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Fast Gradient Descent for Surface Capture Via Differentiable Rendering

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Abstract

Differential rendering has recently emerged as a powerful tool for image-based rendering or geometric reconstruction from multiple views, with very high quality. Up to now, such methods have been benchmarked on generic object databases and promisingly applied to some real data, but have yet to be applied to specific applications that may benefit. In this paper, we investigate how a differential rendering system can be crafted for raw multi-camera performance capture. We address several key issues in the way of practical usability and reproducibility, such as processing speed, explainability of the model, and general output model quality. This leads us to several contributions to the differential rendering framework. In particular we show that a unified view of differential rendering and classic optimization is possible, leading to a formulation and implementation where complete non-stochastic gradient steps can be analytically computed and the full per-frame data stored in video memory, yielding a straightforward and efficient implementation. We also use a sparse storage and coarse-to-fine scheme to achieve extremely high resolution with contained memory and computation time. We show experimentally that results rivaling in quality with state of the art multi-view human surface capture methods are achievable in a fraction of the time, typically around a minute per frame.

1. Introduction

We examine how differential rendering algorithms can be transposed and improved for practical setups such as multi-view surface capture of human subjects, an inherently challenging task due to the complexities of human motion and clothing, hair, self-occlusion, and

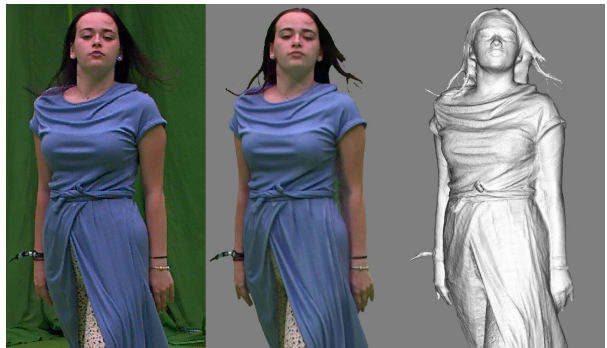


Figure 1. Typical results of our method: input image (left), colored mesh (center), geometry (right)



Figure 2. Close-up on another mesh: input image (left), colored mesh (center), geometry (right)

other corrupting factors. This task is of broad interest for all applications requiring 3D content that reflects and digitizes the real world, such as 3D broadcasting, entertainment, virtual reality, serious games, virtual try on, and is gaining new relevance in light of the push toward the metaverse in the industry. Producing this content in controlled environments with many cameras is also paramount to produce training datasets for data-driven methods addressing the same problems with less views [9, 35], or even monocular input [28, 23]. To be useful, a surface reconstruction pipeline in this context must target several desirable properties. First, visual fidelity and quality of the produced mesh models are of course a priority. Second, efficiency of the algorithm and ease of use are usual requirements, especially because the data is generally acquired in one or

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multiple sequences for reconstruction of motions, which for practical reasons calls for reasonably fast per-frame processing times.

In recent years, differential rendering methods have gathered significant attention from the research community as a new angle to address multi-view reconstruction and image-based rendering problems with high fidelity outputs. This makes them particularly palatable candidates to address the aforementioned quality requirement. Among those, volumetric differential rendering approaches such as the popular NeRF [17] have shown that scene estimation can be cast as a light field problem parameterized by a neural network, and have given rise to a number of more recent volumetric approaches. A rough surface can be extracted from the latter by thresholding the inferred opacity field, but better surface reconstructions can be extracted with dedicated differential rendering approaches centered on a surface parameterization [32, 21, 30]. While all of these methods produce amazing results, they typically require several hours per frame, and tens of hours for some, which rules out the approaches on the basis of tractability, for sequences that can be typically several hundred frames.

Contributions. We take inspiration in a stream of recent works showing that volumetric differential rendering can be significantly accelerated [33, 18], such that they achieve equivalent results to the original Nerf, in a matter of minutes. We show that a volumetric framework can be modified to output quality meshes thanks to the adjunction of appropriate losses. We also show that, with a simple non-neural parameterization analogous to [33] and an appropriate spatial encoding, the problem entirely fits in GPU memory, and can be cast as a pure optimization solved with classic, non-stochastic gradient descent. This yields a straightforward and fully explainable implementation of differential rendering offering a new quality/computation time tradeoff, whose results approach state of the art surface-based differential methods for mildly reflective models of the popular Nerf and DTU benchmarks, and quite significantly improved model quality with respect to classic multi-view surface reconstructions in realistic human capture scenarios. Last, we show that these results are achievable in one to two minutes, an order of magnitude faster than a typical state of the art geometric reconstruction method applied in this context [13].

