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Master's Thesis

Out-of-distribution detection in 3D semantic segmentation

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in partial fullfilment of the requirements for the degree
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Supervised by

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Prof. Dr. Sebastian Houben

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I, the undersigned below, declare that this work has not previously been submitted to this or any other university and that it is, unless otherwise stated, entirely my own work.

Date

Lokesh Veeramacheneni

Abstract

Your abstract

Acknowledgements

Thanks to ....

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Introduction

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1.1 Motivation

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1.1.2 ...

1.2 Challenges and Difficulties

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1.2.3 ...

1.3 Problem Statement

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1.3.2 ...

1.3.3 ...

2

State of the Art

2.1 ....

Use as many sections as you need in your related work to group content into logical groups Don't forget to correctly cite your sources [**?**].

2.2 Limitations of previous work

3

Methodology

Dataset bechmarking is important any task because it allows future researchers to compare and validate their methods. In this thesis, we tried to formulate a benchmark for out of distribution (OOD) detection in 3D datasets and evaluated the benchmarked datasets over the baseline models. In this chapter, we discuss about the benchmarking of datasets particualry how is it done and experimental setup which includes models used and also a description about the process of OOD detection.

3.1 Dataset benchmark formulation

In this era, development of novel architectures in deep learning is made easy by improvement in frameworks such as Pytorch and Tensorflow. These rapidly developed architectures requires a standard benchmarked datasets to compare performance with existing architectures. The process of creating benchmarked datasets with high quality are tedious and requires Herculian effort. Moreover the benchmarking for OOD detection task in 2D is already available in [cite]. The benchmarked datasets in OOD detection for 2D classification setting are MNIST vs Fashion MNIST [cite] or CIFAR vs SUN datasets [cite]. Since this thesis deals with OOD detection in 3D segmentation task and it is first of its kind no such benchmarking is available as best of our knowledge. As discussed in [cite], we chose the datasets for in and out distributions based on the criteria of *relevance*, *representativeness*, *experimentally verified case*, *scalability* and *resuability*. As argued in [cite] one more criteria is *non-redundancy* was tried to maintain and its only possible with hard OOD scenarios where classes doesn't overlap between datasets. In case of soft OOD there are class overlaps but it should not be a problem in OOD detection task.

3.1.1 SemanticKITTI

The first benchmarked datasets are of LiDAR point annotation datasets for 3D semantic segmentation. This thesis also include the study of the available LiDAR datasets, a detailed descripton of datasets and their classes are availbale in appendix [cite]. The discussion here is only confined to the datasets used for benchmarking. For this study we chose the SemanticKITTI dataset [**?**] as an in distribution dataset. We adopted SemanticKITTI becuase of its wide usage in evaluation of 3D semantic segmentation model performance. Moreover the dataset consits of high qualitative and quantative scans. Also the sensor used is Velodyne HDL-64E which is widely used sensor for LiDAR scans as its used in other datasets such

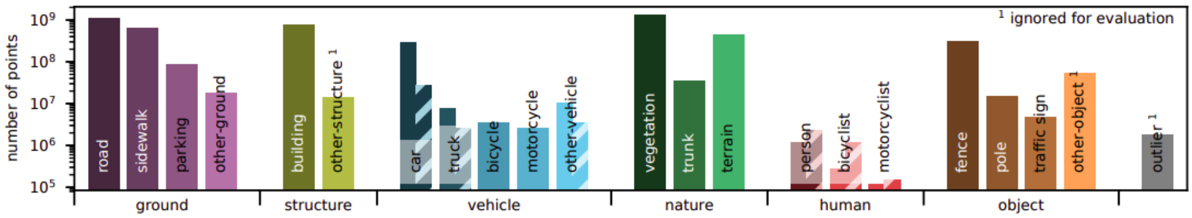

Figure 3.1: Classes in semanticKITTI datset and their distribution in dataset. The hatched bars means a mving object where as solid bar means a non movable object. Image taken from [**?**].

