DC4GS: Directional Consistency-Driven Adaptive Density Control for 3D Gaussian Splatting

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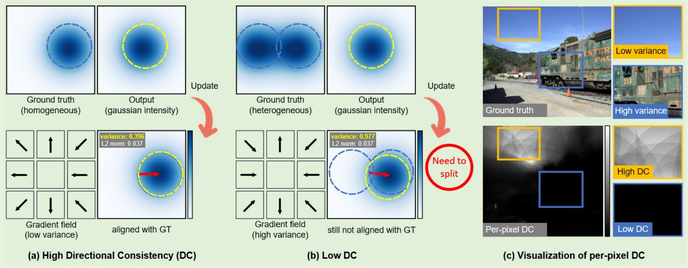
NEURAL INFORMATION PROCESSING SYSTEMS

Motivation

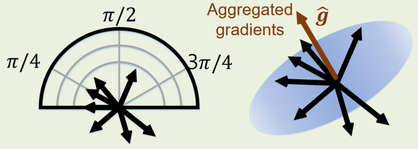


- Conventional ADC often causes redundant splits in homogeneous regions due to relying solely on gradient magnitudes.
- Random sub-primitive placement leads to structural misalignment.
- Incorporating gradient direction consistency enables efficient densification.

Contributions

- Introduction of Directional Consistency (DC) as a criterion to better capture the structural complexity of local positional gradients in 3DGS
- DC-guided split decision so that structurally complex regions are better selected
- DC-guided split scheme so that the DCs of resulting sub-primitives are maximized and thereby their structures are best distinguished.

Directional Consistency



- DC serves as an effective cue for assessing how homogeneous the region represented by a primitive is.
- DC measures the angular coherence of positional gradients within each Gaussian to assess structural homogeneity.
- DC computed as the L2 norm of the circular mean of normalized gradients, where higher DC indicates well-aligned gradients.

DC-weighted split criterion

- DC-guided split Criterion (DCC) combines DC with gradient magnitude to decide which Gaussians should be split:

$$\nabla^{DC}_{\mu_i} L = \frac{1}{v}\sum_{v=1}^{v}\left(1-\kappa_{i,v}\right)\cdot||\hat{g}_{i,v}||$$

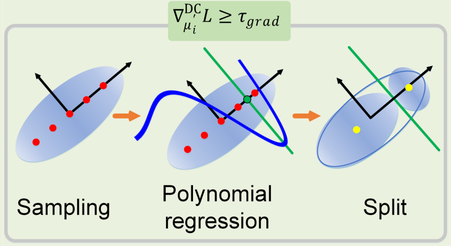
where v is the number of views. $\kappa_{i,v}$ denotes the DC of Gaussian i in view v, and $\hat{g}_{i,v}$ represents the aggregated positional gradient magnitude.

Algorithm 1 Optimization and Densification

$||S||$: maximum Gaussian scale, τ_p, τ_S: thresholds for $\nabla^{DC}_{\mu'} L$ and $||S||$, N: number of split candidates

$M, S, R, C, A \leftarrow$ InitAttributes() ▷ Positions, Scales, Rotations, Colors, Opacities
$\nabla^{DC}_{\mu'} L \leftarrow 0, k \leftarrow 0, \nu \leftarrow 0$ ▷ DC-weighted split criterion, iteration counter, visibility counter
while not converged **do**
  $V, \hat{I} \leftarrow$ SampleTrainingView() ▷ view-projection camera matrix, ground truth
  $I \leftarrow$ Rasterize(M, S, R, C, A, V)
  $L \leftarrow$ Loss$(I, \hat{I})$, $\frac{\partial L}{\partial \mu'} \leftarrow \nabla L$ ▷ backpropagation
  for all Gaussians G_i visible in V **do** ▷ i: index of a Gaussian
    $\nu_i \leftarrow \nu_i + 1, \mu_i \leftarrow M_i$
    $\kappa_i \leftarrow$ EvalDirectionalConsistency$(\frac{\partial L}{\partial \mu'_i})$ ▷ Algo. 2
    $\hat{g}_i \leftarrow \sum_j |\frac{\partial L_j}{\partial \mu'_i}|, \nabla^{DC}_{\mu'_i} L \leftarrow \nabla^{DC}_{\mu'_i} L + (1-\kappa_i) \cdot ||\hat{g}_i||$ ▷ j: pixel position influenced by G_i
    $J_i \leftarrow J_i +$EvalSplitCosts$(\mu_i, S_i, R_i, V, N, \frac{\partial L}{\partial \mu'_i})$ ▷ Algo. 3
  if IsRefinementIteration(k) **then**
    for all Gaussians G_i **do**
      $\nabla^{DC}_{\mu'_i} L \leftarrow (\nabla^{DC}_{\mu'_i} L)/\nu_i$
      if $\nabla^{DC}_{\mu'_i} L > \tau_p$ **and** $\|S_i\| > \tau_S$ **then**
        $x_{\text{opt}} \leftarrow$ PolynomialRegression(J_i, N)
        SplitGaussian$(x_{\text{opt}}, \mu_i, S_i, R_i, C_i, A_i)$ ▷ Algo. 5
      $\nabla^{DC}_{\mu'_i} L \leftarrow 0, J_i \leftarrow 0, \nu_i \leftarrow 0$
  $M, S, R, C, A \leftarrow$ Adam$(\nabla L), k \leftarrow k+1$ ▷ update parameters and increment iteration

