Bird's-Eye-View Scene Graph for Vision-Language Navigation

Rui Liu Xiaohan Wang Wenguan Wang* Yi Yang
ReLER, CCAI, Zhejiang University
https://github.com/DefaultRui/BEV-Scene-Graph

Abstract

Vision-language navigation (VLN), which entails an agent to navigate 3D environments following human instructions, has shown great advances. However, current agents are built upon panoramic observations, which hinders their ability to perceive 3D scene geometry and easily leads to ambiguous selection of panoramic view. To address these limitations, we present a BEV Scene Graph (BSG), which leverages multi-step BEV representations to encode scene layouts and geometric cues of indoor environment under the supervision of 3D detection. During navigation, BSG builds a local BEV representation at each step and maintains a BEV-based global scene map, which stores and organizes all the online collected local BEV representations according to their topological relations. Based on BSG, the agent predicts a local BEV grid-level decision score and a global graph-level decision score, combined with a sub-view selection score on panoramic views, for more accurate action prediction. Our approach significantly outperforms state-of-the-art methods on REVERIE, R2R, and R4R, showing the potential of BEV perception in VLN.

1. Introduction

Vision-language navigation (VLN) task [1] requires an agent to navigate through a 3D environment [2] to a target location, according to natural language instructions. Existing work has made great advances in cross-modal reasoning [3–8], path planning [9–13], and auxiliary tasks for pretraining [14–18]. Their core ideas are learning to relate the language instructions to panoramic images of the environment. Though straightforward, these approaches heavily rely on 2D panoramic observations. As a result, they lack the capacity to preserve scene layouts and 3D structure, which are critical for navigation decision-making in embodied scenes. Moreover, indoor environments [2, 19–21] are characterized by substantial occlusion [22–24], posing challenges for the agent to accurately identify the objects and landmarks referenced by the instructions [1, 25].

*Corresponding author: Wenguan Wang.

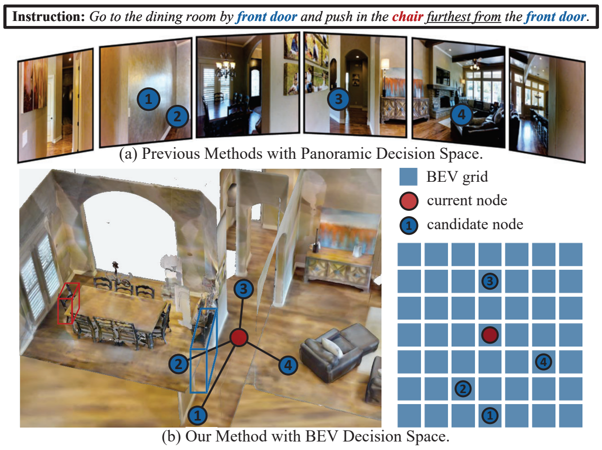


Figure 1: For panoramic view (a), two candidate nodes (1&2) correspond to the same image leading to ambiguity. For Bird's-Eye-View (b), they are represented by discriminative grids (■).

For example (Fig. 1(a)), given the instruction "*Go to the dining room by front door and push in the chair furthest from the front door*", previous approaches [3–5, 14, 15, 17, 26–30] formulate VLN as a sequential text-to-image grounding problem by matching navigable candidate nodes with adjacent panoramic views. At each time step, given a set of subviews captured from different directions, the agent selects a navigable direction as the next step for navigation. However, this strategy tends to introduce ambiguity, when the agent needs to discriminate between multiple candidate nodes corresponding to the same subview. In addition, the agent struggles to ground the associated objects and explore their spatial relation in 3D scene, such as identifying "*the chair furthest from the front door*". Consequently, relying solely on panoramic view presents difficulties in both comprehensive scene perception and efficient navigation.

To address the challenges encountered by panoramic methods, Bird's-Eye-View (BEV) perception emerges as a viable solution, employing discriminative grid representations to model the 3D environment. Meanwhile, BEV grid representation effectively captures spatial context and scene layouts [31, 32], facilitating both perception [33–36] and planning [37–40]. Building upon these insights, we present a BEV Scene Graph (BSG), which harnesses the power of

BEV representation to construct an informative navigation graph. During navigation, the agent collects local BEV representations at each navigable node. A global scene graph is established by connecting these BEV representations topologically. At each step, the agent makes an informed decision by predicting a BEV grid-level decision score and a BSG graph-level decision score, combined with a subview selection score on panoramic views [13, 28, 41].

Specifically, the agent acquires multi-view observations at each step and performs view transformation [35, 42–44] on the corresponding image features. Later, a 3D detection head [44–46] is employed on these BEV representations to predict oriented bounding boxes, encoding object-level geometric and semantic information. During navigation, the node embeddings of BSG are represented by neighboring BEV grids. Then they are updated by querying the overlap region between BEV representations from different steps.

Previous semantic maps in robot navigation, including occupancy grids [47–50] and learnable spatio-semantic representations [51–55], have only provided top-down information without crucial 3D object information. Differently, BSG leverages the BEV representations to achieve consistency between 3D perception and decision-making while encoding geometric context. Our approach is evaluated on three benchmarks (*i.e.*, REVERIE [25], R2R [1], R4R [56]). For the referring expression comprehension in REVERIE, BSG outperforms the state-of-the-art method [28] by $\mathbf{5.14}\%$ and $\mathbf{3.21}\%$ in SR and RGS on the val unseen split, respectively. BSG also achieves $\mathbf{4}\%$ and $\mathbf{3}\%$ improvement in SR and SPL on the test split of R2R, respectively. The impressive results shed light on the promises of BEV perception in VLN task.

