**SegDF: Segment-Based Dynamic Filter in 3D Point Cloud**

**Abstract**

Dynamic objects in lidar data frequently leave undesirable traces in 3D point clouds, degrading the quality of maps and the effectiveness of localization. We present a novel static reconstruction method, called SegDF, that focuses on filtering the potential-mobility elements contacted with the ground in urban environments. Our approach can not only reconstruct maps with low-semantic information, but also remove movable objects at a low cost. Given a pair of registered scans, we generate a curved-voxel map with the assistance of sensor intensities to cluster the scans into instances and populate semantics by geometric classification. To exclude instances that are non-static yet unstable due to inconsistent observations, we monitor volumetric states based on the occupancy change of curved voxels at object level. In addition, our method tightly couples instance segmentation with dynamic detection in order to refine imperfect clustering and enhance the removal precision. SegDF is validated on the KITTI dataset using SemanticKITTI as the ground truth, and it is demonstrated that the proposed can produce a high-quality static instance map.

**Ⅰ. INTRODUCTION**

Leveraging LiDAR odometry [1, 2, 3], location recognition [4, 5, 6], and long-term mapping [7, 8, 9], recent advancements in 3D LiDAR detection and mapping have been reported to encounter an ambiguous environment that contains diverse moving elements such as vehicles, pedestrians, and so forth [10, 11, 12, 13, 14]. Although most autonomous robotic systems always assume that all observations are accessible, excluding dynamic objects as outliers and relying solely on static objects might prevent confusion and increase reliability.

A scan data presents a snapshot of the surroundings, which invariably contains dynamic points with limited interpretability. Since a 3D point cloud map is the accumulation of sequential scan data, there might be traces of dynamic objects, or the ghost trail effect [10, 14], as shown in Fig.1 on the left. These undesirable traces act as fake static obstacles in map and thus impede mobile robots from exhibiting good localization and navigation performance.

Generally, removing dynamic points is always considered as detecting instantaneous changes in registered map. Conventional methods to tackle this problem are mainly divided into two categories: a) rejecting dynamic points timely in map generation [15, 16] and b) post-removing dynamic points with a global map [13, 14]. The proposed focuses on the latter that could be separated into three classes: a) segment-based, b) ray tracing-based, and c) visibility-based methods.

Segment-based methods [15, 17, 18, 19, 20] are straightforward, because it only needs to perform dynamic detection on the objects estimated to be dynamic. To distinguish dynamic and static objects, there are methods based on clustering segmentation [17, 18] or learning-based semantic segmentation [19, 20]. Additional features are required to determine the mobility of objects in clustering methods, however, due to the inconsistent observations caused by restricted viewpoint, the same object might have unstable characteristics in adjacent scans. Learning-based method can directly reject objects labeled as dynamic, but they rely heavily on supervised labels.

Ray tracing-based methods [10, 11, 12, 14, 16] deem that dynamic points just exist momently, only actually static points are always restored in grids. However, being implemented on scans with few dynamic points, these methods need to traverse each point to occupy grids, which leads to unnecessary computational cost.

Visibility-based methods [7, 13, 21] are based on the premise that if a query point is observed behind a previously acquired point in the map, then the previously acquired point is dynamic. But because of the registration errors and occlusions, the above judgment often makes mistakes to remove dynamic points incompletely.

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| Fig. 1 Before (the left) and after (the right) the application of the proposed called SegDF on sequence 05 of SemanticKITTI [14] (top view). The task of our method is to remove dynamic objects highlighted in red in the original map, and build a static instance map including ground, buildings, vegetation and the other stationary objects, which are respectively marked in yellow, brown, green and random color. |

To overcome the aforementioned limitations, we proposed a novel scheme for dynamic removal, called SegDF, which aims to reconstruct a static instance map, as shown in Fig.1 on the right. Our contributions are threefold:

1) We proposed a clustering segmentation based on curved voxel with intensity and design a low-cost recognition strategy utilizing geometric characteristics. Taking [22] as the baseline, we add LiDAR intensity to constrain the curved-voxel searching and optimize the outcomes through growth iterations. Then the geometric recognition distinguishes potential-mobility objects, such as vehicles, pedestrians, being inevitably in contact with the ground (§III-B, §III-C).

