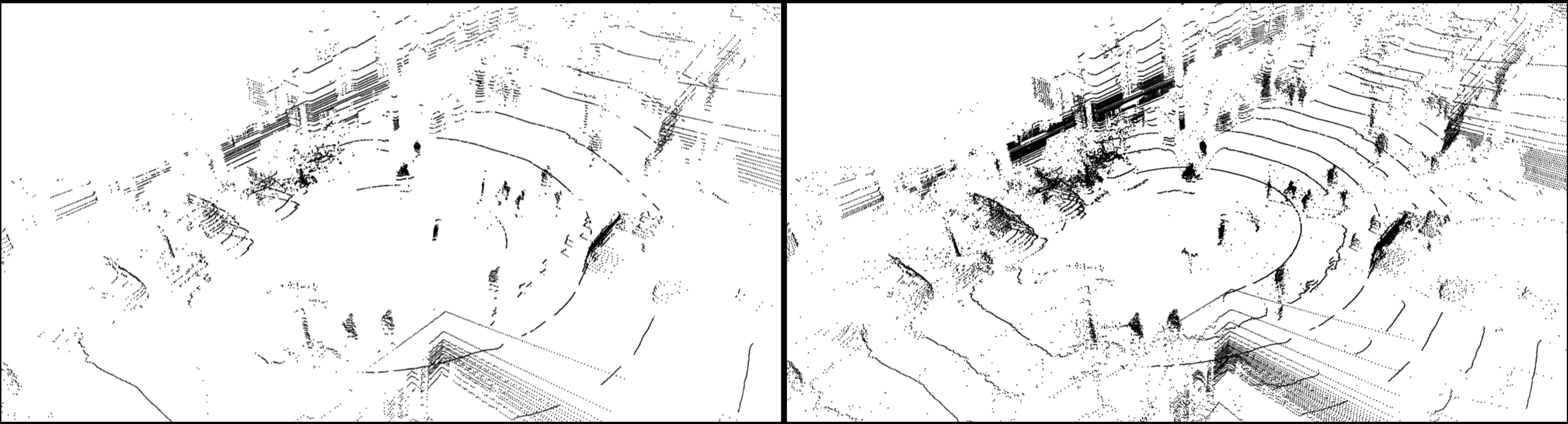

Synthesizing realistic high-resolution LiDAR Point Clouds by Up-Sampling with Neural Networks

Masterthesis

Larissa Triess

Supervisor: Prof. Dr.-Ing. Rainer Ott, INUE

Dr. rer. nat. David Peter, Daimler AG

University of Stuttgart

Institute of Telecommunications

Prof. Dr.-Ing. Stephan ten Brink

Agenda

I. Introduction and Motivation

II. Fundamentals

III. Implemented Network Systems

IV. Results

V. Summary and Outlook

Agenda

Motivation

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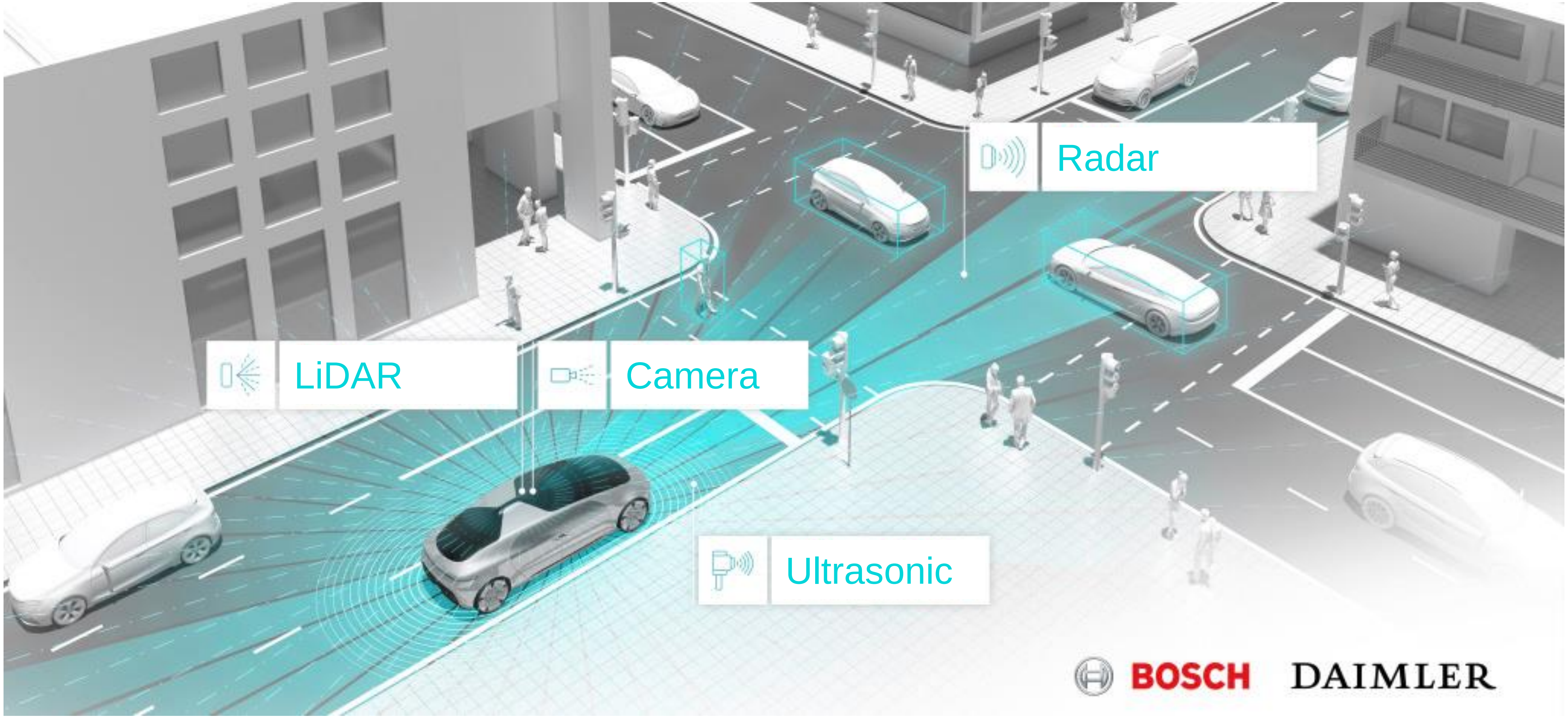

LiDAR Sensor

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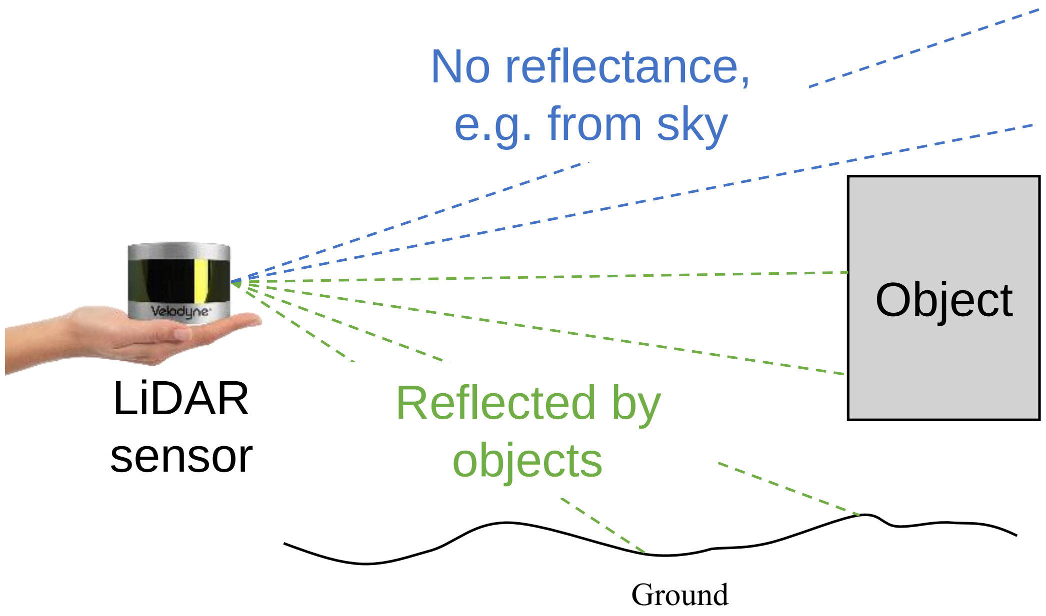
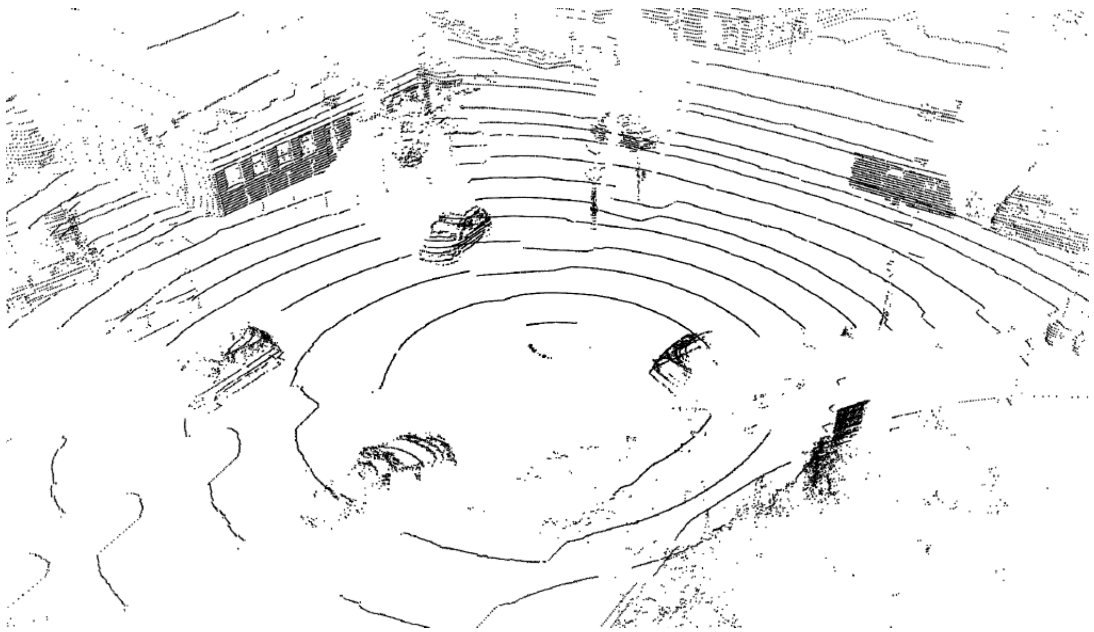
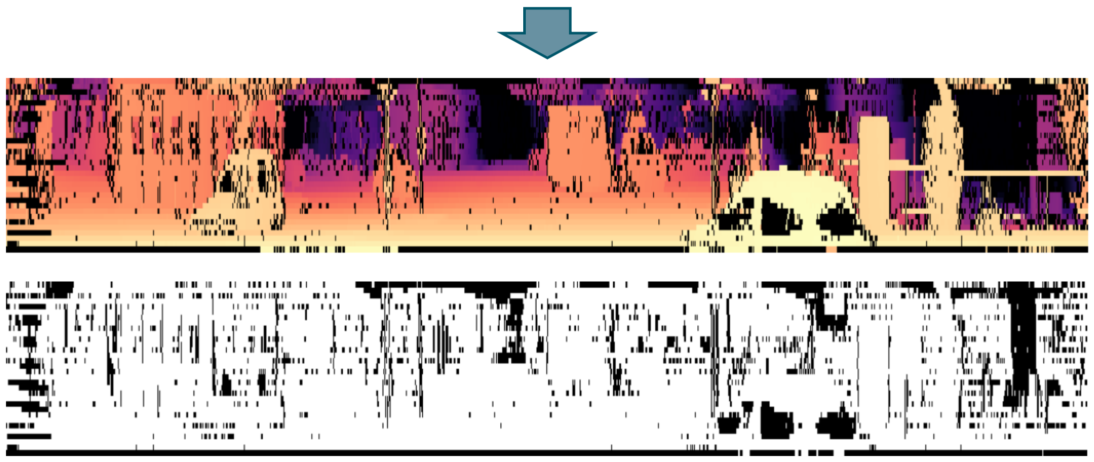