2. Related Work

Vision-Language Navigation (VLN). VLN task [1] has drawn significant attention in embodied AI domain. Early work typically adopts recurrent neural networks with cross-modal attention [1, 3, 5, 57, 58]. Later, various techniques have been developed to improve VLN, including: **i)** using more powerful vision-and-language embedding methods based on pre-trained transformer models [14, 15, 17, 18, 28–30, 59–61]; **ii)** exploiting more supervisory information from environment augmentation [62–64], instruction generation [3, 5, 65–67], and other auxiliary tasks [4, 9, 16, 68, 69]; **iii)** designing more efficient action planning and learning strategies by incorporating self-correction [11, 57], global action space [12, 26, 41, 70, 71], map building [13, 28, 41, 55], knowledge prompts [8, 72, 73], or ensemble of IL [1] and RL [4, 74]; and **iv)** developing more large-scale benchmarks [2, 25, 70, 75–81] and platforms [2, 79–81].

However, existing work heavily relies on panoramic subviews for navigation, suffering from the limitations of 2D perspective view. These limitations, including occlusion and a narrow field of subview, introduce ambiguity in action prediction, thereby hindering efficient navigation. In contrast, we leverage BEV representations to facilitate navigation decision-making through view transformation. These BEV representations encode geometric context of environment under the supervision of BEV-based 3D detection.

Map Representation for Navigation. To achieve accurate navigation, it is critical to develop an efficient representation of surrounding environments. In robot navigation, classical SLAM-based approaches build a map based on geometry and plan the path on this semantic-agnostic map [48, 50, 82, 83]. These approaches are built upon sensors and thus highly susceptible to measurement noises [49, 54]. To explore semantic information, learnable semantic map [10, 47–52, 54, 84] is proposed using the learnable spatial representations from a top-down view. These two types of metric maps focus on dense representations with explicit location information of environment. Moreover, topological maps [12, 13, 28, 41] are developed to model the relationship among sparse nodes in the environment, mitigating the burden of heavy computation. In addition, some efforts build topo-metric maps to combine the advantages of metric and topological maps [55, 85–87].

Existing map-based methods neglect the role of 3D perception for navigation. In contrast, BSG encodes scene layouts and geometric cues by 3D detection for comprehensive scene understanding, eventually facilitating path planning.

Perceptual Organization of 3D Scenes. Scene representation should provide information about both object semantics and layout composition [24, 88–93]. For indoor scene understanding, visual representation can take various forms, including an RGB image and depth map [19–21], voxel grids [94], and point clouds [95, 96]. As pointed by [24], structural representation [6, 97, 98] also plays a significant role, as it models the spatial relationships among different objects. Therefore, modeling visual and structural properties is critical for scene understanding. Recently, BEV feature provides a unified representation for perception and motion planning [31, 32, 37–40].

Motivated by the recent efforts that achieve learnable projection between BEV plane and perspective view [33–35, 42, 43, 99–103], we collect oriented 3D bounding boxes in Matterport3D dataset [2] and perform camera-based BEV perception for embodied amodal detection [22, 104], as opposed to previous point cloud-based detection [105–107]. Under the supervision of 3D detection, we employ BEV feature to establish scene representations that effectively capture object-level geometry information for navigation.

3. Approach

Task Setup. We illustrate our approach using R2R [1] task, where the environment is discretized as a set of navigable nodes and navigability edges. The agent observes the sur-

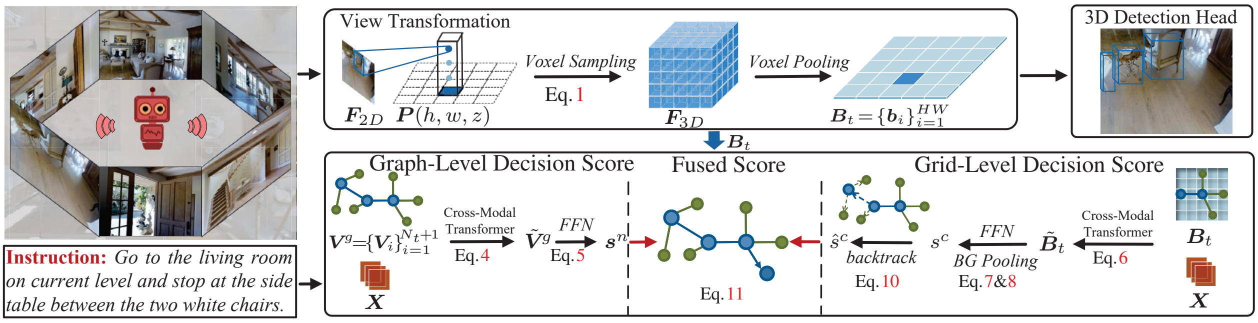


Figure 2: Overview of BSG. View transformation is first employed to project the multi-view images into BEV plane (§3.1). Then, BEV feature is encoded using 3D detection (§3.3). Through the integration of BEV representations during navigation, we predict a graph-level decision score on BSG and a grid-level decision score based on BEV. These scores are fused to facilitate effective decision-making (§3.2).

roundings at each node and finds a route to the target location, specified by the instruction $\mathcal{X}=\{x_l\}_{l=1}^{L}$ with L words.

Panoramic Methods. Previous VLN agents [4, 5, 28, 30] are built as panoramic view selectors [3] where navigable candidate nodes are represented by adjacent observations from different viewing angles. However, the adjacency rule in panoramic navigation will cause multiple candidate nodes to correspond to the same panoramic view, thus introducing ambiguity in action prediction (Fig. 1(a)). In addition, the geometric cues of 3D environment cannot be captured by visual features of 2D panoramic views, such as occluded objects [22, 104, 108, 109] and scene layouts [39, 110].

Our Idea. To overcome the above limitations, we utilize BEV features as geometry-enhanced visual representations, supervised by BEV-based 3D detection. Then, we construct BEV Scene Graph (BSG) online using BEV features (Fig. 1(b)). With BSG, the agent effectively predicts the next step on candidate nodes, which are represented by discriminate BEV grids. Before detailing BEV detection (§3.3), we first introduce how to build BSG (§3.1) and how to predict decision score for action prediction(§3.2).