2) We proposed a fast object-level dynamic filter to track potential-mobility objects by detecting the occupancy of curved-voxel. The structure of curved voxel adapts the spherical emission of 3D LiDAR to reduce the effect of registration errors on dynamic detection; and the instance tracking establishes object connection in adjacent scans to remove weakly associated objects, which lessens computation (§III-D).

3) Considering the inconsistent observations in adjacent scans, we tightly couple segmentation and dynamic removal. In the process of instance tracking, this method combines multi-frame segmentation information to compensate the central-frame segmentation error, thereby improving the accuracy of dynamic removal (§III-E).

**Ⅱ. RELATED WORK**

Dynamic removal is closely related to static map construction. We exclude online methods in this paper since we are primarily concerned with constructing a high-quality static map without regard to processing speed.

**Segmentation-based methods**. After obtaining the motion attributes of each object, it is straightforward to perform dynamic detection. A dynamic selecting method based on Viewpoint Feature Histogram (VFH) is proposed [17], but registration errors make it difficult to achieve constant viewpoint. [18] utilized feature matching to check false correspondences and then used them as seeds to extract clusters from dynamic objects, yet the residuals caused by restricted viewpoint might be mistaken as false matches. Given semantic points with dynamic labels by deep-learning, a map can be constructed by excluding the predicted dynamic points [19, 20]. However, these methods are vulnerable to labeling errors or dynamic objects of unlabeled classes [23].

**Ray tracing-based methods.** Typical methods using Ray tracing [11, 16] count hits and misses of scans in the grid map and remove points in low-occupancy grids. By extension, [12] proposed the removal of dynamic points by traversing a voxel occupancy grid and [10] suggested a combination of object detection and [11]. To reduce the computational burden, [14] fetches bins with potential-mobility by comparing the height difference, and then remove points on the fitting ground. However, this method may fail in irregular environments, because it strictly depends on the spatial distribution.

**Visibility-based methods**. Ray tracing-based methods are computationally expensive, which led to the introduction of visibility-based methods [8, 9, 13]. The assumption that a dynamic point is often followed by a static point that is collinear with it, has incidence angle ambiguity with longer range measurement. To solve this problem, [8] uses normal and incidence angles to represent the state for each point. Furthermore, [13] proposed a pixel-to-window comparison method to take incidence angle ambiguity into account. However, all previous works struggled with the occlusion and registration errors.

**Ⅲ. METHODOLOGY**

The proposed is a post-processing method to reconstruct a static instance map. Assuming that the registration errors due to imperfect pose estimation are tolerable, we examine batch data of a certain length in [24] to validate the quality of the static map.

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| (这张图重做，基本思路没变) |

*A. Problem definition*

Given a point cloud map generated from a set of LiDAR frames {*P*}, we intend to remove dynamic objects in the map. Specifically, we consider the global unified map coordinate *M* and the local sensor query coordinate , where k is the frame index. We assume that the related SE(3) pose (i.e., the transformation matrix from to ) and the frame data in the local coordinate system are known. Additionally, we describe two groups in *M*, with *D* representing the dynamic group and *S* representing the static group, where . The mission thus corresponds to removing the *i-th* dynamic object in . The challenge stated above is phrased formally as

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|  | (1) |
|  | (2) |

where the is the total frame indexes that is equal to .

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| Fig. 3 A visualization of the product (i.e., static/dynamic map segregation) in the point-wise form on the SemanticKITTI [24] sequence 02 (top view) from frame 1120 to frame 1200. The top point cloud map is constructed using scans and SE(3) poses estimated using SuMa [2] for every 2 m  and has many dynamic points from various types of instances (e.g., vehicles, pedestrians, etc.). Our method can successfully separate static instances and dynamic ones, even when urban environments contain a lot of noise. As marked by the boxes in the same color, the effectiveness of our method can be verified by comparing the image frame with the point cloud map. |

Our methods consist of two phases: (i.e., instance segmentation) and. (i.e., dynamic filter between two adjacent frames). A static instance local map equates to the set of static instances after dynamic removal, as shown in Fig. 3, hence the procedure can be stated as

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|  | (3) |
|  | (4) |

where , which represents the transformation of segmented point cloud, from to .