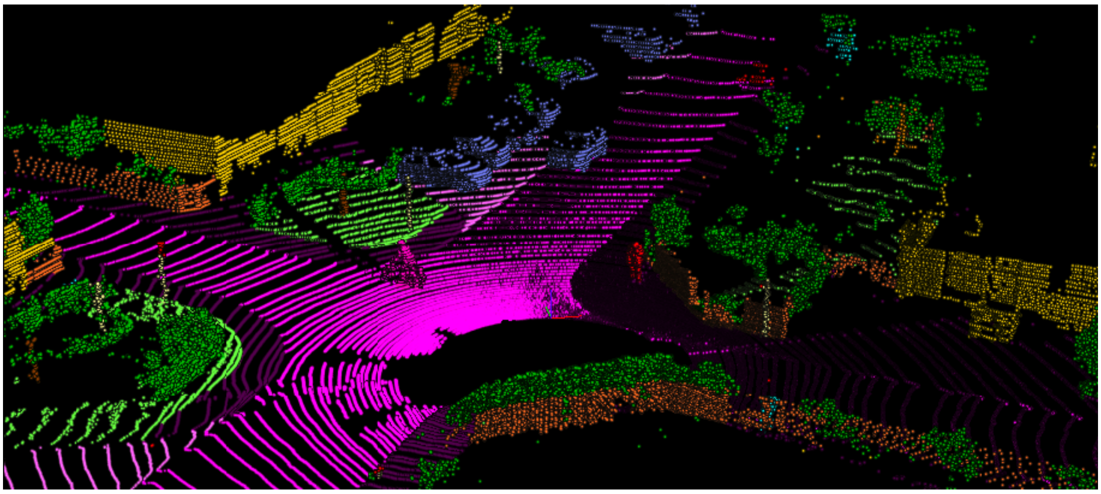

Figure 3.2: Ground truth example of a scan in SemanticKITTI dataset depicting various classes

as [cite]. SemanticKITTI [**?**] is a large dataset with 23201 and 20351 scans for training and testing respectively. The datasets has a gigantic 4549M number of points which are annotated individually. It has 28 classes annotated but only 25 are used for evaluation. The dataset is also publicly available at [cite] for download and API at [cite]. The available classes and their distribution in dataset is given in Figure 3.1. SemanticKITTI is an outdoor autonomous driving dataset as depicted in Figure 3.2.

3.1.2 Stanford 3D Indoor Scene Dataset (S3DIS)

4
Solution

Your main contributions go here

4.1 Proposed algorithm

4.2 Implementation details

5 Evaluation

Implementation and measurements.

6

Results

6.1 Use case 1

Describe results and analyse them

6.2 Use case 2

6.3 Use case 3

7

Conclusions

7.1 Contributions

7.2 Lessons learned

7.3 Future work

8

Notes/Remarks

8.1 Related work - Datasets

LiDAR is one of the central component in the sensor suite for SLAM system in robotic applications [22], [16], [11] and autonomous driving [13]. 3D LiDAR data is preferred because, it can provide the exact replica of 3D geometry of the real world represented in the form of 3D point clouds. Because of these rich features and widespread use of LiDAR sensors, tasks such as 3D object detection [30], [29] and 3D semantic segmentation [17], [1] are becoming more predominant area for research.

In this section, we will discuss about the available 3D LiDAR datasets for 3D semantic segmentation task and classify the datasets based on acquisition methods as in [6]. [6] classifies the available public datasets into three classes based on the data acquisition process. They are *Sequential*, *Static* and *Synthetic* datasets. The data for sequential datasets are collected as frame sequences where mechanical LiDAR is mounted on top of a autonomous driivng platform as in Figure 8.1. Most of the popular autonomous

Figure 8.1: Sequential mounted LiDAR for data collection of Lyft L5 dataset. Image from [12]

driving datasets are of sequential type, but these kind of datasets comes with a drawback of sparse points than other datasets.

Static datasets consists of data collected from a stationary view point by a terrestrial laser scanner. These kind of datasets capture the static information of the realworld whereas the sequential datasets capture the dynamic movements of the surrounding objects. Static datasets find their way in applications such as the urban planning, augmented reality and robotics. Figure 8.2 depcits a terrestrial laser scanner used to capture point cloud of an industrial environment. An advantage with the static datasets, are they can produce highly dense point clouds leading to rich 3D geometric representations.