3.1. BSG Construction

During navigation, the agent collects local BEV representations of surrounding environment online, and constructs a global scene graph gradually. Specifically, at time step t, BSG is denoted as $\mathcal{G}_t=\{\mathcal{V}_t,\mathcal{E}_t\}$, where each node $v\in\mathcal{V}_t$ incorporates observed information (Fig. 3), corresponding to each navigable location in the environment.

View Transformation. At current location v^*, the agent acquires multi-view camera images[1]. We perform *voxel sampling* [31, 32, 35, 44, 111] on each image feature $\boldsymbol{F}_{2D}\in\mathbb{R}^{H_cW_c\times D}$ to construct 3D voxel feature $\boldsymbol{F}_{3D}\in\mathbb{R}^{HWZ\times D}$, where H_cW_c and HW are the spatial dimensions of image feature and BEV plane, respectively. Predefined 3D reference points $\boldsymbol{P}\in\mathbb{R}^{HWZ}$ are used to query the image feature via *cross-attention* for voxel feature (Fig. 2), where HWZ denotes the number of reference points:

$$\boldsymbol{F}_{3D}(h,w,z)=\mathrm{CrossAtt}\big(\boldsymbol{P}(h,w,z),\boldsymbol{F}_{2D}(h_i,w_i)\big). \qquad (1)$$

Then, $\boldsymbol{F}_{3D}$ is squeezed down to BEV space by *voxel pooling* as $\boldsymbol{B}=\{\boldsymbol{b}_i\}_{i=1}^{HW}\in\mathbb{R}^{HW\times D}$, where each grid cell contains a D-sized latent vector, representing the corresponding region in environment. Then, BEV feature is connected with a 3D detection head (*cf.* §3.3) to predict bounding boxes, providing the agent with object-level geometry information.

Node Representation from BEV Grids. At the start of navigation (*i.e.*, $t=0$), BSG $\mathcal{G}_0$ is initialized with the node set $\mathcal{V}_0$ and its associated BEV feature $\boldsymbol{B}_0$ (Fig. 3). It is noted that there is an overlapping region Ω^{o} between $\boldsymbol{B}_t$ and $\boldsymbol{B}_{t+1}$, since the perception range is greater than the moving step. At time step $t+1$, the same spatial region will be captured by different BEV grid features from Ω^{o}. Then, we execute temporal modeling on $\boldsymbol{B}_t$ and $\boldsymbol{B}_{t+1}$ to integrate history information, thereby facilitating the representation of stationary objects [35, 112, 113]. In particular, we adopt *cross-attention* [114] on the grid features to update $\boldsymbol{B}_{t+1}$:

$$\tilde{\boldsymbol{b}}_{j,t+1}=\mathrm{CrossAtt}\big(\boldsymbol{b}_{i,t},\boldsymbol{b}_{j,t+1}\big),\ i,j\in\Omega^{\mathrm{o}}. \qquad (2)$$

Since local scene information is captured by corresponding BEV features, we construct node representations of BSG by incorporating the features of surrounding BEV grids, which are identified by nearest neighbor search [115, 116]. At step $t+1$, for current node v^* and its navigable candidate nodes $\{v_k^+\}_{k=1}^{K_{t+1}}\in\mathcal{V}_{t+1}$, we *average* the BEV grid features of corresponding neighborhood Ω_t^{n}:

$$\boldsymbol{V}_{t+1}=\mathrm{Ave}\big(\{\boldsymbol{b}_{i,t+1}\}_{i\in\Omega_t^{\mathrm{n}}}\big). \qquad (3)$$

Each node representation $\boldsymbol{V}_{t+1}\in\mathbb{R}^{D}$ attends to a certain area. For the candidate nodes that have been observed (or visited) multiple times, we *average* the previous representations as its node embedding [28, 41]. After updating BSG, we preserve $\boldsymbol{B}_{t+1}$ for subsequent action prediction (§3.2).

[1] As there are no specific camera parameters available for panoramic images from the simulator [1], we utilize the images captured by raw camera with intrinsic and extrinsic parameters [2]. Both types of images encompass identical visual content (see Appendix for details).

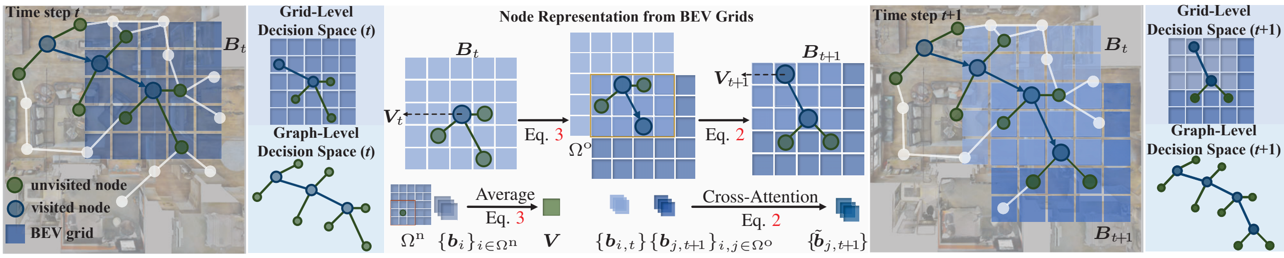


Figure 3: The node embeddings of BSG are represented by BEV grids in their neighborhood. From step t to t+1, BSG is updated using temporal modeling (§3.1). Both global graph-level and local grid-level decision space are also used for accurate action prediction (§3.2).

3.2. BEV-based Navigation Action Prediction

With the current BSG $\mathcal{G}_t = \{\mathcal{V}_t, \mathcal{E}_t\}$ and navigation instruction $\mathcal{X}$, the agent predicts next step by combining grid-level decision score on BEV feature $\boldsymbol{B}_t$ and graph-level decision score on BSG $\mathcal{G}_t$. Following [12, 28], we add a hallucination "stop" node to existing N_t $(=|\mathcal{V}_t|)$ nodes.

