

Local-to-Global Registration for Bundle-Adjusting Neural Radiance Fields

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Abstract

Neural Radiance Fields (NeRF) have achieved photo-realistic novel views synthesis; however, the requirement of accurate camera poses limits its application. Despite analysis-by-synthesis extensions for jointly learning neural 3D representations and registering camera frames exist, they are susceptible to suboptimal solutions if poorly initialized. We propose L2G-NeRF, a Local-to-Global registration method for bundle-adjusting Neural Radiance Fields: first, a pixel-wise flexible alignment, followed by a frame-wise constrained parametric alignment. Pixel-wise local alignment is learned in an unsupervised way via a deep network which optimizes photometric reconstruction errors. Frame-wise global alignment is performed using differentiable parameter estimation solvers on the pixel-wise correspondences to find a global transformation. Experiments on synthetic and real-world data show that our method outperforms the current state-of-the-art in terms of high-fidelity reconstruction and resolving large camera pose misalignment. Our module is an easy-to-use plugin that can be applied to NeRF variants and other neural field applications. The Code and supplementary materials are available at <https://rover-xingyu.github.io/L2G-NeRF/>.

1. Introduction

Recent success with neural fields [46] has caused a resurgence of interest in visual computing problems, where coordinate-based neural networks that represent a field gain traction as a useful parameterization of 2D images [4, 6, 39], and 3D scenes [27, 29, 34]. Commonly, these coordinates are warped to a global coordinate system by camera parameters obtained via computing homography, structure from motion (SfM), or simultaneous localization and mapping (SLAM) [16] with off-the-shelf tools like COLMAP [38], before being fed to the neural fields.

This paper considers the generic problem of simultane-

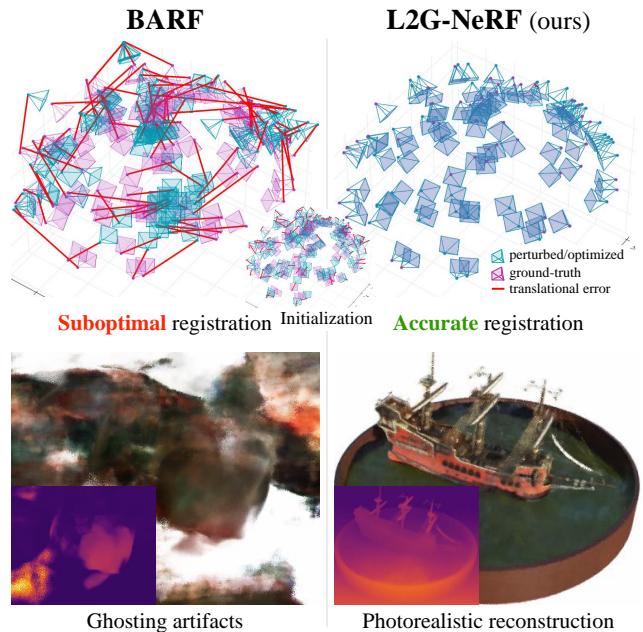


Figure 1. We present **L2G-NeRF**, a new bundle-adjusting neural radiance fields — employing local-to-global registration — that is much more robust than the current state-of-the-art **BARF** [24].

ously reconstructing the neural fields from RGB images and registering the given camera frames, which is known as a long-standing chicken-and-egg problem — registration is needed to reconstruct the fields, and reconstruction is needed to register the cameras.

One straightforward way to solve this problem is to jointly optimize the camera parameters with the neural fields via backpropagation. Recent work can be broadly placed into two camps: parametric and non-parametric. Parametric methods [9, 19, 24, 43] directly optimize global geometric transformations (*e.g.* rigid, homography). Non-parametric methods [21, 31] do not make any assumptions on the type of transformation, and attempt to directly optimize some pixel agreement metric (*e.g.* brightness constancy constraint in optical flow and stereo).

However, both approaches have flaws: parametric meth-

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ods fail to minimize the photometric errors (falling into the suboptimal solutions) if poorly initialized, as shown in Fig. 1, while non-parametric methods have trouble dealing with large displacements (*e.g.* although the photometric errors are minimized, the alignments do not obey the geometric constraint). It is natural, therefore, to consider a hybrid approach, combining the benefits of parametric and non-parametric methods together.

In this paper, we propose L2G-NeRF, a local-to-global process integrating parametric and non-parametric methods for bundle-adjusting neural radiance fields — the joint problem of *reconstructing* the neural fields and *registering* the camera parameters, which can be regarded as a type of classic photometric bundle adjustment (BA) [3, 11, 25]. Fig. 2 shows an overview. In the first non-parametric stage, we initialize the alignment by predicting a local transformation field for each pixel of the camera frames. This is achieved by self-supervised training of a deep network to optimize standard photometric reconstruction errors. In the second stage, differentiable parameter estimation solvers are applied to a set of pixel-wise correspondences to obtain a global alignment, which is then used to apply a soft constraint to the local alignment. In summary, we present the following contributions:

- We show that the optimization of bundle-adjusting neural fields is sensitive to initialization, and we present a simple yet effective strategy for local-to-global registration on neural fields.
- We introduce two differentiable parameter estimation solvers for rigid and homography transformation respectively, which play a crucial role in calculating the gradient flow from the global alignment to the local alignment.
- Our method is agnostic to the particular type of neural fields, specifically, we show that the local-to-global process works quite well in 2D neural images and 3D Neural Radiance Fields (NeRF) [29], allowing for applications such as image reconstruction and novel view synthesis.

2. Related Work

SfM and SLAM. Given a set of input images, SfM [2, 36, 37, 40, 41] and SLAM [15, 30, 32, 47] systems aim to recover the 3D structure and the sensor poses simultaneously. They reconstruct an explicit geometry (*e.g.* point clouds) and estimate camera poses through image registration via associating feature correspondences [10, 30] or minimizing photometric errors [3, 14], followed by BA [3, 11, 25].

However, the explicit point clouds assume a diffuse surface, hence cannot model view-dependent appearance. And the sparse nature of point clouds also limits downstream vision tasks, such as photorealistic rendering. In contrast,

L2G-NeRF encodes the scenes as coordinate-based neural fields, which is qualified for solving the high-fidelity visual computing problems.

Neural Fields. Recent advances in neural fields [46], which employ coordinate-based neural networks to parameterize physical properties of scenes or objects across space and time, have led to increased interest in solving visual computing problems, caused more accurate, higher fidelity, more expressive, and memory-efficient solutions. They have seen widespread success in problems such as image synthesis [4, 6, 39], 3D shape [8, 27, 34], view-dependent appearance [5, 17, 29, 33], and animation of humans [7, 35, 44].

While impressive results have been achieved by the above neural fields, they have a common drawback — the requirement of *camera parameters*. Our proposed L2G-NeRF allows us to circumvent such requirements.

Bundle-Adjusting Neural Fields. Since neural fields are end-to-end differentiable, camera parameters can be jointly estimated with the neural fields. The optimization problem is known to be non-convex, and is reflected by NeRF- [43], in which the authors jointly optimize the scene and cameras for forward-facing scenes. Adversarial objective is utilized [26] to relax forward-facing assumption and supports inward-facing 360° scenes. The method [19] is further developed to learn the camera intrinsics. BARF [24] shows that bundle-adjusting neural fields could benefit from coarse-to-fine registration. Recent approaches employ Gaussian activations [9] or Sinusoidal activations [45] to overcome local minima in optimization.

Nevertheless, these parametric methods directly optimize global geometric transformations, which are prone to falling into suboptimal solutions if poorly initialized. Non-parametric methods [21, 31] directly optimize decent local transformations based on brightness constancy constraints, whereas they can not handle large displacements. We show that by combining the parametric and non-parametric methods together with a simple local-to-global process, we can achieve surprising anti-noise ability, allowing utilities for various NeRF extensions and other neural field applications.

3. Approach

We first present the formulation of recovering the neural field jointly with geometric transformations. Given a set of images $\{\mathcal{I}_i\}_{i=1}^M$, we aim to jointly find the parameters Θ of the neural field \mathcal{R} and the geometric transformation matrices $\{\mathbf{T}_i\}_{i=1}^M$ that minimize the photometric error between renderings and images. Let $\{\mathbf{x}^j\}_{j=1}^N$ be the query coordinates and \mathcal{I} be the imaging function. The problem can be formulated with a synthesis-based objective:

$$\min_{\{\mathbf{T}_i\}_{i=1}^M, \Theta} \sum_{i=1}^M \sum_{j=1}^N (\|\mathcal{R}(\mathbf{T}_i \mathbf{x}^j; \Theta) - \mathcal{I}_i(\mathbf{x}^j)\|_2^2). \quad (1)$$

