RAPiD-Seg: Range-Aware Pointwise Distance Distribution Networks for 3D LiDAR Segmentation

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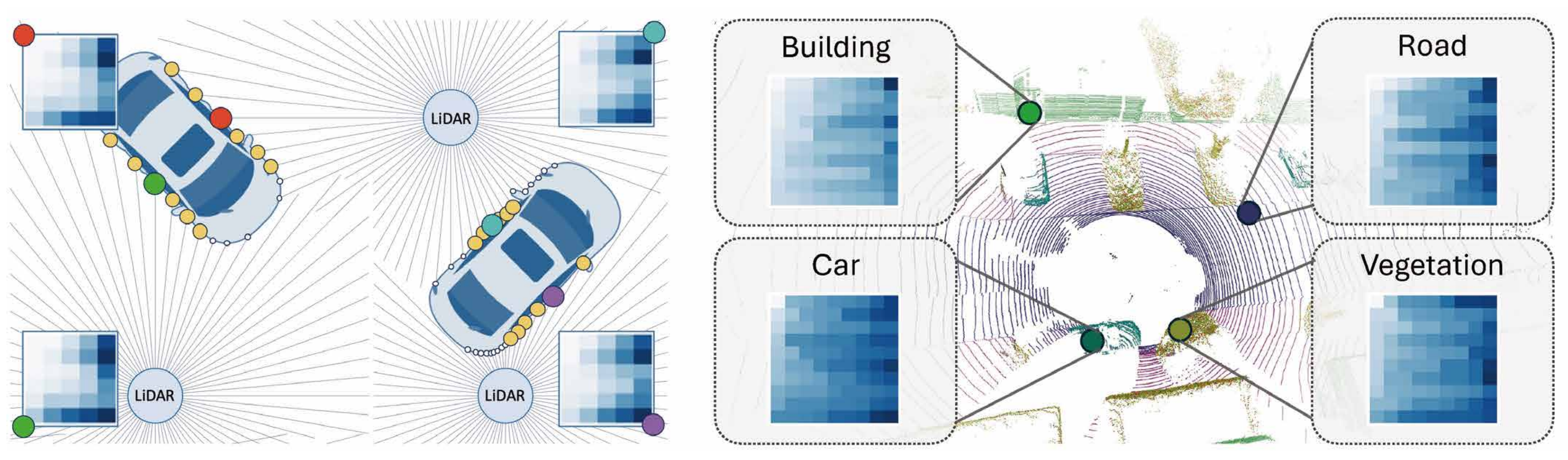
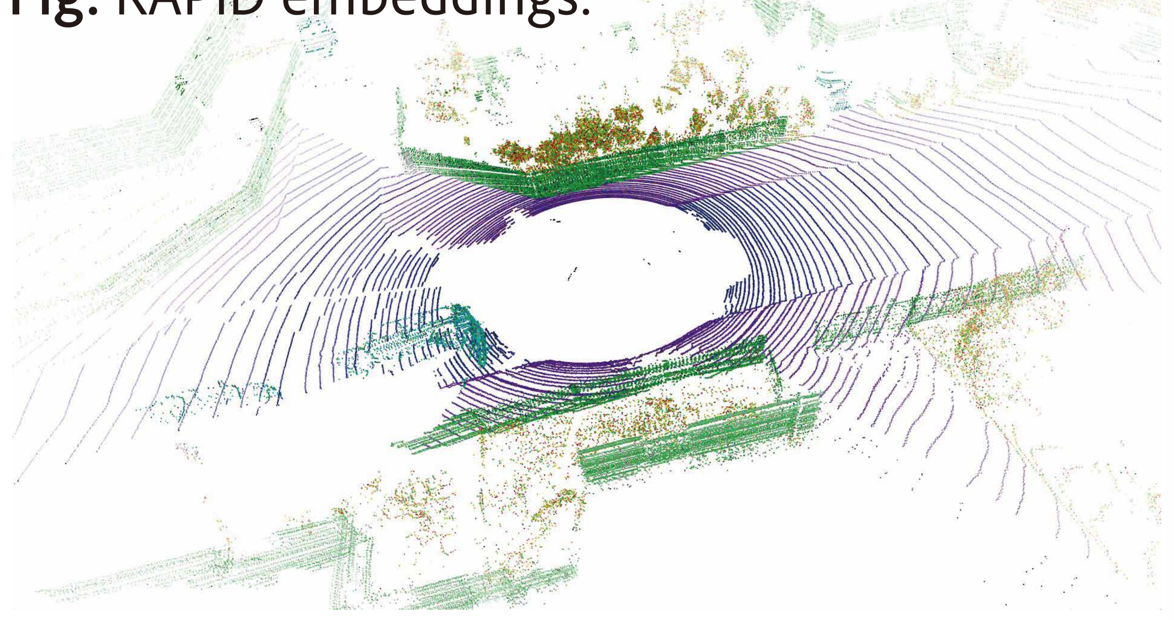
Motivation & Contributions

