

StructVPR: Distill Structural Knowledge with Weighting Samples for Visual Place Recognition

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Abstract

Visual place recognition (VPR) is usually considered as a specific image retrieval problem. Limited by existing training frameworks, most deep learning-based works cannot extract sufficiently stable global features from RGB images and rely on a time-consuming re-ranking step to exploit spatial structural information for better performance. In this paper, we propose StructVPR, a novel training architecture for VPR, to enhance structural knowledge in RGB global features and thus improve feature stability in a constantly changing environment. Specifically, StructVPR uses segmentation images as a more definitive source of structural knowledge input into a CNN network and applies knowledge distillation to avoid online segmentation and inference of seg-branch in testing. Considering that not all samples contain high-quality and helpful knowledge, and some even hurt the performance of distillation, we partition samples and weigh each sample's distillation loss to enhance the expected knowledge precisely. Finally, StructVPR achieves impressive performance on several benchmarks using only global retrieval and even outperforms many two-stage approaches by a large margin. After adding additional re-ranking, ours achieves state-of-the-art performance while maintaining a low computational cost.

1. Introduction

Visual place recognition (VPR) is a critical task in autonomous driving and robotics, and researchers usually regard it as an image retrieval problem [28, 30, 54]. Given a query RGB image from a robot, VPR aims to determine whether the robot has been to this place before and to identify the corresponding images from a database. Extreme environmental variations are challenging to methods, especially long-term changes (seasons, illumination, vegetation)

(a) SEG is better than RGB (b) RGB is better than SEG

Figure 1. Examples of query images and ground truths. The marked number represents the recall performance of two pre-trained branches on ground truths. (a) shows the scene with illumination variation and seasonal changes, where segmentation images are more recognizable. (b) shows the scene with changing perspectives, where RGB images are more recognizable.

and dynamic occlusions. Therefore, learning discriminative and robust features is essential to distinguish places.

There has been a commonly used two-stage strategy that retrieves candidates with global features and then re-ranks them through local descriptor matching, where re-ranking is time- and resource-consuming but dramatically improves the recall performance. The improvement is because geometric verification based on local features provides rich and explicit structural information, which has stronger robustness to VPR than appearance information in some aspects, such as shape, edge [3], spatial layout, and category [13]. Considering that segmentation (SEG) images have rich structural information, we tried some empirical studies using RGB and SEG as network input for VPR. We find that these two modalities have their advantages and disadvantages at the sample level, which means that better performance can be achieved if both modalities are appropriately fused. As Figure 1 shows, both modalities have specific cases they are better at recognizing.

Based on the above discussion, we attempt to use the SEG modality to enhance structural knowledge in global RGB feature representation, achieving comparable performance to re-ranking while maintaining low computational

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cost. Complementarity of the two modalities on samples, scriptors has achieved superior performances [5, 11, 24, 32]. that is, some samples may contain harmful knowledge for Global descriptors can be generated by directly extracting RGB, inspires us to perform knowledge enhancement selec- [8, 16, 38, 40, 58] or aggregating local descriptors. For ag- gregation, traditional methods have been incorporated into tively. Therefore, we propose a new knowledge distillation CNN-based architectures [1, 31]. To achieve a good com- promise between accuracy and ef ciency, a widely used ar- modality to the RGB modality. Speci cally, StructVPR chitecture is to rank the database by global features, and uses RGB images and encoded segmentation label maps fathen re-rank the top candidates [29, 43]. Many studies have separate pre-training with VPR loss, uses two pre-trainedveried its validity [42, 45, 46, 48].

branches to partition samples, and then weights the distil- Recently, many methods [35–37, 56, 57] try to intro- lation loss to selectively distill the high-quality knowledge duce semantics into RGB features by using attention mech- of the pre-trained seg-branch into the nal RGB network. anism or additional information. TransVPR [51] introduces Note that the concept of “sample” is a sample pair with a the attention mechanism to guide models to focus on in- query and a labeled positive. Compared with non-selectivevariant regions and extract robust representations. DAS- distillation methods [9] and previous selective distillation GIL [23] uses multi-task architecture with a single shared works [50], StructVPR can exactly mine those suitable sam- encoder to create global representation, and uses domain ples on which the teacher network performs good and betteradap- tation to align models on synthetic and real-world than the student and distinguish the importance of sampled- datasets. Based on [23], [34] focuses on ltering semantic knowledge for KD. Moreover, overly re ned segmentation information via an attention mechanism.