2. Related Work

Multi-view capture. A very large corpus of work examines the problem of retrieving 3D models of human subjects from multiple cameras. We can roughly classify these methods along two lines. First, *model-*

based methods use a pre-defined shape template or human deformation model and fit it to observations. Initially pioneered with subject-specific articulated templates using different image features such as stereo matches or silhouettes [5, 25, 29, 7], later methods have used human-generic parameterization based on shape spaces [2, 16] allowing them to estimate both pose and shape identity parameters simultaneously [4]. Later models may include clothing to complete the initially naked mesh [34], and have been increasingly being enhanced with hybrid neural components to represent surface details on top of a human core parameterization [1]. In so doing the approaches target the ability to fit surfaces with more variability and detail, but they are still intrinsically constrained by the underlying represented shape space with inherent precision limits. For this reason lower-level *surface reconstruction approaches* are still metrologically relevant and used for detailed surface capture. Finding their roots in classic reconstruction approaches such as multi-view stereo [8, 27, 11, 24], they have been demonstrated to yield very high quality results in the multi-view capture case [19, 6, 22, 13]. Yet they are sometimes prone to artifacts and incompleteness issues, and are still generally slow, typically taking from several minutes to a few hours depending on the scene complexity, both issues we target improvements for in our proposal.

Differential rendering methods. Recent methods exploiting differentiable rendering are able to recover complete scenes to a great accuracy, even in challenging conditions with reflective and translucent materials. They can be roughly classified in two categories: surface-based and volume-based. *Surface methods* model the surface implicitly as an isosurface of a level set. In [20], the level set is sampled at regular intervals along each ray to find the first intersection with the surface, where the color is evaluated. [32], [14] replaced the level set with a signed distance function to find the isosurface more efficiently with sphere tracing. These methods are susceptible to local minima because the gradients are computed only at the current location of the surface. They avoid this by relying on segmentation masks which constrain the surface to be inside the visual hull. In contrast, *volumetric methods* do not aim at recovering a surface at all. The scene is modelled by a radiance field and opacity volume, which contain color and opacity information at each point in space. An image is created by accumulating color and opacity along rays by marching in the volume. Lambertian materials can be approximated by a constant color, as shown by [15], but direction-dependant encodings are necessary to handle reflective surfaces. [17], later improved by [3], optimize a view-dependant radi-

ance field for novel view synthesis, at which they excel. [21], [30] and [31] can be classified as hybrid methods. They parameterize the density of a radiance field by an underlying signed distance function, which can be rendered and optimized as a radiance field. They avoid local minima more easily than surface methods since the gradients are defined in a band of controllable width near the surface. The main downside of these methods is that they need many hours of optimization. The new volumetric methods [33], [26] and [18] addressed that issue and obtain results comparable to [17] in a few minutes and even a few seconds in the case of [18]. However, they are not able to recover meshes of good quality since the scene is encoded as a radiance field. We chose to base our method on differentiable volumetric rendering, taking inspiration from [33]. Our goal is slightly different since we want to recover a mesh, not a radiance field, and that the background should not be part of the reconstruction.

3. Methodology

Our goal is to extract a surface given a set of multi-view calibrated images \mathcal{I}_n and background images \mathcal{B}_n . The background images are typically available in performance capture setups by recording the acquisition room when empty, giving a strong cue to isolate the subject of interest. We use a differential volume reconstruction as proxy, for which we adjunct appropriate regularization losses (section 3.2), such that a surface is easily extractible from the resulting opacity volume.

3.1. Rendering model

The reconstruction volume contains two volumetric fields: opacity and color. The actual parameterization of the opacity field varies a lot between methods, ranging from a regular voxel grid [26], a sparse grid [33], hash tables [18], or a fully connected neural network [17]. The color field has special parameterizations to achieve view dependant effects: a neural network [17], neural features fed to a smaller neural net [18, 26] or spherical harmonics [33]. Independently from the actual parameterization, all volumetric differentiable rendering methods are based on the non-linear optimization of the following problem:

$$\mathcal{L}_{\text{photo}} = \sum_{r \in \text{rays}} \|\mathbf{C}(r) - \mathbf{C}_{\text{gt}}(r)\| \quad (1)$$

where $\mathbf{C}_{\text{gt}}(r)$ is the ground truth color of the pixel from which the ray r originates. $\mathbf{C}(r)$ is the color obtained by sampling the volume at regular intervals along the ray r and accumulating color and opacity information over a finite range. The dependence of the variables on

a particular ray is omitted for convenience. We define the following quantities:

$$\alpha_i \in [0, 1] \quad \text{transparency of a sample} \quad (2)$$

$$\mathbf{c}_i \in [0, 1]^3 \quad \text{color of a sample} \quad (3)$$

We opt for a sparse grid representation similar to [33], where color and transparency are obtained by interpolating from neighboring grid samples. Since the samples are regularly spaced, they can be indexed by an integer along the ray.