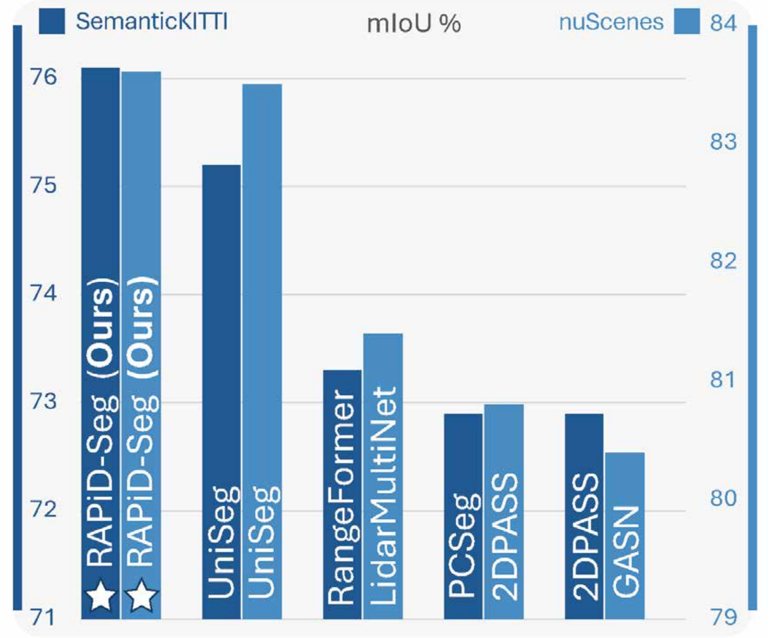
Range-Aware Pointwise Distance Distribution (RAPiD) is the feature for 3D LiDAR segmentation that ensures robustness to rigid transformations and viewpoints through isometry-invariant metrics.



- **A novel method for embedding RAPiD** with class-aware double nested AE to optimize the embedding of high-dimensional features, balancing efficiency and fidelity.
- **A novel open-source network architecture RAPiD-Seg** and supporting training methodology for LiDAR segmentation.
- **SoTA LiDAR segmentation performance** in terms of mIoU on SemanticKITTI (76.1) and nuScenes (83.6) dataset.

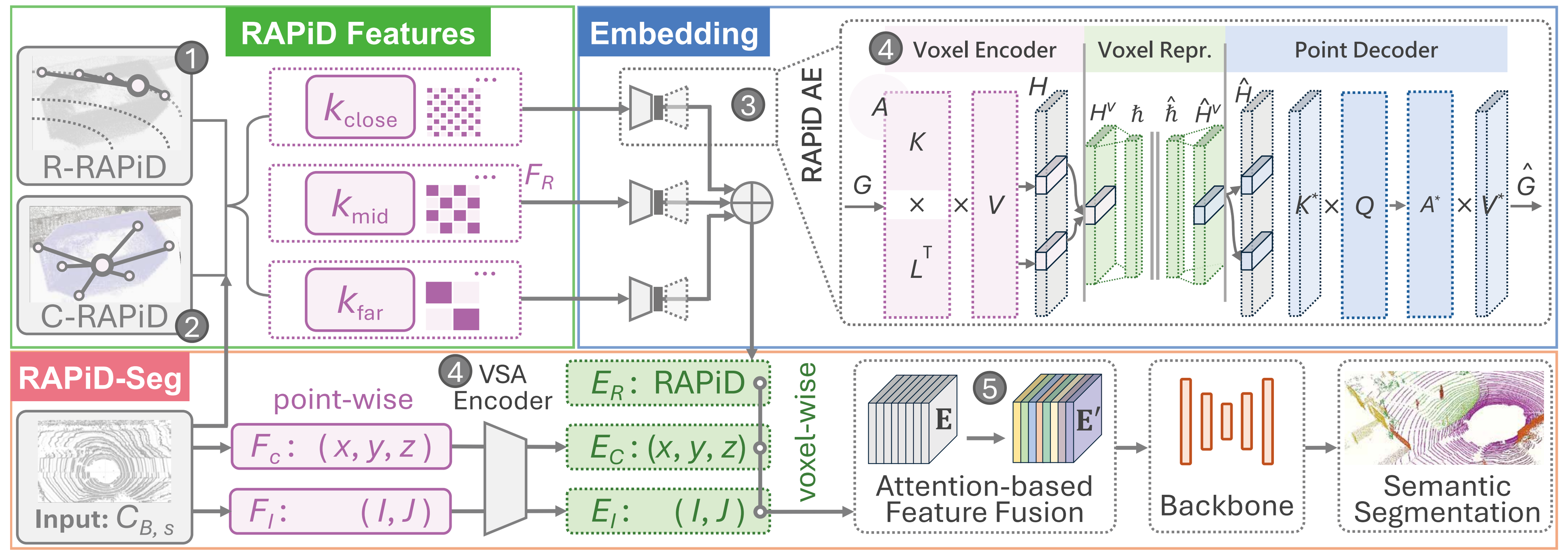
Fig. RAPiD embeddings.