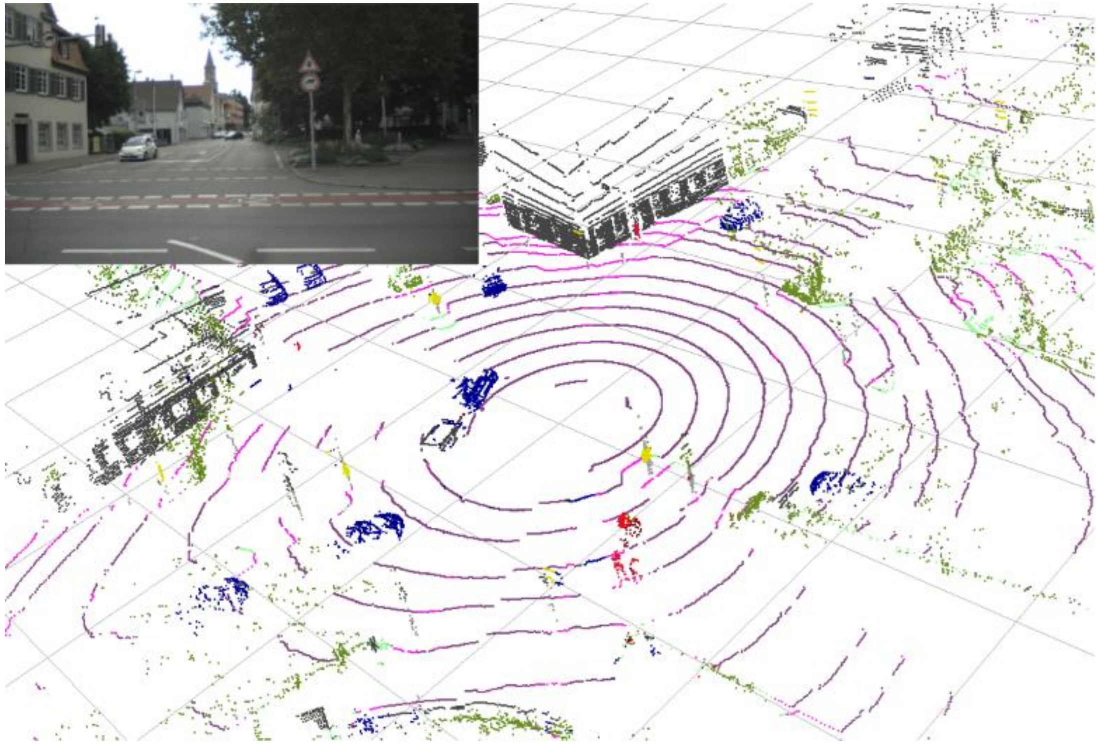




Dataset

	Training	Validation	Testing
	62 %	13 %	25 %
Original frames	343,926	73,473	137,636
Optimized frames	57,324	12,261	22,983

- Urban and rural scenes
- Single sensor mounted on roof of vehicle
- Sequence based dataset split
- Total dataset equals 15.5 hours of recording



- road
- sidewalk
- person
- rider
- vehicle
- truck
- bicycle
- construction
- pole
- traffic sign
- vegetation
- terrain

Agenda

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System Overview

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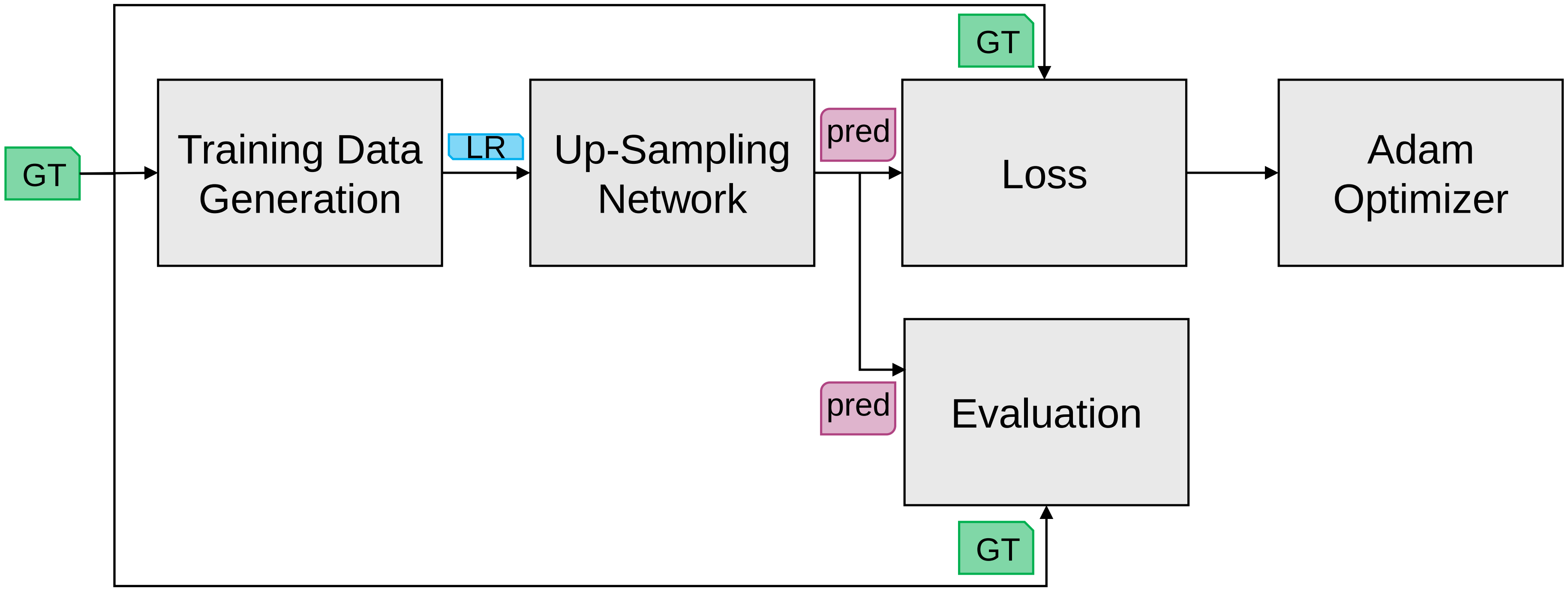

GT High-resolution ground truth data (H, W)
LR Low-resolution network input (H/2, W)
pred Predicted high-resolution output (H, W)

Up-Sampling Network

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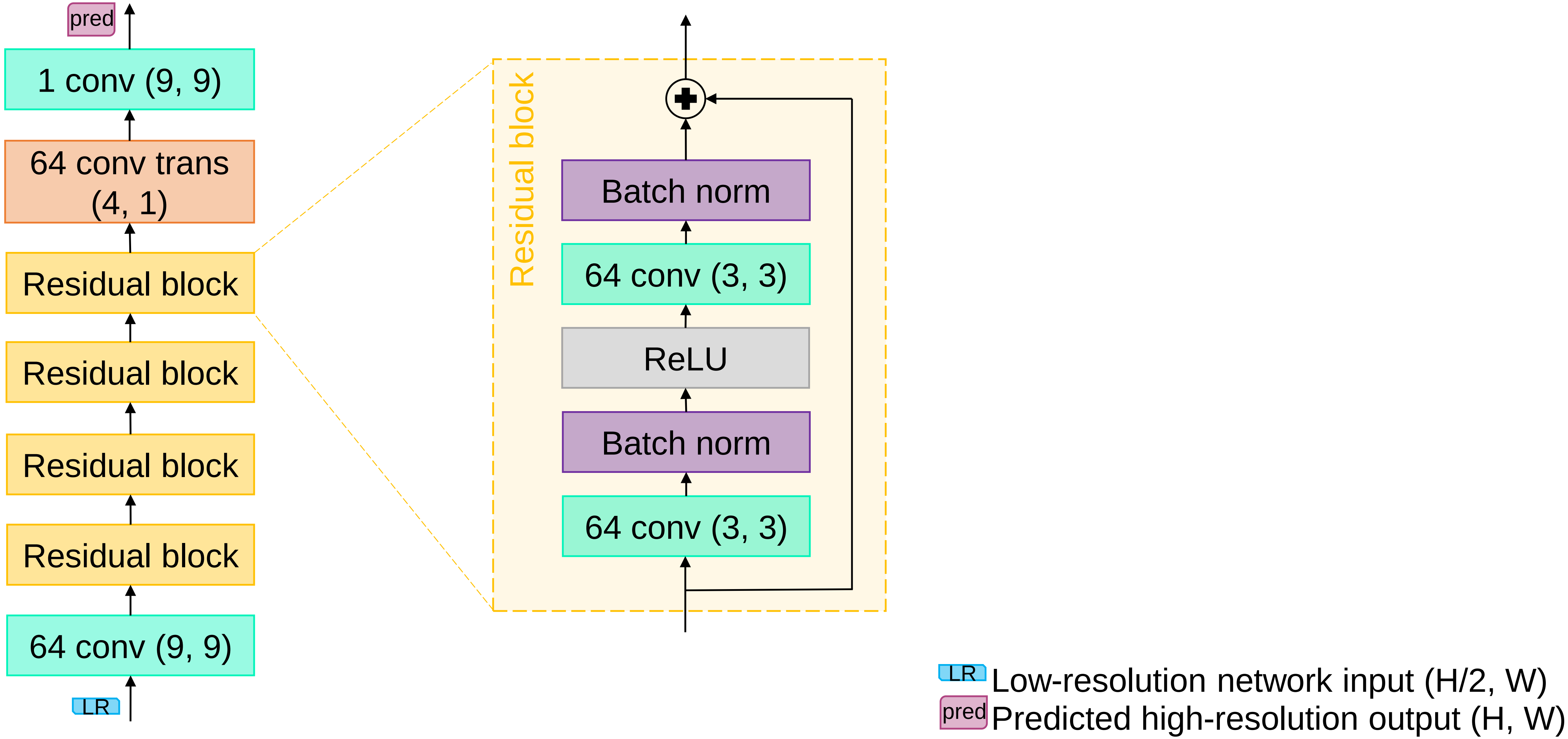

Loss Functions / Evaluation Metrics

L2-Loss or Mean Squared Error (MSE)

$$\mathrm{MSE} = \frac{1}{HW}\sum_{h,w} \left| d_{h,w}^{pred} - d_{h,w}^{gt} \right|^2$$

L1-Loss or Mean Absolute Error (MAE)

$$\mathrm{MAE} = \frac{1}{HW}\sum_{h,w} \left| d_{h,w}^{pred} - d_{h,w}^{gt} \right|$$

H, W – height and width LiDAR image; $d_{h,w}$ distance at position h, w

Loss Functions / Evaluation Metrics

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L2-Loss or Mean Squared Error (MSE)

$$\mathrm{MSE} = \frac{1}{HW} \sum_{h,w} \left| d_{h,w}^{pred} - d_{h,w}^{gt} \right|^2 \cdot \mathrm{valid}_{h,w}$$

L1-Loss or Mean Absolute Error (MAE)

$$\mathrm{MAE} = \frac{1}{HW} \sum_{h,w} \left| d_{h,w}^{pred} - d_{h,w}^{gt} \right| \cdot \mathrm{valid}_{h,w}$$

Extension for point cloud up-sampling:

$\mathrm{valid}_{h,w} \in \{0, 1\}$

0 – missing measurement
1 – valid point

H, W – height and width LiDAR image; $d_{h,w}$ distance at position h, w

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Implemented Network Systems

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Traditional Methods (Baseline)