BSG-based Graph-level Decision Score. The word embeddings $\boldsymbol{X} \in \mathbb{R}^{L\times D}$ and node embeddings $\boldsymbol{V}^g = \{\boldsymbol{V}_n\}_{n=1}^{N_t+1} \in \mathbb{R}^{(N_t+1)\times D}$ are fed into a *cross-modal* encoder [117] with several *cross-attention* and *self-attention* layers to model the relations between instruction and graph representations:

$$\tilde{\boldsymbol{V}}^g = \{\tilde{\boldsymbol{V}}_n\}_{n=1}^{N_t+1} = \mathrm{CrossMod}\big([\boldsymbol{V}^g, \boldsymbol{X}]\big), \tag{4}$$

where $[\cdot]$ indicates the concatenation operation. After that, we adopt a feed-forward network (*FFN*) to predict the global graph-level decision score $s^n \in \mathbb{R}^{N_t+1}$ of $\mathcal{G}_t$:

$$\boldsymbol{s}^g = \{s_n^g\}_{n=1}^{N_t+1} = \mathrm{FFN}\big(\tilde{\boldsymbol{V}}^g\big). \tag{5}$$

BEV-based Grid-Level Decision Score. Grid-level decision score on $\boldsymbol{B}_t$ is crucial for the agent to understand the 3D scene and learn effective navigation policies. A similar *cross-modal* transformer [117] is used to mine fine-grained visual clues and object-related textual information from the instructions, such as "*front door*" and "*the chair furthest from the front door*":

$$\tilde{\boldsymbol{B}}_t = \{\tilde{\boldsymbol{b}}_i\}_{i=1}^{HW} = \mathrm{CrossMod}\big([\boldsymbol{B}_t, \boldsymbol{X}]\big). \tag{6}$$

Then the instruction-aware representations $\tilde{\boldsymbol{B}}_t$ is used to predict local grid-level decision score $s^l \in \mathbb{R}^{HW}$ by *FFN*:

$$\boldsymbol{s}^l = \{s_i^l\}_{i=1}^{HW} = \mathrm{FFN}\big(\tilde{\boldsymbol{B}}_t\big). \tag{7}$$

We propose a distance-dependent weighted pooling to convert the grid-level score s^l to local candidate score $s^c \in \mathbb{R}^{K_t+1}$ (containing the stop node) [1, 25]. For k-th navigable candidate node, the score is calculated as follows:

$$s_k^c = \sum\nolimits_{i\in\Omega_k^{\mathrm{n}}} W_{k,i} s_i^l, \tag{8}$$

where Ω_k^{n} is the grid neighborhood of k-th candidate node (*cf.* Eq. 3), and $\boldsymbol{W}_k = [W_{k,i}]_{i=1}^{|\Omega_k^{\mathrm{n}}|}$ is a truncated *Bivariate Gaussian* weight, as the contribution of BEV grids to candidate nodes is considered contingent on relative distance:

$$W_{k,i} = \hat{g}(\Delta x_{k,i}, \Delta y_{k,i}), \tag{9}$$

where $(\Delta x_{k,i}, \Delta y_{k,i})$ is the relative coordinates of the i-th BEV grid center to k-th candidate node coordinates, $\hat{g}(\cdot)$ is normalized Bivariate Gaussian probability $\mathcal{N}(\boldsymbol{\mu}_{x,y}, \boldsymbol{\sigma}_{x,y})$, $\boldsymbol{\mu}_{x,y}$ is the mean vector, and $\boldsymbol{\sigma}_{x,y}$ is the covariance matrix.

Fused Action Prediction. To fuse the global graph-level decision score and local grid-level decision score, a backtracking strategy [12, 28] is adopted to convert the local score $s^c \in \mathbb{R}^{K_t+1}$ into global space $\hat{s}^c \in \mathbb{R}^{N_t+1}$. Specifically, when navigating to the nodes that are not connected to the current node, we assume the agent needs to backtrack through the visited candidate nodes as:

$$\hat{s}^c = \begin{cases} s_{\mathrm{back}}, & \text{if backtrack},\\ s^c, & \text{otherwise}. \end{cases} \tag{10}$$

More specifically, we compute a backtracking score for unconnected nodes in $\mathcal{V}_t$ by summing the decision scores of visited candidate nodes as s_{back}. Then, a weight W_f is employed to fuse the local and global decision scores:

$$s_n = W_f \hat{s}_n^c + (1 - W_f) s_n^g. \tag{11}$$

Using the fused prediction, BSG can complement existing works [12, 28, 41] with global action space. We will adopt a previous method [28] as basic agent for experiment (*cf.* §4).

3.3. BEV Representation Encoding

BEV detection endows the agent with awareness of object-level geometry information, facilitating more accurate action prediction [118, 119]. In this section, we learn 3D object detection on the top of BEV feature (see §3.1) [33–35]. Accordingly, the details on collecting a Matterport3D-based detection dataset for embodied amodal perception [22, 23, 120], called Matterport3D^2, will be presented. We also introduce the details of detection head.

Multi-view Image Acquisition. To enable an agent to perceive the surroundings through camera, we build a new 3D detection dataset Matterport3D^2 on multi-view images captured by camera [2], which differs from the previous whole-scene detection [19–21, 110] based on point clouds [95, 96].

During navigation, the agent revolves around the direction of gravity to capture the RGB images in 90 building-scale scenes. The original dataset [2] provides information on the object center and segments throughout the entire scene.

Amodal Perception for Embodied Agent. Apart from recognizing the semantics and shapes for visible part of the object, the ability to perceive the whole of an occluded object (*i.e.*, amodal perception) [22, 104, 108, 109] is also significant for navigation. Since occlusion frequently occurs in the indoor scenes, embodied amodal perception aids the agent in comprehending the persistence of scene layouts that objects possess extents and continue to exist even when they are occluded. We consider the occlusion relationship between objects on center visibility criterion, *i.e.*, an object is considered to be visible if its center is not occluded. To determine the visibility of objects in each image from multi-views, we project the object center onto the multi-view image planes and ascertain whether it is located within the camera frustum [21, 121]. Specifically, we establish the transformation from 3D world coordinates to pixel coordinates in the image using the intrinsic and extrinsic parameters of the camera. Then, we obtain a group of corresponding objects for the multi-view images (more details are shown in Appendix).