Methodology

RAPiD-Seg Architecture is a double nested AE structure with a novel class-aware embedding objective, to reduce computational costs while providing feature learning capacity.

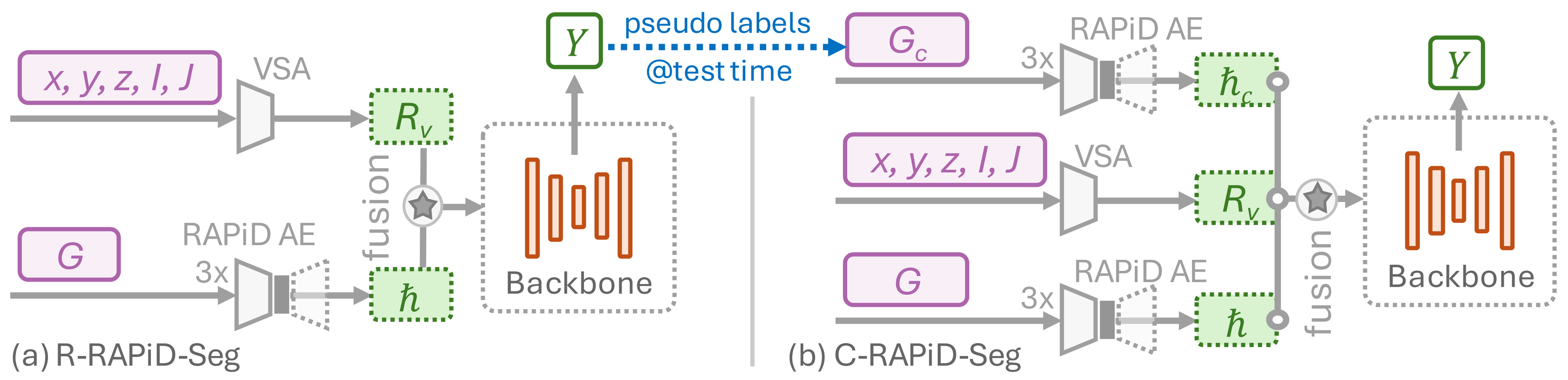


The k-point RAPiD in region P_{RoI} is defined as:

$$\mathrm{RAPiD}\,(P_{\mathrm{RoI}}; k) = \mathrm{sort}\left([\ \mathrm{sort}\,([\ \boldsymbol{\rho}_{j,1}, \ldots, \boldsymbol{\rho}_{j,k}\ ])\ ]_{j=1}^{u} \right),$$

$\forall l \in \{1, \ldots, k\}, j \in \{1, \ldots, u\}$, $\boldsymbol{\rho}_{j,l}$ is given by:

$$\boldsymbol{\rho}_{j,l} = \left\| \left[\boldsymbol{p}_j - \boldsymbol{p}_{j,l},\ \ g\left(r_j\right) - g\left(r_{j,l}\right) \right] \right\|_2,$$



- **(a) R-RAPiD-Seg**. We first construct the lightweight R-RAPiD-Seg network for fast 3D segmentation.
- **(b) C-RAPiD-Seg**. We then train the C-RAPiD-Seg network to facilitate the embedding fidelity within individual semantic classes.

Experiments

Tab. Results on SemanticKITTI test set.