*B. Intensity-assisted curved-voxel clustering*

After pre-processing such as ground extraction and intensity rectification, intensity is added to constrain the curved-voxel clustering [22] and refine the results by iterative growth.

**Ground extraction**. The majority of each frame's raw data consists of ground points, which may affect the segmentation of other instances [25]; consequently, it is necessary to separate the ground before clustering. Moreover, the ground is utterly immobile, thus dynamic detection should not be conducted on it. We extract ground from the point cloud by multi-region plane fitting, to solve the uneven ground scene [26].

**Intensity rectification**. The sensor intensity indicates the surface properties (e.g., roughness, reflectance, etc.) on objects composed of various materials. However, the intensity channel is noisy because it is influenced not only by surface properties, but also by acquisition geometry (e.g., distance) and instrument effects (e.g., transmitted energy) [27]. Thus, Intensity rectification is necessary to reduce the influence of insignificant factors, yet, it is impossible to totally correct the true value of intensity through a mathematical model. In order to use intensity efficiently, the local connection of objects is established through the continuity of intensities in adjacent spaces, as shown in Fig. voxel内的方差.

We solely consider the effect of distance , and incidence angle on raw intensity during the scanning period. Assuming that is constant, hence the rectified intensity can be formed as

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|  | (5) |

**Curved-voxel clustering assisted by intensity.** We transform cartesian coordinates to spherical ones, , which consists of the radial distance , the polar angle, and the azimuth angle [22]. Curved-voxel with intensity is redefined as *CVI*, a spatial unit comprised of three constituents: a) spherical coordinates, b) the average of intensity *AV*, which represents local reflectance, and c) the covariance of intensity *COV*, which represents credibility of the rectification.

Then the thresholds of average *threAV* and covariance *threCOV* are defined to respectively measure the intensity continuity in adjacent spaces, and the reliability of rectification. The fundamental components of is as follows

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|  | (6) |

where , , and are unit size parameters for each spherical direction.

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| Fig. 4 Steps of the proposed, using a bird-eye view. In Step 1, we convert cartesian coordinate into spherical one and build a sparse CVI map that managed by hash table. In Step 2, CVIs in the same color represent good continuity on intensity map (bottom), which constrains the CVI search in clustering (top). In Step 3, A refinement based on intensity map has been performed through iterative growth. In Step 4, points in well related CVIs are combined into clusters. |

We describe our proposed segmentation method in Algorithm 1, as shown in Fig. 4. We firstly implement a preliminary procedure to extract ground by [37] and rectify intensity (line 1~2). Then we convert the cartesian coordinates of no-ground points into spherical ones (line 3) and build sparse CVI map that managed by hash table (line 4). Notably, to maintain the sparse representation of the hash table, only CVIs with at least one point are stored. After establishing the CVI map, we combine each point with its neighbor CVIs, whose difference of AV between target CVI is less than the *threAV* (line 5~13). This method makes the intensity continuity in the adjacent spaces equal to the local consistency of one object. After obtaining an initial list of clusters, a novel iterative growth is adopted to refine the outcomes (line 14 ~ 19). We traverse each cluster to find its neighbor clusters through CVI search, and all the neighbors must satisfy *threAV* and their *COV* is less than *threCOV.*

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| Algorithm 1: **Curved-voxel clustering assisted by intensity** |
| **Input:** , {, }, and {*threAV*, *threCOV*} |
| **Output:** |
| 1: **Extract ground:** remove ground points in [26] |
| 2: R**ectify intensity:** in local region normal vector incident vector,  formula (6) |
| 3: Convert-to-Spherical ( |
| 4: hash-table Build-CVI (*X*, , , , *AV*, *COV*) |
| 5: **for** in **do** |
| 6: **if** is already included in a cluster **then** |
| 7: **continue** |
| 8: **end if** |
| 9: Neighbor () CVI-search **and**  < *threAV* |
| 10: Combine-clusters (, Neighbor ()) |
| 11: **if** is still not included in any cluster **then** |
| 12: assign-cluster (, Neighbor ()) into |
| 13: **end for** |
| 14: **for** cluster in **do** |
| 15: **for** in **do** |
| 16: Neighbors () CVI-Search  **and**  < *threAV* , *COV* < *threCOV* |
| 17: Neighbors () get-clusters (Neighbors ()) |
| 18: Combine-clusters (, Neighbors ()) |
| 19: **end for** |
| 20: **return** |

