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Relation-aware place recognition network for large-scale point clouds

Key words: Relation-aware; Point cloud; Place recognition; Deep learning

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Motivation

- In large-scale urban environments, many scene elements, such as buildings, trees, and lamp posts, exhibit similar geometric characteristics across different locations. Consequently, relying solely on geometric feature representations may produce ambiguous scene representations. In contrast, the relative spatial arrangements and contextual interactions among neighboring structures often provide more distinctive cues for place recognition, as places with similar local appearances may still differ significantly in their spatial configurations. Motivated by this observation, we propose a novel relation-aware network (RA-Net) for large-scale point cloud-based place recognition, which jointly exploits local relational information and global features to learn more discriminative scene representations.

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Main idea

- We propose a spatial relation feature extraction (SRFE) module that learns relation-aware contextual information within local neighborhoods. Instead of treating neighboring points equally during feature aggregation, the SRFE module adaptively exploits contextual cues by jointly considering feature discrepancies and relative spatial information among neighboring points.
- A global feature extraction (GFE) module is proposed to enhance scene representation by incorporating global contextual information into pointwise features. Specifically, max pooling is employed to capture the most salient feature responses across the scene, while feature interaction between the global context representation and point features is used to enrich the feature embedding.
- The effectiveness of the proposed approach is rigorously evaluated on four benchmark datasets, demonstrating superior performance compared to state-of-the-art (SOTA) methods.

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Method

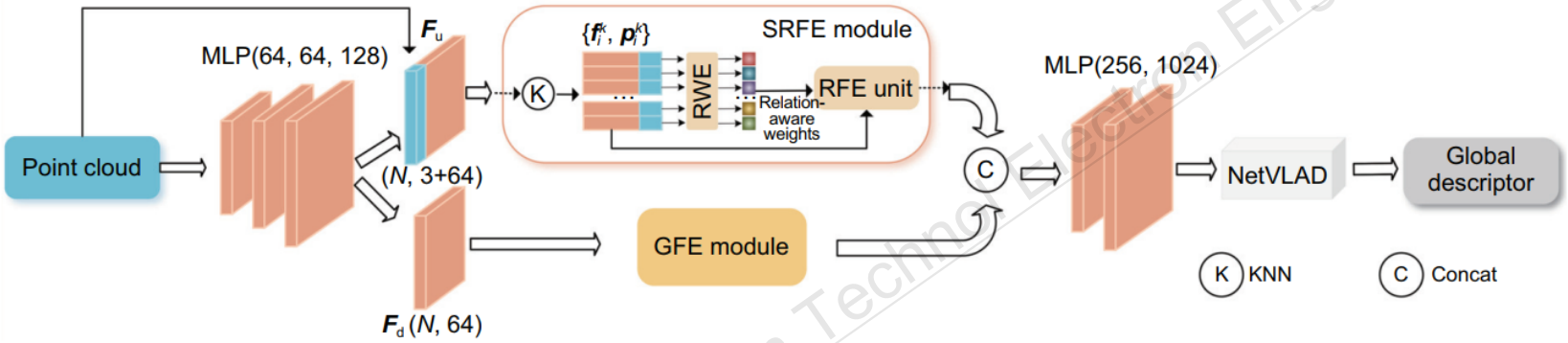


Fig. 1 Overview of the RA-Net architecture. N denotes the number of points, and k denotes the number of nearest neighbors. KNN: k-nearest neighbor

The feature $\boldsymbol{F}_{\mathrm{u}}$ and the 3D coordinates of points are fed into the SRFE module. First, the relation-aware weight estimation (RWE) unit learns relation-aware weights within local neighborhoods by jointly considering feature representations and relative spatial information. Subsequently, the relation feature extraction (RFE) unit exploits feature differences and relative geometric information among neighboring points under the guidance of the learned relation-aware weight. By emphasizing relational patterns, the RFE unit captures informative spatial relation patterns that are not fully represented by local feature similarity alone.

