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Master Thesis Proposal

Out-of-distribution detection in 3D semantic segmentation

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1 Introduction

Many robotic [38] [31], and autonomous driving systems [25] deployed in the real world, dynamic environments now use LiDAR as the primary sensor. The 3D LiDAR data acquired offers a true-size replica of rich 3D geometry and can be represented as a 3D point cloud format or using 2D grids such as range image representation [28]. Semantic scene understanding is one of the key components of autonomous driving systems. Semantic segmentation is an important task in semantic scene understanding. Semantic segmentation requires the labelling of each data point (3D point in LiDAR/pixel in camera) with its corresponding class.

The existing models for 3D semantic segmentation are highly complex and uncertain about their detections [6]. This uncertainty in addition to input as out-of-distribution (OOD) objects questions the safety and performance of the 3D semantic segmentation models. One such real-world example is a Tesla autopilot stopping after misdetecting a billboard with "STOP" written on it as a traffic stop sign [24]. Another such failure is the same autopilot detecting the moon as a yellow sign and slows the car [24]. In all the above scenarios, the model is unable to detect the object as OOD and resulting in undesired outcomes. [27], [5], [9], and [2] define OOD as the input classes which are not included in the training set. This is because most of the training sets of datasets were assumed as a closed world, that means the predictions during inference are made on a predefined set of classes. When deployed in the real world the autonomous agent will encounter a new class which leads to dangerous situations as specified in the above example which is still an unsolved problem. Figure 1 displays an example semantic space with decision boundaries between four classes in the training set and one OOD class represented in black. The training classes were vegetation, buildings, trunk and car, whereas the OOD class is a pole. During inference, the pole class is classified as trunk which is a wrong prediction. The ideal behaviour of the classifier is to specify this is an unknown class object and thus probably request for human input. In this thesis, we will try to extend the classifier to detect these unknown objects by exploring OOD detection methods and also quantified uncertainty.

A decade-long study has been performed on the task of semantic segmentation, [49] refers to all the traditional approaches based on handcrafted features. With

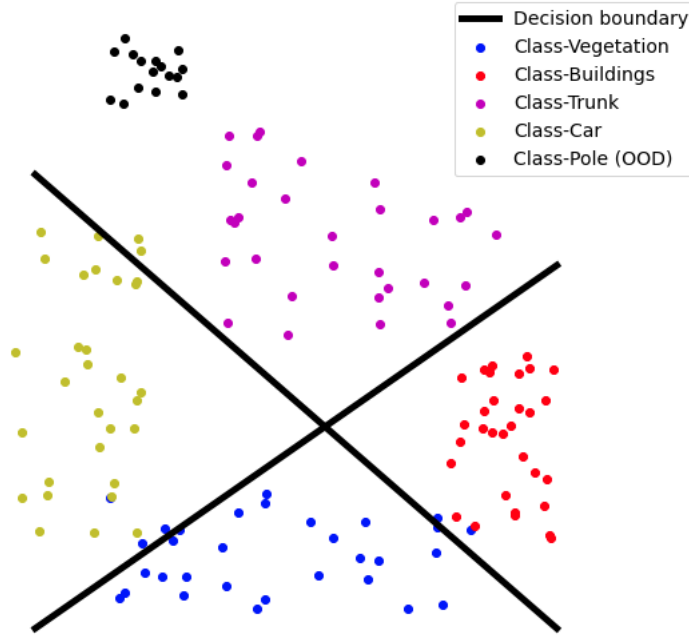


Figure 1: Representation of the semantic space with the decision boundaries of four classes in training set in colour and the points in black are of OOD

the advent of deep learning, a richer feature representation led to mapping input to semantic labels as an end to end procedure. The most popular 3D semantic segmentation datasets in the context of autonomous driving are Semantic KITTI [4], nuScenes-lidarSeg [8] and Sydney Urban [12] collected by various sensors are publicly available. 3D semantic segmentation datasets are limited in size and diversity because labelling is intensive and requires special skills to handle.

3D semantic segmentation models include point-based methods such as PointNet++ [33], RandLA-Net [20], and many more. There also exist image-based methods which employ various projection algorithms and popular methods in this segment include SqueezeSegV3 [44], RangeNet++ [28], and SalsaNext [11]. Graph-based and voxel-based methods are some of their kind to solve the task of 3D semantic segmentation. In the later sections, we will discuss the problem statement, corresponding related work and the project plan.

1.1 Problem Statement

In this thesis, we study the application of out-of-distribution (OOD) detection over the 3D semantic segmentation problem in the context of autonomous driving. Notably, we study the 3D semantic segmentation datasets available and create a benchmark for in-distribution and out-distribution for the OOD setting.