$$T_k = \prod_{j < k} \alpha_j \quad \text{partial transmittance} \quad (4)$$

$$\mathbf{C}_k = \sum_{j \leq k} (1 - \alpha_j) \mathbf{c}_j T_j \quad \text{partial color} \quad (5)$$

$$\mathbf{C} = \sum_{k < \infty} (1 - \alpha_k) \mathbf{c}_k T_k + T_\infty \mathbf{C}_{\text{bg}} \quad (6)$$

Note that for our purposes, a simple extension of the integration allows to account for the background \mathbf{C}_{bg} in the final integrated color \mathbf{C} , when all ray opacities sampled before are transparent. We opt for the convention that $\alpha = 0$ for fully opaque media and $\alpha = 1$ for transparent regions. Figure 3 shows the transmittance value T_k along two rays. The transmittance starts at 1 but may not be 0 at the exit. In that case, the background is blended additively at the end of the integration.

The color and transparency of a particular sample are obtained by linear interpolation of the 8 closest voxels: $\alpha = \text{lerp}(\bar{\alpha})$ and $\mathbf{c} = \text{lerp}(\bar{\mathbf{c}})$, where the bar above a letter denotes voxels' values. We drop the indices for convenience. Following [33], we achieve view dependent effects, *e.g.* diffuse lighting and some specular lighting, by using spherical harmonics (SH):

$$\bar{\mathbf{c}}(\mathbf{v}) = \sum_{l=0}^B \sum_{m=-l}^l Y_{l,m}(\mathbf{v}) \beta_{l,m} \quad (7)$$

where \mathbf{v} is the unit direction of a ray, $\beta_{l,m} \in [-1, 1]^3$ are the coefficients controlling the color and B is the number of SH bands. We typically use 0, 1 or 2 for B ,

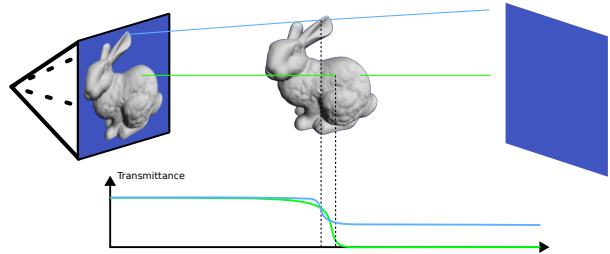


Figure 3. Volumetric integral example

which translates to 4, 13 and 28 coefficients per voxel respectively (including α). The $Y_{l,m}(x, y, z)$ functions are simple, computation-friendly polynomials.

3.2. Losses and regularization

Robust photometric loss. Let $\|x\|_{\mathcal{H}} = x^2$ if $x < \epsilon$ else $\epsilon(|x| - \frac{\epsilon}{2})$ the robust Huber norm. If x is a vector, we take the sum of the norms applied component-wise. We opt for a robust differentiable version of the photometric loss:

$$\mathcal{L}_{\text{photo}} = \sum_{r \in \text{rays}} \|\mathbf{C}(r) - \mathbf{C}_{\text{gt}}(r)\|_{\mathcal{H}} \quad (8)$$

Spatial Regularization. Following [33], we use a total variation regularization over all voxels:

$$\mathcal{L}_{\text{smooth } \alpha} = \sum_{\text{voxels}} \|\nabla \bar{\alpha}\|_2^2 \quad (9)$$

We also use a similar term on the voxels’ color coefficients $\beta_{l,m}$. Since we use a sparse voxel grid, we have to define boundary values for the computation of the spatial gradients: we distinguish between the inside of the object and the outside. We enforce $\alpha = \eta$ inside and $\alpha = 1$ outside where η is a small positive value. Our coarse-to-fine scheme (4.2) allows for the inside and outside regions to be determined. We make sure α is never zero to avoid a division by zero in the computation of the gradients. We use black color boundary values for the inside and outside regions. Enforcing boundary values promotes a smooth and monotonous progression of the opacity which helps remove some volumetric noise and allows an easy extraction of a mesh by using marching cubes on $\bar{\alpha}$.

Ray color consistency. Following [26], we also use a per-sample regularization:

$$\mathcal{L}_{\text{sample}} = \sum_{\text{samples}} \|\mathbf{c}_k - \mathbf{C}\|_{\mathcal{H}} T_k(1 - \alpha_k) \quad (10)$$

The purpose of this term is to favor voxel colors to be consistent with the input color observed by the ray, and avoid the sometimes observed ray-dependent overfitting in NeRF, where input colors can be explained by a sum of view-dependent color contributions dispersed among a wider and non physically meaningful range of voxels along a ray, with each individual color potentially far from the color observed by the ray. We empirically observe in particular that this term drastically improves the case of surface grazing rays where two voxel color explanations may otherwise coexist between the background color and the actual surface color. The term also acts as a direct voxel color supervision term which favors better convergence.