Last type of 3D LiDAR datasets are synthetic datasets. As the name suggests these datasets are generated from the computer simulation. Figure 8.3 depcits a simulated point cloud in a synthtic dataset

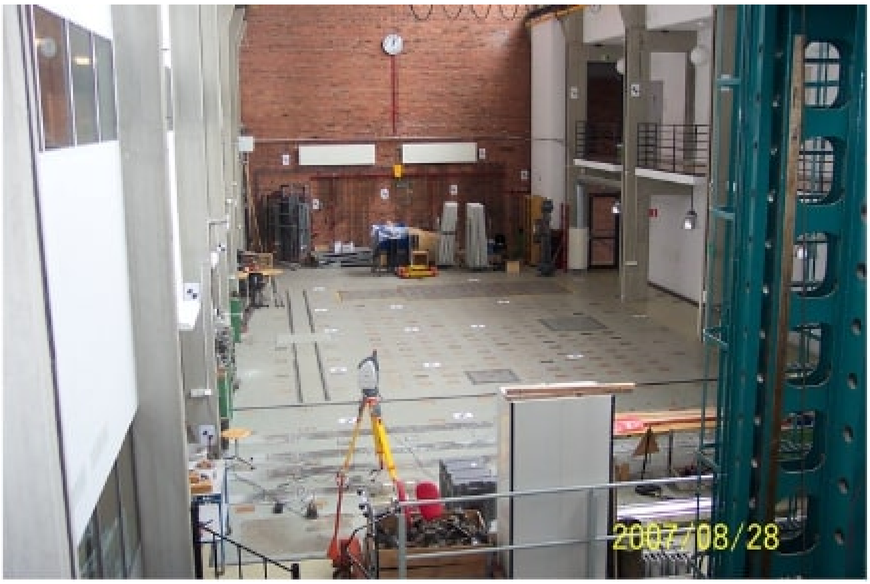

Figure 8.2: Terrestrial laser scanner in an industrial environment with the laser scanner mounted on a yellow tripod in the left corner of the floor. Image taken from [18]

called SynthCity. Eventhough synthetic datasets can be generated in large scale with cheap cost, they lack the accuracy in detail when compared to the point clouds generated from real world.

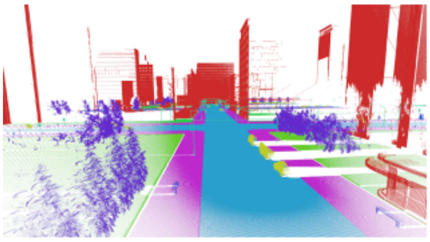

Figure 8.3: Illustration of a scene in synthetic dataset called SynthCity. Image taken from [9]

The datasets belonging to the each acquisition type are summed up in Table 8.1. Most of the datasets from the Table 8.1 are taken from [6] and also as a part of this study, additional new datasets were added to the list. The newly added datasets include DALES (#cite), ScanObjectNN (#cite) in static mode and AIO Drive (#cite), Toronto3D (#cite) are additions in the sequential mode. [6] also classifies GTAV (#cite) dataset as synthetic 3D LiDAR but the corresponding paper doesn't report any LiDAR dataset and proposed only 2D datasets for segmentation. The limited number of datasets in 3D LiDAR allowed us to study the characteristics of each individual datasets such as each class, data distribution and features of each point in point cloud. It is summarized in Table (#ref) in Appendix (#chapter number)

acquisition mode	dataset	frames	points (in million)	classes	scene type
static	Oakland[14]	17	1.6	44	outdoor
	Paris-lille-3D[19]	3	143	50	outdoor
	Paris-rue-Madame[20]	2	20	17	outdoor
	S3DIS[2]	5	215	12	indoor
	ScanObjectNN[23]	-	-	15	indoor
	Semantic3D[10]	30	4009	8	outdoor
	TerraMobilita/IQmulus[24]	10	12	15	outdoor
	TUM City Campus[7]	631	41	8	outdoor
	DALES[25]	40 (tiles)	492	8	outdoor
sequential	A2D2[8]	41277	1238	38	outdoor
	AIO Drive[26]	100	-	23	outdoor
	KITTI-360[28]	100K	18000	19	outdoor
	nuScenes-lidarseg[4]	40000	1400	32	outdoor
	PandaSet[27]	16000	1844	37	outdoor
	SemanticKITTI[3]	43552	4549	28	outdoor
	SemanticPOSS[15]	2988	216	14	outdoor
	Sydney Urban[5]	631	-	26	outdoor
	Toronto-3D[21]	4	78.3	8	outdoor
synthetic	SynthCity[9]	75000	367.9	9	outdoor