is not helpful, and the importance of all semantic classes Knowledge Distillation. It is an effective way to varies for VPR. Hence, we cluster original classes accord- enrich models with knowledge distillation (KD) [17]. It ing to the sensitivity to objects in VPR and introduce prior extracts speci c knowledge from a stronger model (i.e., information of labels via weighted one-hot encoding. “teacher”) and transfer to a weaker model (i.e., “student”)

Our main contributions can be highlighted as follows: through additional training signals. There has been a large body of work on transferring knowledge with the same 1) The overall architecture avoids the computation and in- modality, such as model compression [4, 7, 21] and domain ference of segmentation during testing by distilling the adaptation [2, 26]. However, the data or labels for some modality, where segmentation images are pre-encoded into- modalities might not be available during training or test- weighted one-hot label maps to extract structural infor- ing, so it is essential to distill knowledge between different mation for VPR. 2) To the best of our knowledge, there modalities [39, 55]. [12, 22] generate a hallucination net- is no previous work in VPR concerning selecting suitable work to model depth information and enforce it for RGB samples for distillation. StructVPR forges a connection descriptors learning. In this way, the student learns to simu- between sample partition with student network participat- late a virtual depth that improves the inference performance. ing and weighted knowledge distillation for each sample. In this work, we construct a weighted knowledge distilla- 3) We perform comprehensive experiments on key bench- tion architecture to distill and enhance high-quality struc- marks. StructVPR performs better than global methods tural knowledge into RGB features.

and achieves comparable performance to many two-stage Nevertheless, these previous works enhance the tar- (global-local) methods. The consistent improvement in get model by transferring knowledge on each training sam- all datasets corroborates the effectiveness and robustnessple from the teacher model, rarely discussing the difference of StructVPR. Experimental results show that StructVPR about knowledge among samples [14, 27]. Wangl. [50] achieves SOTA performance with low computational cost proposes to select suitable samples for distillation through compared with global methods, and it is also competitive analyzing the teacher network. Differently, our solution with most two-stage approaches [6, 20]. StructVPR with re- considers both pre-trained teacher and student network in ranking outperforms the SOTA VPR approaches (4%475 sample partition and weight the distillation loss for samples. absolute increase on Rec@5 compared with the best base- line [51]).

2. Related Work

Visual Place Recognition. Most of the research on utilize segmentation images to embed rich structural knowl- VPR has focused on constructing better image representa- edge into RGB global retrieval and achieve comparable per- formance to two-stage methods. The key idea of StructVPR a single RGB image is to use global descriptors or local is very general: selectively distill high-quality and helpful descriptors. More recently, using CNNs to build local de- knowledge into a single-input model by weighting samples.

3. Methodology

Figure 2. Illustration of the proposed pipeline. We first pre-train two branches with VPR supervision to extract structural knowledge, and then we perform of line group partition and weighting on samples. Then weighted knowledge distillation and VPR supervision are performed in Stage II. During testing, StructVPR avoids the computation and inference of segmentation, using only the trained model in Stage II. More importantly, it can maximize the efficiency of distilling high-quality knowledge.

StructVPR includes two training stages: structural knowledge extraction and group partition, and weighted knowledge distillation. Figure 2 explains how StructVPR works.

3.1. Overview

Given an input RGB image I^R , its pairwise segmentation image I^S is extracted by an open-source semantic segmentation model and converted into a fixed-size label map via segmentation label map encoding (SLME) module.

Then the seg-branch and rgb-branch are pre-trained with VPR loss. Based on the two pre-trained branches and designed evaluation rules, training sets can be partitioned and different groups represent samples with different performances of seg-branch and rgb-branch. Given the domain knowledge in VPR, the concept of “sample” is generalized as a sample pair of a query and a positive. There are two specific aspects of domain knowledge: First, VPR datasets are often organized into query and database in which each query image q has a set of positive samples p^q and a set of negative samples n^q . Second, the knowledge to be enhanced is feature invariance and robustness under changes between sample pairs in a scene.

Moreover, a weighting function is defined, and we perform weighted knowledge distillation and vanilla VPR supervision in Stage II.