Regular Architecture

Multi-Task Learning

Feature Reconstruction

Semantically Guided

Learning-based approaches

Implemented Network Systems

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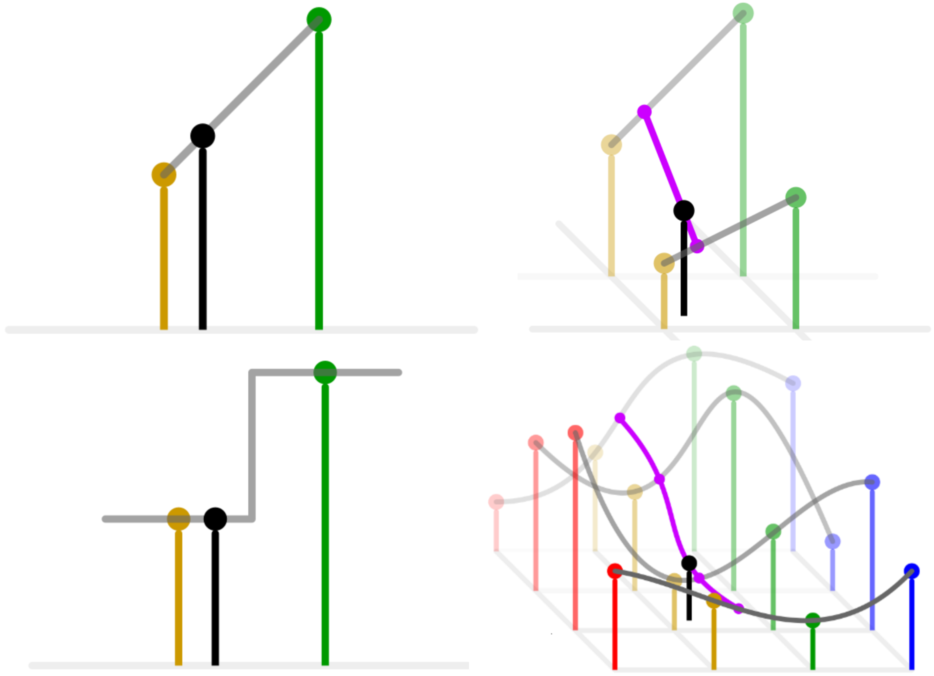

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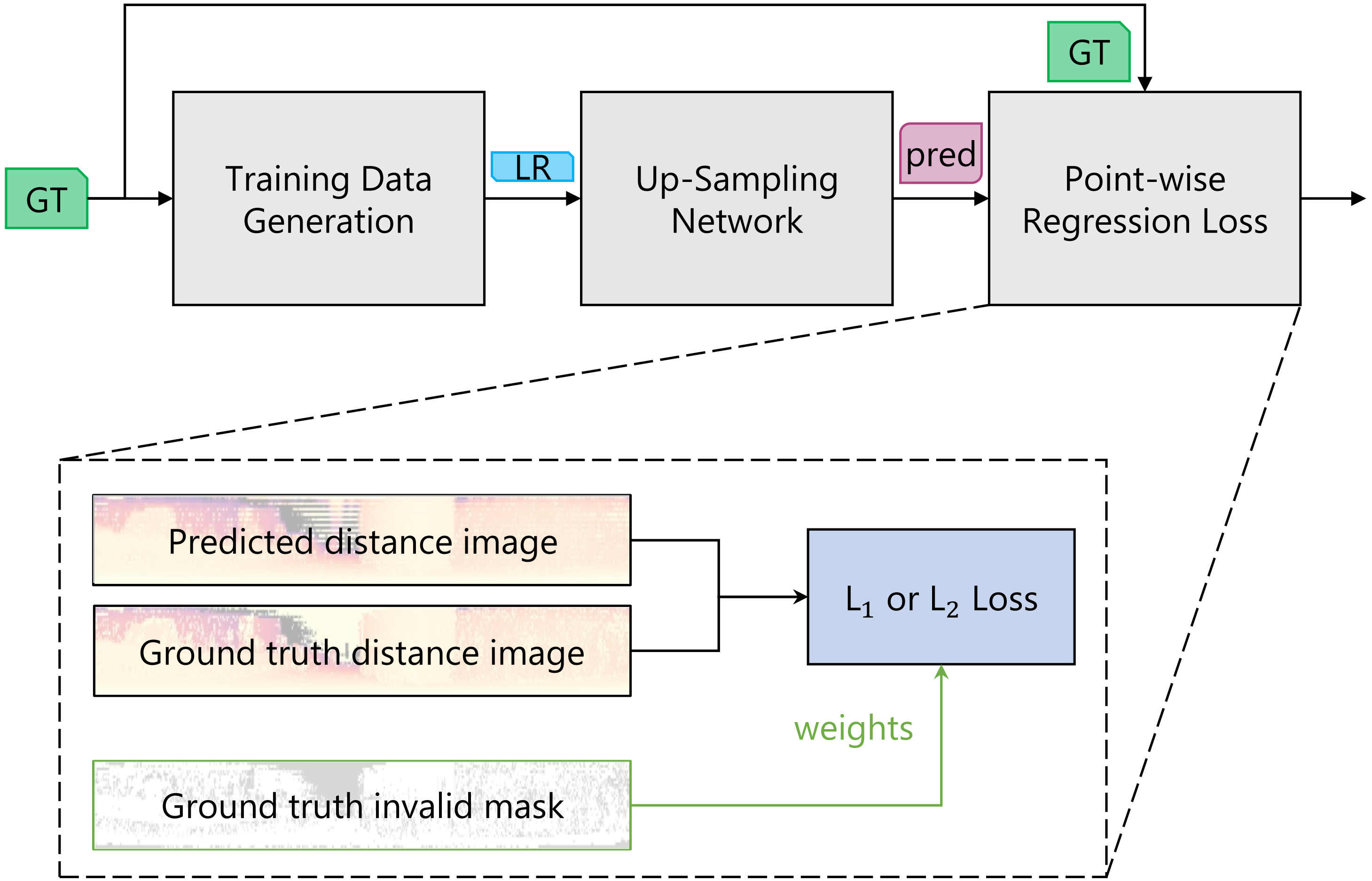

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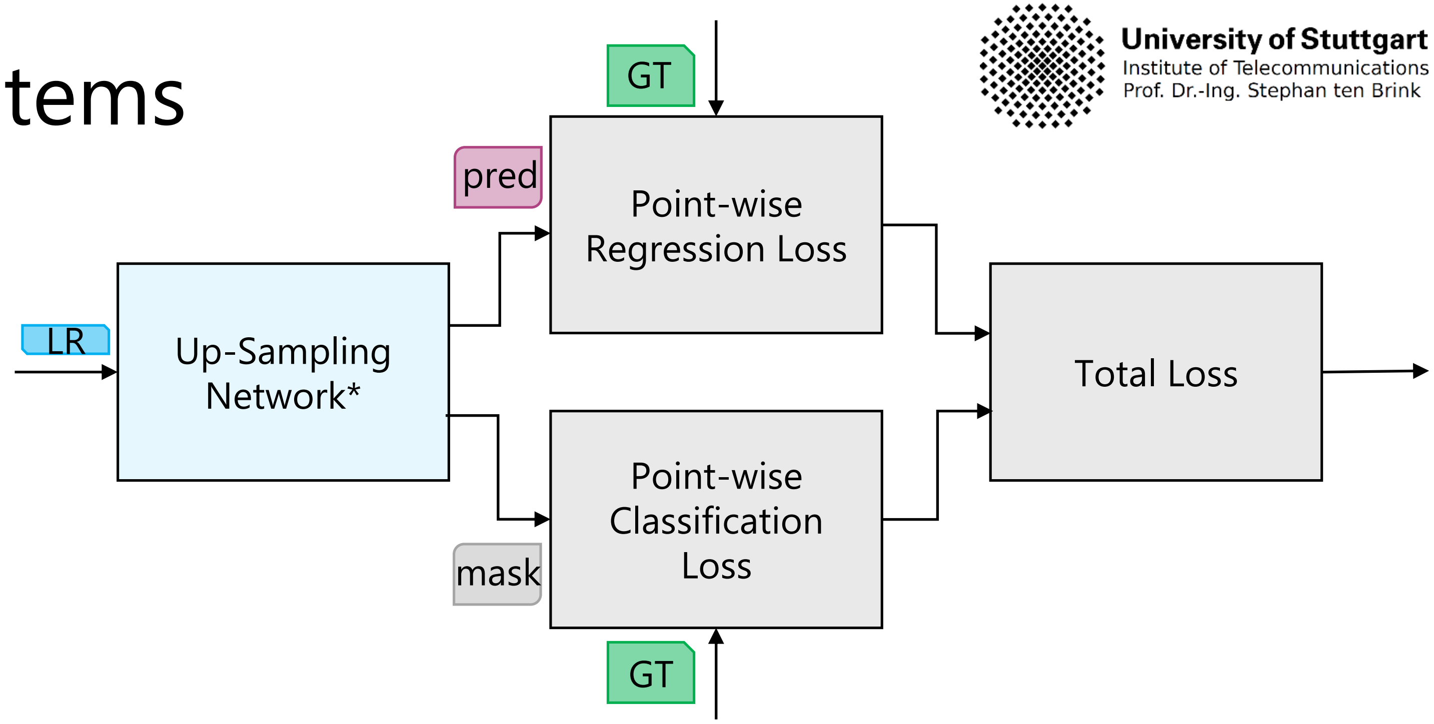