At the same time, the feature $\boldsymbol{F}_{\mathrm{u}}$ is fed into the GFE module, which aggregates local features using max pooling. The max-pooling operation helps capture the most prominent features $\boldsymbol{F}_{\mathrm{m}}$. The feature $\boldsymbol{F}_{\mathrm{d}}$ is multiplied by the prominent features $\boldsymbol{F}_{\mathrm{m}}$. The result is added to the reshaped $\boldsymbol{F}_{\mathrm{m}}$ to obtain the enhanced feature $\boldsymbol{F}_{\mathrm{a}}$. The original features $\boldsymbol{F}_{\mathrm{d}}$ and $\boldsymbol{F}_{\mathrm{a}}$ are then concatenated and fed into an MLP layer. The GFE module effectively enhances key features to improve the uniqueness of the global descriptor.

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Method

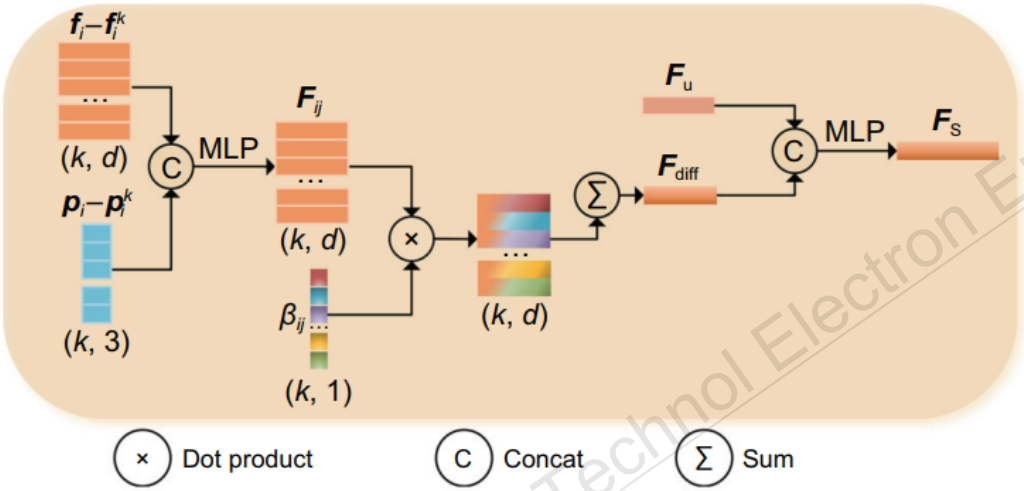


Fig. 2 Network of the RFE unit. d denotes the dimension of the features

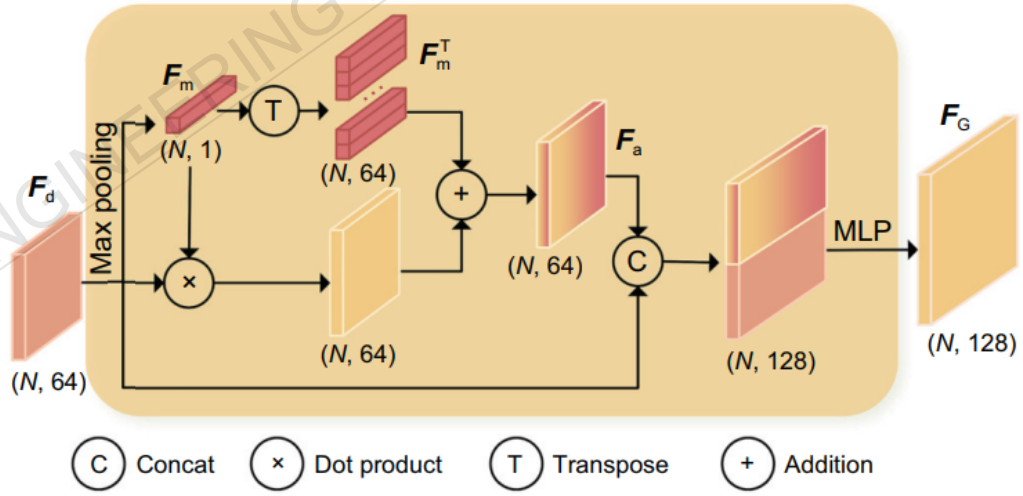


Fig. 3 Network of the GFE module

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Results

Table 1 AR@1% for different models trained on the Oxford dataset

Method	AR@1% (%)			
	Oxford	U.S.	R.A.	B.D.
PointNetVLAD (Uy and Lee, 2018)	81.01	77.82	69.75	65.30