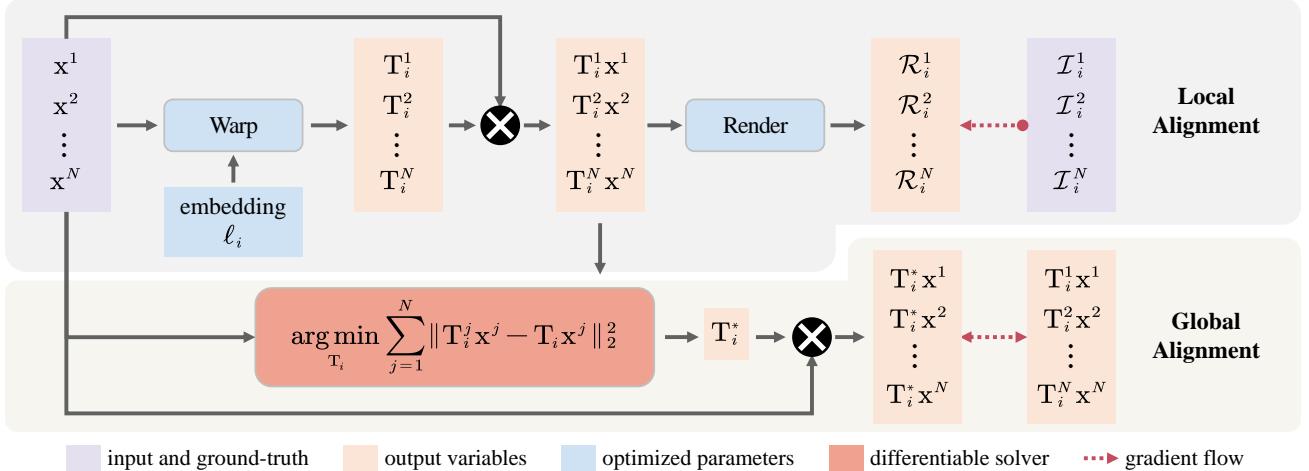


Figure 2. Overall pipeline of proposed framework. Our model has two main branches: 1) Based on query coordinates $\{\mathbf{x}^j\}_{j=1}^N$ and frame-dependent embeddings $\{\ell_i\}_{i=1}^M$, a warp neural field \mathcal{W} constructs pixel-wise local transformations $\{\mathbf{T}_i^j\}_{i=1,j=1}^{M,N}$ and transforms query coordinates into a global coordinate system. Then the color can be rendered via a neural field \mathcal{R} to minimize the photometric error between renderings $\{\mathcal{R}_i\}_{i=1}^M$ and images $\{\mathcal{I}_i\}_{i=1}^M$. 2) A differentiable parameter estimation solver produces frame-wise global transformations $\{\mathbf{T}_i^*\}_{i=1}^M$ condition on the pixel-wise correspondences. The query coordinates are then transformed to apply a global geometric constraint.

As this is a nonlinear problem, gradient-based optimization is the method of choice. However, as natural images are typically complex signals, gradient-based registration is susceptible to suboptimal solutions if poorly initialized. Therefore, we propose a simple yet effective strategy for local-to-global registration. The key idea is to apply a pixel-wise flexible alignment that optimizes photometric reconstruction errors individually, followed by a frame-wise alignment to globally constrain the local geometric transformations, which acts like a soft extension of Eq. (1):

$$\min_{\{\mathbf{T}_i^j\}_{i=1,j=1}^{M,N}, \Theta} \sum_{i=1}^M \sum_{j=1}^N (\|\mathcal{R}(\mathbf{T}_i^j \mathbf{x}^j; \Theta) - \mathcal{I}_i(\mathbf{x}^j)\|_2^2 + \lambda \|\mathbf{T}_i^j \mathbf{x}^j - \mathbf{T}_i^* \mathbf{x}^j\|_2^2), \quad (2)$$

where the pixel-wise local transformations $\{\mathbf{T}_i^j\}_{i=1,j=1}^{M,N}$ are modeled by a warp neural field \mathcal{W} parametrized by Φ , along with frame-dependent embeddings $\{\ell_i\}_{i=1}^M$:

$$\mathbf{T}_i^j = \mathcal{W}(\mathbf{x}^j; \ell_i, \Phi), \quad (3)$$

and the frame-wise global transformations $\{\mathbf{T}_i^*\}_{i=1}^M$ are solved by using differentiable parameter estimation solvers on the pixel-wise correspondences:

$$\mathbf{T}_i^* = \arg \min_{\mathbf{T}_i} \sum_{j=1}^N \|\mathbf{T}_i^j \mathbf{x}^j - \mathbf{T}_i \mathbf{x}^j\|_2^2. \quad (4)$$

3.1. Neural Image Alignment (2D)

To develop intuition, we first consider the case of a 2D neural image alignment problem. More specifically, let $\mathbf{x} \in$

\mathbb{R}^2 be the 2D pixel coordinates and $\mathcal{I} : \mathbb{R}^2 \rightarrow \mathbb{R}^3$, we aim to optimize a 2D neural field parameterized as the weights Θ of a multilayer perceptron (MLP) $f_{\mathcal{R}} : \mathbb{R}^2 \rightarrow \mathbb{R}^3$:

$$\mathcal{R}(\mathbf{T}\mathbf{x}; \Theta) = f_{\mathcal{R}}(\mathbf{T}\mathbf{x}; \Theta), \quad (5)$$

while also solving for geometric transformation parameters as $\mathbf{T} = [\mathbf{R}|\mathbf{t}] \in \text{SE}(2)$ or $\mathbf{T} \in \text{SL}(3)$, where $\mathbf{R} \in \text{SO}(2)$ and $\mathbf{t} \in \mathbb{R}^2$ denote the rigid rotation and translation, and $\mathbf{T} \in \text{SL}(3)$ denotes the homography transformation matrix, respectively. We use another MLP with weights Φ to model the coordinate-based warp neural field $f_{\mathcal{W}} : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ condition on the frame-dependent embedding ℓ :

$$\mathcal{W}(\mathbf{x}; \ell, \Phi) = \exp(f_{\mathcal{W}}(\mathbf{x}; \ell, \Phi)), \quad (6)$$

where the operator $\exp(\cdot)$ denotes the exponential map from Lie algebra $\mathfrak{se}(2)$ or $\mathfrak{sl}(3)$ to the Lie group $\text{SE}(2)$ or $\text{SL}(3)$, which ensures that the optimized transformation matrices \mathbf{T} lie on the Lie group manifold during the gradient-based optimization.

3.2. Bundle-Adjusting Neural Radiance Fields (3D)

We then discuss the 3D case of recovering the 3D scene representation from Neural Radiance Fields (NeRF) [29] jointly with the camera poses. NeRF encodes a 3D neural field by an MLP $f_{\mathcal{R}} : \mathbb{R}^3 \rightarrow \mathbb{R}^4$ to predict the RGB color $\mathbf{c} \in \mathbb{R}^3$ and volume density $\sigma \in \mathbb{R}$ for each input 3D point¹. We first formulate the rendering operation of NeRF in the camera view space. Given pixel coordinates $\mathbf{u} \in \mathbb{R}^2$ and denoting its homogeneous coordinates as $\mathbf{x} = [\mathbf{u}; 1]^T \in \mathbb{R}^3$, we can express a 3D point along the viewing ray at depth z_i

as $z_i \mathbf{x}$ and query the quantity $\mathbf{y} = [\mathbf{c}; \sigma]^\top = f_{\mathcal{R}}(z_i \mathbf{x}; \Theta)$, where Θ is the network parameters. The rendering color \mathcal{R} at pixel location \mathbf{x} is extracted by volume rendering via

$$\mathcal{R}(\mathbf{x}) = \int_{z_{\text{near}}}^{z_{\text{far}}} T(\mathbf{x}, z) \sigma(z \mathbf{x}) \mathbf{c}(z \mathbf{x}) dz, \quad (7)$$

where $T(\mathbf{x}, z) = \exp(-\int_{z_{\text{near}}}^z \sigma(z' \mathbf{x}) dz')$, and z_{near} and z_{far} are bounds on the depth range of interest. We refer our readers to Levoy [23] and Mildenhall *et al.* [29] for a more detailed treatment on volume rendering. In practice, the above integral formulations are approximated numerically via quadrature on discrete K points at depth $\{z_1, \dots, z_K\}$ sampled along the ray. It involves K evaluations of the network $f_{\mathcal{R}}$, whose outputs $\{\mathbf{y}_1, \dots, \mathbf{y}_K\}$ are further composited through volume rendering. We can summarize the ray compositing function as $g : \mathbb{R}^{4K} \rightarrow \mathbb{R}^3$ and rewrite $\mathcal{R}(\mathbf{x})$ as $\mathcal{R}(\mathbf{x}) = g(\mathbf{y}_1, \dots, \mathbf{y}_K)$. Note that g is differentiable but deterministic, *i.e.*, no learnable parameters are associated.

Here the camera poses are parametrized by $\mathbf{T} = [\mathbf{R}|\mathbf{t}] \in \text{SE}(3)$, where $\mathbf{R} \in \text{SO}(3)$ and $\mathbf{t} \in \mathbb{R}^3$. Next, a 3D point $z_i \mathbf{x}$ in the camera view space can be transformed to the 3D world coordinates through a 3D rigid transformation. Therefore, the synthesized RGB value at pixel \mathbf{x} becomes a function of the geometric transformations \mathbf{T} as

$$\mathcal{R}(\mathbf{T}\mathbf{x}; \Theta) = g(f_{\mathcal{R}}(\mathbf{T}z_1 \mathbf{x}; \Theta), \dots, f_{\mathcal{R}}(\mathbf{T}z_K \mathbf{x}; \Theta)). \quad (8)$$

Similar to neural image alignment, We use another MLP with weights Φ to model the coordinate-based warp neural field $f_{\mathcal{W}} : \mathbb{R}^2 \rightarrow \mathbb{R}^6$ condition on the frame-dependent embedding ℓ :

$$\mathcal{W}(\mathbf{x}; \ell, \Phi) = \exp(f_{\mathcal{W}}(\mathbf{x}; \ell, \Phi)), \quad (9)$$

where the operator $\exp(\cdot)$ denotes the exponential map from Lie algebra $\mathfrak{se}(3)$ to the Lie group $\text{SE}(3)$.