Spherical harmonics parsimony. We penalize non-constant SH coefficients ($l > 0$) to prioritize the constant term which empirically resolves more details for quasi-Lambertian surfaces in our experiments:

$$\mathcal{L}_{\text{SH-parsimony}} = \sum_{\text{voxels}} \|\beta_{l,m}\|_{\mathcal{H}} \quad (11)$$

Ballooning occupancy bias. Regions of an object with no texture or texture not visible at lower resolutions of our coarse-to-fine strategy are harder to reconstruct, because the coexistence of multiple photoconsistent surface hypotheses usually results in a spreaded band of multiple low opacity voxels, impossible to convert to a mesh. A simple workaround is to artificially promote more opaque voxels, effectively inflating the surface like a balloon:

$$\mathcal{L}_{\text{ballooning}} = \sum_{\text{voxels}} \bar{\alpha}^2 \quad (12)$$

This strategy works well when the surface is close to the visual hull, typically true of human capture scenes, but can prevent good convergence for scenes with deep concavities or many fine structures.

Color normalization. Additionally, we estimate a per camera gain and bias value to account for differences in exposures, similarly to [15]:

$$\mathbf{C}_{\text{gt}} = g \mathbf{C}_{\text{uncorrected gt}} + b \quad (13)$$

$$\mathbf{C}_{\text{bg}} = g \mathbf{C}_{\text{uncorrected bg}} + b \quad (14)$$

3.3. Gradient descent

A key insight of [33] is to show that the neural component in NeRF is less important to the result than the differential rendering logic. [33] relies on auto-differentiation, but additional control and finetuning can be gained by computing the relatively simple analytical gradients, taking this notion a step further. This elegantly brings the experience gained about scene reconstruction with neural differential rendering methods to the realm of classic optimization. We here give the final expressions for the opacity derivative of the photometric term for illustration. Consider a particular sample of values α_k and \mathbf{c}_k from a particular ray of integral \mathbf{C} :

$$\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \alpha_k} = \frac{\partial \mathcal{L}_{\text{photo}}}{\partial \mathbf{C}} \frac{\partial \mathbf{C}}{\partial \alpha_k} \quad (15)$$

$$\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \mathbf{C}} = \|\mathbf{C} - \mathbf{C}_{\text{gt}}\|_{\mathcal{H}}' \quad (16)$$

$$\frac{\partial \mathbf{C}}{\partial \alpha_k} = -\mathbf{c}_k T_k + \frac{\mathbf{C} - \mathbf{C}_k}{\alpha_k} \quad (17)$$

We march once per ray to build T_∞ and \mathbf{C} , then march a second time to build $\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \alpha_k}$ that we store for each sample of each ray, according to the formula above. We can then compute derivatives with respect to the values $\bar{\alpha}$ of a particular voxel with the chain rule:

$$\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \bar{\alpha}} = \sum_{r \in \text{rays}} \sum_{k \in \mathcal{S}(r)} \frac{\partial \mathcal{L}_{\text{photo}}}{\partial \alpha_k} \frac{\partial \alpha_k}{\partial \bar{\alpha}} \quad (18)$$

$\mathcal{S}(r)$ is the set of samples on ray r to which the voxel of interest contributes. Instead of taking all these contributions into account explicitly, we read interpolated values of the per-sample gradients:

$$\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \bar{\alpha}} \approx \sum_{\text{cameras}} \text{lerp}\left(\frac{\partial \mathcal{L}_{\text{photo}}}{\partial \alpha}\right) \quad (19)$$

Figure 4 shows our double interpolation: on the left, each sample interpolates values from the 8 nearest voxels’ centers to produce a gradient. On the right, each voxel reads gradients from the 8 nearest samples.

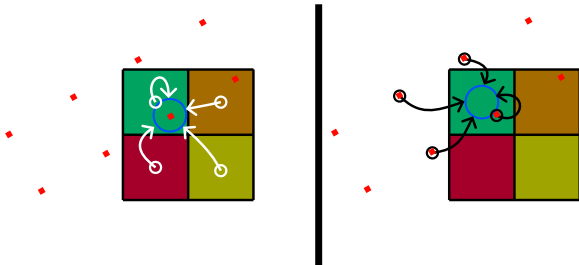


Figure 4. Gradient interpolation

The computations are analogous for the partial derivatives with respect to voxel colors, and for the similarly ray-based $\mathcal{L}_{\text{sample}}$ loss. The gradients of the voxel-wise regularizations $\mathcal{L}_{\text{smooth } \alpha}$, $\mathcal{L}_{\text{SH parsimony}}$ and $\mathcal{L}_{\text{ballooning}}$ are much simpler since they only involve a voxel and its immediate neighbors. For instance the gradient of $\mathcal{L}_{\text{smooth } \alpha}$ is:

$$\frac{\partial \mathcal{L}_{\text{smooth } \alpha}}{\partial \bar{\alpha}} = -\Delta \bar{\alpha} \quad (20)$$

We provide all gradient derivations as supplemental.