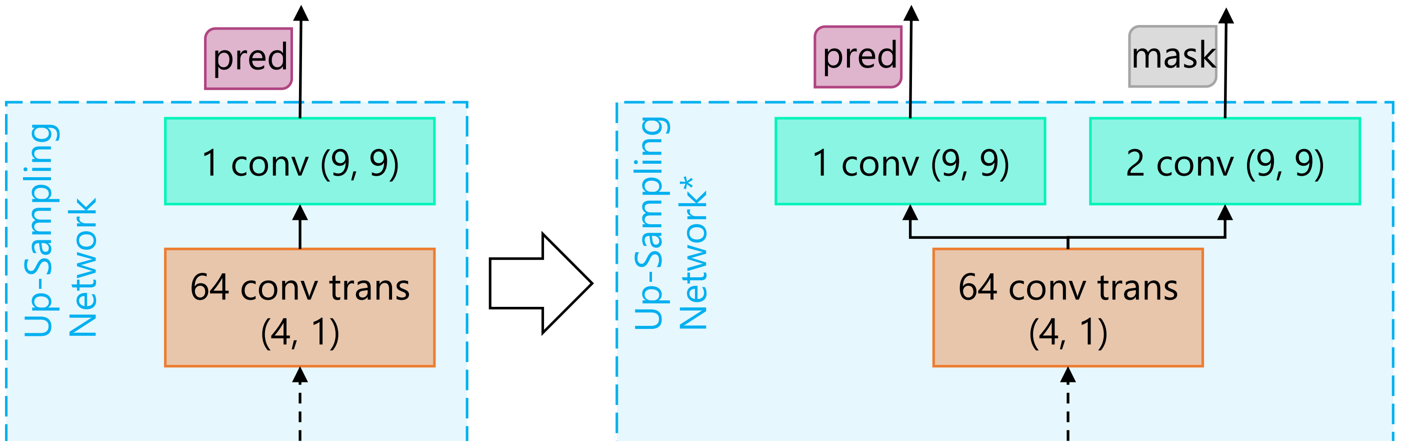

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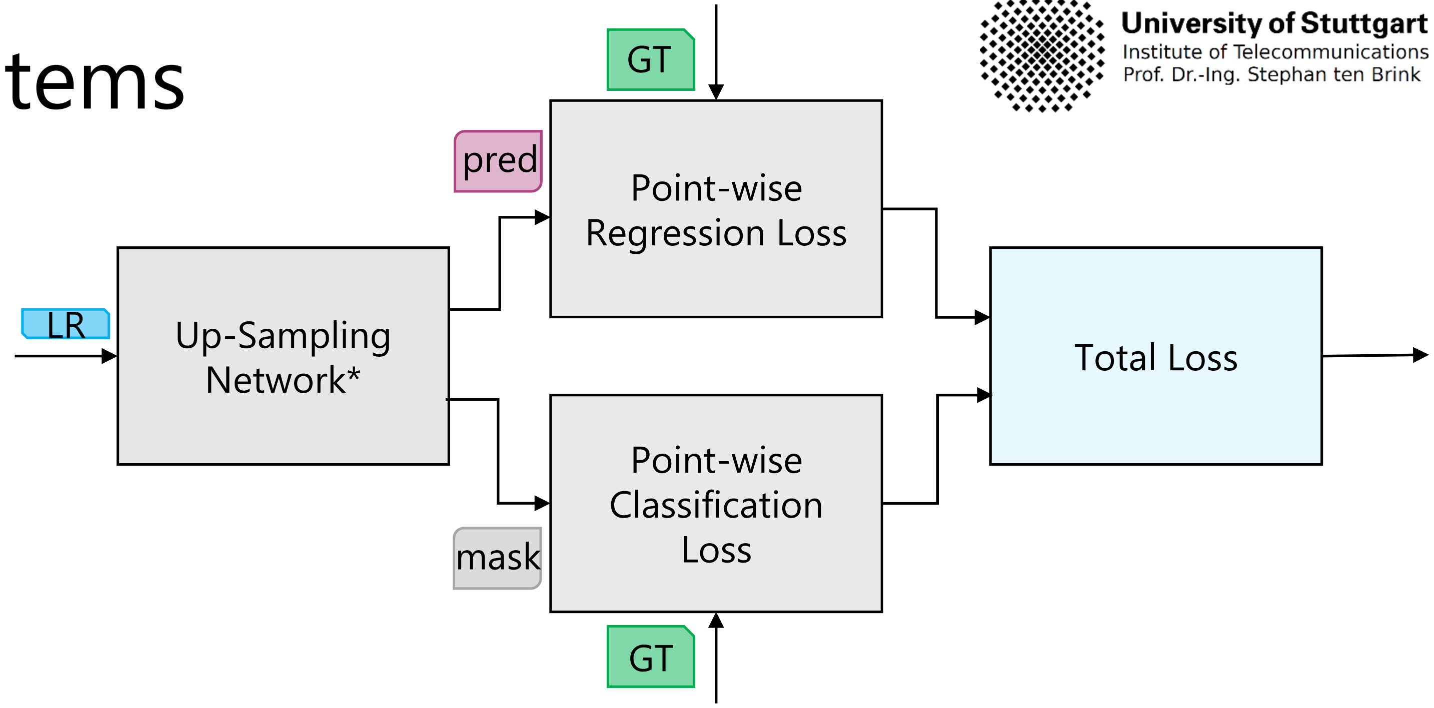

Traditional Methods (Baseline)

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Semantically Guided

$$\mathcal{L}_{\text{total}} = (1-p)\,\mathcal{L}_r + p\,\mathcal{L}_c \qquad p = \text{const}$$

$$\mathcal{L}_{\text{total}} = \frac{1}{2\sigma_r^2}\,\mathcal{L}_r + \log\sigma_r + \frac{1}{\sigma_c^2}\,\mathcal{L}_c + \log\sigma_c$$

Trainable Variables

Implemented Network Systems

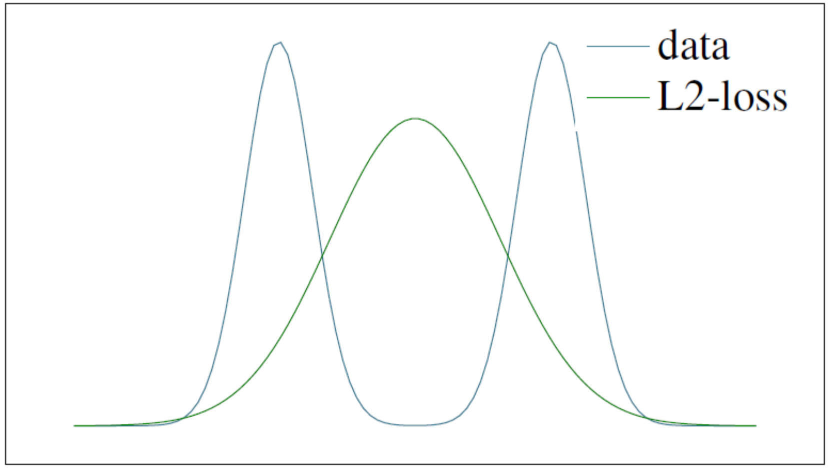
Traditional Methods (Baseline)

Regular Architecture

Multi-Task Learning

Feature Reconstruction

Semantically Guided



input

output

ground truth

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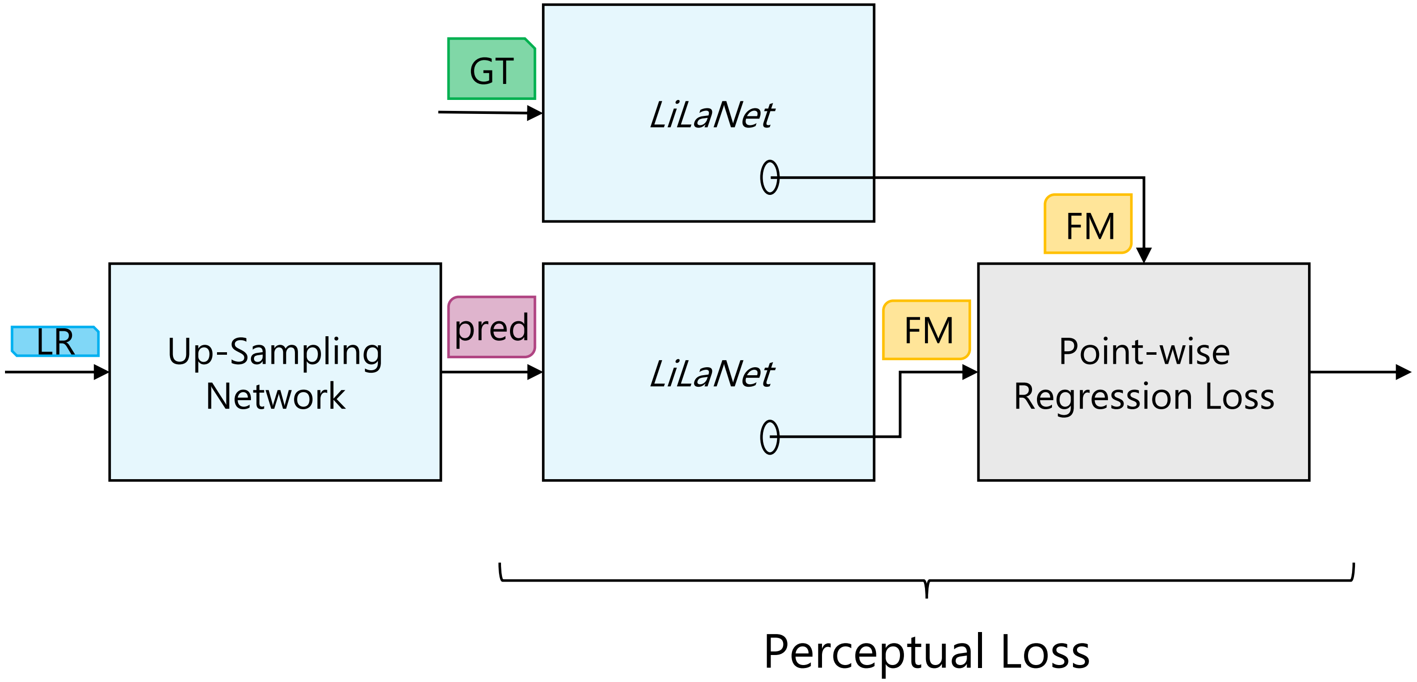
Traditional Methods (Baseline)

Regular Architecture

Multi-Task Learning

Feature Reconstruction

Semantically Guided



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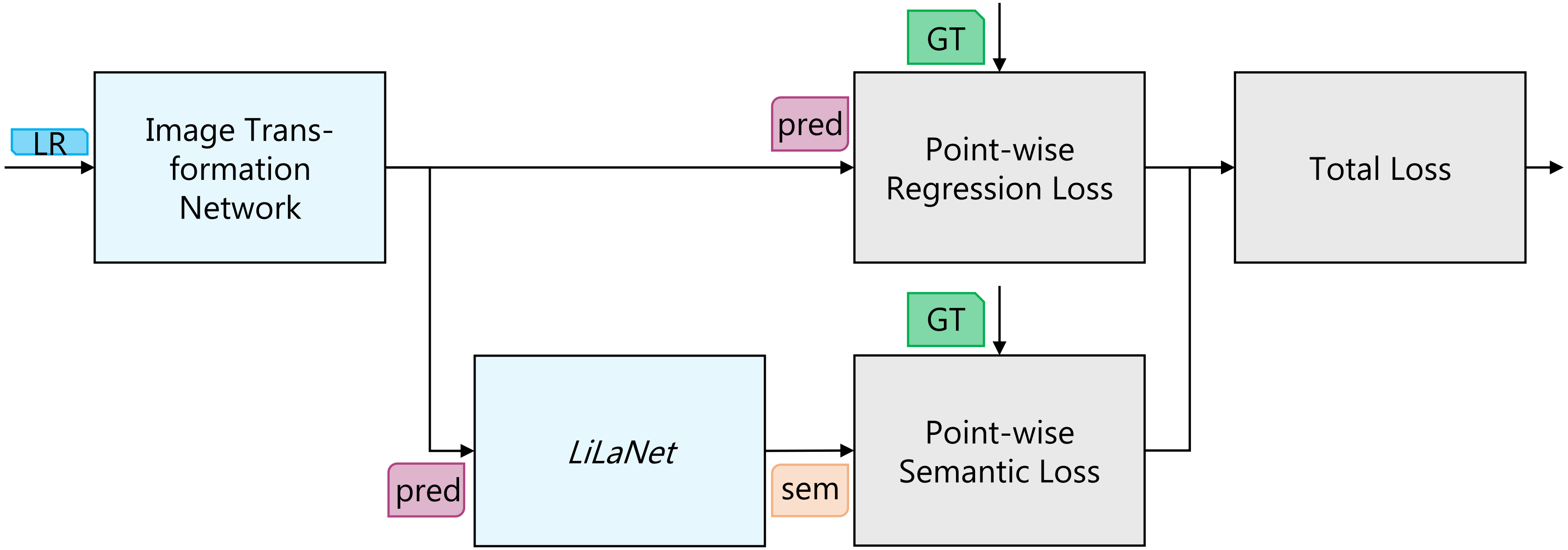

Agenda

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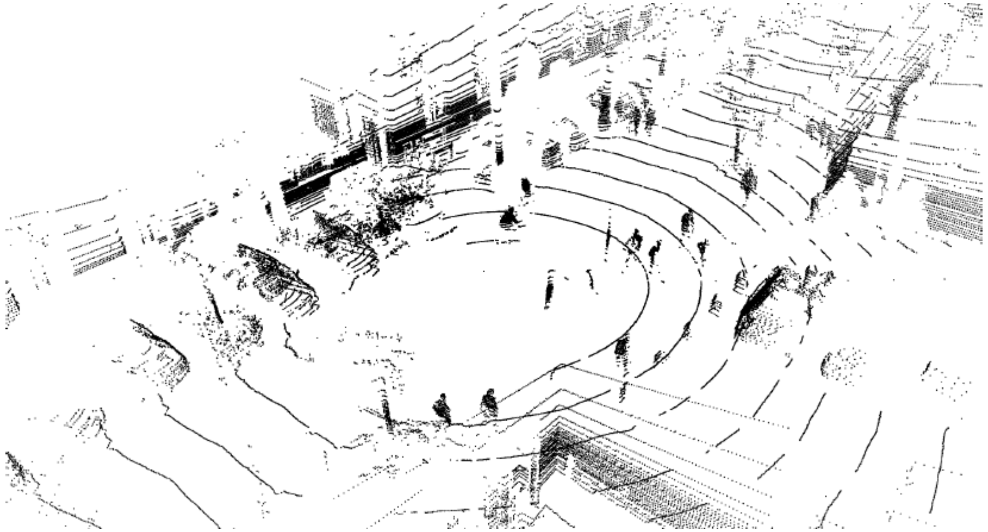
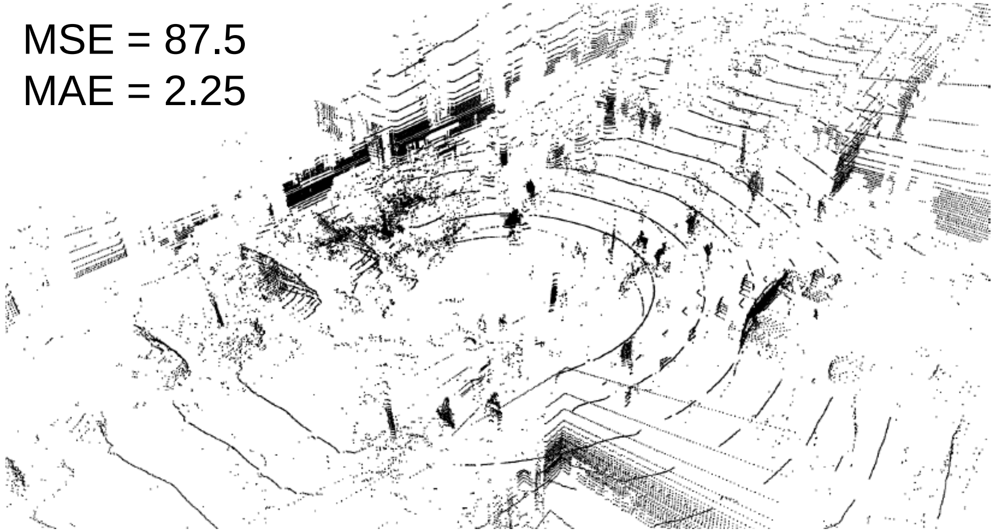
Results – L1 vs. L2 Loss