3.3. Differentiable Parameter Estimation

The local-to-global process allows L2G-NeRF to discover the correct registration with an initially flexible pixel-wise alignment and later shift focus to constrained parametric alignment. We derive the gradient flow of global alignment objective $\mathcal{L}_i^j = \|\mathbf{T}_i^j \mathbf{x}^j - \mathbf{T}_i^* \mathbf{x}^j\|_2^2$ w.r.t. the parameters Φ of warp neural field \mathcal{W} as

$$\frac{\partial \mathcal{L}_i^j}{\partial \Phi} = \frac{\partial \mathcal{L}_i^j}{\partial \mathbf{T}_i^j} \frac{\partial \mathbf{T}_i^j}{\partial \Phi} + \frac{\partial \mathcal{L}_i^j}{\partial \mathbf{T}_i^*} \sum_{j=1}^N \frac{\partial \mathbf{T}_i^*}{\partial \mathbf{T}_i^j} \frac{\partial \mathbf{T}_i^j}{\partial \Phi}. \quad (10)$$

Such that a differentiable solver is of critical importance to calculating the gradient of \mathbf{T}_i^* w.r.t. \mathbf{T}_i^j then backpropagated to update the parameters Φ . Next, we elaborate two

¹In practice, $f_{\mathcal{R}}$ is also conditioned on the viewing direction [29] for modeling view-dependent effects, which we omit here for simplicity.

differentiable solvers for rigid and homography transformation, respectively.

Rigid parametric alignment. In the rigid parametric alignment problem, we assume $\{\mathbf{T}^j \mathbf{x}^j\}_{j=1}^N$ is transformed from $\{\mathbf{x}^j\}_{j=1}^N$ by an unknown global rigid transformation $\mathbf{T} = [\mathbf{R}|\mathbf{t}] \in \text{SE}(2)$ or $\mathbf{T} = [\mathbf{R}|\mathbf{t}] \in \text{SE}(3)$. To solve this classic orthogonal Procrustes problem [18], we define centroids of $\{\mathbf{x}^j\}_{j=1}^N$ and $\{\mathbf{T}^j \mathbf{x}^j\}_{j=1}^N$ as

$$\bar{\mathbf{x}} = \frac{1}{N} \sum_{j=1}^N (\mathbf{x}^j) \quad \text{and} \quad \bar{\mathbf{T}\mathbf{x}} = \frac{1}{N} \sum_{j=1}^N (\mathbf{T}^j \mathbf{x}^j). \quad (11)$$

Then the cross-covariance matrix \mathbf{H} is given by

$$\mathbf{H} = \sum_{j=1}^N (\mathbf{x}^j - \bar{\mathbf{x}})(\mathbf{T}^j \mathbf{x}^j - \bar{\mathbf{T}\mathbf{x}})^\top. \quad (12)$$

We use Singular Value Decomposition (SVD) to decompose \mathbf{H} as introduced in [20, 42]:

$$\mathbf{H} = \mathbf{U} \mathbf{S} \mathbf{V}^\top. \quad (13)$$

Thus the optimal transformation minimizing Eq. (4) is given in closed form by

$$\mathbf{R} = \mathbf{V} \mathbf{U}^\top \quad \text{and} \quad \mathbf{t} = -\mathbf{R}\bar{\mathbf{x}} + \bar{\mathbf{T}\mathbf{x}}. \quad (14)$$

Homography parametric alignment. In the homography parametric alignment problem, we assume $\{\mathbf{x}^{j'} = \mathbf{T}^j \mathbf{x}^j\}_{j=1}^N$ is transformed from $\{\mathbf{x}^j\}_{j=1}^N$ by an unknown homography transformation $\mathbf{T} \in \text{SL}(3)$. Written element by element, in homogenous coordinates, we get the following constraint:

$$\begin{bmatrix} \mathbf{x}_1^{j'} \\ \mathbf{x}_2^{j'} \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{T}_{11} & \mathbf{T}_{12} & \mathbf{T}_{13} \\ \mathbf{T}_{21} & \mathbf{T}_{22} & \mathbf{T}_{23} \\ \mathbf{T}_{31} & \mathbf{T}_{32} & \mathbf{T}_{33} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1^j \\ \mathbf{x}_2^j \\ 1 \end{bmatrix}. \quad (15)$$

Rearranging Eq. (15) as [1], we get $\mathbf{A}^j \mathbf{h} = \mathbf{0}$, where

$$\mathbf{A}^j = \begin{bmatrix} 0 & 0 & 0 & -\mathbf{x}_1^j & -\mathbf{x}_2^j & -1 & \mathbf{x}_2^{j'} \mathbf{x}_1^j & \mathbf{x}_2^{j'} \mathbf{x}_2^j & \mathbf{x}_2^{j'} \\ \mathbf{x}_1^j & \mathbf{x}_2^j & 1 & 0 & 0 & 0 & -\mathbf{x}_1^{j'} \mathbf{x}_1^j & -\mathbf{x}_1^{j'} \mathbf{x}_2^j & -\mathbf{x}_1^{j'} \end{bmatrix} \quad (16)$$

$$\mathbf{h} = (\mathbf{T}_{11}, \mathbf{T}_{12}, \mathbf{T}_{13}, \mathbf{T}_{21}, \mathbf{T}_{22}, \mathbf{T}_{23}, \mathbf{T}_{31}, \mathbf{T}_{32}, \mathbf{T}_{33})^\top$$

Given the set of correspondences, we can form the linear system of equations $\mathbf{A}\mathbf{h} = \mathbf{0}$, where $\mathbf{A} = (\mathbf{A}^1 \dots \mathbf{A}^N)^\top$. Thus we can solve the Homogeneous Linear Least Squares problem and calculate the non-trivial solution by SVD decomposition:

$$\mathbf{A} = \mathbf{U} \mathbf{S} \mathbf{V}^\top = \sum_{l=1}^9 \sigma_l \mathbf{u}_l \mathbf{v}_l^\top, \quad (17)$$

where singular value σ_l represents the reprojection error. Then we take the singular vector \mathbf{v}_9 that corresponds to the smallest singular value σ_9 as the solution of \mathbf{h} , and reshape it into the homography transformation matrix \mathbf{T} .

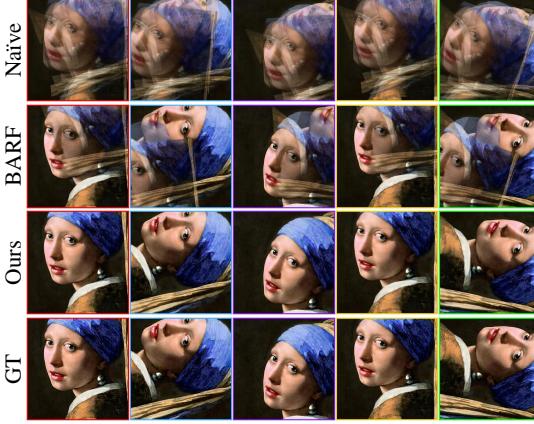


Figure 3. Color-coded patch reconstructions of neural image alignment under **rigid** perturbations. The optimized warps are shown in Fig. 5 with corresponding colors. L2G-NeRF is able to recover accurate alignment and photorealistic image reconstruction with local-to-global registration, while baselines result in suboptimal alignment.



Figure 4. Color-coded patch reconstructions of neural image alignment under **homography** perturbations.

4. Experiments

We first unfold the validation of L2G-NeRF and baselines on a 2D neural image alignment experiment, and then show that the local-to-global registration strategy can also be generalized to NeRF [29] for learning 3D neural fields from both synthetic data and photo collections.

4.1. Neural image Alignment (2D)

We choose two representative images of “Girl With a Pearl Earring” renovation ©Koorosh Orooj ([CC BY-SA 4.0](#)) and “cat” from ImageNet [12] for rigid and homography image alignment experiments, respectively. As shown in Fig. 3 and Fig. 4, given $M = 5$ patches from the image generated with rigid or homography perturbations, we optimize Eq. (2) to find the rigid transformation $\mathbf{T} \in \text{SE}(2)$ or

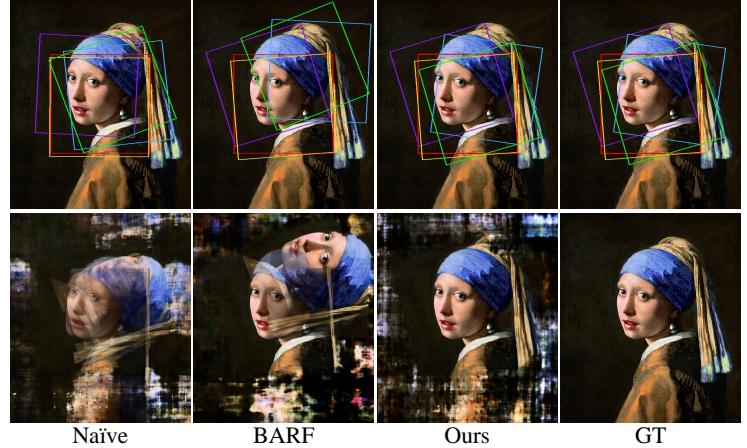


Figure 5. Qualitative results of neural image alignment experiment under **rigid** perturbations. Given color-coded image patches, we aim to recover the alignment (top row) *and* the neural field of the entire image (bottom row).

Method	Rigid perturbations		Homography perturbations	
	Corner error (pixels) ↓	Patch PSNR ↑	Corner error (pixels) ↓	Patch PSNR ↑
Naïve	120.00	14.83	55.80	21.79
BARF [24]	110.20	17.78	30.21	23.24
Ours	0.31	29.25	0.76	31.93

Table 1. Quantitative results of neural image alignment experiment under **rigid** and **homography** perturbations. L2G-NeRF optimizes for more accurate alignment and patch reconstruction compared to the baselines.