3.4. Surface extraction

We extract meshes from the voxel opacity grid using marching cubes on the transparency values $\bar{\alpha}$. The color is computed per pixel at rasterization time by sampling the volume at the location of the unprojected pixel, taking into account the view direction when evaluating the SH basis. The threshold for the extraction of the isosurface is chosen manually and fixed for all datasets at 0.81. This simple strategy proves very effective provided the optimization converged to an SDF-like distribution of transparency values.

4. Sparsity and coarse-to-fine strategies

Most differential rendering methods have to deal with two main sources of inefficiencies: a complex parameterization and the redundant sampling of empty space. Our parameterization is as simple as possible: a sparse voxel grid with a two-level data structure. We also use a coarse-to-fine strategy to ensure a quick convergence, by starting with down-scaled images and a coarse grid that we progressively upscale. We avoid sampling empty space in two ways: first, we classically compute the visual hull [12] for a rough estimate of the location of the surface, and second, we precompute integration ranges for all rays as determined by the estimation in the previous hierarchy level. The combination of the coarse-to-fine and sparse storage allows to focus the method on relevant portions of space while targeting very high resolution, millimetric voxels in our capture experiments, with contained compute times and memory.

4.1. Ray culling

To speedup convergence, we cull rays that don’t initially intersect with the visual hull. Also, we reserve initial voxels using the visual hull’s bounding box, in the space regions visible by at least one ray. Our sparse grid, inspired from [33], is stored as a 3D array of voxel tile pointers, as illustrated by 5, where tiles contain 4^3 voxels. The voxels are initialized with a black color and $\alpha = 0.98$. We compute a very similar sparse structure for the rays forming 2D tile bundles. We precompute integration ranges for each ray bundle, illustrated by the red frustums, by marching in our structure once. An integration range is a list of continuous sub-ranges, which skip empty space and stop when the transmittance is low. We sort the tiles in Morton order for improved cache coherence.

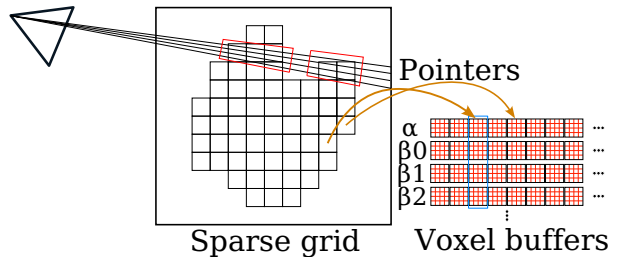


Figure 5. Sparse structure

4.2. Coarse-to-fine strategy

We start the optimization at a coarse resolution for both the grid and the images. After convergence has been reached for the current level, we remove the empty

tiles and mark full tiles. We upscale the sparse structure at twice the resolution by linearly interpolating the voxels of the previous one. We switch to images with higher resolution and recompute integration ranges for the new bundles of rays. We determine which tiles are empty and which are full by computing the transmittance from each camera to each voxel.

4.3. Implementation details

We implement our optimization and visualization framework with C++ and OpenGL compute shaders. For integration, the rays are bundled in groups of 8 for better cache coherency. We use an integration step size equal to the diagonal of a voxel when marching in the volume. For datasets without backgrounds, we require segmentation masks and we apply an additional loss $\mathcal{L}_{\text{mask}} = \sum_{\text{rays}} (T_{\infty} - \text{mask})^2$ where *mask* is a binary image. The different losses are weighted by coefficients that we keep constant for all the experiments (see supplemental). We use the ADAM optimizer. We store all the voxel coefficients on 8 bit integers. All computations use 32 bit floats but the gradients are also stored on 8 bits with the 1,5,2 format. Since the gradients are small, we apply a bias in the exponent to avoid underflow when converting to 8 bits.

5. Evaluations

All our experiments were run on a Quadro RTX 5000 GPU with 16GB of video memory. We mark by a cross the table entries for which we were not able to either run the particular experiment (due to video memory limitations) or that the paper did not provide means of computing it. We list the optimization timings and peak memory used in our experiments. An additional two seconds are required to load the images, compute the visual hull and initialize our data structures. More qualitative results are shown in the supplementary.