3.2. Segmentation Label Map Encoding

It is nontrivial to convert segmentation images to a standard format before inputting them into the seg-branch, as each image contains a different number of semantic instances. As shown in Figure 2, the segmentation label map

encoding (SLME) function encodes segmentation information to standard inputs of CNNs, including three steps: formatting, clustering, and weighting.

Firstly, like LabelEnc [19], we use a $C \times H \times W$ tensor to represent segmentation images, where W equals the RGB image size and C is the number of semantic classes. Regions of the c -th class are filled with positive values in the c -th channel and 0 in other channels.

Secondly, derived from human experience, we incorporate the semantic labels that have similar effects on VPR, such as cars and bicycles being re-labeled as “dynamic objects”. It does this because too fine-grained segmentation will interfere with VPR like noises [34], which distracts model’s “attention” and increase the difficulty of model convergence, shown in Figure 3. Moreover, a large will lead to excessive computation. Moreover, this step lets models focus on useful parts and reduces computational costs.

Finally, based on the idea that each semantic class plays a different role in VPR task, we weigh positive values in the encoding as prior information to guide the optimization of models and accelerate their convergence. The attention mechanism of the human brain will allow humans to focus on iconic objects, such as buildings, while ignoring dynamic objects, such as pedestrians. In Section 4.4, experimental results corroborate our idea.

3.3. Structural Knowledge Extraction

In the first training stage, we train seg-branch and rgb-branch to extract structural knowledge into features and prepare for subsequent group partition.

Figure 3. Visualization of clustered semantic classes. From left to right are RGB images, 6-class segmentation images, and original segmentation images. It can be seen that the label space after clustering is cleaner for VPR.

Rgb-branch. We use MobileNetV2 [41] as our lightweight extractor. We remove the global average pooling layer and fully connected (FC) layer to obtain global features. According to the resolution of the feature maps, the backbone can be divided into 5 stages. The output feature maps are denoted as $F_1^R, F_2^R, F_3^R, F_4^R, F_5^R$, and the global feature is denoted as F^R .

Seg-branch. Considering that segmentation label maps are more straightforward and have a higher semantic level than the paired RGB images, we adopt the depth stream in MobileSal [53] as the feature extractor in seg-branch. It has five stages with same strides and is not as large a capacity as MobileNetV2, denoted MobileNet-L in our paper. The output feature maps of five stages are denoted as $F_1^S, F_2^S, F_3^S, F_4^S, F_5^S$, and the global feature is represented as F^S .

Multi-level Concatenation (MC). In Figure 4, we first apply a global max pooling (GMP) layer to each feature map, F_i , to compute single-level features, like

$$f_i = \text{L2Norm}(\text{GMP}(F_i)); \quad (1)$$

and concatenate the features from the last 3 layers:

$$x = \text{L2Norm}(\text{Concat}([f_3; f_4; f_5])); \quad (2)$$

where x is the unified representation of global features.

Triplet VPR Loss. In two training stages, we adopt triplet margin loss [44] on $(q; p; n)$ as supervision:

$$L_{\text{vpr}}(x) = \max(d(x_q; x_p) - d(x_q; x_n) + m; 0); \quad (3)$$

where x_q, x_p , and x_n refer to global features of query, positive and negative samples. $d(\cdot)$ computes the L2 distance of two feature vectors, and m is a constant parameter.

3.4. Group Partition on Training Set

As mentioned above, not all samples contain high-quality and helpful teacher knowledge for the student, and even some will hurt the student's performance. So what we

Figure 4. Visualization of Multi-level Concatenation.

need to do is to distill the expected knowledge precisely. This section addresses this problem simply yet effectively by selecting suitable samples.

Previous sample-based selective distillation works [14, 27, 50] rarely consider the student network with specific prior knowledge, resulting in a lack of teacher-student interaction in cross-modal cases. To avoid this, we let the two pre-trained branches in Section 3.3 participate in seeking a more accurate partition.

Partition Strategy. For convenience, "samples" mentioned below refer to sample pairs (see Section 3.1). In this section, we first did some preliminary empirical research, and we found that both pre-trained models have low VPR loss on training sets, but their Recall@performance cannot achieve 100% on training sets. Therefore, the performance of the two branches on a sample pair, can be compared as follows: the ranking of the positive p in the recall list of the query q .