The other major issue, we address in this thesis is the OOD detection methods themselves. Existing OOD detection methods are developed on 2D classification tasks and applicability of these methods on 3D semantic segmentation tasks is not studied. This is also challenging because the existing OOD methods are not easily adaptable to the 3D segmentation models because segmentation involves multi class classification and moreover high dimensionality of the 3D data.

The research questions answered by this thesis are:

- R1** How to create a benchmark over 3D segmentation datasets for the OOD setting?, i.e., create the in-distribution and out-distribution datasets.
- R2** How to extend current OOD detection methods from 2D classification task to 3D semantic segmentation?
- R3** Is uncertainty quantification an effective approach to classify OOD detection in 3D semantic segmentation models?
- R4** How to evaluate the OOD detections over the 3D semantic segmentation task?

2 Related Work

In this related work, we discuss the methods involving 3D semantic segmentation, out-of-distribution (OOD) detection methods and performance metrics available.

2.1 3D semantic segmentation

The existing deep learning methods for 3D semantic segmentation is divided into 4 types based on their mode of input. The first one is point-based methods, these

type of methods perform operations directly on the raw point clouds. These type of methods are more popular and vastly used. Some of the well-known methods in this category are PointNet [32], PointNet++ [33], RandLA-Net [20], SPLATNet [36], TangentConvolution [37], ShellNet [47], PointCNN [26].

The second most kind of deep learning method for 3D semantic segmentation is Image-based methods. These methods require the projection of the 3D point clouds into range images or multi-view images. This projection allows these methods to employ well developed and advanced 2D semantic segmentation methods like ResNet as in [39]. Popular methods in this category include SqueezeSegV3 [44], RangeNet++ [28], 3D-MiniNet [1], SalsaNext [11], LiSeg [46], KPRNet [21] use range image representation.

The other two kinds of methods are voxel-based methods and graph-based methods. Voxel-based methods require a small preprocessing of converting raw point clouds to voxels. Some methods using voxels are 3D U-Net [1], Cylinder3D [48]. Dynamic graph CNN [43], GAC Net [42] are few graph-based methods available.

There exists a few open 3D LiDAR semantic segmentation datasets. Oakland [29], TUM city campus [13], Semantic3D [17], Paris-lille-3D [35], S3DIS [3] are a few datasets with static LiDAR and has point annotations. The other type of datasets includes sequential data. These type of datasets include Semantic KITTI [4], A2D2 [15], nuScenes-lidarSeg [8], KITTI-360 [45], Sydney Urban [12] and they have point annotations. There also exist 3D box annotations with sequential data and they are KITTI [14], H3D [30], and DENSE [7]. GTA-V [34] and SynthCity [16] are only a few synthetic datasets available for 3D semantic segmentation.

2.2 OOD detection

The OOD detection methods are broadly divided into the threshold, non-threshold, uncertainty and generative methods. Generative methods will not be studied in this thesis because these methods are out of the scope of the project. All the OOD methods discussed below are evaluated on the 2D classification task and no approach was deduced for the 3D semantic segmentation task.

2.2.1 Threshold based

These methods employ a threshold-based detector. The well-known OOD detector is Maximum Softmax Probability (MSP) proposed in [18]. This method considers the max of the softmax output and decides an OOD based on the confidence threshold. Since the softmax scores can be overconfident [27] proposed ODIN which uses calibrated confidence score which uses temperature scaling. Apart from calibrated confidence score, ODIN also makes use of noise perturbations in input. Combining these two, a threshold-based detector is applied at the end. [23] proposed Mahalanobis distance as a confidence score. In addition to this score, noise perturbations were added to the input as in ODIN. The score is calculated at all layers then ensembled and given to threshold-based detector.

2.2.2 Non-threshold based

[19] proposed Outlier Exposure which makes use of a large, unlabeled auxiliary dataset to improve the OOD detection performance. Then a new classifier is utilized with a distinct objective function. [10] proposes a novel method for improvement of robustness of OOD detection called Adversarial Learning with inlier and Outlier Exposure (ALOE) which served as an extension to Outlier Exposure proposed by [19].

2.2.3 Uncertainty-based

[22] uses ensembled models to evaluate epistemic uncertainty and utilizes predictive entropy to classify the in distribution and out-of-distribution samples. [40] uses a novel radial basis function approach to calculate the epistemic uncertainty and argues OOD can be detected using epistemic uncertainty. The above methods evaluate the uncertainty on 2D models, there exists only [6] which apply the deep ensemble technique, Dropout and Dropconnet to the 3D semantic segmentation models to evaluate the uncertainty.