5.1. Evaluation on DTU

The DTU dataset [10], composed of 49 to 64 close-up pictures of various objects, is particularly challenging for multi-view reconstruction algorithms. First, the high resolution images (1600x1200) have inconsistent lighting conditions due to the robot arm casting shadows on the objects, and second, only the front is visible in most scenes. This makes it hard to compute an accurate visual hull so we manually fit a tight bounding box around the objects. Since the dataset does not provide background images, we use the segmentation masks of [32]. Table 1 shows some quantitative results for a subset of the scenes with the DTU average chamfer-*l1* distances metric. We compare against the results of [32] and [30], both in terms of geometry and

appearance. We make a distinction between the images obtained by rasterization (raster columns) and the image obtained by computing the volumetric integral (vol columns). The PSNR attained in the latter is slightly higher than in the former since more voxels contribute to the value of a pixel. Our method works best for highly textured, non-specular materials (scans 65, 106, 114, 122) and yields bloated / caved-in surfaces otherwise (scans 24, 37, 110). Note that the windows of the house (scan 24) are well reconstructed since they provide a strong texture gradient even at low resolutions. Our chamfer distance is slightly below [32] and [30] but our method achieves higher PSNR. We used only one band of spherical harmonics ($B = 1$) since there is not enough video memory for two. We also had to reconstruct scan 24 without the last row of cameras for the same reason.

Scan	IDR		Neus		Ours $B = 1$				
	Chamfer	PSNR	Chamfer	PSNR	Chamfer	PSNR (raster)	PSNR (vol)	Time (s)	vram (GB)
24	1.743	23.30	0.831	x	2.8932	24.43	25.03	98.5	14.3
37	x	x	1.101	x	3.4356	22.026	23.05	97.5	14.1
65	0.892	23.95	0.721	x	1.0942	25.26	26.37	78.0	12.2
106	0.728	22.81	0.532	x	1.4070	28.35	30.59	95.9	12.9
110	1.10	21.26	1.416	x	2.9493	25.36	28.47	93.2	13.5
114	0.450	25.36	0.331	x	0.7607	24.36	25.54	84.6	11.9
122	0.706	27.06	0.552	x	1.0001	31.18	32.71	63.3	10.3
mean	0.936	23.96	0.79	x	2.05	25.7	27.1	88.7	12.9

Table 1. Quantitative evaluation on the DTU dataset.

5.2. Human benchmark

We test our method on 3 free meshes from *renderpeople.com*, with 60 rendered viewpoints in a circle around the objects, rendered on a white background. We report the mean Chamfer distances (centimeters) in table 2. Points further than 5 centimeters are ignored similarly to the DTU evaluation protocol (green points in Fig.6).

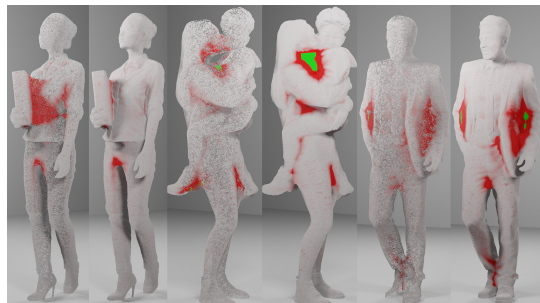


Figure 6. Chamfer heatmaps, [13] (left), ours (right), on 3 models.

Our method performs on par or better than SOTA [13] on this data, while executing around 20 times faster. Note also that, although they are widely used for quantitative reference, such semi-synthetic datasets

have intrinsic limitations such as lacking reflective component realism or fine-scale geometric details (*e.g. ripples in clothing, hair strands*). As in renderpeople, this often directly results from limitations of the capture method used to obtain the reference geometry itself, which we are attempting to address.

	Mei	Fabienne	Dennis
Our method	0.44	0.45	0.62
Leroy <i>et al.</i> [13]	0.44	0.49	0.62

Table 2. Chamfer evaluation (lower is better).

5.3. Evaluation on Nerf’s synthetic dataset

We also compare again [17] and [33] on the Nerf synthetic dataset. This dataset is composed of 8 scenes imaged by 100 cameras arranged in an hemisphere. The appearance is evaluated with another set of 200 cameras, different from the training set. The cameras have a lower resolution than for the DTU dataset (800^2) and the objects have highly reflective surfaces and intricate geometry. Since there is no actual background, we convert the transparency of the images to a segmentation mask. The quantitative results are summarized in table 3. We report the averaged PSNR values given in [33]. As with the DTU dataset, our method performs encouragingly except for very strong reflective surfaces.

Scene	Nerf PSNR	Plenocels PSNR	Ours $B = 1$				Ours $B = 2$			
			PSNR (raster)	PSNR (vol)	Time (s)	vram (GB)	PSNR (raster)	PSNR (vol)	Time (s)	vram (GB)
chair			26.48	26.28	27.1	5.4	27.59	26.72	53.6	6.2
drums			21.85	21.56	25.6	5.6	22.22	21.90	39.9	6.2
ficus			25.06	26.78	24	5.3	26.32	28.03	30.5	5.6
hotdog			28.45	28.12	40.9	5.9	28.77	28.57	68.1	6.8
lego			26.52	26.31	33.4	6.4	26.68	26.40	64.2	7.3
mic			24.22	24.66	17.2	3.8	25.55	25.64	33.0	4.1
materials			22.28	24.11	24.9	5.9	23.30	24.40	40.4	6.5
ship			26.48	26.44	65.8	8.8	27.05	26.91	153.3	10.2
mean	31.01	31.71	25.2	25.5	32.3	5.9	25.9	26.0	60.4	6.6

Table 3. Quantitative evaluation on NeRF’s synthetic dataset.