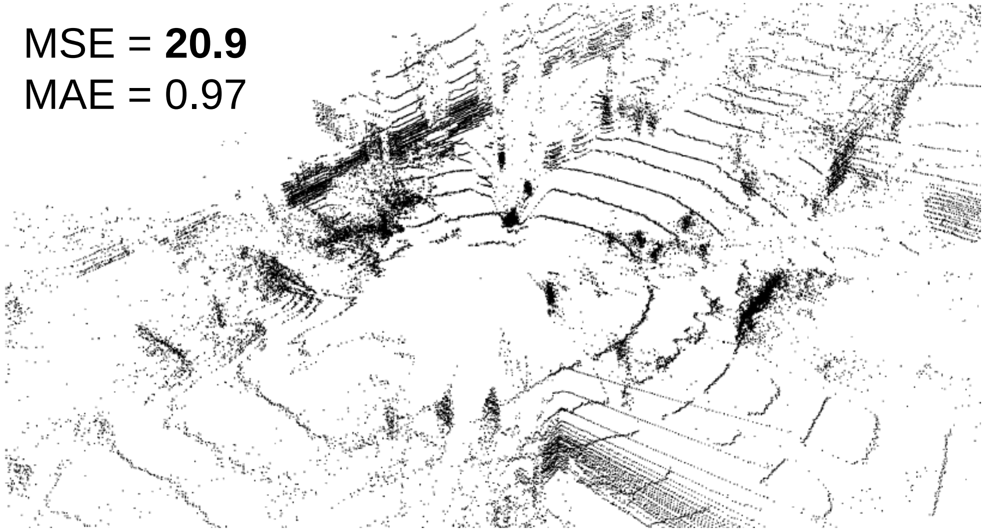


Ground Truth



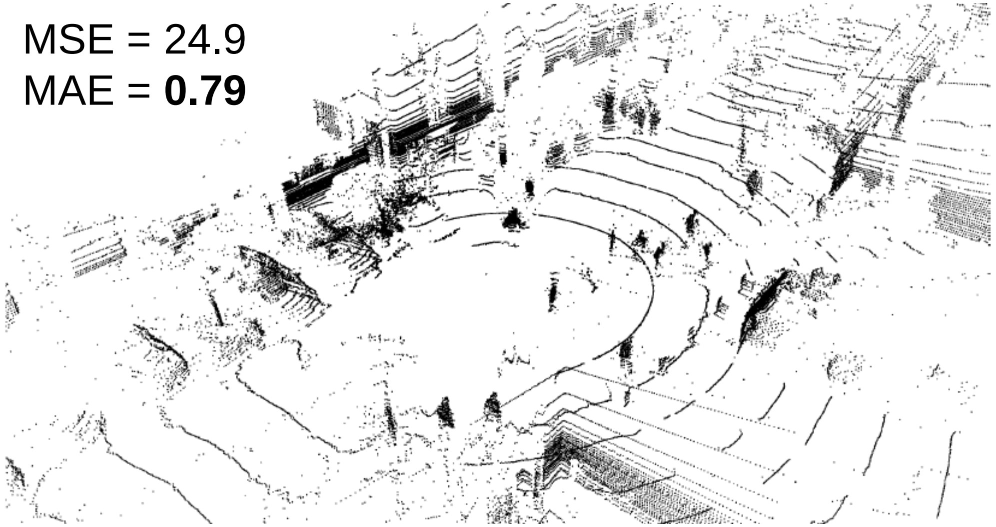
Bilinear

MSE = 87.5
MAE = 2.25



L2-Loss

MSE = **20.9**
MAE = 0.97

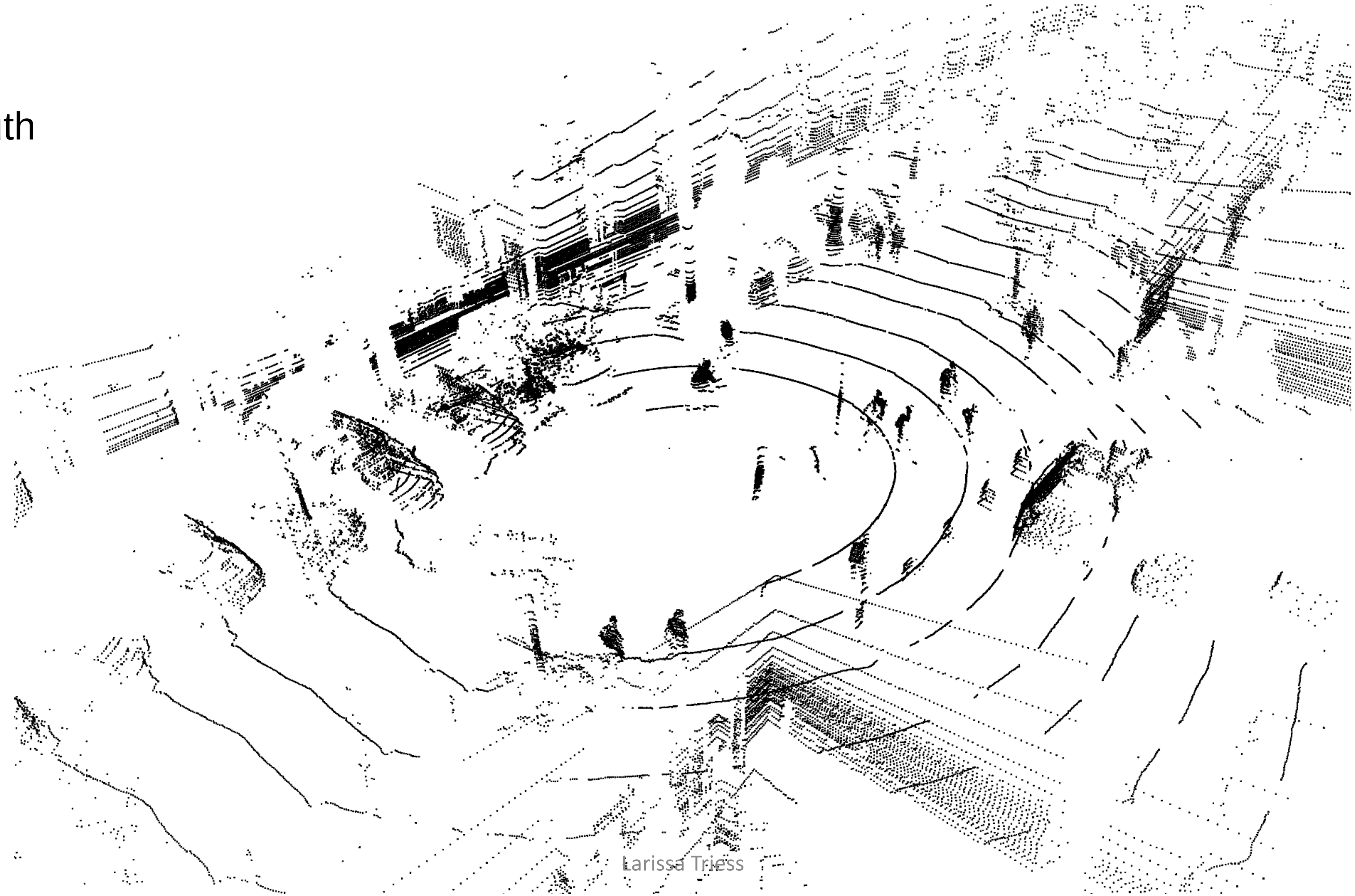


L1-Loss

MSE = 24.9
MAE = **0.79**

Results – L1 vs. L2 Loss

Ground Truth



Results – L1 vs. L2 Loss

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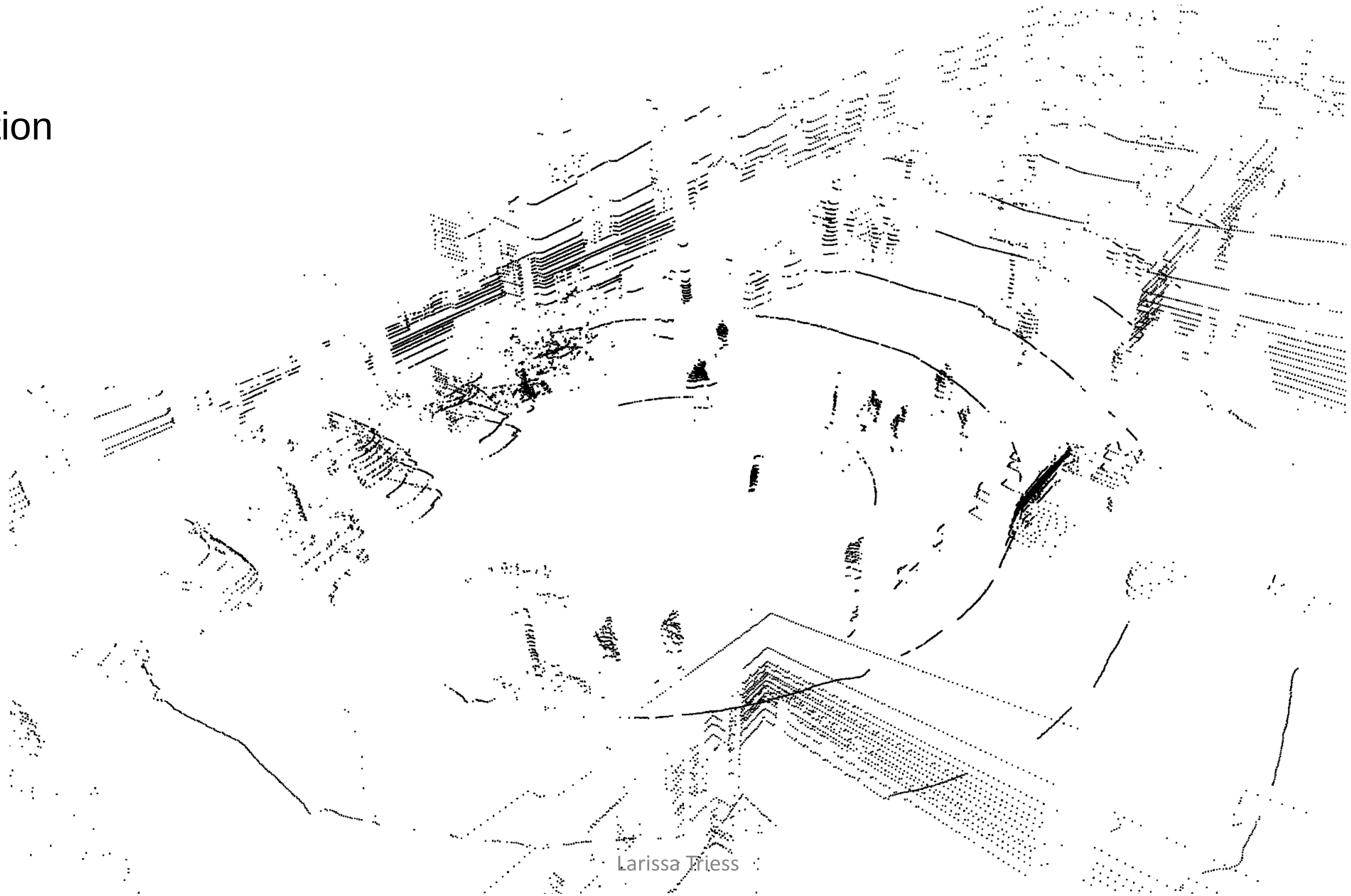
Low resolution