Table 8.1: 3D LiDAR datasets classified based on the acquisition type. Table updated from [6]

A

Design Details

Your first appendix

B

Parameters

Your second chapter appendix

References

[1] Iñigo Alonso, Luis Riazuelo, Luis Montesano, and Ana C. Murillo. 3d-mininet: Learning a 2d representation from point clouds for fast and efficient 3d lidar semantic segmentation. *IEEE Robotics and Automation Letters*, 5(4):5432–5439, 2020. doi: 10.1109/LRA.2020.3007440.

[2] Iro Armeni, Ozan Sener, Amir R. Zamir, Helen Jiang, Ioannis Brilakis, Martin Fischer, and Silvio Savarese. 3d semantic parsing of large-scale indoor spaces. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2016.

[3] Jens Behley, Martin Garbade, Andres Milioto, Jan Quenzel, Sven Behnke, Cyrill Stachniss, and Jurgen Gall. Semantickitti: A dataset for semantic scene understanding of lidar sequences. In *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)*, October 2019.

[4] Holger Caesar, Varun Bankiti, Alex H Lang, Sourabh Vora, Venice Erin Liong, Qiang Xu, Anush Krishnan, Yu Pan, Giancarlo Baldan, and Oscar Beijbom. nuscenes: A multimodal dataset for autonomous driving. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pages 11621–11631, 2020.

[5] Mark De Deuge, Alastair Quadros, Calvin Hung, and Bertrand Douillard. Unsupervised feature learning for classification of outdoor 3d scans. In *Australasian Conference on Robitics and Automation*, volume 2, page 1, 2013.

[6] Biao Gao, Yancheng Pan, Chengkun Li, Sibo Geng, and Huijing Zhao. Are we hungry for 3d lidar data for semantic segmentation? a survey of datasets and methods. *IEEE Transactions on Intelligent Transportation Systems*, pages 1–19, 2021. doi: 10.1109/TITS.2021.3076844.

[7] Joachim Gehrung, Marcus Hebel, Michael Arens, and Uwe Stilla. An approach to extract moving objects from mls data using a volumetric background representation. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, 4, 2017.

[8] Jakob Geyer, Yohannes Kassahun, Mentar Mahmudi, Xavier Ricou, Rupesh Durgesh, Andrew S Chung, Lorenz Hauswald, Viet Hoang Pham, Maximilian Mühlegg, Sebastian Dorn, et al. A2d2: Audi autonomous driving dataset. *arXiv preprint arXiv:2004.06320*, 2020.

[9] David Griffiths and Jan Boehm. Synthcity: A large scale synthetic point cloud. *arXiv preprint arXiv:1907.04758*, 2019.

[10] Timo Hackel, Nikolay Savinov, Lubor Ladicky, Jan D Wegner, Konrad Schindler, and Marc Pollefeys. Semantic3d. net: A new large-scale point cloud classification benchmark. *arXiv preprint arXiv:1704.03847*, 2017.

[11] Wolfgang Hess, Damon Kohler, Holger Rapp, and Daniel Andor. Real-time loop closure in 2d lidar slam. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1271–1278, 2016. doi: 10.1109/ICRA.2016.7487258.

[12] John Houston, Guido Zuidhof, Luca Bergamini, Yawei Ye, Long Chen, Ashesh Jain, Sammy Omari, Vladimir Iglovikov, and Peter Ondruska. One thousand and one hours: Self-driving motion prediction dataset. *arXiv preprint arXiv:2006.14480*, 2020.

[13] Bo Li, Tianlei Zhang, and Tian Xia. Vehicle detection from 3d lidar using fully convolutional network. *arXiv preprint arXiv:1608.07916*, 2016.