C. Geometric classification

Intensity-assisted curved-voxel clustering obtains multiple objects, but instance segmentation should identify each object. We use geometric features [6, 28, 29] to distinguish dynamic instances. The dimension of the geometric feature vector is 110, which consists of two parts:

1) Eigenvalue: This descriptor is merged into a 7-dimensional feature vector. In accordance with [6, 28], we compute the linearity, planarity, scattering, omni-variance, anisotropy, eigen-entropy, change of curvature measures, and primary orientation. It utilizes the aggregated global characteristics to precisely describe the geometric distribution of objects.

2) Spatial scale: This descriptor consists of Minimum height, Maximum height, and scale in a 3-dimensional feature vector, which naturally represents the scale information and reduce the noisy from global changes.

Compared to the learning-based method, the geometric classification is more robust. To meet the requirements of low semantic information, we classify the clusters into three categories: a) vegetation (e.g., trees and grass), b) buildings (e.g., walls and fences), and c) potential-mobility objects (e.g., vehicles, pedestrians). In order to intuitively distinguish the three categories with limited information, we devised a hierarchical classification criterion. Due to buildings seem flat in most scans, we extract them by utilizing region growth and restrict them through planarity and change of curvature. Being quite complex, vegetation is difficult to be recognized, so we apply planarity, omni-variance, anisotropy and spatial scale to classify this category. Excluding buildings and vegetation, the rest of clusters contacted with ground, such as vehicles, pedestrians, billboards, and so forth, are possibly in moving, so they are all considered potential-mobility objects in environment. (fig)

D. *Dynamic removal in object tracking*

To remove dynamic instances, we apply an object tracking-based strategy. Only potential-mobility elements are identified throughout this process. This concept effectively eliminates the issue of inconsistent observation of the same objects in successive scans, and the voxel search optimizes the processing speed of a single frame. In addition, to boost the accuracy of object tracking, we select a specific amount of frames to initialize the instance results and tightly couple the tracking and instance segmentation processes.

We discuss our proposed dynamic removal strategy in Algorithm 2. After obtaining and , we assemble them into the same curved-voxel map and perform an object-level registration (line 1). Then, for each instance with potential mobility in , we find its neighbor instance by curved-voxel searching and calculate the occupancy to check the observation consistency (line 5~8).

Registering the segmentation results from both frames in the same curved-voxel map, we utilize the amount of instance coverage and voxel occupancy changes to characterize the nature of motion. Notably, the above procedure is entirely based on curved-voxel tracking, which may not only lower the cost but also modify the instance in a flexible manner. According to this criterion, the motion properties of objects in can be divided into four categories:

*1) High Dynamic (HD) Objects:* Due to the unpredictability of observations in , interpreting high-mobility objects is exceedingly difficult. We divide it into two types: a) cannot be covered, meaning there is no voxel occupancy link; and b) may be covered, however the voxel occupancy is variable. Objects with high dynamic qualities, such as vehicles, pedestrians, etc., tend to have fast translation speeds. (line 9 ~ 12).

*2) High Static (HS) Objects:* Non-moving objects, such as parked vehicles, crates, etc., could be properly tracked in , provided they occupy one or more instances and satisfy a specific occupancy ratio. (line 13 ~ 18).

(3，4点不确定需不需要留下)

3) Object Split: We only conduct dynamic detection for objects with high mobility. However, due to the inconsistent observation of the two adjacent frames, different types of objects will establish contact after geometric recognition. To solve this problem, the proposed splits the object in the previous frame according to the observation occupancy (line 15).

4) Object Fusion: Faced with a one-to-many search, if the attributes of multiple objects searched are the same, they will be fused (line 18).