Results – L1 vs. L2 Loss

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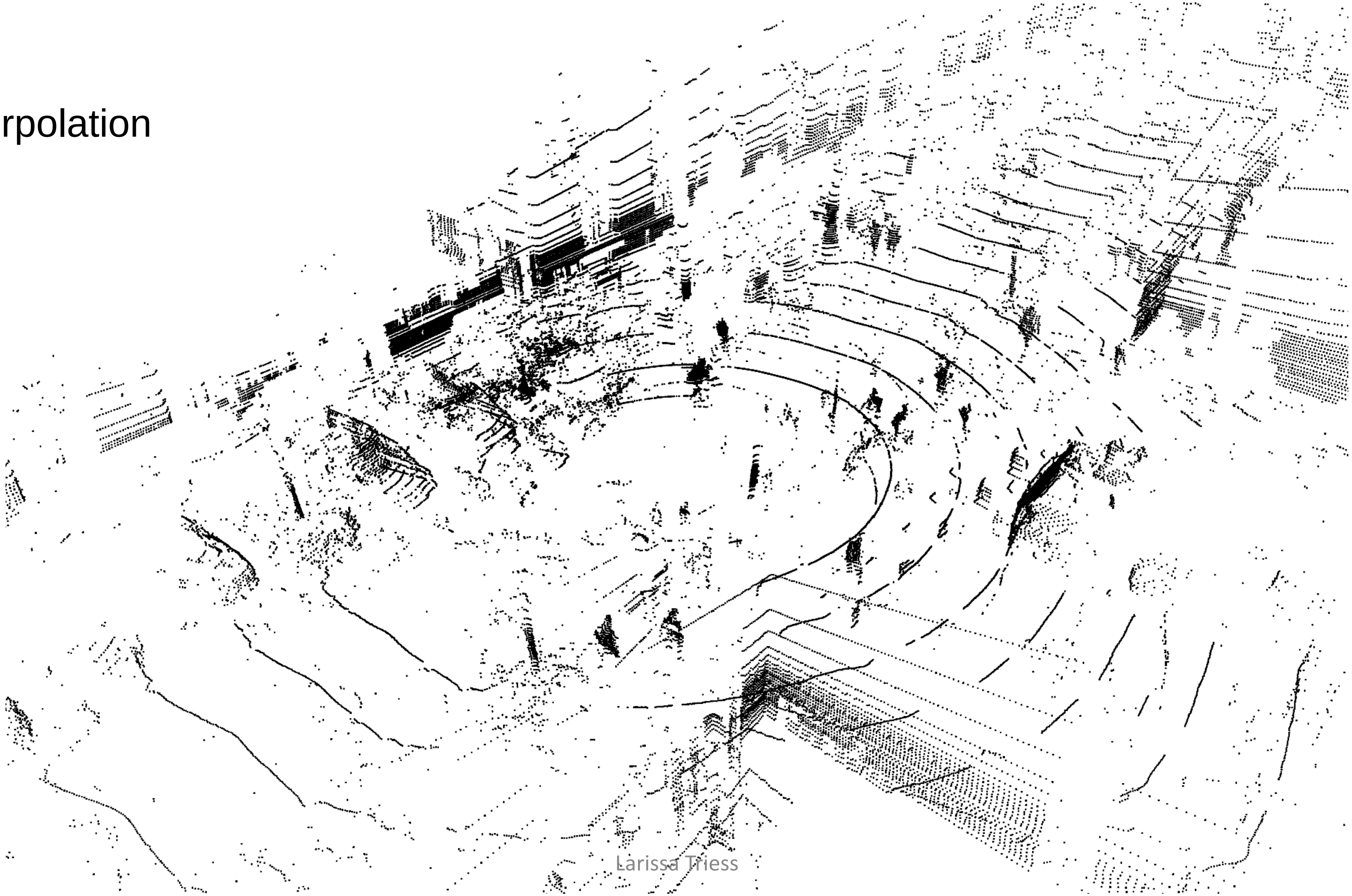
Bilinear interpolation



Results – L1 vs. L2 Loss

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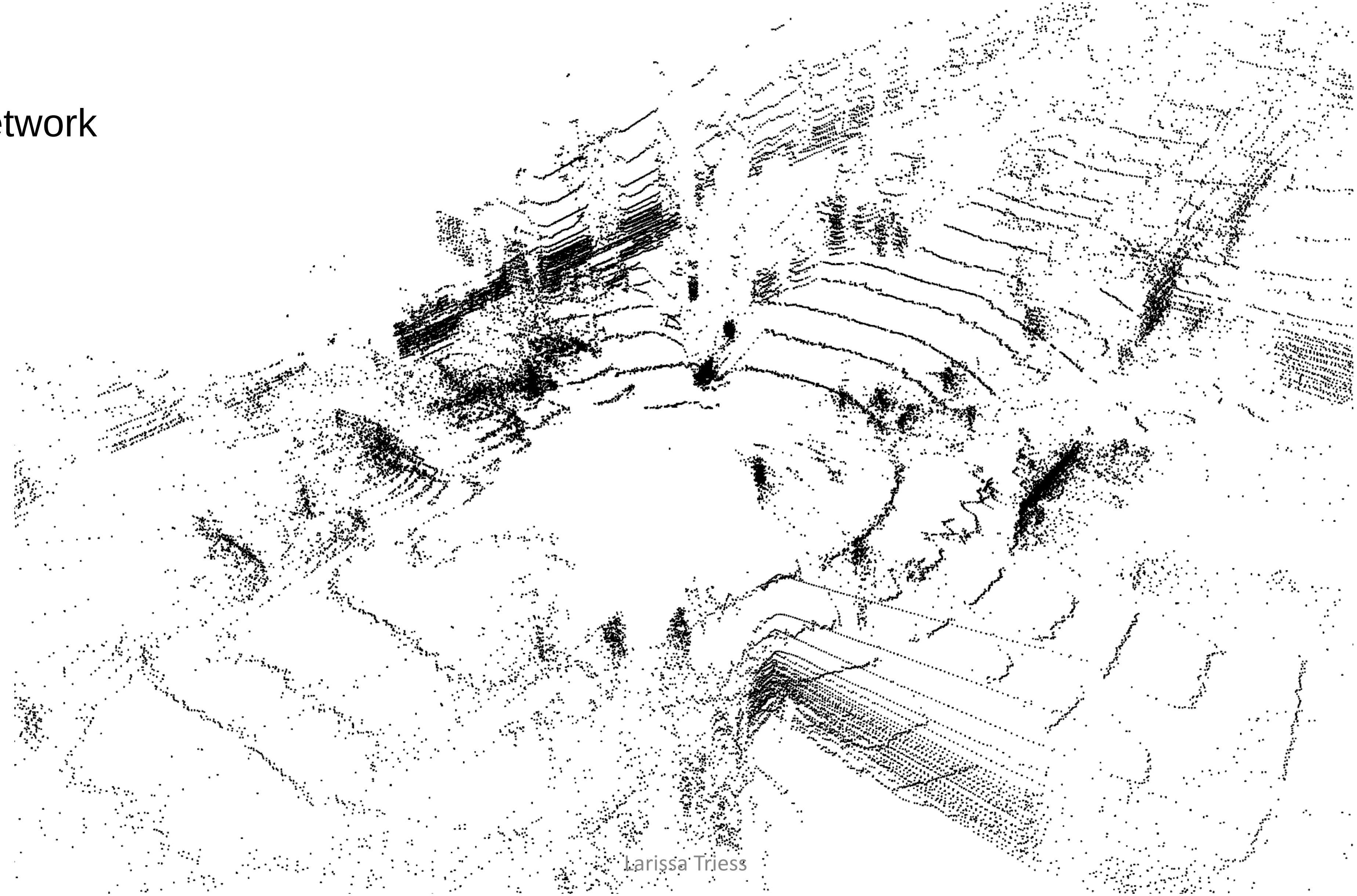
Regular Network
L2-Loss