For convenience, recall rankings of samples of seg-branch and rgb-branch are denoted as r_s and r_r , respectively. As shown in Figure 2, specific definitions for partitioning training sets are as follows:

$$\begin{aligned} D_1 &= \{ (q; p) | x_{r_s} \leq N_t; y_{r_r} > N_t; g \} \\ D_2 &= \{ (q; p) | x_{r_s} > N_t; y_{r_r} \leq N_t; g \} \\ D_3 &= \{ (q; p) | y_{r_r} < x_{r_s} \leq N_t; g \} \\ D_4 &= \{ (q; p) | x_{r_s} > N_t; g \} \end{aligned}$$

where D_1 represents the set of samples with less than or equal to N_t and greater than N_t , and so on. N_t is a constant hyper-parameter. Intuitively, D_1 is the most essential and helpful group for knowledge distillation.

3.5. Weighted Knowledge Distillation

In order to accurately reflect the impacts of samples, here we weigh the distillation loss based on group partition in Section 3.4. This way, helpful samples are emphasized, and harmful samples are neglected.

Weighting Function. Instead of using several constant weights for different groups, we define a function to refine the weights on samples from two perspectives. One is the knowledge levels of the teacher on each sample; the higher the knowledge level, the greater the weight. Another is the knowledge gap between the teacher and the student; the greater the gap, the greater the weight.

Finally, the weight function is defined as:

$$w(q; p) = \begin{cases} 1 + \frac{\min(N_m, y)}{4 \ln(1+x)} \cdot \frac{x}{y}; & (q; p) \in D_1 \\ 1 + \frac{y}{5 \ln(1+x)} \cdot \frac{x}{y}; & (q; p) \in D_2 \\ 1 + \frac{y}{4 \ln(1+x)} \cdot \frac{x}{y}; & (q; p) \in D_3 \\ 0; & (q; p) \in D_4 \end{cases}; \quad (4)$$

where the non-zero part of w is proportional to y and inversely proportional to x . In other words, w is proportional to the performance of the seg-branch on p . This function makes each sample determine its learning degree.

Feature-based Distillation. In Stage II, the backbone structure of RGB feature extractor is also MobileNetV2, and the global feature is denoted as x^D . Because x^D and x^S for an image pair $(I^R; I^S)$ are not in the same domain and same dimension, we embed x^D via an additional linear layer in the second-stage training, called transformation function T . We adopt loss [18] in our distillation process:

$$L_{kd}(I) = - \sum_{(q; p) \in D_1} x_I^S \cdot T(x_I^D)^2; \quad (5)$$

where n is the negative sample corresponding to $(q; p)$ in the second-stage training. Note that x_I^S corresponds to the trained seg-branch in Stage I.

Hence, the extraction model in Stage II can be trained by minimizing the loss as:

$$L(q; p; n) = L_{vpr}(x^D) + \sum_{(q; p; n) \in D} L_{kd}(I); \quad (6)$$

4. Experiments and Analysis

4.1. Datasets and Evaluation

Datasets with still challenging variations are considered in our work, and the summary is shown in Table 1: Mapillary Street Level Sequences (MSLS) [52], Pittsburgh [49], and Nordland [47]. Compared with MSLS, Pittsburgh contains many urban buildings shot at close range from non-horizontal perspectives, resulting in insufficient categories and instances contained in segmentation images. That is, MSLS has obvious structural information, while Pittsburgh has relatively weak structural information. So we train models on these two datasets separately to illustrate that datasets do not limit the effectiveness of StructVPR.

For all datasets, ReCall is used. A given query is regarded to be correctly localized if at least one of the top retrieved database images is within a ground truth tolerance of default configuration for these datasets [33, 49, 52].

4.2. Implementation Details

Our method is implemented in PyTorch. To obtain segmentation images, we use open-source models.

¹In the main paper, we only show the results of one model, and the rest are in the Supplementary Material, which demonstrates that StructVPR is compatible with many models.

Table 1. Summary of datasets for evaluation. ++, +, and indicate degrees from high to low.

Dataset	Structural information	Environment		Variation			
		Urban	Suburban	View	Light	Long-term	Dynamic
MSLS [52]	++	X	X	+	+	+	+
Nordland [47]	+		X			++	
Pittsburgh [49]		X		+			+

are resized to 640 × 480. In the SLME module C is set as 6, including vegetation, dynamic objects, sky, ground, buildings, and other objects, and initial encoded values are 0.5, 0.5, 1, 1, 2, 2. For rgb-branch, we use MobileNetV2 as the backbone, remove the FC layer, and add the MC layer (Section 3.3) (dim=448). For seg-branch, we build a smaller backbone than MobileNetV2 and concatenate the last three levels to conduct global features (dim=480). For group partition strategy, $N_t = 10$ and $N_m = 20$.