3D Oriented Bounding Box Generation. We spatially register all objects into an egocentric coordinate system at each panoramic viewpoint. To annotate the objects, we utilize a custom algorithm (*cf.* Appendix) which automatically generates 3D oriented bounding boxes (OBB) for 17 categories of indoor objects, as opposed to the axis-aligned bounding box (AABB) annotations with a fixed yaw angle of zero in the original dataset [2]. OBB surrounds the outline of the objects more tightly than AABB, resulting in more accurate route planning for VLN (see Table 10). In addition, the amodal detection on Matterport3D^2 follows the same train/val/test splits as previous VLN tasks [1, 25].

Bipartite Matching for BEV Detection. We construct the 3D detection head [33–35] upon BEV features $\boldsymbol{B}$ on Matterport3D^2. A bipartite matching loss [44–46, 122] is used to establish a correspondence between the ground-truth and box prediction, which consists of a focal loss [123] for class labels and a $L1$ loss for bounding box regression. We evaluate different BEV methods [34, 35, 42, 44] for indoor detection (see Table 8). Note that BSG is not constrained to any specific BEV model, allowing for seamless integration of advanced BEV frameworks for VLN.

3.4. Implementation Details

For ease of training, we employ a separate training strategy of the BEV detection and navigation policy networks, as the initial perception module cannot offer a correct feedback (or rewards) to the navigation policy [22, 23]. Therefore, BSG utilizes BEV features encoded by BEVFormer [35]. Following recent VLN practice [14, 15, 17, 29], pretraining and finetuning paradigm is adopted on a basic model [28] equipped with BSG. In this section, we will mainly introduce the details of BSG branch and present the detailed results in Table 4 (see Appendix for more details).

Voxel Sampling. For view transformation, we introduce the *voxel sampling* here (Eq. 1). The default size of BEV queries is 11×11 with four reference points (*i.e.*, $Z = 4$) for each query, and the perception ranges are $[-5.0\ m, 5.0\ m]$ for x and y axes. Considering the practical height of camera and rooms in [2], the predefined height anchors are uniformly sampled from $[-1.0\ m, 2.0\ m]$ for z axis. The number of neighboring grids for node embedding is 9 (Eq. 3).

BSG Architecture. Following the recent transformer-based methods [14, 17, 18, 28–30], the pretrained LXMERT [117] is utilized for initialization. We use 9, 2, and 4 transformer layers in the text encoder and cross-modal encoder (Eq. 4&6), respectively. We keep the other parameters consistent with prior works [28, 117]. During the finetuning process, the similar structure variants in the cross-modal encoder are adopted as previous studies [17, 28]. The fused weight W_f in Eq. 11 is set to 0.5. For the Bivariate Gaussian weight (Eq. 9), $\boldsymbol{\mu}_{x,y}$ is the zero vector, and $\boldsymbol{\sigma}_{x,y}$ is the diagonal matrix with diagonal elements of 2. We set the weight of 0.7 for OCM and 0.3 for [28].

Pretraining. For the R2R [1] and R4R [56], we adopt the *Masked Language Modeling* (MLM) [60, 114] and *Single-step Action Prediction* (SAP) [17, 30] as auxiliary tasks in the pretraining stage. For REVERIE [25], an additional *Object Grounding* (OG) [28, 124] is used for object reasoning. During the pretraining stage, we train the model with a batch size of 32 for 100k iterations, using Adam optimizer [125] with 1e-4 learning rate. Four RTX 3090 GPUs are used for network training, and only one pretraining task is adopted at each mini-batch with the same sampling ratio.

Finetuning. Following standard protocol [17, 28], we finetune the pretrained network with a mixture of *teacher-forcing* [126] and *student-forcing* on different VLN datasets. On REVERIE, the OG loss [28, 124] is also employed for finetuning, and a predefined weight 0.20 is adopted to balance navigation and object grounding. Moreover, we set the learning rate to 1e-5 and batch size to 8 with 25k iterations.

Inference. Once trained, the agent is capable of route planning while considering object context and scene layouts (§3.3). During the testing phase, we update BSG online (§3.1) and predict a fused action score (§3.2). The agent is forced to stop if it exceeds the maximum action steps [1].

4. Experiment

We first provide the results on VLN benchmarks (§4.1). To verify efficacy of core model designs, we conduct a set of diagnostic studies (§4.2). For comprehensive analysis, we investigate the impact of BEV perception on VLN (§4.3).

Models	REVERIE *val seen*						REVERIE *val unseen*						REVERIE *test unseen*					
	TL↓	OSR↑	SR↑	SPL↑	RGS↑	RGSPL↑	TL↓	OSR↑	SR↑	SPL↑	RGS↑	RGSPL↑	TL↓	OSR↑	SR↑	SPL↑	RGS↑	RGSPL↑
RCM [4]	10.70	29.44	23.33	21.82	16.23	15.36	11.98	14.23	9.29	6.97	4.89	3.89	10.60	11.68	7.84	6.67	3.67	3.14
FAST-MATTN [25]	16.35	55.17	50.53	45.50	31.97	29.66	45.28	28.20	14.40	7.19	7.84	4.67	39.05	30.63	19.88	11.61	11.28	6.08
SIA [124]	13.61	65.85	61.91	57.08	45.96	42.65	41.53	44.67	31.53	16.28	22.41	11.56	48.61	44.56	30.80	14.85	19.02	9.20
RecBERT [30]	13.44	53.90	51.79	47.96	38.23	35.61	16.78	35.02	30.67	24.90	18.77	15.27	15.86	32.91	29.61	23.99	16.50	13.51
Airbert [29]	15.16	48.98	47.01	42.34	32.75	30.01	18.71	34.51	27.89	21.88	18.23	14.18	17.91	34.20	30.28	23.61	16.83	13.28
HAMT [17]	12.79	47.65	43.29	40.19	27.20	25.18	14.08	36.84	32.95	30.20	18.92	17.28	13.62	33.41	30.40	26.67	14.88	13.08
HOP [18]	13.80	54.88	53.76	47.19	38.65	33.85	16.46	36.24	31.78	26.11	18.85	15.73	16.38	33.06	30.17	24.34	17.69	14.34
TD-STP [71]	–	–	–	–	–	–	–	39.48	34.88	27.32	21.16	16.56	–	40.26	35.89	27.51	19.88	15.40
DUET [28]	13.86	73.86	71.75	63.94	57.41	51.14	22.11	51.07	46.98	33.73	32.15	23.03	21.30	56.91	52.51	36.06	31.88	22.06
LANA [67]	15.91	74.28	71.94	62.77	59.02	50.34	23.18	52.97	48.31	33.86	32.86	22.77	18.83	57.20	51.72	36.45	32.95	22.85
Ours	15.26	**78.36**	**76.18**	**66.69**	**61.56**	**54.02**	24.71	**58.05**	**52.12**	**35.59**	**35.36**	**24.24**	22.90	**62.83**	**56.45**	**38.70**	**33.15**	**22.34**