PCAN (Zhang WX and Xiao, 2019)	83.90	79.13	71.15	66.90
DH3D (Du et al., 2020)	84.26	81.50	72.10	68.39
LPD-Net (Liu Z et al., 2019)	94.53	95.93	90.72	87.50
EPC-Net (Hui et al., 2022)	95.20	95.42	88.10	84.24
SOE-Net (Xia et al., 2021)	96.40	93.17	91.47	88.45
SVT-Net (Fan et al., 2022)	97.80	96.50	92.70	90.70
HiTPR-F8 (Hou et al., 2022)	94.64	94.01	89.11	88.31
SAGE-Net (Hao et al., 2024)	96.36	97.54	93.00	90.72
LPS-Net (Liu CX et al., 2024)	97.01	98.13	93.35	90.41
RA-Net	97.43	98.58	94.62	91.38

Table 2 AR@1 for different models trained on the Oxford dataset

Method	AR@1 (%)			
	Oxford	U.S.	R.A.	B.D.
PointNetVLAD (Uy and Lee, 2018)	62.76	63.01	56.18	57.21
PCAN (Zhang WX and Xiao, 2019)	69.05	62.49	56.99	58.14
DH3D (Du et al., 2020)	73.28	64.44	57.92	60.08
LPD-Net (Liu Z et al., 2019)	85.62	85.68	83.39	80.89
EPC-Net (Hui et al., 2022)	86.86	86.33	79.18	77.79
SOE-Net (Xia et al., 2021)	89.37	82.46	82.92	83.33
SVT-Net (Fan et al., 2022)	93.70	90.10	84.30	85.50
HiTPR-F8 (Hou et al., 2022)	87.77	86.00	81.32	81.80
SAGE-Net (Hao et al., 2024)	90.04	93.03	86.08	86.08
HiBi-Net (Shu and Kwon, 2024)	87.46	87.81	85.76	83.03
LPS-Net (Liu CX et al., 2024)	91.56	92.14	85.49	84.70
RA-Net	92.71	95.48	87.90	86.84