Training. In both training stages, MobileNetV2 is used as the RGB feature extractor and is initialized with the pre-trained weights on ImageNet [25], and MobileNet-L is initialized with random parameters in seg-branch. In both training stages, we train models on two datasets: Pittsburgh 30k for urban imagery (Pittsburgh dataset) and MSLS for all other conditions. The MSLS training set provides GPS coordinates and compass angles, so images most similar to the query field of view are selected as positive samples. Considering that the Pittsburgh 30k dataset only has location labels, the weakly supervised positive mining strategy proposed in [1] is adopted. Further details are presented in the Supplementary Material.

4.3. Comparisons with State-of-the-Art Methods

Baselines. We compared our method against several state-of-the-art image retrieval-based localization solutions, including two methods using global descriptors only: NetVLAD [1] and SFRS [15], and four methods which additionally perform re-ranking using spatial verification of local features: DELG [6], Patch-NetVLAD [20], SP-SuperGlue and TransVPR [51]. DELG, Patch-NetVLAD, and TransVPR jointly extract global and local features for image retrieval, while SP-SuperGlue re-ranks NetVLAD retrieved candidates by using SuperGlue [43] matcher to match SuperPoint [10] local features. For Patch-NetVLAD, we tested its speed-focused and performance-focused configurations, denoted as Patch-NetVLAD-s and Patch-NetVLAD-p, respectively. More installation details are explained in the Supplementary Material.

Re-ranking Backend. Candidates obtained through global retrieval are often re-ranked using geometric verification or feature fusion. In this paper, our main contribution is based on extracting global features, so we use two classic re-ranking methods (i.e., RANSAC and SuperGlue) as the backend to compare with the other two-stage algorithms.

Table 2. Comparison to SOTA methods on datasets. The results of global retrieval and re-ranking with local features are shown.

Method		Venue	MSLS val			MSLS challenge			Nordland test			Pittsburgh30k test		
			R@1	R@5	R@10	R@1	R@5	R@10	R@1	R@5	R@10	R@1	R@5	R@10
Global retrieval	NetVLAD [1]	CVPR'16	53.1	66.5	71.1	28.6	38.3	42.9	11.5	17.6	21.9	81.9	91.2	93.7
	SFRS [15]	ECCV'20	58.8	68.2	71.8	30.7	39.3	42.9	14.3	23.1	27.3	71.1	81.0	84.9
	DELG [6]	ECCV'20	68.4	78.9	83.1	37.6	50.5	54.6	27.0	43.3	50.0	79.0	89.0	92.7
	Patch-NetVLAD-s [20]	CVPR'21	63.5	76.5	80.1	36.1	49.9	55.0	18.1	33.2	41.1	81.3	91.1	93.4
	Patch-NetVLAD-p [20]	CVPR'21	70.0	80.4	83.8	38.1	51.2	55.3	24.8	39.4	48.0	83.7	91.8	94.0
	TransVPR [51]	CVPR'22	70.8	85.1	89.6	48.0	67.1	73.6	31.3	53.6	64.8	73.8	88.1	91.9
	(A) Ours		83.0	91.0	92.6	64.5	80.4	83.9	56.1	75.5	82.9	85.1	92.3	94.3
Re-ranking	SP-SuperGlue [10, 43]	CVPR'20	78.1	81.9	84.3	50.6	56.9	58.3	37.9	41.2	42.6	87.2	94.8	96.4
	DELG [6]	ECCV'20	83.9	89.2	90.1	56.5	65.7	68.3	64.4	70.8	72.7	89.9	95.4	96.7
	Patch-NetVLAD-s [20]	CVPR'21	77.2	85.4	87.3	48.1	59.4	62.3	50.9	62.7	66.5	88.0	94.5	95.6
	Patch-NetVLAD-p [20]	CVPR'21	79.5	86.2	87.7	51.2	60.3	63.9	62.7	71.0	73.5	88.7	94.5	95.9
	TransVPR [51]	CVPR'22	86.8	91.2	92.4	63.9	74.0	77.5	77.8	86.8	89.3	89.0	94.9	96.2
	(B) Ours-SP-RANSAC		87.3	91.4	92.8	65.5	76.3	81.3	76.8	86.3	90.1	89.4	95.2	96.5
	(B) Ours-SP-SuperGlue		88.4	94.3	95.0	69.4	81.5	85.6	83.5	93.0	95.0	90.3	96.0	97.3

SuperPoint [10] descriptors are used as our local features. For SuperGlue, we use the official implementation and configuration. For RANSAC, the maximum allowed reprojection error of inliers is set to 24.

