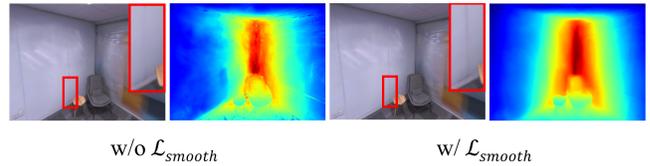


Figure 6: The effect of depth smooth regularization loss on the rendered image and depth map.

Metrics	$\alpha_1=0.0$ $\alpha_2=1.0$	$\alpha_1=0.1$ $\alpha_2=0.9$	$\alpha_1=0.3$ $\alpha_2=0.7$	$\alpha_1=0.5$ $\alpha_2=0.5$	$\alpha_1=0.7$ $\alpha_2=0.3$	$\alpha_1=0.9$ $\alpha_2=0.1$	$\alpha_1=1.0$ $\alpha_2=0.0$
PSNR \uparrow	43.802	43.820	43.859	43.877	43.932	43.841	43.812
SSIM \uparrow	0.986	0.986	0.987	0.987	0.988	0.987	0.985
LPIPS \downarrow	0.018	0.017	0.017	0.016	0.016	0.018	0.019

Table 4: Performance variations with respect to changes in the weights α_1 and α_2 of the uncertainty on the Replica “office 0”.

between Method-C and Method-D, where the improvements in reconstruction performance are visually apparent. Finally, when the NVS technique was applied, Method-E achieved superior performance in both rendering quality and depth reconstruction. Furthermore, in terms of model compactness, Method-E significantly reduces the number of Gaussians compared to Method-D, resulting in approximately a 60 MB reduction in map size. The NVS optimization helps eliminate or merge redundant keyframe Gaussians, thereby minimizing unnecessary overhead.

We further analyzed the impact of the uncertainty score parameters in Eq. (7) on the effectiveness of view selection. Table 4 shows the effect of the α_1 and α_2 . The largest eigenvalue primarily captures uncertainty in high-frequency regions, while the positional gradient focuses on low-frequency areas. Thus, α_1 and α_2 serve to balance these two complementary measures. If either value is too large, uncertainty estimation becomes biased and less effective. Therefore, we empirically determined suitable α_1 and α_2 values for balanced and accurate estimation.

5 Conclusion

We present a novel online mapping approach for high-quality 3DGS modeling that introduces uncertainty estimation directly within Gaussians. Our method utilizes an uncertainty-aware view selection strategy to extract the most informative views, improving the completeness of 3DGS models. Additionally, we develop a framework that integrates an online MVS technique, maintaining consistency in 3D information throughout the modeling process. Extensive experiments show that the proposed approach surpasses state-of-the-art dense SLAM methods, demonstrating outstanding performance, especially in complex outdoor environments. To the best of our knowledge, this is the first work to introduce non-keyframe selection in a 3DGS-based SLAM framework. The proposed formulation is general and applicable to various SLAM systems.

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