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Results

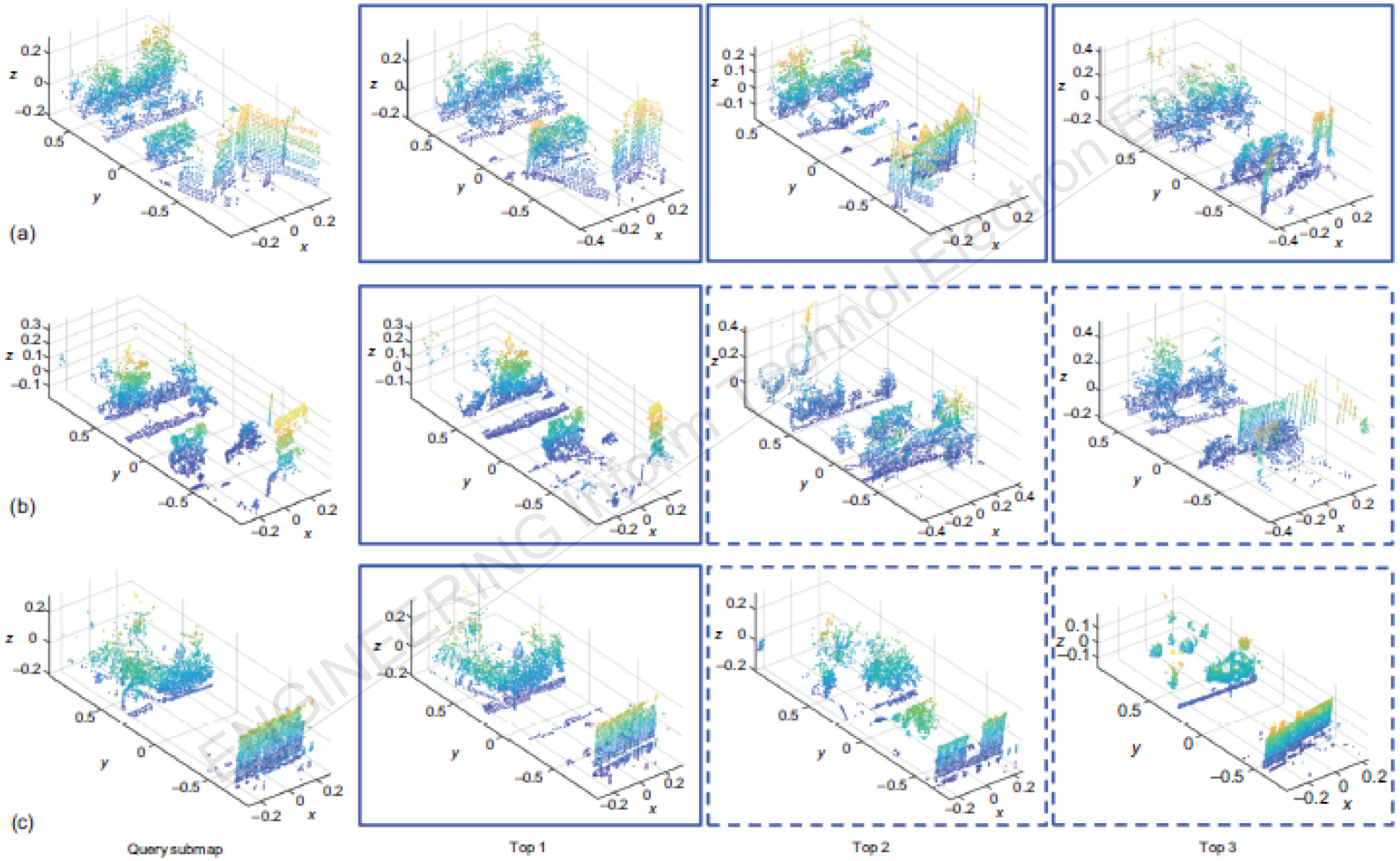
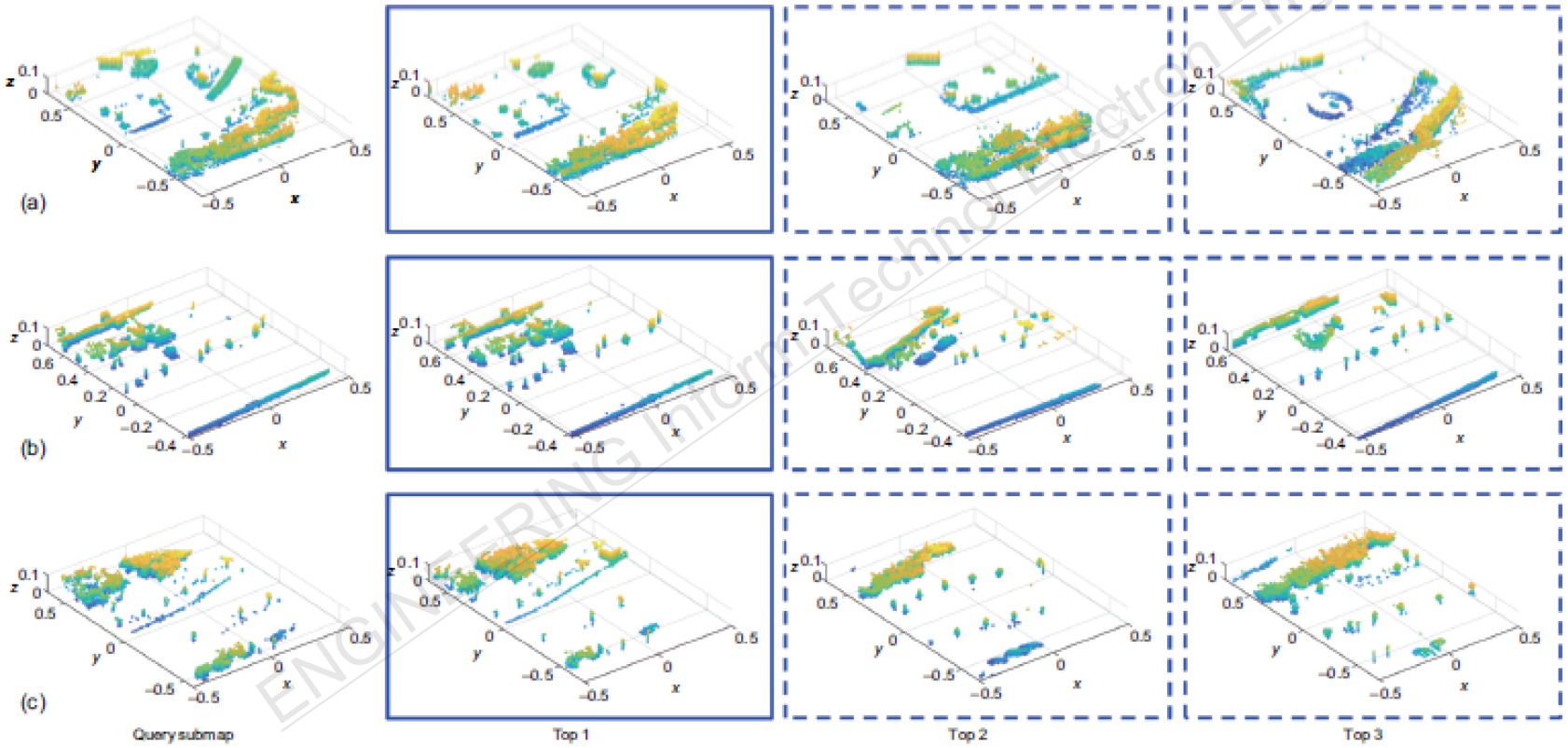