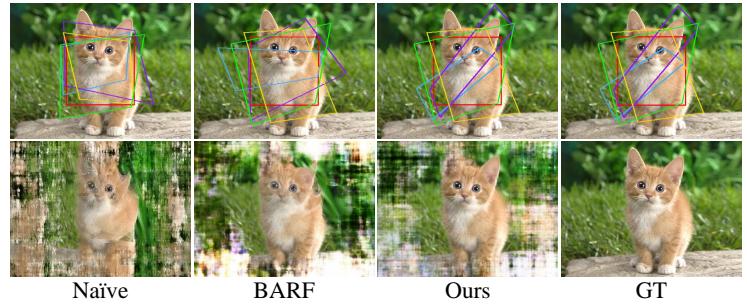


Figure 6. Qualitative results of neural image alignment experiment under **homography** perturbations.

homography transformation $\mathbf{T} \in \text{SL}(3)$ for each patch with network f_W , and learn the neural field of the entire image (Fig. 5 and Fig. 6) with network f_R at the same time. We initialize all M patches with a center crop and anchor the warp of the first patch as identity, so the recovered neural image would be implicitly aligned to the raw image.

Experimental settings. We evaluate our proposed method against a bundle-adjusting extension of the naïve 2D neural field, dubbed as Naïve, and the current state-of-the-art BARF [24], which employs a coarse-to-fine strategy for registration. We use the default coarse-to-fine scheduling, architecture and training procedure of neural field f_R for both BARF and L2G-NeRF. For L2G-NeRF, We use a ReLU MLP for f_W with six 256-dimensional hidden units, and use the embedding with 128 dimensions for each image to model the frame-dependent embeddings $\{\ell_i\}_{i=1}^M$. We set

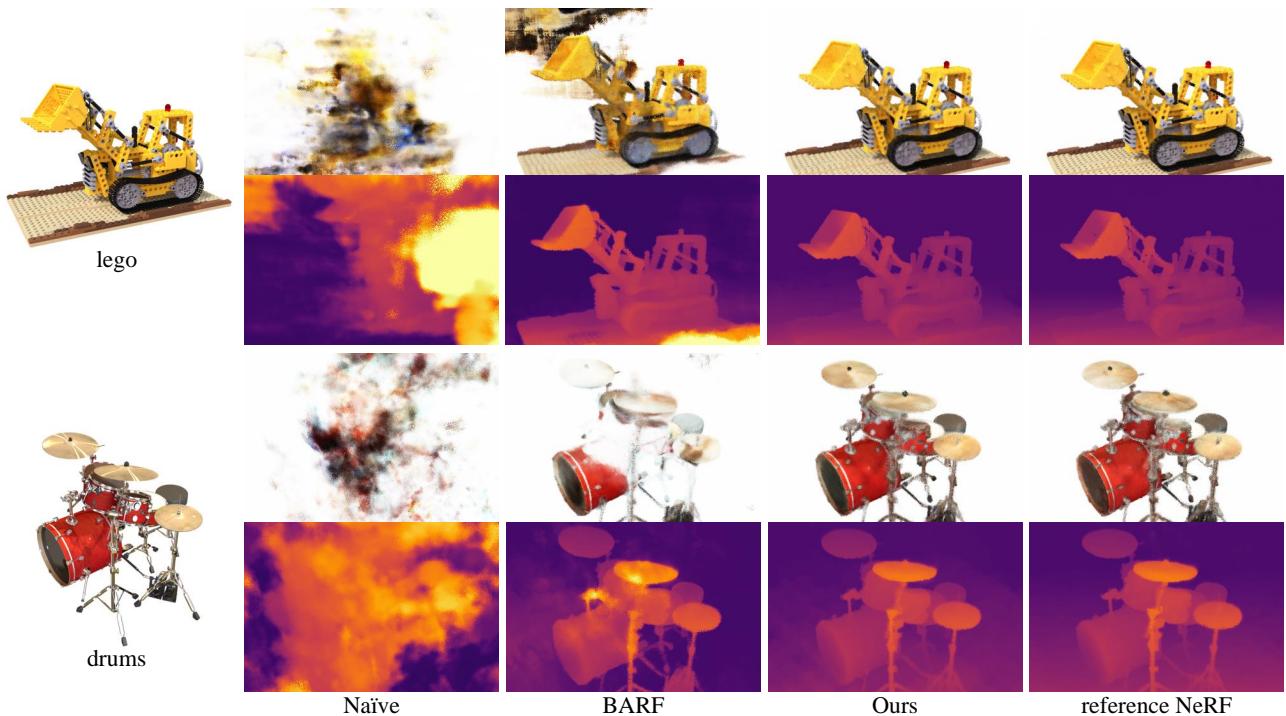


Figure 7. Qualitative results of bundle-adjusting neural radiance fields on synthetic scenes. We visualize the image synthesis (top) and the expected depth through ray compositing (bottom). L2G-NeRF achieves comparable visual quality to the reference NeRF (trained under ground-truth camera poses), while baselines result in suboptimal registration, leading to synthesis artifacts.

multiplier λ of the global alignment objective to 1×10^2 . **Results.** We visualize the rigid and homography registration results in Fig. 5 and Fig. 6. Alignment with Naïve results in ghosting artifacts in the recovered neural image due to large misalignment. On the other hand, alignment with BARF improves registration results but still falls into the suboptimal solutions, and struggles with image reconstruction. As L2G-NeRF discovers the precise geometric warps of all patches, L2G-NeRF can optimize the neural image with high fidelity. We report the quantitative results in Table 1, where we use the mean average corner error (L2 distance between the ground truth corner position and the estimated corner position) [13, 22] and PSNR as the evaluation criteria for registration and reconstruction, respectively. The image alignment experiment demonstrates the general advantage of local-to-global registration for both rigid and homography registration for 2D neural fields, which can be easily extended to other geometric transformations.

4.2. NeRF (3D): Synthetic Objects

This section investigates the problem of learning 3D neural fields with Neural Radiance Fields (NeRF) [29] from imperfect camera poses. We experiment with the 8 synthetic object-centric scenes provided by Mildenhall *et al.* [29], which consist of $M = 100$ rendered images with ground-truth camera poses for each scene for training.

Experimental settings. For each scene, we synthetically

perturb the camera poses $\mathbf{T} \in \text{SE}(3)$ with additive noise $\xi \in \mathfrak{se}(3)$ and $\xi \sim \mathcal{N}(\mathbf{0}, n\mathbf{I})$ as initial poses, where the multiplier n is scene-dependent and given in the supplementary materials. We assume known camera intrinsics and minimize the objective in Eq. (2) for optimizing the 3D neural fields f_R and the warp field f_W that finds rigid transformations relative to the initial poses. We evaluate L2G-NeRF against a naïve extension of the original NeRF model that jointly optimizes poses, dubbed as Naïve, and the coarse-to-fine bundle-adjusting neural radiance fields (BARF) [24].

Implementation details. Our implementation of NeRF and BARF follows [24]. For L2G-NeRF, We use a 6-layer ReLU MLP for f_W with 256-dimensional hidden units. We set multiplier λ of the global alignment objective to 1×10^2 and employ the Adam optimizer to train all models for 200K iterations with a learning rate that begins at 5×10^{-4} for the 3D neural field f_R , and 1×10^{-3} for the warp field f_W , and exponentially decays to 1×10^{-4} and 1×10^{-8} , respectively. We follow the default coarse-to-fine scheduling for both BARF and L2G-NeRF.

Evaluation criteria. We follow BARF [24] to evaluate the quality of registration by pre-aligning the optimized poses to the ground truth with Procrustes analysis. For evaluating view synthesis, we run an additional step of test-time photometric optimization on the trained models [24, 25, 48] to factor out the registration error. We report the average rotation and translation errors for registration and PSNR, SSIM

Scene	Camera pose registration						View synthesis quality											
	Rotation ($^{\circ}$) \downarrow			Translation \downarrow			PSNR \uparrow			SSIM \uparrow			LPIPS \downarrow					
	Naïve	BARF	Ours	Naïve	BARF	Ours	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF
Chair	1.39	2.58	0.14	60.32	10.43	0.28	14.13	27.84	30.99	31.93	0.83	0.92	0.95	0.96	0.39	0.06	0.05	0.04
Drums	7.99	4.54	0.06	78.20	19.19	0.40	11.63	21.92	23.75	23.98	0.61	0.87	0.90	0.90	0.62	0.14	0.10	0.10
Ficus	3.13	1.65	0.26	48.78	5.46	1.11	14.30	25.85	26.11	26.66	0.83	0.93	0.93	0.94	0.33	0.07	0.06	0.05
Hotdog	7.04	2.42	0.27	58.37	14.98	1.42	15.10	27.34	34.56	34.90	0.74	0.93	0.97	0.97	0.42	0.06	0.03	0.03
Lego	7.82	9.93	0.09	81.93	47.42	0.37	11.36	14.48	27.71	29.29	0.61	0.69	0.91	0.94	0.56	0.29	0.06	0.04
Materials	5.57	0.68	0.06	47.56	4.97	0.28	11.51	26.29	27.60	28.54	0.64	0.92	0.93	0.94	0.49	0.08	0.06	0.05
Mic	4.43	10.44	0.10	77.47	45.66	0.44	13.14	12.20	30.91	31.96	0.85	0.76	0.97	0.97	0.43	0.41	0.05	0.04
Ship	11.10	23.90	0.19	112.01	90.62	0.61	9.41	8.19	27.31	28.06	0.50	0.50	0.85	0.86	0.64	0.63	0.13	0.12
Mean	6.06	7.02	0.15	70.58	29.84	0.61	12.57	20.51	28.62	29.42	0.70	0.82	0.93	0.94	0.49	0.22	0.07	0.06

Table 2. Quantitative results of bundle-adjusting neural radiance fields on synthetic scenes. L2G-NeRF outperforms the baselines on all evaluation criteria, and successfully optimizes for camera registration while achieving high-quality view synthesis that is comparable to the reference NeRF model (trained under ground-truth camera poses). Translation errors are scaled by 100.