Results – L1 vs. L2 Loss

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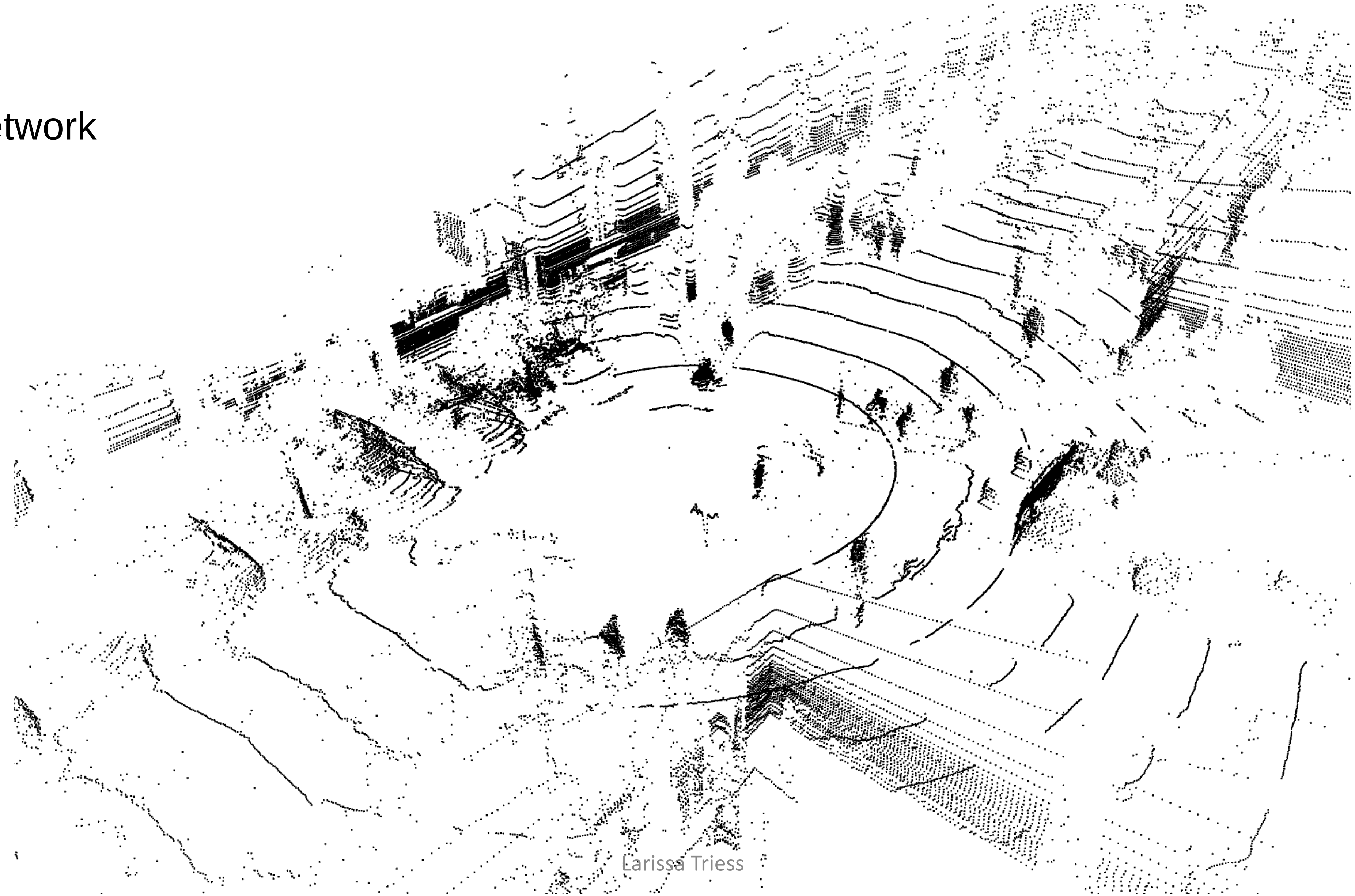
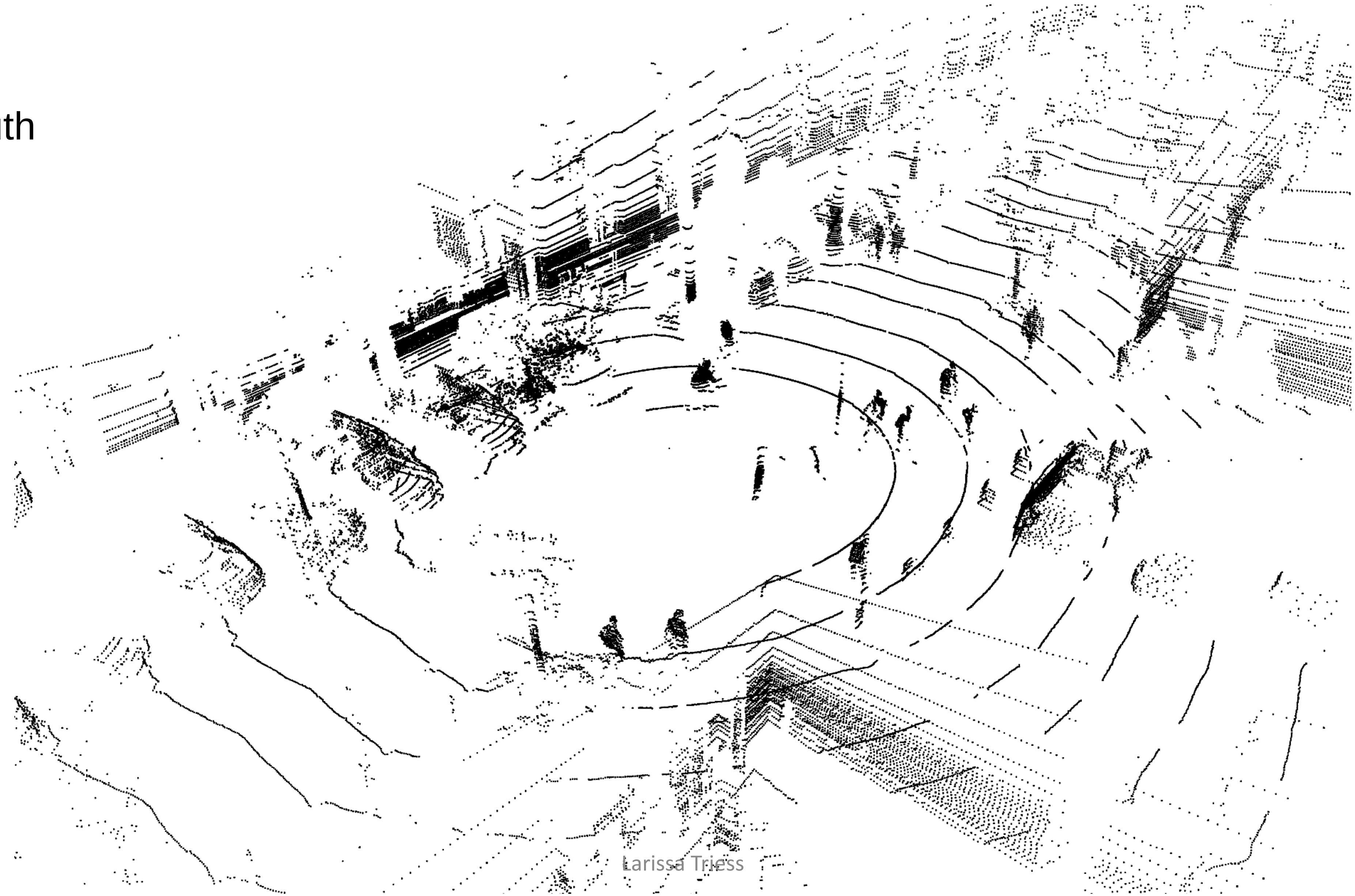
Regular Network
L1-Loss



Results – L1 vs. L2 Loss

Ground Truth



Evaluation per Object Class

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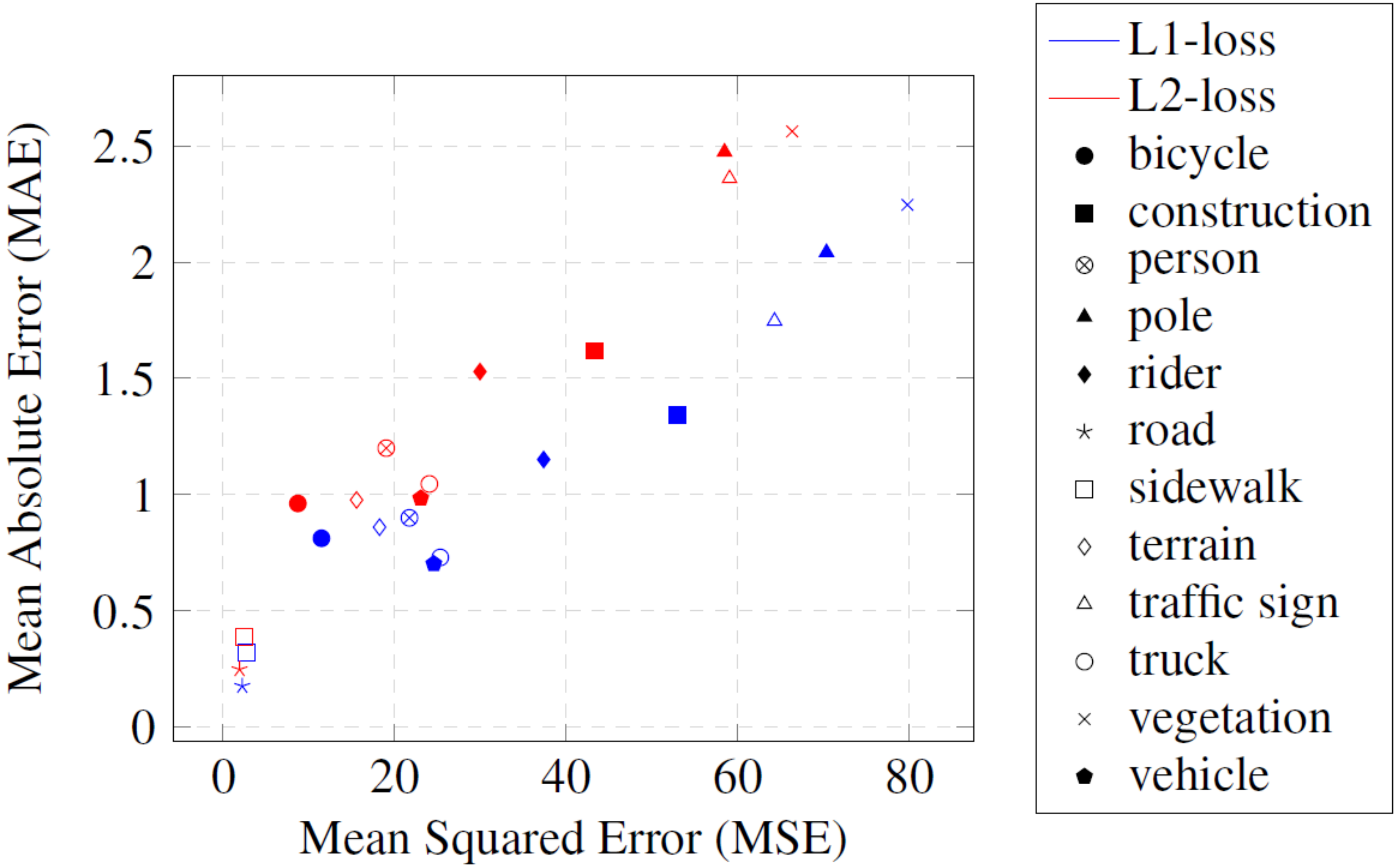

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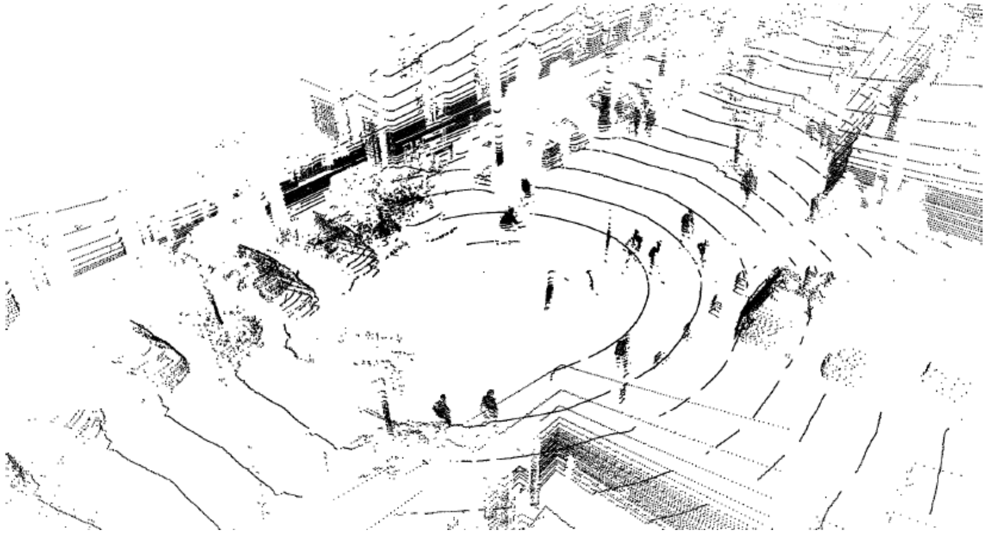
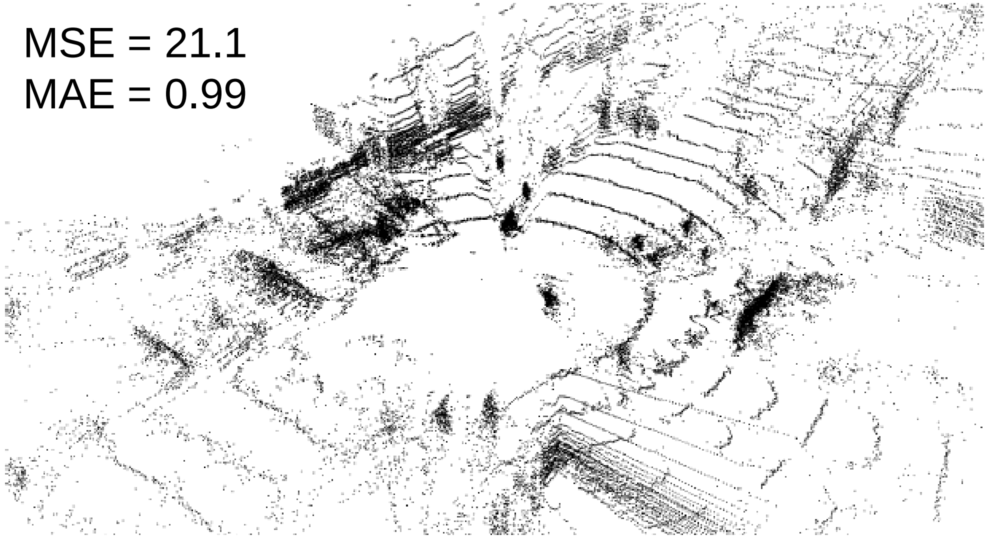
Results – Multi-Task Learning