Table 1: Quantitative comparison results on REVERIE [25]. '–': unavailable statistics. See §4.1 for more details.

4.1. Performance on VLN

Datasets. The experiments are conducted on three datasets. REVERIE [25] contains high-level instructions describing target locations and objects, with a focus on grounding remote target objects. R2R [1] contains 7,189 shortest-path trajectories, each associated with three step-by-step instructions. The dataset is split into *train*, *val seen*, *val unseen*, and *test unseen* sets with 61, 56, 11, and 18 scenes, respectively. R4R [56] is an extended variant of R2R by concatenating two adjacent trajectories with longer instructions.

Evaluation Metric. Following the standard setting [1, 3, 17] of VLN task, we use five metrics for evaluation, *i.e.*, Success Rate (SR), Trajectory Length (TL), Oracle Success Rate (OSR), Success rate weighted by Path Length (SPL), and Navigation Error (NE). Two additional evaluation metrics, Remote Grounding Success rate (RGS) and Remote Grounding Success weighted by Path Length (RGSPL), are used for REVERIE [25, 28, 30]. For R4R [17, 41, 56], Coverage weighted by Length Score (CLS), normalized Dynamic Time Warping (nDTW), and Success rate weighted nDTW (SDTW) are adopted (more details in Appendix).

Performance on REVERIE [25]. Table 1 compares our model with the recent state-of-the-art VLN models on REVERIE dataset. We find that our model outperforms previous approaches across all the evaluation metrics on the three splits. Notably, on the *val unseen* split, our model outperforms the previous best model DUET [28] by $\mathbf{5.14}\%$ on SR, $\mathbf{1.86}\%$ on SPL and $\mathbf{3.21}\%$ on RGS. On the more challenging *test unseen* split, we improve over the baseline by $\mathbf{3.94}\%$ on SR, $\mathbf{2.64}\%$ on SPL, and $\mathbf{1.27}\%$ on RGS. This demonstrates the effectiveness of our architecture design.

Performance on R2R [1]. Table 2 presents the comparison results on R2R dataset. We can find that our approach sets new state-of-the-arts for most metrics. For instance, on *val unseen*, our model yields SR and SPL of $\mathbf{74}$ and $\mathbf{62}$, respectively, while those for the baseline method [28] are 72 and 60. Our approach improves the performance of DUET by solid margins on *test unseen* (*i.e.*, 69→**73** for SR, 59→**62** for SPL). In addition, it also shows significant performance gains in terms of NE (*i.e.*, $3.65 \rightarrow \mathbf{3.19}$).

Models	R2R *val unseen*				R2R *test unseen*			
	TL↓	NE↓	SR↑	SPL↑	TL↓	NE↓	SR↑	SPL↑
Seq2Seq [1]	8.39	7.81	22	–	8.13	7.85	20	18
SF [3]	–	6.62	35	–	14.82	6.62	35	28
EnvDrop [5]	10.70	5.22	52	48	11.66	5.23	51	47
AuxRN [16]	–	5.28	55	50	–	5.15	55	51
PREVALENT [15]	10.19	4.71	58	53	10.51	5.30	54	51
RelGraph [6]	9.99	4.73	57	53	10.29	4.75	55	52
Active Perception [26]	20.60	4.36	58	40	21.60	4.33	60	41
RecBERT [30]	12.01	3.93	63	57	12.35	4.09	63	57
HAMT [17]	11.46	2.29	66	61	12.27	3.93	65	60
SOAT [27]	12.15	4.28	59	53	12.26	4.49	58	53
EGP [12]	–	4.83	56	44	–	5.34	53	42
GBE [70]	–	5.20	54	43	–	5.18	53	43
SSM [41]	20.7	4.32	62	45	20.4	4.57	61	46
CCC [66]	–	5.20	50	46	–	5.30	51	48
HOP [18]	12.27	3.80	64	57	12.68	3.83	64	59
LANA [67]	12.0	–	68	62	12.6	–	65	60
TD-STP [71]	–	3.22	70	63	–	3.73	67	61
DUET [28]	13.94	3.31	72	60	14.73	3.65	69	59
Ours	14.90	**2.89**	**74**	**62**	14.86	**3.19**	**73**	**62**