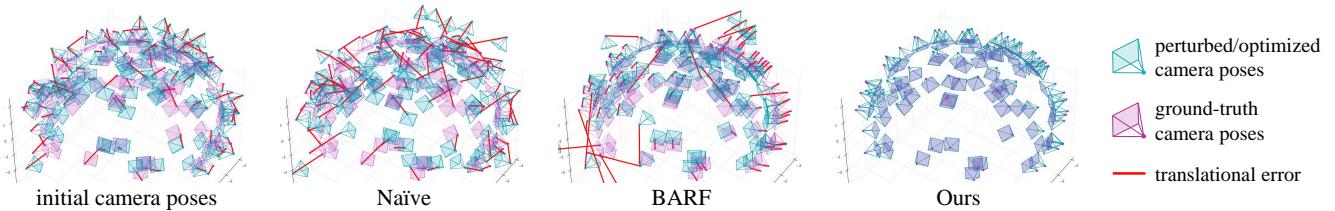


Figure 8. Visual comparison of the initial and optimized camera poses (Procrustes aligned) for the *lego* scene. L2G-NeRF successfully aligns all the camera frames while baselines get stuck at suboptimal solutions.

and LPIPS [49] for view synthesis.

Results. We visualize the results in Fig. 7, which are quantitatively reflected in Table 2. On both sides of reconstruction and registration, L2G-NeRF achieves the best performance. Fig. 8 shows that L2G-NeRF can achieve near-perfect registration for the synthetic scenes. Naïve NeRF suffers from suboptimal registration and ghosting artifacts. BARF is able to recover a part of the pose misalignment and produce plausible reconstructions. However, it still suffers from blur artifacts like the fog effect around the objects. This fog effect is the consequence of BARF’s attempt to reconstruct the scenes with half-baked registration. As a reference, we also compare the view synthesis quality against standard NeRF (ref. NeRF) trained under ground-truth poses, showing that L2G-NeRF can achieve comparable view synthesis quality, albeit initialized from large camera pose misalignment.

4.3. NeRF (3D): Real-World Scenes

We further investigate the challenging problem of learning 3D neural fields with NeRF in real-world scenes, where the camera poses are *unknown*. We evaluate our method and baselines on the standard benchmark LLFF dataset [28], which consists of 8 real-world forward-facing scenes captured by hand-held cameras.

Experimental settings. We initialize all cameras with the *identity* transformation, *i.e.* $\mathbf{T}_i = \mathbf{I} \ \forall i$, and assume known

camera intrinsics (provided by the dataset). We compare against the Naïve extension of NeRF [29], BARF [24], and use the same evaluation criteria described in Sec. 4.2.

Implementation details. We follow the same architectural settings and coarse-to-fine scheduling from the BARF [24]. For simplicity, We train without additional hierarchical sampling. We train all models for 200K iterations with a learning rate of 1×10^{-3} for the 3D neural field f_R decaying to 1×10^{-4} , and 3×10^{-3} for the warp field f_W decaying to 1×10^{-8} . We use the same architecture of the warp field for L2G-NeRF described in Sec. 4.2.

Results. Quantitative results are summarized in Table 3. Naïve NeRF diverges to incorrect camera poses, which in turn results in particularly poor view synthesis, that cannot compete with BARF. In contrast, L2G-NeRF achieves competitive registration errors compared to BARF while outperforming the others on all view synthesis criteria. Actually, we note that the camera poses provided in LLFF are also estimations from SfM packages [38]; therefore, the pose evaluation is a noisy indication. Based on the fact that more accurate registration yields more photorealistic view synthesis, we recommend using view synthesis quality as the primary criterion for real-world scenes. The high-fidelity visual quality shown in Fig. 9 highlights the ability of L2G-NeRF to joint registration and reconstruction from scratch.

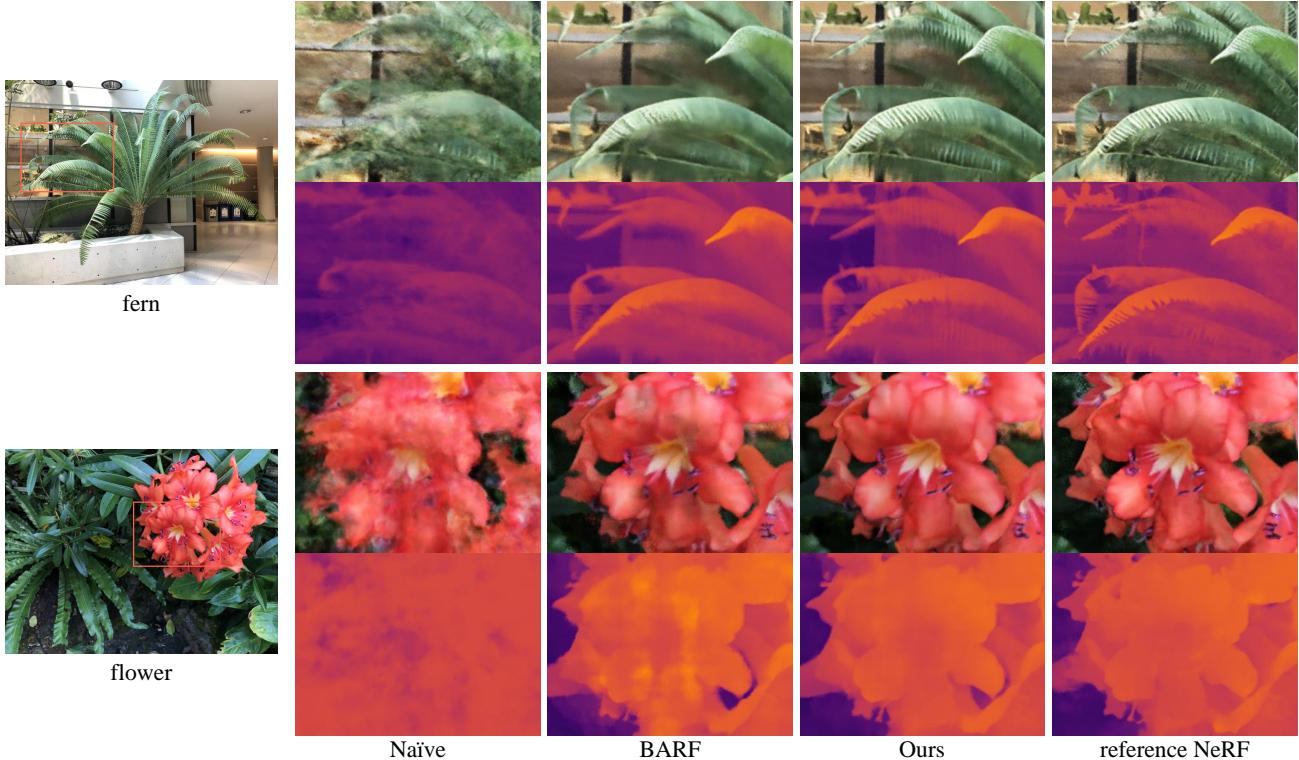


Figure 9. Qualitative results of bundle-adjusting neural radiance fields on real-world scenes. While BARF and L2G-NeRF can jointly optimize poses and scenes, L2G-NeRF produces higher fidelity results, which is competitive to reference NeRF trained under SfM poses.

Scene	Camera pose registration						View synthesis quality											
	Rotation ($^{\circ}$) \downarrow			Translation \downarrow			PSNR \uparrow			SSIM \uparrow			LPIPS \downarrow					
	Naïve	BARF	Ours	Naïve	BARF	Ours	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF
Fern	8.05	0.17	0.20	1.74	0.19	0.18	16.28	23.88	24.57	24.19	0.39	0.71	0.75	0.74	0.54	0.31	0.26	0.25
Flower	22.41	0.31	0.33	5.81	0.22	0.24	12.28	24.29	24.90	22.97	0.21	0.71	0.74	0.66	0.66	0.20	0.17	0.26
Fortress	171.77	0.41	0.25	47.90	0.33	0.25	11.56	29.06	29.27	26.12	0.29	0.82	0.84	0.79	0.83	0.13	0.11	0.19
Horns	29.42	0.11	0.22	12.83	0.16	0.27	8.94	23.29	23.12	20.45	0.22	0.74	0.74	0.63	0.82	0.29	0.26	0.41
Leaves	79.47	1.13	0.79	12.42	0.24	0.34	9.10	18.91	19.02	13.71	0.06	0.55	0.56	0.21	0.80	0.35	0.33	0.58
Orchids	41.75	0.60	0.67	19.99	0.39	0.41	9.93	19.46	19.71	17.26	0.09	0.57	0.61	0.51	0.81	0.29	0.25	0.31
Room	175.06	0.31	0.30	65.48	0.28	0.23	11.48	32.05	32.25	32.94	0.31	0.94	0.95	0.95	0.85	0.10	0.08	0.07
T-rex	166.21	1.38	0.89	55.02	0.86	0.64	9.17	22.92	23.49	21.86	0.16	0.78	0.80	0.74	0.86	0.20	0.16	0.25
Mean	86.77	0.55	0.46	27.65	0.33	0.32	11.09	24.23	24.54	22.44	0.22	0.73	0.75	0.65	0.77	0.23	0.20	0.29

Table 3. Quantitative results of bundle-adjusting neural radiance fields on real-world scenes. L2G-NeRF outperforms baselines and achieves high-quality view synthesis that is competitive to reference NeRF trained under SfM poses. Translation errors are scaled by 100.

5. Conclusion

We present Local-to-Global Registration for Bundle-Adjusting Neural Radiance Fields (L2G-NeRF), which is demonstrated by extensive experiments that can effectively learn the scene representations and resolve large camera pose misalignment at the same time. By establishing a unified formulation of bundle-adjusting neural fields, we demonstrate that local-to-global registration is beneficial for both 2D and 3D neural fields, allowing for various appli-

cations of diverse neural fields. Code and models will be made available to the research community to facilitate reproducible research.