2.3 Metrics for OOD detection

There are a few metrics that deal with OOD detection and they include

2.3.1 Area Under Receiver Operating characteristic Curve (AUROC)

AUROC portrays the discrimination ability of the model between positive and negative cases. It is calculated as the area under the ROC curve which in turn is calculated from true positive rate (TPR) and false-positive rate (FPR) across various decision-thresholds. The value of AUROC ranges between 0.0 and 1.0 with 0.5 being worst (random classifier) and 1.0 being best.

2.3.2 Area Under Precision-Recall Curve (AUPRC)

The area under the precision-recall curve is calculated as AUPRC. The curve shows the tradeoff between various thresholded precision and recall. The interpretation of AUPRC is trickier than AUROC. In AUROC the baseline is 0.5 as its random classifier but for AUPRC its fraction of positives ($\frac{\text{positive examples}}{\text{total examples}}$). This implies that various classes have various baseline AUPRC values.

2.3.3 FPR at 95% TPR

This metric calculates the FPR on OOD samples when the TPR is at 95% in distribution samples.

2.3.4 Mean Intersection-over-Union (mIOU)

The metrics discussed till now evaluate the performance on OOD detection, but this metric is used to evaluate the performance of the 3D semantic segmentation model. It is calculated as IOU over all the classes and it is given by

$$mIOU = \frac{1}{C} \sum_{x=1}^C \frac{TP_x}{TP_x + FP_x + FN_x}$$

where C is the number of classes and TP_x, FP_x, FN_x are the true positives, false positives and false negatives of class x.

3 Project Plan

In this section, the project plan including work packages, tasks and timeline for each task is proposed.

3.1 Work Packages

The bare minimum will include the following packages:

WP1 Literature Search

- Literature search on the existing 3D datasets on semantic segmentation for benchmarking.
- Literature search on the existing 3D models for semantic segmentation.
- Literature search over the out-of-distribution methods.

WP2 Dataset OOD benchmark proposal

- 3D semantic segmentation dataset collection for benchmarking.
- Benchmark datasets for in-distribution and out-distribution.

WP3 Experimentation

- Extend an existing 3D semantic segmentation model as baseline model for the out-of-distribution detection problem.
- Extend the state-of-the-art (SOTA) 3D semantic segmentation model for the out-of-distribution detection problem.

WP4 Evaluation

- Evaluate the baseline model and SOTA model on the proposed evaluation methods.
- Compare both the model on OOD detection

WP5 Project Report

- Write the report

3.2 Milestones

- M1 Literature search
- M2 Dataset benchmarking
- M3 Models implementation
- M4 Evaluation and comparison
- M5 Report submission

3.3 Deliverables

Minimum Viable

- Systematic literature survey of methods over
 - Datasets in 3D semantic segmentation
 - Existing out-of-distribution methods
 - Semantic segmentation models on 3D datasets
- Proposal of benchmarking datasets for out-of-distribution detection in 3D semantic segmentation
- Study of uncertainty quantification in 3D semantic segmentation models
- Implementation of method which uses quantified uncertainty for OOD detection

Expected

- Systematic evaluation of the implemented OOD detection method over the proposed dataset
- Extension of the state-of-the-art model for OOD detection
- Evaluation and comparison of the extended state-of-the-art model to baseline algorithm

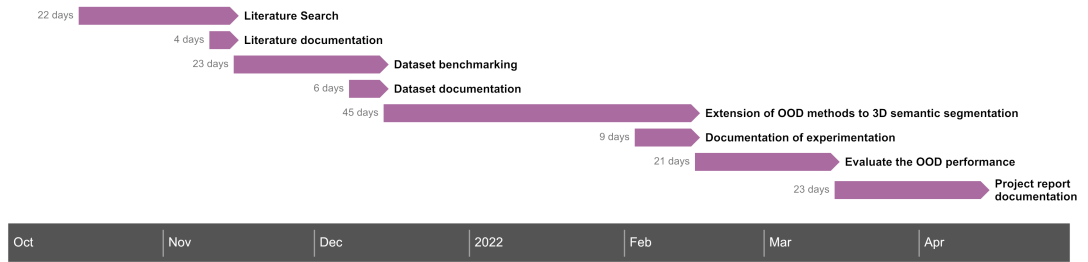
Desired

- Proposal of a refinement over the current OOD model for higher performance

3.4 Project Schedule

The detailed plan of tasks in duration of 6 months of thesis is given in figure 1.

Figure 2: Illustration of project timeline over the period of six months



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