Fig. 5 Visualizations of retrieval results of RA-Net on the Oxford dataset. In these visualizations, the first column displays three different query point clouds, while the following three columns show the top-3 retrieved submaps. The query point clouds contain buildings and trees (a), highly incomplete buildings (b), and low shrubs, a regularly shaped building wall, and curbs (c). The solid-line quadrilaterals denote positive matches, and the dotted-line quadrilaterals denote incorrect matches

Results



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Fig. 6 Visualizations of retrieval results of RA-Net on the U.S. (a), R.A. (b), and B.D. (c) datasets. The solid-line quadrilaterals denote positive matches, and the dotted-line quadrilaterals denote incorrect matches

Results

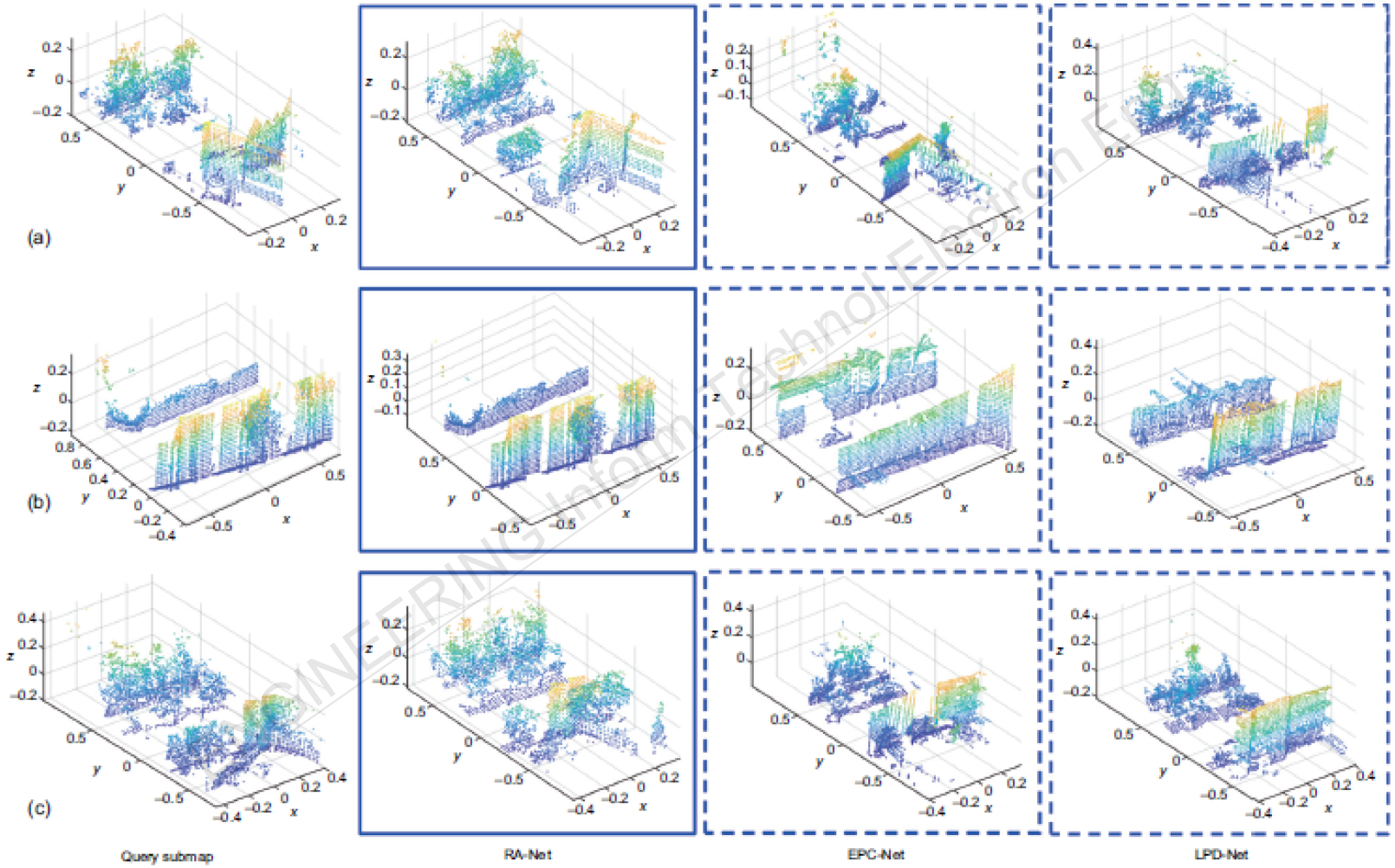


Fig. 7 Comparison of different methods on the Oxford dataset. The first column presents different query submaps, and the subsequent three columns show the retrieval results for our RA-Net, EPC-Net, and LPD-Net. The query point clouds contain structurally diverse trees and incomplete building walls (a), regularly shaped buildings (b), and trees and planes (c). The solid-line quadrilaterals represent successful retrievals, while dotted-line quadrilaterals indicate failures