Although local-to-global registration is much more robust than current state-of-the-art [24], L2G-NeRF still can not recover camera poses from scratch (identity transformation) for inward-facing 360° scenes, where large displacements of rotation exist. Specific methods such as epipolar geometry and graph optimization could be employed to handle these issues.

Here we provide more implementation details and experimental results. We encourage readers to view the supplementary video for an intuitive experience about different types of bundle-adjusting neural radiance fields.

A. Additional Implementation Details

A.1. Time Consumption

We implement all experiments on a single NVIDIA GeForce RTX 2080 Ti GPU. As shown in Table 4, L2G-NeRF takes about 4.5 and 8 hours for training in synthetic objects and real-world scenes, respectively, while training BARF [24] takes about 8 and 10.5 hours. As a reference, we also compare time consumption against the ref. NeRF [29] trained under ground-truth poses (without the requirement of optimizing poses), showing that L2G-NeRF can achieve comparable time consumption. The time analysis indicates that calculating the gradient w.r.t. local pose (local-to-global registration) is more efficient than calculating the gradient w.r.t. global pose (global registration).

A.2. Additional Experimental Settings

For each object of synthetic scenes, we perturb the camera poses with additive noise as initial poses. The 6-DoF perturbation is parametrized by $\mathbf{T} = [\mathbf{R}|\mathbf{t}] \in \text{SE}(3)$, where $\mathbf{R} \in \text{SO}(3)$, $\mathbf{t} \in \mathbb{R}^3$, and \mathbf{R} is generated by exponential map $\exp(\mathbf{r})$ from the Lie algebra $\mathfrak{so}(3)$ to the Lie group $\text{SO}(3)$. The additive rotation noise $\mathbf{r} \in \mathfrak{so}(3)$ and translation noise $\mathbf{t} \in \mathbb{R}^3$ are distributed as $\mathbf{r} \sim \mathcal{N}(\mathbf{0}, n_r \mathbf{I})$ and $\mathbf{t} \sim \mathcal{N}(\mathbf{0}, n_t \mathbf{I})$, where the multiplier n_r and n_t are scene-dependent and given in Table 5.

We set the multiplier λ of the global alignment objective to 1×10^2 for both the neural image alignment experiment and learning NeRF from imperfect camera poses with synthetic object-centric scenes. To further solve the challenging problem of learning NeRF in forward-facing LLFF scenes from *unknown* poses, we float the multiplier λ between 1×10^2 and 1×10^5 to achieve preferable results for specific scenes, which are summarized in Table 6.

B. Ablation Studies

We propose a local-to-global registration method that combines the benefits of parametric and non-parametric methods. The key idea is to apply a pixel-wise alignment that optimizes photometric reconstruction errors $\sum_{i=1}^M \sum_{j=1}^N \|\mathcal{R}(\mathbf{T}_i^j \mathbf{x}^j; \Theta) - \mathcal{I}_i(\mathbf{x}^j)\|_2^2$, followed by a frame-wise alignment $\sum_{i=1}^M \sum_{j=1}^N \lambda \|\mathbf{T}_i^j \mathbf{x}^j - \mathbf{T}_i^* \mathbf{x}^j\|_2^2$ to globally constrain the geometric transformations. We evaluate our proposed L2G-NeRF against an ablation (w/o \mathcal{L}_{global}), which builds upon our full model by eliminating the global alignment objective, *i.e.*, $\lambda = 0$. The ablation is equivalent to a local registration method, while BARF is the

Scene		BARF	Ours	ref. NeRF
Synthetic objects		08:18	04:35	04:30
Real-World scenes		10:38	07:42	07:25

Table 4. Average training time (hh:mm).

Scene	Chair	Drums	Ficus	Hotdog	Lego	Materials	Mic	Ship
n_r	0.01	0.05	0.03	0.04	0.07	0.04	0.04	0.09
n_t	0.4	0.5	0.3	0.4	0.5	0.3	0.5	0.7

Table 5. Multiplier of pose perturbation for synthetic scenes.

Scene	Fern	Flower	Fortress	Horns	Leaves	Orchids	Room	T-rex
λ	1×10^2	1×10^3	1×10^5	1×10^5	1×10^2	1×10^2	1×10^5	1×10^5

Table 6. Multiplier of global alignment objective for LLFF scenes.

chosen representative global registration method, such that we unfold the comparison with both of them.

B.1. Ablation on NeRF (3D): Synthetic Objects

We first investigate the ablation study of learning NeRF from imperfect camera poses. As a reference, we also compare the view synthesis quality against reference NeRF trained under ground-truth poses. We experiment with 8 synthetic object-centric scenes [29]. The results in Fig. 11 and Table 7 show that L2G-NeRF achieves better performance than the ablation w/o \mathcal{L}_{global} . Fig. 10 further illustrates that L2G-NeRF can achieve near-perfect registration while the ablation w/o \mathcal{L}_{global} suffers from suboptimal solutions.

B.2. Ablation on NeRF (3D): Real-World Scenes

We then investigate the ablation study of learning 3D neural fields with NeRF in real-world scenes where the camera poses are *unknown*. We evaluate on the standard benchmark LLFF dataset [28]. Quantitative results are summarized in Table 7. The ablation w/o \mathcal{L}_{global} diverges to incorrect camera poses (visualized in Fig. 12), which in turn results in particularly poor view synthesis (shown in Fig. 13). L2G-NeRF outperforms the ablation w/o \mathcal{L}_{global} and achieves high-quality view synthesis that is competitive to reference NeRF trained under S/M poses.

B.3. Ablation on Neural Image Alignment (2D)

We further concrete analysis on the homography image alignment experiment and visualize the results in Fig. 14. Alignment with w/o \mathcal{L}_{global} results in distorted artifacts (cat ears) in the recovered neural image due to ambiguous registration. This is the consequence of w/o \mathcal{L}_{global} 's attempt to directly optimize the pixel agreement metric, which minimizes photometric errors but does not obey the geometric constraint (global alignments). As L2G-NeRF discovers precise warps, it optimizes neural image with high fidelity.

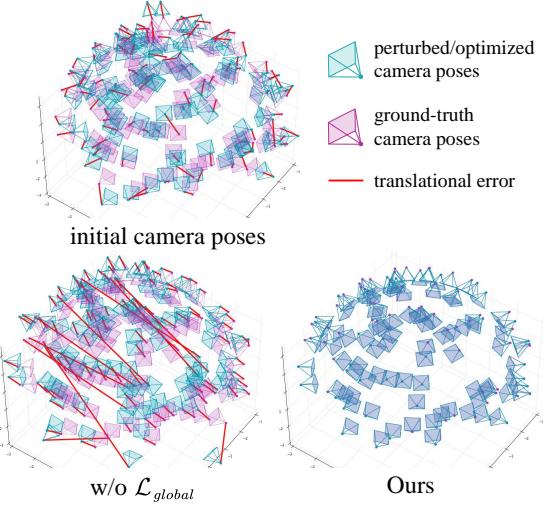


Figure 10. Visual comparison of ablation study about optimized camera poses (Procrustes aligned) for *hotdog* object. Full L2G-NeRF successfully aligns camera frames while w/o \mathcal{L}_{global} gets stuck at suboptimal solutions.

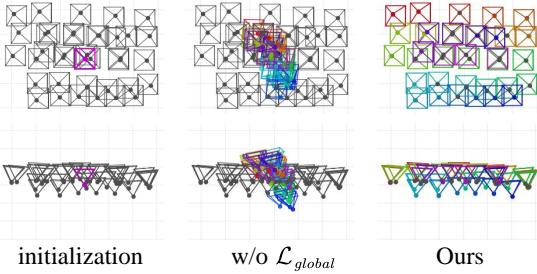


Figure 12. Visualization of ablation about registration for *room* scene (Procrustes aligned). Results from L2G-NeRF highly agree with SfM [38] (colored in black), whereas w/o \mathcal{L}_{global} results in suboptimal alignment.

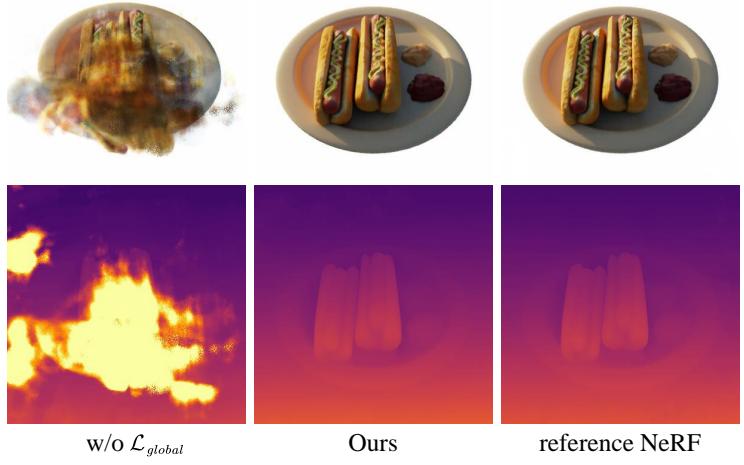


Figure 11. Ablation study of NeRF on *hotdog* synthetic object. We visualize the image synthesis (top) and the expected depth through ray compositing (bottom). Full L2G-NeRF achieves comparable synthesis quality to the reference NeRF (trained under perfect camera poses), while ablation w/o \mathcal{L}_{global} results in suboptimal registration, leading to synthesis artifacts.



Figure 13. Ablation study of NeRF on *room* real-world scenes from *unknown* camera poses. Compared to a reference NeRF model trained with camera poses provided by SfM, L2G-NeRF can effectively optimize for the poses jointly with the scene representation. Ablation w/o \mathcal{L}_{global} diverges to incorrect localization and hence poor synthesis quality.