(待做类似于segmatch上下比较的图，表明跟踪)

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| Algorithm 2: **Dynamic removal in object tracking** |
| **Input**: } and , and |
| the threshold of occupancy *threOccu* |
| **Output**: in , and |
| after compensation |
| 1: **Registration**: Inverse (, and |
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| 2: **for** cluster in **do** |
| 3: Convert-to-Spherical () |
| 4: Neighbor () Build-CVI () |
| 5: **for** **do** |
| 6: **if** find in hash-table () **then** |
| 7: Neighbors () check cluster |
| 8: **end if** |
| 9: **if** Size (Neighbors ()) = 0 **then** |
| 10: add into |
| 11: **else if** Size (Neighbors ()) > 0 **and** Satisfy (*threOccu*)**then** |
| 12: add into |
| 13: **else if** Size (Neighbors ()) > 0 **and** no-Satisfy (*threOccu*)**then** |
| 14: add into |
| 15: Split (Neighbors ()) |
| 16: **else if** Size (Neighbors ()) > 0 **and** Satisfy (*threOccu*)**then** |
| 17: add into |
| 18: Fuse (Neighbors ()) |
| 19: **end if** |
| 20: **end for** |
| 21: **return** and |

*Ⅳ. EXPERIMENTAL RESULTS*

*A. Dataset*

We use the KITTI odometry dataset [40] and the SemanticKITTI dataset [14] to evaluate our static map construction performance qualitatively and quantitatively. The SemanticKITTI contains scan-wise labeled data and the related LiDAR SLAM-based SE(3) poses. Furthermore, the SemanticKITTI offers point-wise annotations, points labeled with specific class (252, 253, 254, 255, 256, 257, and 259) are defined as ground-truth dynamic points to be erased. We notice that we did not include unlabeled points, whose label index is zero, since if we did, dynamic points would arise and the original map could no longer function as a static ground truth map.

In general, the number of static points in the map is too much larger than the number of dynamic points, and the majority of frames contain no or few dynamic points; hence, it is difficult to determine at a glance whether the dynamic points have been successfully removed. As shown in Fig. 3 and Fig. 4, we manually selected the frames from the SemanticKITTI [14] that have the maximum number of occurrences of dynamic objects in order to objectively evaluate the algorithms. Obviously, our proposed is applicable to the entirety of Fig. 1's map, which focuses on demonstrating the long-term effect of constructing a static instance map.

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| Fig. 4 The visualization of result using the evaluation criteria on SemanticKITTI [14] sequence 09 from frame 1325 to frame 1375. The TP, FP, TN, FN respectively mean correctly estimated static, falsely preserved dynamic (i.e., static that is actually dynamic), correctly eliminated dynamic and falsely removed static (i.e., static that should not be removed). Furthermore, we annotate FP and FN to highlight them. |

*B. Parameter settings*

We used LiDAR SLAM-based poses predicted by SuMa [41] following the various sequences SemanticKITTI [14] to prove the feasibility of the proposed method in noisy situations and consider less accurate pose estimation.

In the process of front-end instance segmentation, the setting of parameters is very important. Trying to maintain more original points on the premise of ensuring the segmentation accuracy, we set the LiDAR visible minimum distance is 2 m and maximum distance is 50 m. Additionally, we set , , and the threshold , . During backend dynamic filtering, since two consecutive frames will cause inconsistent observations due to viewing angle problems, we set the minimum pose difference is 2 m and the smallest curved-voxel occupancy is 0.6.

*C. Evaluation Criteria*

The proposed refers to the static status as positive (P) and the dynamic status as negative (N). Then the estimates and are expressed as

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| and | (5) |

where TP, FP, TN, and FN represent true positive, false positive, true negative, and false negative point sets, respectively.

Using this equation, we can redefine the problem as reducing the number of FP and FN points within the static and dynamic estimates.

We used both SemanticKITTI’s ground-truth map and our resulted map voxel down-sampled with 0.05 m size cell. In the specific evaluation process, we adopt the method of point-to-point search from the ground truth to the dynamic and the static, and the search radius is 0.1m. For the sake of fairness, we will register the above three in the same coordinate system and use the same search radius, which means that the estimated value of each original point is determined by voting in the neighborhood. In Fig. 4, to quantitatively depict the results of dynamic filtering, the TP, FP, TN, and FN points are indicated in green, pink, blue, and orange, respectively.

D、*Static map quality*

(待做一个表格，关于kitti的多个序列的某段，考虑：

去除实例分割速度，

潜在动态物体判定个数

动态剔除速度，

动态点去除准确率)

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*E. Limitation*

(实例分割错误，动态去除不完整)

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