5.4. Ablations

We ablate our regularizations and coarse-to-fine scheme in table 4 and figure 7 on Nerf’s mic model. Varying the number B of SH bands has the highest impact on quality and performance. The surface has a strong tendency to buckle when the reflectance cannot be well approximated by the SH decomposition. We mitigate this effect to some extent with our ballooning regularization but it creates a global bloating of the surface that can be hard to overcome in some scenes. Not using the parsimony term results in a faded base color and creates additional buckling, even though the overall color is more vibrant.

The influence of the color normalization term can only be characterized on real data where per-camera exposure discrepancies actually occur, as opposed to

	B=2	B=1	B=0	no ballooning	no SH parsimony	Coarse (left) to fine (right)			
PSNR raster	25.9	24.3	23.0	25.7	25.7	23.3	24.2	24.8	25.9
PSNR vol	25.7	24.6	23.4	25.7	25.7	23.0	24.4	25.3	25.8

Table 4. Ablations on the mic model

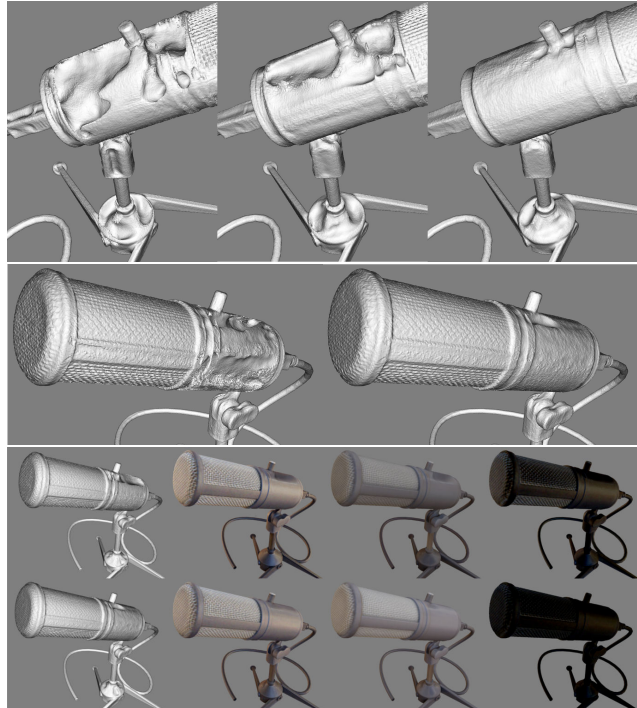


Figure 7. Top: $B = 0$ (right), $B = 1$ (center), $B = 2$ (left) Center: No ballooning term (right), with ballooning (left) Bottom: Without SH parsimony term (top row) vs with (bottom row). From left to right: geometry, mesh colors, $\beta_{0,0}$ only, specularity only

	with color normalization		without color normalization	
	PSNR raster	PSNR vol	PSNR raster	PSNR vol
cartwheel t=182	22.6	26.7	21.8	25.3
run t=168	24.6	29.0	23.5	26.9
dance t=367	23.4	26.1	22.5	24.9

Table 5. PSNR on real data

synthetic datasets which don’t show any. Table 5 ablates our color normalization optimization term on three frames of our captured data, showing the increase of PSNR resulting from inclusion of the term.

5.5. Limitations

Our method aggressively culls inner volumes identified through ballooning (in green in Fig. 8, left), to focus and bias the inference toward the surface, helping each new sparsity level to create blocks in the surface hypothesis vicinity. While this allows very speedy inference in most cases, it also means the method may miss some concavity information, which also shows in the PSNR figures, still however delivering a compelling speed/quality trade-off. Furthermore, the inside of our

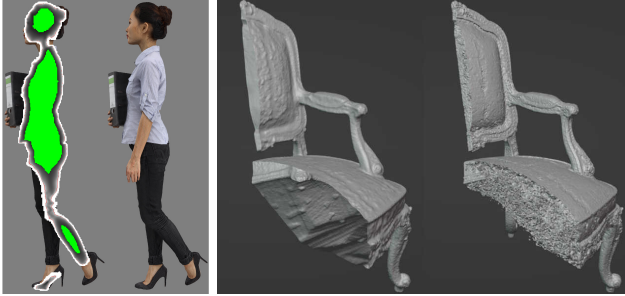


Figure 8. Sectional view of the opacity field (left), Ours (center), [18] (right)

extracted meshes is completely free of artifacts, contrary to applying marching cubes on other volumetric methods such as [18] (Fig. 8, right).