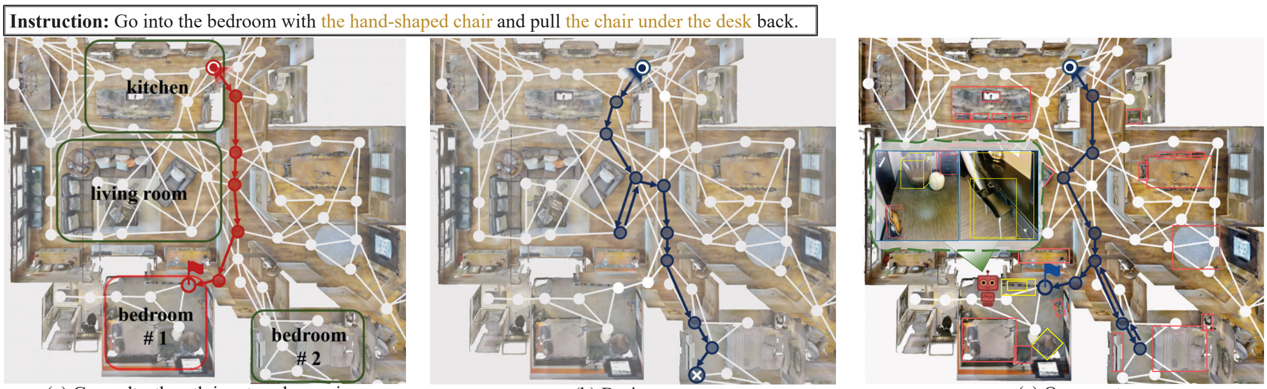
Table 2: Quantitative results on R2R [1] (more details in §4.1).

Models	R4R *val unseen*				
	NE↓	SR↑	CLS↑	nDTW↑	SDTW↑
SF [3]	8.47	24	30	–	–
RCM [4]	–	29	35	30	13
EGP [12]	8.00	30	44	37	18
SSM [41]	8.27	32	53	39	19
RelGraph [6]	7.43	36	41	47	34
RecBERT [30]	6.67	44	51	45	30
HAMT [17]	6.09	45	58	50	32
LANA [67]	–	43	60	52	32
Ours	6.12	**47**	59	**53**	**34**

Table 3: Quantitative results on R4R [56] (more details in §4.1).

Performance on R4R [56]. Table 3 shows results on R4R dataset. Our approach outperforms others in most metrics and leads to a promising gain on SR (*i.e.*, $45 \rightarrow \mathbf{47}$).

Visual Results. As shown in Fig. 4, "bedroom" is a critical landmark for instruction execution. There are two bed-



(a) Groundtruth path in a top-down view (b) Basic agent (c) Our agent

Figure 4: A representative visual result on REVERIE dataset [25] (§4.1). There are two bedrooms and it is difficult to distinguish between them. The basic agent in (b) steps into the bedroom #2 and ends in failure. With BSG, our agent in (c) returns back to the correction direction and succeeds according to the object context and scene layouts.

#	Models	REVERIE			R2R	
		SR↑	SPL↑	RGS↑	SR↑	SPL↑
1	Basic agent [28]	46.98	33.73	32.15	71.52	60.36
2	BEV Branch	39.03	25.73	25.09	65.56	52.21
3	***w/o.*** detection	49.25	32.44	33.21	72.65	60.20
4	Full model	**52.12**	**35.59**	**35.36**	**73.73**	**62.33**

Table 4: Ablation study of overall design on *val unseen* of REVERIE [25] and R2R [1]. See §4.2 for more details.

#	$\lvert\Omega^n\rvert$	REVERIE			R2R	
		SR↑	SPL↑	RGS↑	SR↑	SPL↑
1	4	51.33	34.34	34.86	72.89	62.07
2	9	**52.12**	**35.59**	**35.36**	**73.73**	**62.33**
3	16	51.71	34.11	34.54	73.26	61.99

Table 5: Ablation study of node embeddings on *val unseen* of REVERIE [25] and R2R [1]. See §4.2 for more details.

Updating	REVERIE			R2R	
	SR↑	SPL↑	RGS↑	SR↑	SPL↑
w/o. BEV updating	50.30	34.05	35.05	72.29	60.77
w. BEV updating	**52.12**	**35.59**	**35.36**	**73.73**	**62.33**

Table 6: Ablation study of *BEV updating* on *val unseen* of REVERIE [25] and R2R [1]. See §4.2 for more details.

rooms in the environment, which have different objects and geometric context (Fig. 4(a)). However, the basic agent [28] navigates a wrong bedroom #2 and finally fails (Fig. 4(b)). In Fig. 4(c), the BSG enables our agent to perceive the object-aware 3D information, finding "the chair under the desk" and "hand-shaped chair" to accomplish the task.

4.2. Diagnostic Experiment

To assess the efficacy of essential components of BSG, detailed ablation studies are conducted and the results of *val unseen* split of REVERIE [25] and R2R [1] are shown.

Overall Design. We first investigate the effectiveness of

#	Models	Decision Space		REVERIE			R2R	
		Graph	Grid	SR↑	SPL↑	RGS↑	SR↑	SPL↑
1	Basic agent [28]	–	–	46.98	33.73	32.15	71.52	60.36
2	Variants	✓		50.18	33.94	33.66	73.02	60.76
3			✓	48.25	34.34	34.02	72.79	61.54
4*			✓	51.27	34.56	35.20	73.10	61.88
5	Full model	✓	✓	**52.12**	**35.59**	**35.36**	**73.73**	**62.33**

Table 7: Ablation study of fused decision-making on *val unseen* of REVERIE [25] and R2R [1]. '$*$' denotes using uniform weight instead of *Bivariate Gaussian* (Eq. 8). More details in §4.2.

our overall design. The results presented in row #1, #2, and #4 of Table 4 indicate that adding BEV branch leads to a promising gain over the basic agent [28] across all metrics. From row #3 and #4, we improve the model by using additional detection loss $\mathbf{2.87}\%$ on SR of REVERIE, $\mathbf{3.15}\%$ on RGS of REVERIE, and $\mathbf{2.13}\%$ on SPL of R2R.

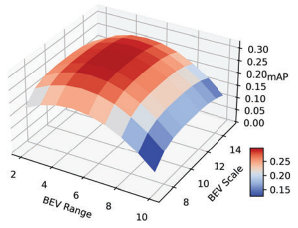
Neighborhood for Node Embeddings. We next validate the design of node embeddings. For each navigable candidate node, we employ its neighboring grid representations to construct the node embeddings (*cf.* Eq. 3). In Table 5, it can be observed that insufficient neighboring grids, as seen in rows #1 and #2, cannot represent the node well for navigation. On the other hand, from row #2 and #3, selecting too many neighboring grids can impact the discriminability of node embeddings due to a large number of overlap between candidate neighborhoods (see Fig. 3).