Quantitative comparison. Table 2 compares ours against the retrieval approaches. There are two settings for StructVPR: (A) global feature similarity search and (B) global retrieval followed by re-ranking with local feature matching (SP-RANSAC, SP-SuperGlue). In the experiments, we first compare our global model with all methods. Then re-ranking algorithms are used as our backend to compare with those two-stage algorithms. For all two-stage methods, the top 100 images are further re-ranked.

In setting (A), ours-global convincingly outperforms all compared global methods by a large margin on MSLS validation, MSLS challenge, and Nordland datasets. Compared with the best global baseline, the absolute increments on Recall@1 are 12.2%, 16.5% and 14.8%, and the ones on Recall@5 are 5.9%, 13.3% and 21.9% respectively. More importantly, ours-global is better than almost all two-stage ones on Recall@5 and Recall@10 which shows the potential of our method for improvement on Recall@1. Ours-global also achieves SOTA results on Pitts30k dataset, with a 1.4% increment on Recall@1 over Patch-NetVLAD. We observe that the global model trained on MSLS shows a significant improvement compared with previous SOTA methods, while the one by Pitts is relatively mediocre. Such results are due to differences in datasets, that is, whether the scene contains enough structural information. This experimental phenomenon also proves that datasets do not limit StructVPR: on datasets with obvious structural information, it can effectively improve performance; on datasets with insignificant structural information, it can achieve effective distillation without hurting the RGB performance.

In setting (B), ours-SP-SuperGlue achieves SOTA per-

Table 3. Latency and memory footprint. The following data is measured on NVIDIA GeForce RTX 3090 GPU and Intel Xeon Gold 6226R CPU. For global retrieval methods, matching time and memory requirements are negligible.

	Method	Extraction latency (ms)	Matching time (s)	Memory (MB)
Global retrieval	NetVLAD [1]	40		
	SFRS [15]	207		
	Ours	2.25		
Re-ranking	SP-SuperGlue [10, 43]	35	6.4	1.93
	DELG [6]	199	45.7	0.37
	Patch-NetVLAD-s [20]	42.5	3.29	1.82
	Patch-NetVLAD-p [20]	625	25.6	44.14
	TransVPR	8	3.5	1.17

formance on all datasets, illustrating the importance of global retrieval compared with SP-SuperGlue. Ours-SP-SuperGlue outperformed the best baseline (TransVPR) on key benchmarks by an average of 3.53% (absolute increase) and by 4.48% (absolute increase).

Please refer to Supplementary Material for detailed qualitative results.

Latency and memory footprint. In real-world VPR systems, latency and resource consumption are important factors. As shown in Table 3, latency and memory requirements refer to processing a single query image.

Ours, with only the global retrieval step, has a great advantage in latency over all other algorithms. Ours-SP-SuperGlue achieves SOTA recall performance, and the extra computational latency and memory are the same as SP-SuperGlue. It is 5.3 times and 16.8 times faster than DELG and Patch-NetVLAD-p in feature extraction, and it is 7.1 times and 4 times faster than them in spatial matching.

In summary, previous high-accuracy two-stage methods mainly rely on re-ranking, which comes at a high computational cost. On the contrary, our global retrieval results

Figure 5. Qualitative results. In these examples, StructVPR successfully retrieves matching reference images, while rgb-branch produces incorrect place matches.

Table 4. Comparison to other fusion solutions on MSLS. Extraction latency includes the time to generate segmentation images.

Arch	MSLS val			MSLS challenge			Extraction latency (ms)
	R@1	R@5	R@10	R@1	R@5	R@10	
SEG	67.7	80.0	83.1	43.4	58.9	65.8	4+ 385
RGB	75.8	85.3	87.3	55.1	71.9	76.4	2.25
Multi-task	75.3	86.2	88.7	56.8	72.3	77.1	2.25
C-feat	75.5	86.5	88.8	55.9	73.3	78.1	6.25+ 385
C-input	<u>77.7</u>	<u>88.4</u>	<u>91.4</u>	<u>59.7</u>	<u>76.9</u>	<u>81.2</u>	21.6+ 385
KD(Ours)	83.0	91.0	92.6	64.5	80.4	83.9	2.25

are good with low computational cost, achieving a better balance of accuracy and computation.