Scene	Camera pose registration						View synthesis quality											
	Rotation ($^{\circ}$) \downarrow			Translation \downarrow			PSNR \uparrow				SSIM \uparrow				LPIPS \downarrow			
	Global	Local	L2G	Global	Local	L2G	Global	Local	L2G	ref.	Global	Local	L2G	ref.	Global	Local	L2G	ref.
Synthetic objects	7.02	3.63	0.15	29.84	14.34	0.61	20.51	22.70	28.62	29.42	0.82	0.85	0.93	0.94	0.22	0.14	0.07	0.06
Real-World scenes	0.55	23.82	0.46	0.33	10.66	0.32	24.23	20.71	24.54	22.44	0.73	0.64	0.75	0.65	0.23	0.33	0.20	0.29

Table 7. Quantitative results of ablation study about bundle-adjusting neural radiance fields. L2G-NeRF outperforms the local registration method (ablation w/o \mathcal{L}_{global}) and global registration method (BARF) on the average evaluation criteria of both synthetic objects and real-world scenes, which reveals the advantage of our local-to-global registration process. Translation errors are scaled by 100.

C. Additional Results

C.1. NeRF (3D): Synthetic Objects

We report additional qualitative results of learning 3D neural fields with NeRF from imperfect camera poses for

synthetic objects in Fig. 15. The baselines still perform poorly, while L2G-NeRF can achieve near-perfect registration (reflected in Fig. 16) and render images with comparable visual quality against reference NeRF that trained under ground-truth poses.

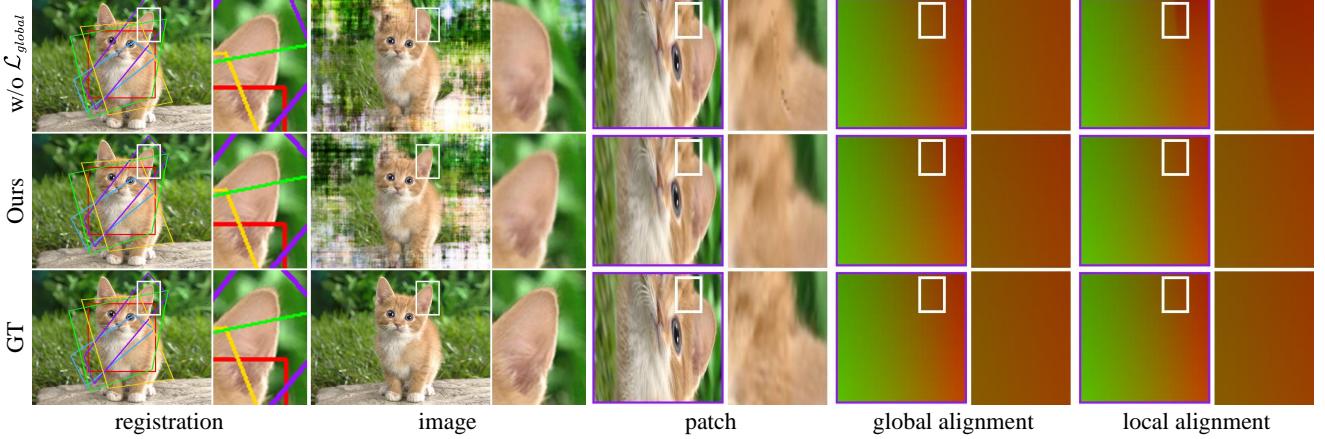


Figure 14. Ablation study of the neural image alignment experiment. Given color-coded image patches, we aim to recover the alignment and the neural representation of the entire image. L2G-NeRF is able to recover accurate alignment and high-fidelity image reconstruction, while w/o \mathcal{L}_{global} falls into false local alignments that do not obey the geometric constraint (global alignments), which results in ambiguous registration and distorted reconstruction (cat ears).

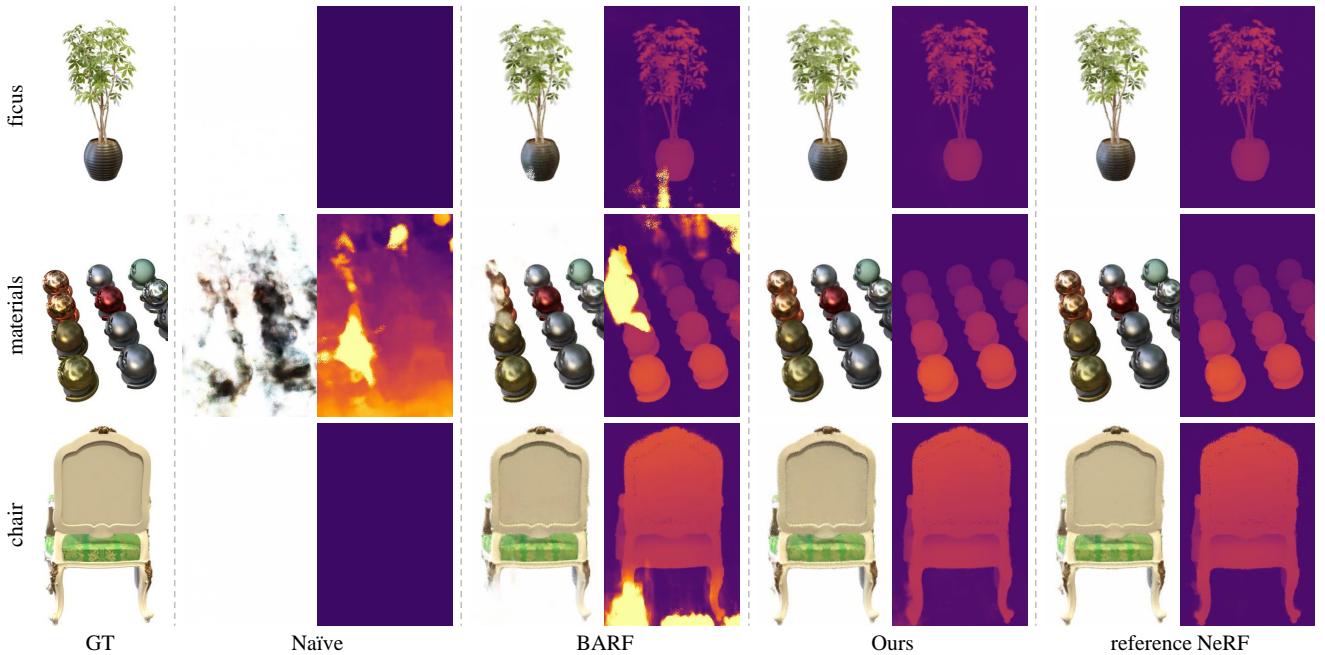


Figure 15. Additional qualitative results of bundle-adjusting neural radiance fields on synthetic scenes. We visualize the image synthesis (left) and the expected depth through ray compositing (right). L2G-NeRF achieves comparable visual quality to the reference NeRF (trained under ground-truth camera poses), while baselines result in suboptimal registration, leading to synthesize artifacts.

C.2. NeRF (3D): Real-World Scenes

We report additional qualitative results of learning NeRF for the standard LLFF dataset in Fig. 17, where camera poses are *unknown*. L2G-NeRF successfully recovers the 3D scene with higher fidelity than baselines. Fig. 18 shows that the recovered camera poses from L2G-NeRF agree more with those estimated from SfM methods than BARF.

We take one step further to experiment with images captured using an iPhone under challenging camera pose distri-

bution. Fig. 19 and Fig. 21 indicate the advantage of L2G-NeRF in registering images captured under large displacements and sparse views, while baselines exhibit artifacts (Fig. 20 and Fig. 22) due to unreliable registration, which is reflected in Table 8. Moreover, the difficulty of registering from sparse views prevents SfM from finding accurate poses, which results in broken stripes on the synthesis of reference NeRF trained under SfM poses in *foods* scene. This further demonstrates the effectiveness of removing the requirement of pre-computed SfM poses.

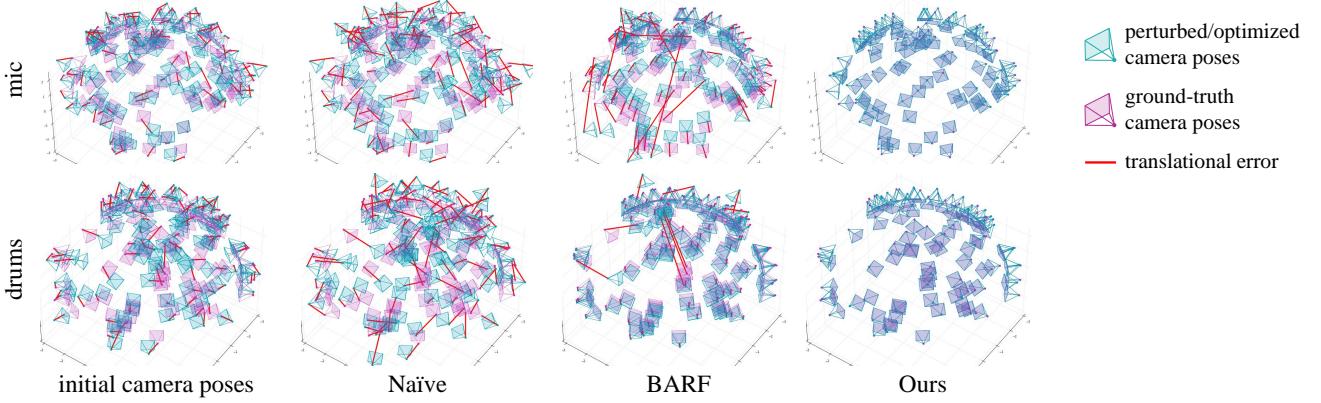


Figure 16. Additional visual comparison of the optimized camera poses (Procrustes aligned) for the *mic* and *drums* objects. L2G-NeRF successfully aligns all the camera frames while baselines get stuck at suboptimal solutions.