DC-guided split



- DC-guided Split (DCS) guides sub-primitive placement by minimizing a DC-based cost, ensuring each sub-primitive lies in a distinct, locally homogeneous region.
- DCS aligns split decisions along the Gaussian's principal axis and uses polynomial regression to efficiently estimate the optimal split location.

Experimental Results

Method	Mip-NeRF360					Tanks&Temples					Deep Blending				
	PSNR ↑	SSIM ↑	LPIPS ↓	Prim.	Mem.	PSNR ↑	SSIM ↑	LPIPS ↓	Prim.	Mem.	PSNR ↑	SSIM ↑	LPIPS ↓	Prim.	Mem.
Plenoxels * [8]	23.080	0.626	0.463	-	2.1GB	21.080	0.719	0.379	-	2.3GB	23.060	0.795	0.510	-	2.7GB
iNGP-big * [25]	25.590	0.699	0.331	-	48MB	21.920	0.745	0.305	-	48MB	24.960	0.817	0.390	-	48MB
Mip-NeRF360 * [2]	27.690	0.792	0.237	-	8.6MB	22.220	0.759	0.257	-	8.6MB	29.400	0.901	0.245	-	8.6MB
3DGS [14]	27.414	0.812	0.218	3350K	792MB	23.655	0.844	0.179	1893K	447MB	29.394	0.898	0.248	2833K	670MB
Scaffold-GS [22]	27.651	0.810	0.226	5460K	164MB	24.018	0.851	0.174	2470K	74MB	30.252	0.904	0.255	1710K	51MB
GES [10]	27.040	0.796	0.248	1543K	365MB	23.640	0.842	0.191	930K	220MB	29.562	0.903	0.249	1606K	380MB
LPM [37]	27.589	0.820	0.212	3426K	810MB	23.878	0.847	0.183	1824K	431MB	29.483	0.901	0.245	2525K	597MB
Pixel-GS [44]	27.537	0.822	0.190	5622K	1329MB	23.759	0.853	0.151	4598K	1087MB	28.812	0.891	0.252	4623K	1093MB
AbsGS [38]	27.504	0.818	0.191	3149K	744MB	23.636	0.852	0.162	1332K	315MB	29.500	0.900	0.237	1961K	463MB
AbsGS (60K iter.)	27.539	0.817	0.189	3162K	748MB	24.039	0.855	0.156	1313K	311MB	29.275	0.895	0.240	1962K	464MB
3DGS+DC4GS	27.486	0.814	0.217	2968K	701MB	23.786	0.845	0.179	1703K	402MB	29.565	0.901	0.245	2644K	625MB
Scaffold-GS+DC4GS	27.653	0.810	0.225	4790K	144MB	24.016	0.849	0.177	2080K	62MB	30.063	0.903	0.257	1350K	40MB
GES+DC4GS	27.090	0.797	0.248	1323K	313MB	23.515	0.841	0.194	816K	193MB	29.632	0.904	0.248	1487K	352MB
LPM+DC4GS	27.556	0.819	0.218	2712K	641MB	23.892	0.846	0.186	1502K	355MB	29.584	0.903	0.244	2350K	555MB
Pixel-GS+DC4GS	27.620	0.824	0.191	5009K	1184MB	23.930	0.855	0.150	4106K	971MB	29.181	0.896	0.246	4284K	1013MB
AbsGS+DC4GS	27.625	0.826	0.188	2615K	618MB	24.121	0.859	0.159	1093K	258MB	29.654	0.905	0.235	1499K	354MB

- Overall, when DC4GS is integrated into the baselines, it consistently improves them to competitive or superior quality.
- DC4GS better preserves connected structures such as window frames and railings, which often appear fragmented or discontinuous in the baseline results.

Acknowledgement

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