BEV Updating Strategy. At each step, we update BEV features by *cross-attention*, and then use the modified BEV grids to revise node embeddings (*cf.* Eq. 2). In Table 6, the variant of model that does not include *BEV updating* leads to inferior performance compared to full model.

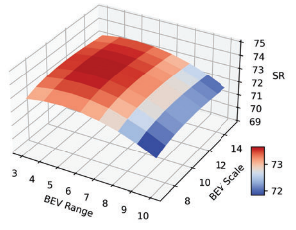
Fused Decision-Making. The results in row #1, #2, and #3 of Table 7 suggest that both graph and grid-level decision space of BSG facilitate the navigation (*cf.* §3.2). From row #4, using *Bivariate Gaussian* weights results in better

BEV Models	Matterport3D^2 mAP↑	mAR↑	REVERIE SR↑	SPL↑	RGS↑	R2R SR↑	SPL↑
LSS [42]	0.188	0.270	50.83	34.43	33.19	72.25	61.30
BEVDepth [34]	0.252	0.443	51.06	34.35	34.13	72.77	61.38
BEVFormer [35]	**0.299**	**0.488**	**52.12**	**35.59**	**35.36**	**73.73**	**62.33**

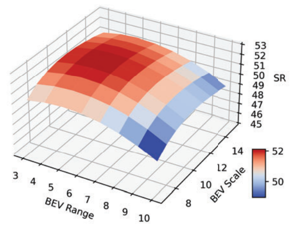
Table 8: Ablation study of different BEV models on *val unseen* of REVERIE [25] and R2R [1]. See §4.3 for more details.



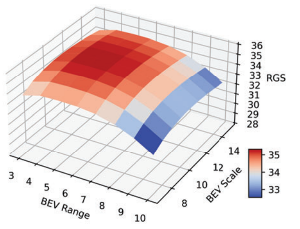
(a) mAP on Matterport3D^2



(b) SR on R2R



(c) SR on REVERIE



(d) RGS on REVERIE

Figure 5: Ablation study of BEV scale and perception range on *val unseen* of REVERIE [25] and R2R [1] (more details in §4.3).

performance compared to assigning uniform weights, as it takes into account the varying contribution of each BEV grid to the node based on the relative distances.

4.3. Analysis on BEV Encoding

In this section, we present the detection results on *val unseen* of Matterport3D^2. For evaluation, we utilize mean Average Precision (mAP) and mean Average Recall (mAR), with Intersection over Union (IoU) thresholds of 0.50, following standard protocols [19, 20, 127, 128]. Then, we provide a quantitative analysis of how BEV detection affects VLN performance, including different types of BEV models (*depth prediction* [34, 42] and *voxel sampling* [35]) and the ablation study on the superior model [35].

Different BEV Models. We first compare several representative open-source BEV models [34, 35, 42], which are divided into two aspects based on different view transformations. BEVFormer [35] utilizes voxel sampling to encode 2D features to 3D space (*cf.* Eq. 1), while LSS [42] and BEVDepth [34] employ 2D features to predict depth information and then lift these features to 3D space. Note that BEVDepth [34] requires explicit depth information as additional supervision. As listed in Table 8, BEVFormer [35] outperforms all other methods with **0.299** mAP and **0.488** mAR. We adopt BEVFormer [35] as our BEV baseline.

#	Z	Matterport3D^2 mAP↑	mAR↑	REVERIE SR↑	SPL↑	RGS↑	R2R SR↑	SPL↑
1	2	0.260	0.443	51.49	35.07	**36.27**	72.81	60.50
2	4	**0.299**	**0.488**	**52.12**	**35.59**	35.36	**73.73**	**62.33**
3	8	0.266	0.438	50.98	33.56	35.34	72.30	60.44

Table 9: Ablation study of reference points on *val unseen* of REVERIE [25] and R2R [1]. See §4.3 for more details.

Annotation	Matterport3D^2 mAP↑	mAR↑	REVERIE SR↑	SPL↑	RGS↑	R2R SR↑	SPL↑
AABB	0.266*	0.491*	49.25	32.44	34.14	73	60
OBB	0.299	0.488	**52.12**	**35.59**	**35.36**	**74**	**62**

Table 10: Ablation study of OBB and AABB on *val unseen* of REVERIE [25] and R2R [1]. '$*$' denotes the detection performance on AABB annotations. See §4.3 for more details.

Moreover, our performance can be further improved with more advanced BEV models.

BEV Scale and Perception Range. We next delve into the core parameters of our BEV, *i.e.*, scale and perception range (*cf.* Eq. 1). The results are summarized in Fig. 5. We find that different scales and perception ranges will affect detection accuracy (*cf.* Eq. 1). Since node representations are associated with BEV features (*cf.* §3.1), better detection performance can bring more gain to navigation.

Reference Points. Table 9 presents a comprehensive analysis of the number of reference points proposed in §3.1. Reference points enable the sampling of multi-view features and their integration into BEV feature (*cf.* §3.1).

OBB *vs* AABB for Perception and Navigation. The oriented bounding box (OBB) is more commonly used in 3D perception of real-world scenarios, such as collision detection [129, 130] and grasp detection [131–133], compared to the axis-aligned box (AABB). In Table 10, using the OBB, the agent's perception performance is better as it provides accurate orientation and scale information (*cf.* §3.3), resulting in the improved performance in all navigation tasks.

5. Conclusion

Scene understanding is crucial for intelligent navigation in 3D environments. However, current VLN agents rely solely on panoramic observations, lacking the capacity to preserve 3D layouts and geometric cues, and hence limiting their planning ability. In this paper, we propose a BEV scene graph (BSG) for 3D perception-based VLN, that enables the agent to perceive the scene and access the object layouts. By fusing BSG-based action score and BEV grid-level action score, our approach achieves promising results. This highlights the great potential of BEV perception in VLN.

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