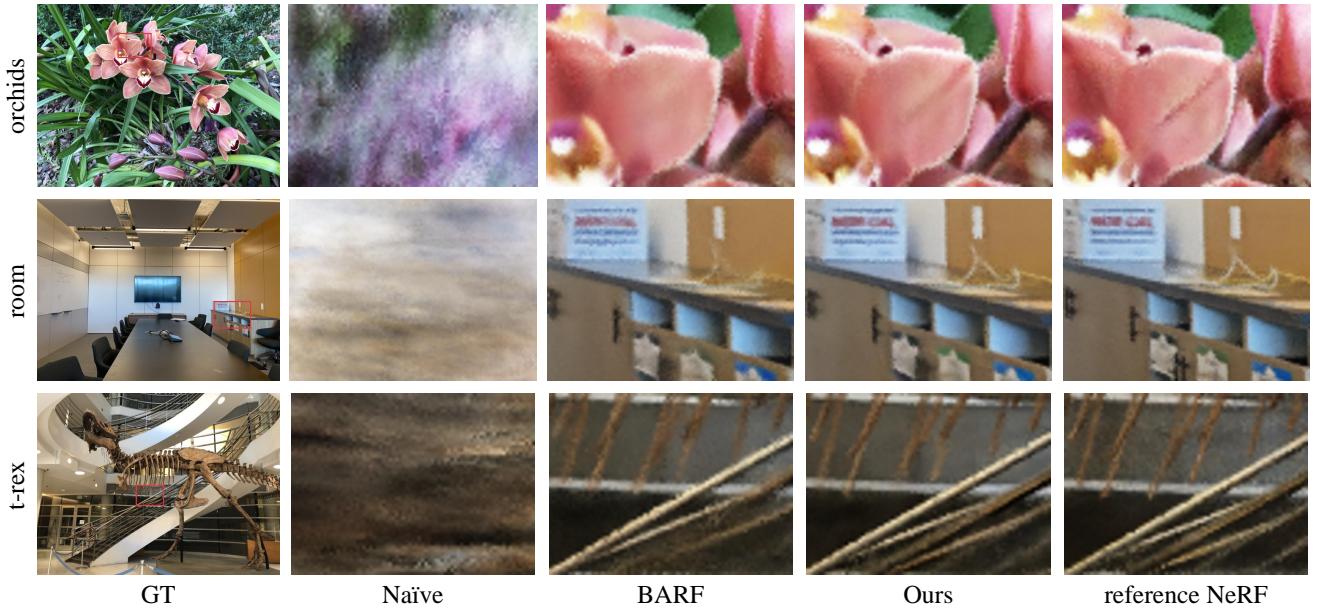


Figure 17. Additional novel view synthesis results of NeRF on real-world scenes (LLFF dataset) from *unknown* camera poses. L2G-NeRF can optimize for scene representations of much higher quality than baselines, while achieving the comparable quality of the reference NeRF model trained with camera poses provided by SfM [38].

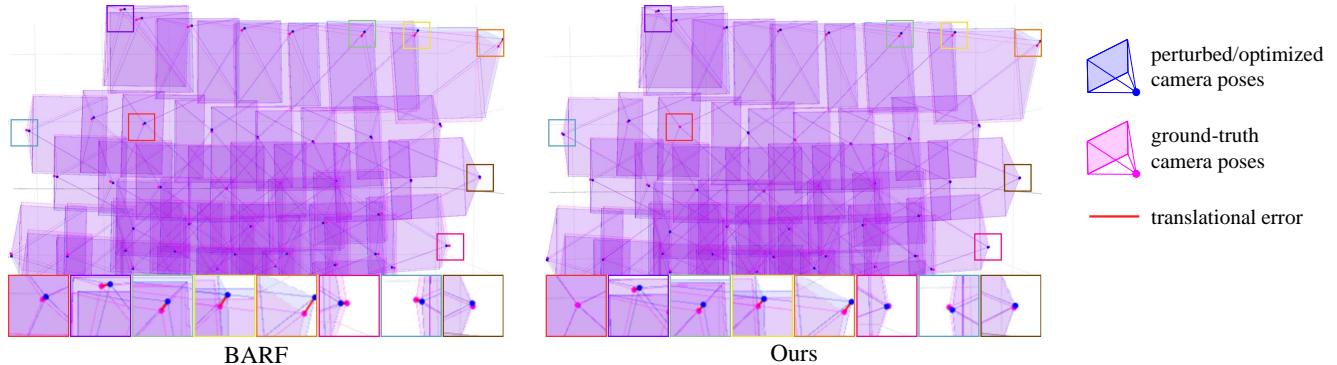


Figure 18. Visual comparison of the optimized camera poses (Procrustes aligned) for the *t-rex* real-world scene. L2G-NeRF successfully recovers the camera poses from *identity* transformation, which achieves fewer errors than BARF.

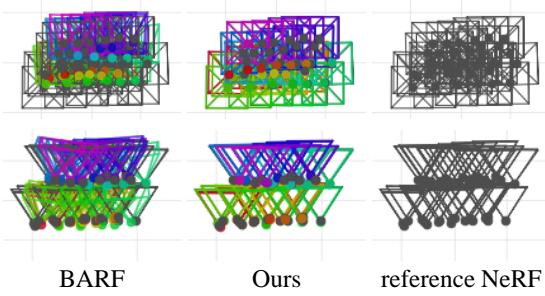


Figure 19. Visual comparison of optimized camera poses (Procrustes aligned) for the challenging *toys* scene captured under large displacements (hierarchical camera poses). L2G-NeRF successfully aligns all camera frames, which highly agrees with SfM [38] camera poses (colored in black), while BARF gets stuck at suboptimal solutions.

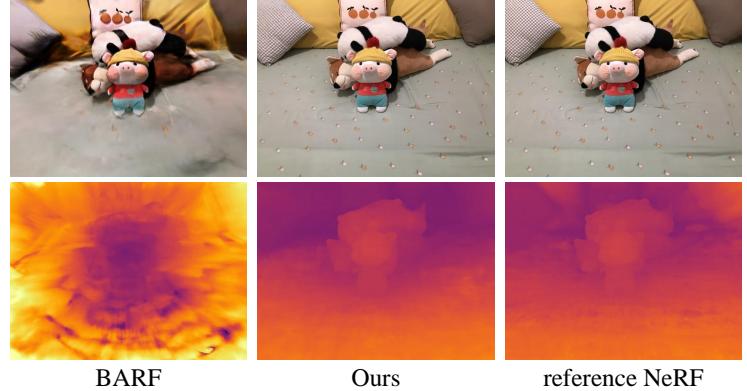


Figure 20. Results of NeRF on *toys* scene. L2G-NeRF achieves comparable synthesis quality to the reference NeRF (trained under SfM camera poses). But BARF fails to recover the proper geometry, which results in artifacts.

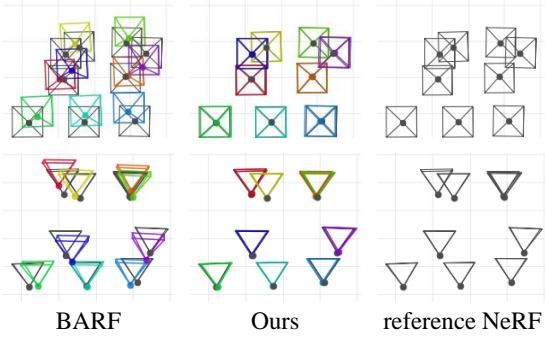


Figure 21. Visual comparison of optimized camera poses for the challenging *foods* scene captured under sparse views. Results from L2G-NeRF highly agree with SfM, whereas BARF results in suboptimal alignment.

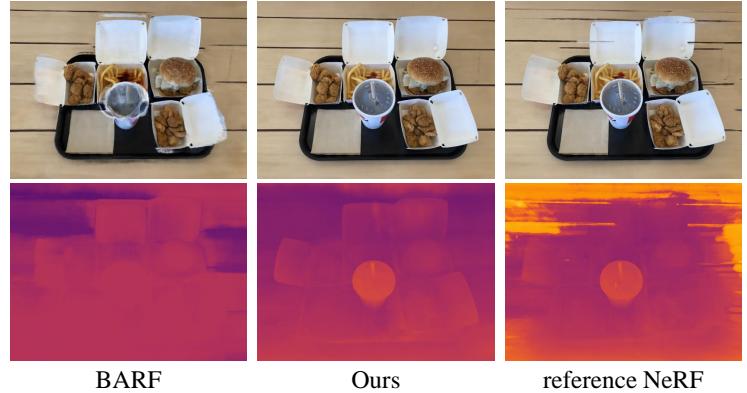


Figure 22. Results of NeRF on *foods* scene. L2G-NeRF outperforms BARF and even achieves better performance than reference NeRF in the scene where SfM [38] struggles with finding accurate registration from sparse views.

Scene	Camera pose registration						View synthesis quality											
	Rotation ($^{\circ}$) \downarrow			Translation \downarrow			PSNR \uparrow			SSIM \uparrow			LPIPS \downarrow					
	Naïve	BARF	Ours	Naïve	BARF	Ours	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF	Naïve	BARF	Ours	ref. NeRF
Toys	14.22	179.73	0.42	6.14	24.84	0.33	15.55	11.29	29.58	32.90	0.57	0.49	0.94	0.96	0.50	0.77	0.06	0.04
Foods	5.30	10.99	0.31	7.76	10.15	0.62	19.11	18.02	31.83	24.58	0.71	0.68	0.95	0.89	0.23	0.26	0.05	0.13

Table 8. Quantitative results of bundle-adjusting neural radiance fields on real-world scenes captured using an iPhone under large displacements (*toys*) or sparse views (*foods*). L2G-NeRF outperforms baselines and even achieves better performance than reference NeRF that trained under SfM poses in the Foods scene, which is hard for SfM to find accurate camera poses. Translation errors are scaled by 100.

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