Results

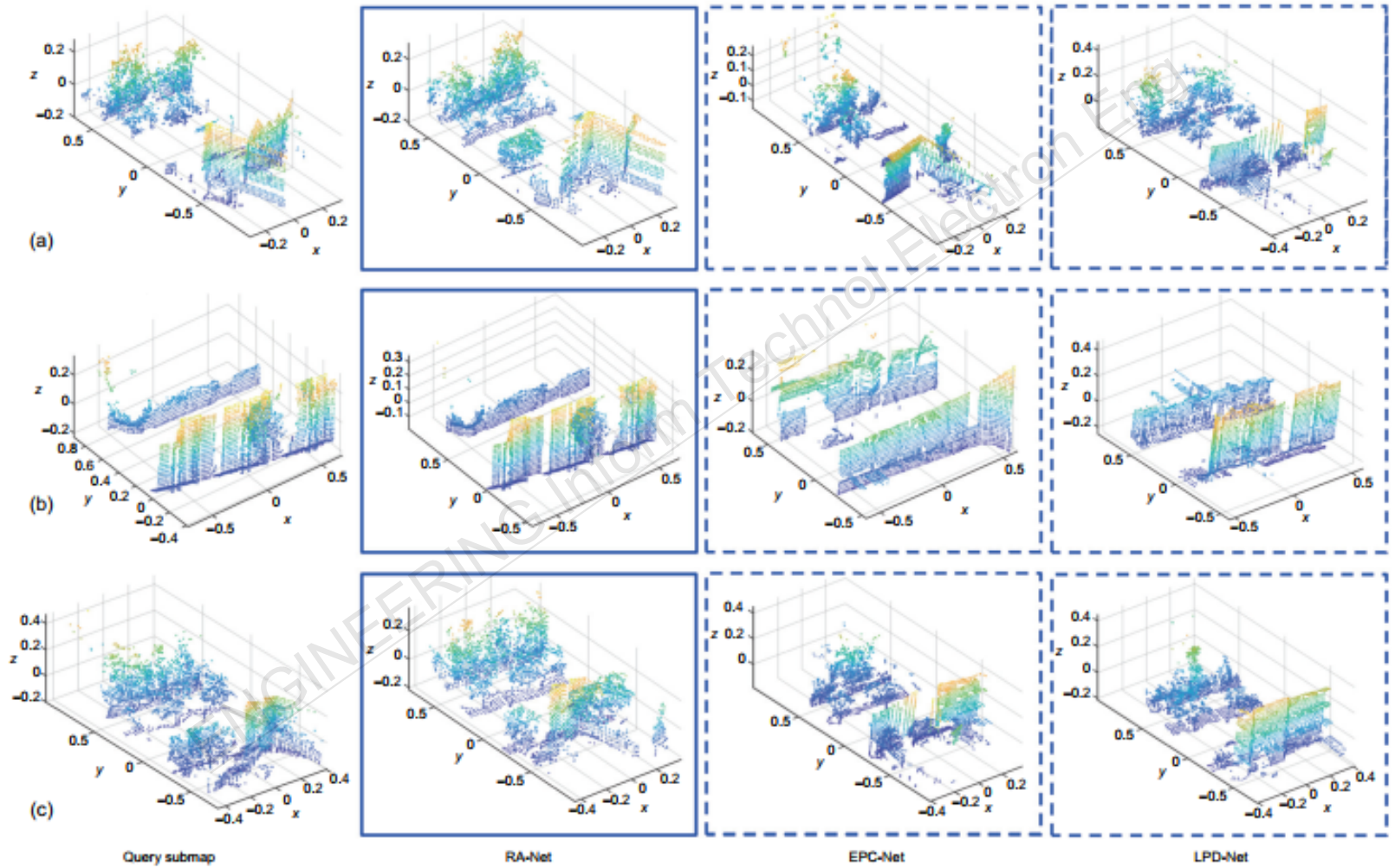


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Conclusions

In this paper, we propose a novel point cloud-based place recognition network RA-Net. By learning relation-aware local representations and incorporating global contextual information, the proposed method generates more discriminative scene descriptors for robust large-scale place recognition. Extensive experiments on benchmark datasets demonstrate that the proposed RA-Net achieves superior performance compared to SOTA methods.

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