Method	mIoU	car	bicy	moto	truc	o.veh	ped	b.list	m.list	road	park	walk	o.gro	build	fenc	veg	trun	terr	pole	sign
Cylinder3D [64]	68.9	97.1	67.6	63.8	50.8	58.5	73.7	69.2	48.0	92.2	65.0	77.0	32.3	90.7	66.5	85.6	72.5	69.8	62.4	66.2
AF2S3Net [7]	69.7	94.5	65.4	**86.8**	39.2	41.1	**80.7**	80.4	74.3	91.3	68.8	72.5	**53.5**	87.9	63.2	70.2	68.5	53.7	61.5	71.0
RPVNet [56]	70.3	97.6	68.4	68.7	44.2	61.1	75.9	74.4	73.4	**93.4**	70.3	**80.7**	33.3	93.5	72.1	86.5	75.1	71.7	64.8	61.4
SDSeg3D [27]	70.4	97.4	58.7	54.2	54.9	65.2	70.2	74.4	52.2	90.9	69.4	76.7	41.9	93.2	71.1	86.1	74.3	71.1	65.4	70.6
GASN [61]	70.7	96.9	65.8	58.0	59.3	61.0	80.4	**82.7**	46.3	89.8	66.2	74.6	30.1	92.3	69.6	87.3	73.0	72.5	66.1	**71.6**
PVKD [17]	71.2	97.0	67.9	69.3	53.5	60.2	75.1	73.5	50.5	91.8	70.9	77.5	41.0	92.4	69.4	86.5	73.8	71.9	64.9	65.8
2DPASS [58]	72.9	97.0	63.6	63.4	61.1	61.5	77.9	81.3	74.1	89.7	67.4	74.7	40.0	93.5	**72.9**	86.2	73.9	71.0	65.0	70.4
PCSeg [36]	72.9	97.5	51.2	67.6	58.6	68.6	78.3	80.9	**75.6**	92.5	71.5	78.3	36.9	93.1	71.4	85.4	73.6	69.9	66.1	68.7
RangeFormer [22]	73.3	96.7	69.4	73.7	59.9	66.2	78.1	75.9	58.1	92.4	73.0	78.8	42.4	92.3	70.1	86.6	73.3	72.8	66.4	66.6
▲UniSeg [37]	75.2	**97.9**	**71.9**	75.2	63.6	74.1	78.9	74.8	60.6	92.6	74.0	79.5	46.1	93.4	72.7	**87.5**	**76.3**	**73.1**	**68.3**	68.5
RAPiD-Seg (Ours)	**76.1**	97.7	71.1	76.2	**72.5**	**80.7**	79.9	79.1	59.8	91.8	**78.2**	78.6	46.0	**93.6**	72.1	86.9	74.6	72.3	65.9	68.5

Tab. Component-wise ablations.

RAPiD Features: Geometric	Reflectivity	Embedding	Attention	mIoU	Δ
				70.04	(**Baseline**)
			✓	70.46	(+**0.42**)
✓				71.21	(+**1.17**)
✓	✓			71.93	(+**1.89**)
✓	✓	✓		72.15	(+**2.11**)
	✓	✓	✓	71.80	(+**1.76**)
✓		✓	✓	72.32	(+**2.28**)
✓	✓		✓	72.78	(+**2.74**)
✓	✓	✓	✓	**73.02**	(+**2.98**)

Tab. Effects of k at various ranges.

	PDD [53]				RAPiD (ours)			
	k_{near}	k_{mid}	k_{far}	mIoU	k_{near}	k_{mid}	k_{far}	mIoU
SemK	7	7	7	64.74 (**-7.1**)	7	7	7	72.04 (+**0.2**)
SemK	5	5	5	65.18 (**-6.6**)	5	5	5	72.28 (+**0.5**)
SemK	10	7	5	66.23 (**-5.6**)	**10**	**7**	**5**	**73.02** (+1.2)
nuScene	6	6	6	72.19 (**-6.5**)	6	6	6	78.76 (+**0.1**)
nuScene	3	3	3	73.68 (**-5.0**)	3	3	3	79.43 (+**0.8**)
nuScene	8	6	3	72.24 (**-6.4**)	**8**	**6**	**3**	**79.91** (+1.3)

Tab. Performance of different variants.

Method	mIoU %	car	ped	o.gro	pole
Baseline	70.0	97.2	78.1	35.4	63.5
R-RAPiD-Seg	72.3 (+**2.3**)	97.4	77.4	**45.0**	62.4
C-RAPiD-Seg	**73.0** (+3.0)	**97.7**	**79.3**	44.6	**66.4**

Fig. Qualitative results comparing our results and PCSeg baseline.