5.6. Qualitative comparison on real data

We compare with the state of the art surface capture method [13] in Figure 9, on data captured by our multi-camera setup. It is composed of 68 2048×2048 RGB cameras arranged in an hemisphere with a radius of approximately 4 meters. Our method provides a drastic improvement in the reconstruction of all high frequency details, such as cloth wrinkles, face features, which are mostly smoothed out with [13]. The distinct geometry of fingers and veins are clearly visible in Figure 2, despite the noisy input. We want to emphasize that all of these results were routinely obtained in less than a minute of computation time. The meshes obtained contain 5 million triangles on average, with each triangle projecting on areas smaller than one pixel thanks to our sparse coarse-to-fine scheme. We use 4 levels of detail in our coarse-to-fine strategy, with voxels of 1.25 mm at the finest resolution.

6. Conclusion and future work

We have presented a simple and efficient differentiable rendering implementation, targeted at multi-view surface capture problems. Our coarse-to-fine strategy and custom gradient descent optimization allows fast convergence on a single GPU, typically in a minute. Our choice of regularization adapts the differential volumetric rendering framework for the recovery of highly detailed meshes, where previous methods had many imperfections such as holes and noise or take several orders of magnitude longer. Additionally, we show that computing analytical gradients is not particularly complex thanks to a simple parameterization, casting differential rendering as a classic optimization. The framework can be extended in many directions, with other appearance models to better handle specular reflections. In particular, the high pixel precision

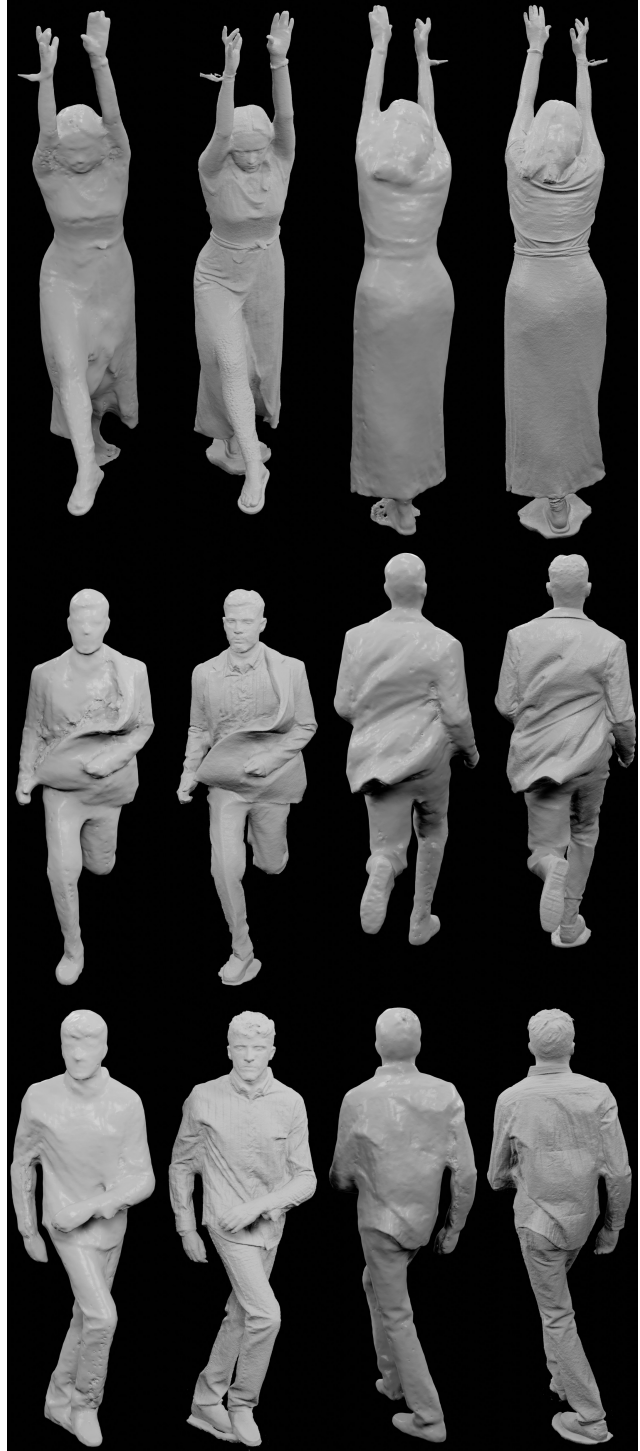


Figure 9. Ours (columns 2 & 4) vs [13] (columns 1 & 3)

achieved in our capture experiments suggest that the method would also benefit from better sub-pixel denoising models and camera calibration refinement.

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