4.4. Ablation Studies

We conduct several ablation experiments to validate the proposed modules in our work. The results on MSLS are given here, and the results on other datasets are presented in the Supplementary Material.

Fusion Solutions. In the preliminary empirical studies, it has been demonstrated that segmentation images benefit VPR, and many solutions can achieve the fusion of two modalities in global retrieval. Here we give several feasible solutions and compare them:

- **Concat-input:** Concatenate RGB image and encoded segmentation label map in channel as input and train the model. Segmentation is required during testing.
- **Concat-feat:** Two feature vectors from two separate models are concatenated into a global feature. Segmentation is required during testing.
- **Multi-task:** Use the encoder-decoder structure, share the encoder with two tasks, and use the segmentation map as the supervision of the decoder. Segmentation is not required during testing.
- **Knowledge distillation (Ours):** Segmentation is not required during testing.

We train and compare them on MSLS and count the extraction latency during testing. Extraction latency is the time to obtain global features from a single RGB image.

As shown in Table 4, all fusion algorithms perform better than the two separate branches (RGB, SEG) on the MSLS dataset. But the performance of Concat-feat is limited,

Figure 6. Performance of seg-branch with different number of clustered classes on (a) MSLS val. and (b) MSLS test dataset.

which may be due to a lack of coherence between two modalities. Although both Concat-input and KD perform relatively well, Concat-input requires additional processing of segmentation images during testing and has a larger model compared with KD. Neither Multi-task nor KD use segmentation images during testing. However, it is worth noting that the training of Multi-task has high requirements for parameter tuning, and KD is more direct and interpretable than Multi-task. Here we qualitatively demonstrate the advantages that StructVPR brings in Figure 5.

Segmentation label map encoding. The number of original semantic labels of the open-source model is 150. In Section 3.2, we use an encoding function to convert segmentation images into weighted one-hot label maps. Considering that C and the prior weight setting are the most important hyper-parameters for our work, we perform ablation experiments on them. We also test C = 3; 150 in seg-branch for the number of clustered classes. After clustering, the redefined 3 categories are sky & ground, dynamic objects, and static objects. In addition, we present the results of different prior weight settings for C = 6.

Figure 6 shows the results on the MSLS dataset. It can be seen that a too-small value of C is not advisable, which will lose the uniqueness of the scene in our view, and the performance is poor when C = 150, which means that too fine-grained segmentation makes training more difficult. Finally, C is set as 6. α stands for the opposite weight configuration: 0.5 for static objects and other objects, 2 for dynamic objects and vegetation. Comparing the results of unweighted and two weighted cases, we can qualitatively conclude that introducing appropriate prior weights can guide the model to converge better. Further analysis on prior weights is presented in the Supplementary Material.

Group partition strategy and the impact of groups. This paper proposes that not all samples are helpful in distillation and selects samples by group partitioning. At the same time, we propose using two pre-trained branches to participate in group partition together, instead of just using a separate one, to improve the accuracy of group partition and further achieve more accurate weighted KD. In this ex-

Figure 7. Visualization of different group partition strategies. Compared with our strategy (GP-D), which uses two models, both GP-S and GP-R have only one model involved in the partition.

Table 5. Performance of selective distillation with different samples. None refers to the rgb-branch without distillation and All refers to non-selective distillation.

Group for distillation	Sample ratio	MSLS val			MSLS challenge		
		R@1	R@5	R@10	R@1	R@5	R@10
None	0%	75.8	85.3	87.3	55.1	71.9	76.4
All	100%	78.4	87.4	90.1	59.1	73.5	79.3
D ₁	4.11%	78.8	<u>89.2</u>	91.1	<u>62.3</u>	76.8	80.9
D ₂	50.67%	80.0	88.8	90.6	59.1	75.5	79.3
D ₃	14.77%	77.7	87.4	89.2	57.8	74.4	79.1
S ₁	69.55%	<u>81.6</u>	88.9	<u>91.2</u>	62.2	<u>77.2</u>	<u>82.0</u>
S ₂ (D ₄)	30.45%	71.6	83.7	85.1	48.2	63.9	68.7
R ₁	73.24%	79.3	87.6	88.9	57.0	74.1	78.2
R ₂	26.76%	73.8	82.7	85.6	51.0	67.0	72.3
Ours	69.55%	83.0	91.0	92.6	64.5	80.4	83.9

periment, we perform selective KD to verify the importance of each group, which is a degenerate version of weighting for samples. In our expectation, samples of different groups should have different effects on distillation.