[14] Daniel Munoz, J. Andrew Bagnell, Nicolas Vandapel, and Martial Hebert. Contextual classification with functional max-margin markov networks. In *2009 IEEE Conference on Computer Vision and Pattern Recognition*, pages 975–982, 2009. doi: 10.1109/CVPR.2009.5206590.

[15] Yancheng Pan, Biao Gao, Jilin Mei, Sibo Geng, Chengkun Li, and Huijing Zhao. Semanticposs: A point cloud dataset with large quantity of dynamic instances, 2020.

[16] Benjamin J Patz, Yiannis Papelis, Remo Pillat, Gary Stein, and Don Harper. A practical approach to robotic design for the darpa urban challenge. *Journal of Field Robotics*, 25(8):528–566, 2008.

[17] Charles R Qi, Li Yi, Hao Su, and Leonidas J Guibas. Pointnet++: Deep hierarchical feature learning on point sets in a metric space. *arXiv preprint arXiv:1706.02413*, 2017.

[18] Yuriy Reshetyuk. A unified approach to self-calibration of terrestrial laser scanners. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(5):445–456, 2010. ISSN 0924-2716.

[19] Xavier Roynard, Jean-Emmanuel Deschaud, and François Goulette. Paris-lille-3d: A large and high-quality ground-truth urban point cloud dataset for automatic segmentation and classification. *The International Journal of Robotics Research*, 37(6):545–557, 2018.

[20] Andrés Serna, Beatriz Marcotegui, François Goulette, and Jean-Emmanuel Deschaud. Paris-rue-Madame database: a 3D mobile laser scanner dataset for benchmarking urban detection, segmentation and classification methods. In *4th International Conference on Pattern Recognition, Applications and Methods ICPRAM 2014*, Angers, France, March 2014.

[21] Weikai Tan, Nannan Qin, Lingfei Ma, Ying Li, Jing Du, Guorong Cai, Ke Yang, and Jonathan Li. Toronto-3d: A large-scale mobile lidar dataset for semantic segmentation of urban roadways. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops*, pages 202–203, 2020.

[22] Sebastian Thrun, Mike Montemerlo, Hendrik Dahlkamp, David Stavens, Andrei Aron, James Diebel, Philip Fong, John Gale, Morgan Halpenny, Gabriel Hoffmann, et al. Stanley: The robot that won the darpa grand challenge. *Journal of field Robotics*, 23(9):661–692, 2006.

[23] Mikaela Angelina Uy, Quang-Hieu Pham, Binh-Son Hua, Thanh Nguyen, and Sai-Kit Yeung. Revisiting point cloud classification: A new benchmark dataset and classification model on real-world data. In *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)*, October 2019.

[24] Bruno Vallet, Mathieu Brédif, Andrés Serna, Beatriz Marcotegui, and Nicolas Paparoditis. Terramobilita/iqmulus urban point cloud analysis benchmark. *Computers & Graphics*, 49:126–133, 2015. ISSN 0097-8493.

[25] Nina Varney, Vijayan K Asari, and Quinn Graehling. Dales: A large-scale aerial lidar data set for semantic segmentation. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops*, pages 186–187, 2020.

[26] Xinshuo Weng, Yunze Man, Dazhi Cheng, Jinhyung Park, Matthew O'Toole, and Kris Kitani. All-In-One Drive: A Large-Scale Comprehensive Perception Dataset with High-Density Long-Range Point Clouds. *arXiv*, 2020.

[27] Pengchuan Xiao, Zhenlei Shao, Steven Hao, Zishuo Zhang, Xiaolin Chai, Judy Jiao, Zesong Li, Jian Wu, Kai Sun, Kun Jiang, Yunlong Wang, and Diange Yang. Pandaset: Advanced sensor suite dataset for autonomous driving. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, pages 3095–3101, 2021. doi: 10.1109/ITSC48978.2021.9565009.

[28] Jun Xie, Martin Kiefel, Ming-Ting Sun, and Andreas Geiger. Semantic instance annotation of street scenes by 3d to 2d label transfer. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2016.

[29] Bin Yang, Wenjie Luo, and Raquel Urtasun. Pixor: Real-time 3d object detection from point clouds. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2018.

[30] Yin Zhou and Oncel Tuzel. Voxelnet: End-to-end learning for point cloud based 3d object detection. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 4490–4499, 2018.