We compare our standard partition strategy (GP-D) with two degenerate configurations, as shown in Figure 7:

- Group partition with seg-branch (GP-S). Only the teacher network participates in the group partition.
- Group partition with rgb-branch (GP-R). Only the student network participates in the group partition.

For selective KD, GP-D uses samples belonging to D_1, D_2, D_3 , GP-R uses S_1 , and GP-S uses S_1 . The meaning of S_1, S_1, S_1, S_1 can refer to Section 3.4.

As shown in Table 5, we select a single group, in turn, to participate in distillation and evaluate its effectiveness. The results show that D_2 and R_2 harm distillation and other groups have different degrees of positive impact. It stands for non-selective KD using all samples in KD. However, its results are not as good as S_1 and D_1 , indicating that the quality of samples is as important as the quantity for KD. So it is necessary to select suitable samples in distillation.

In this experiment, GP-S performs better than GP-R, and GP-D degenerates to GP-S. Furthermore, our partitioning strategy will show a considerable advantage over GP-S in weighted knowledge distillation.

Weighting distillation loss. We compare our weighting function (Eq. (4)) with constant weights to illustrate the importance of fine-grained weight assignment for samples.

Table 6. Performance of weighted distillation with different weights. The weights correspond to S_1, S_2 and D_1, D_2, D_3, D_4 , and GP-S(1-0) is equal to GP-D(1-1-1-0).

Weight	MSLS val			MSLS challenge		
	R@1	R@5	R@10	R@1	R@5	R@10
GP-S(1-0)	81.6	88.9	91.2	62.2	77.2	82.0
GP-D(8-4-1-0)	<u>82.2</u>	88.9	91.5	62.3	<u>78.9</u>	82.4
GP-S($^l(q;p)$)	79.7	<u>89.5</u>	<u>92.0</u>	<u>62.7</u>	78.4	<u>83.7</u>
GP-D($^l(q;p)$)	83.0	91.0	92.6	64.5	80.4	83.9

We have verified the importance of the groups above, which guides the design Eq. (4). The more essential samples for distillation, the higher the weight.

To further illustrate the advantages of GP-D, we also compare GP-D and GP-S with weighting functions. For GP-S, Eq. (4) degenerates into the following form:

$$w^l(q;p) = \begin{cases} 1 + \frac{1}{4 \ln(1 + \frac{1}{RN_s})}; & (q;p) \in S_1 \\ 0; & (q;p) \in S_2 \end{cases} \quad (7)$$

where the performance gap between the student network and the teacher network cannot be reflected on samples.

In Table 6, GP-D(8-4-1-0) performs better than GP-S(1-0), and GP-D($^l(q;p)$) is better than GP-S($^l(q;p)$), which illustrate the importance of precise partition. Moreover, for both GP-D and GP-S, the weight function performs better than the discrete constant weights, respectively, showing the advantages of setting weights for each sample.

5. Discussion

Conclusion. In this paper, we address the problem of using segmentation information to enhance the structural knowledge in RGB global representations, attempting to replace the re-ranking process. To avoid the computation of segmentation during testing, we use the framework of knowledge distillation. We find that the teacher's knowledge is not the more, the better; samples have different impacts on knowledge distillation, and some are even harmful. So we propose a weighted knowledge distillation method to partition samples and weigh the distillation loss for each sample. Experimental results show that StructVPR achieves SOTA performance among methods with only RGB global retrieval. Compared with two-stage methods, it is competitive with a better balance of accuracy and computation.

Limitations and Future Work. Nevertheless, some challenges remain. The clustered number and encoding values of semantic labels are chosen from five settings (Figure 6), and it calls for further advancements (details in Appendix). Considering the robustness of StructVPR to SLME, smaller SEG models can be used to reduce costs. Furthermore, we believe that StructVPR is applicable to other tasks or modalities as long as multi-modal information is complementary at the sample level for tasks.

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