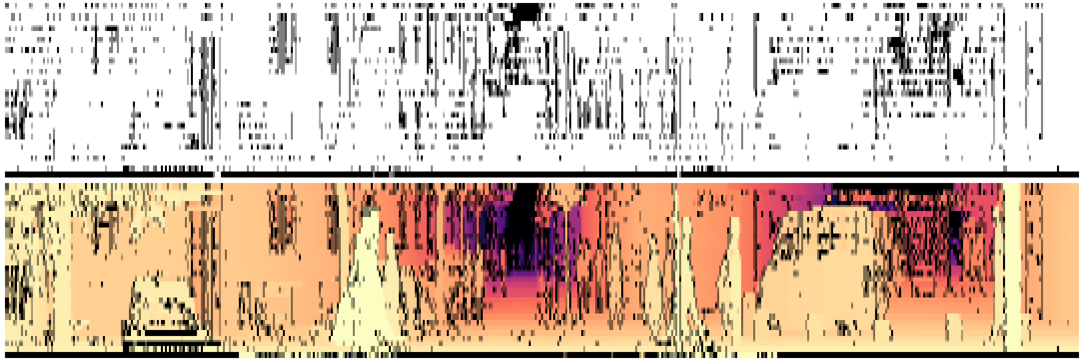
Ground Truth



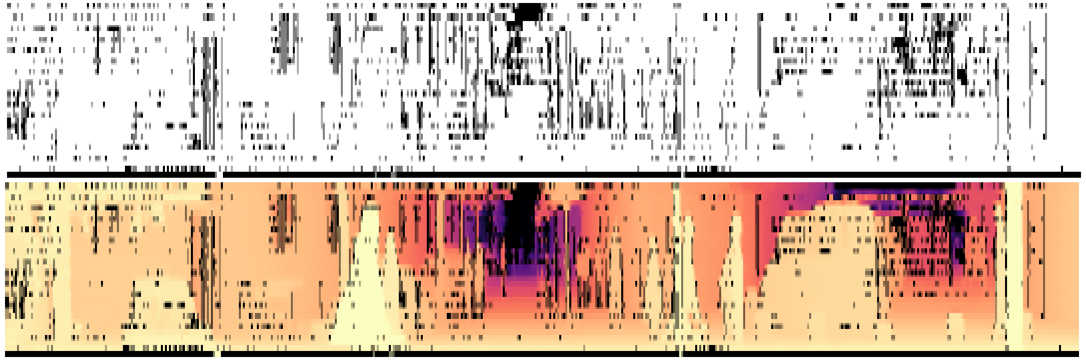
Multi-Task Learning

MSE = 21.1
MAE = 0.99





IoU = 0.82



Results – Feature Reconstruction

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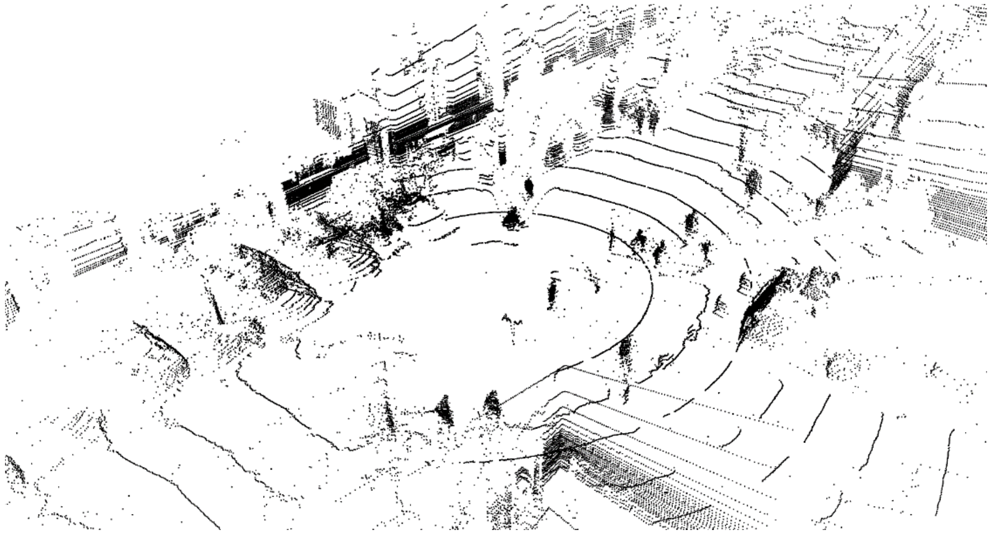
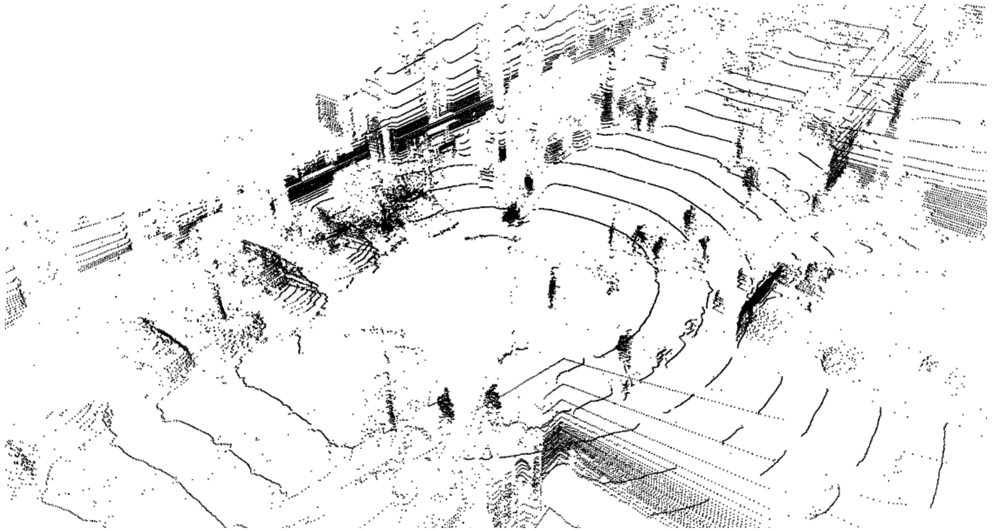


Regular Network trained with L1-Loss

MSE = 24.9, MAE = 0.79



Fine-tuned Feature Reconstruction Network

MSE = 30.6, MAE = 1.15

Similar or better perceptual quality though higher point-wise errors

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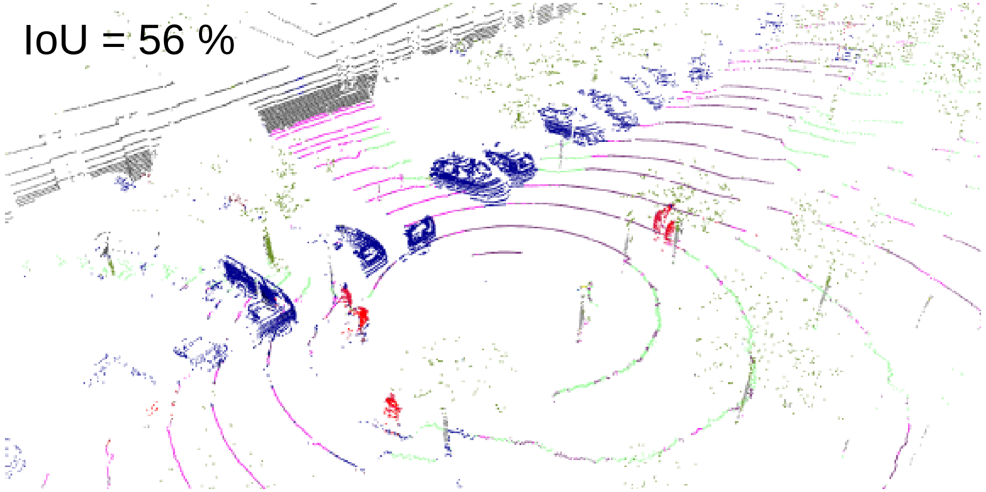
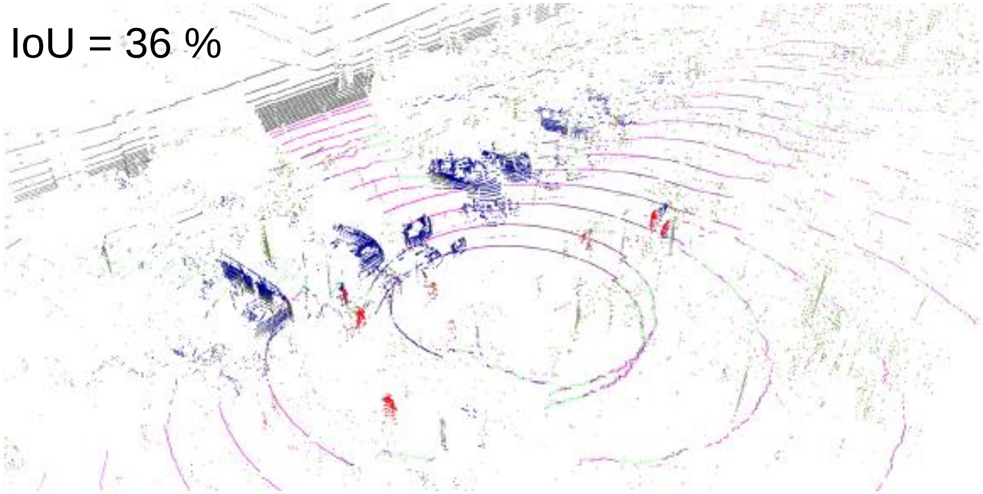
Semantic Segmentation Assessment

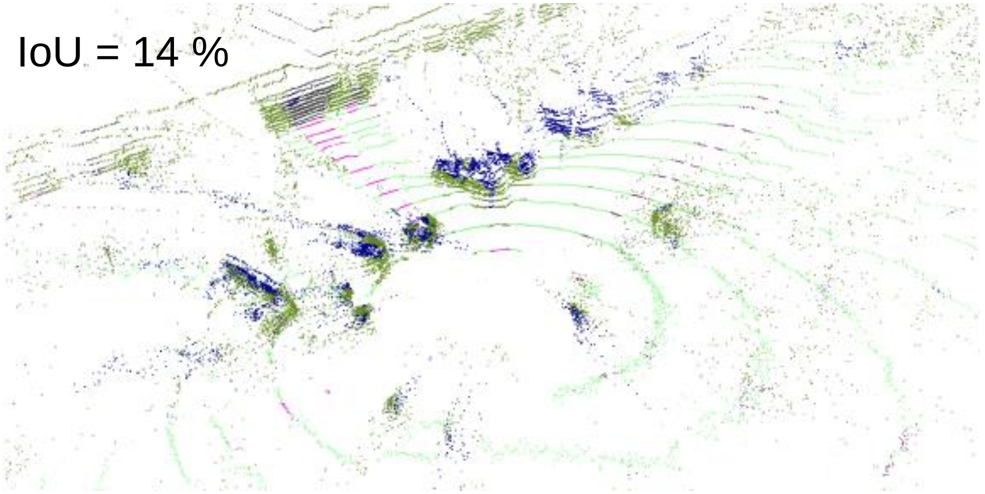
Ground Truth



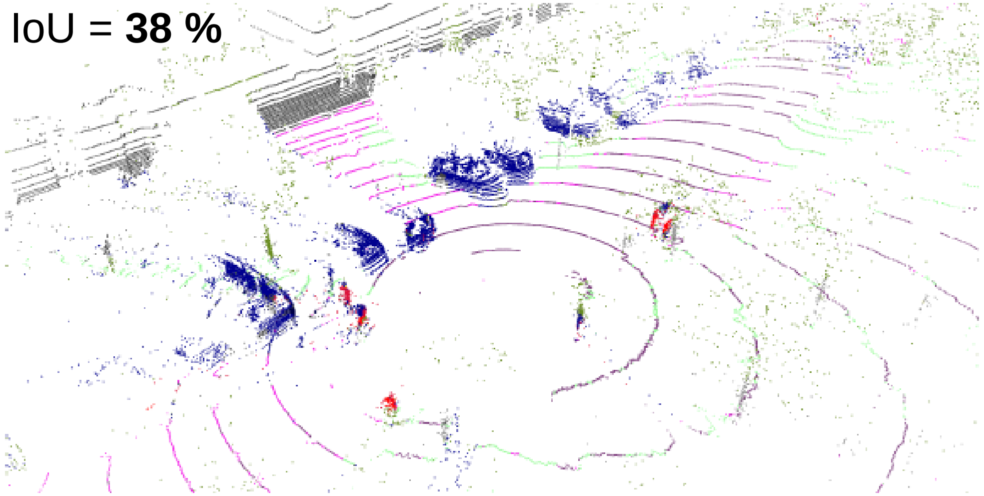
Bilinear



L2-Loss



L1-Loss



Mean Opinion Score Testing*

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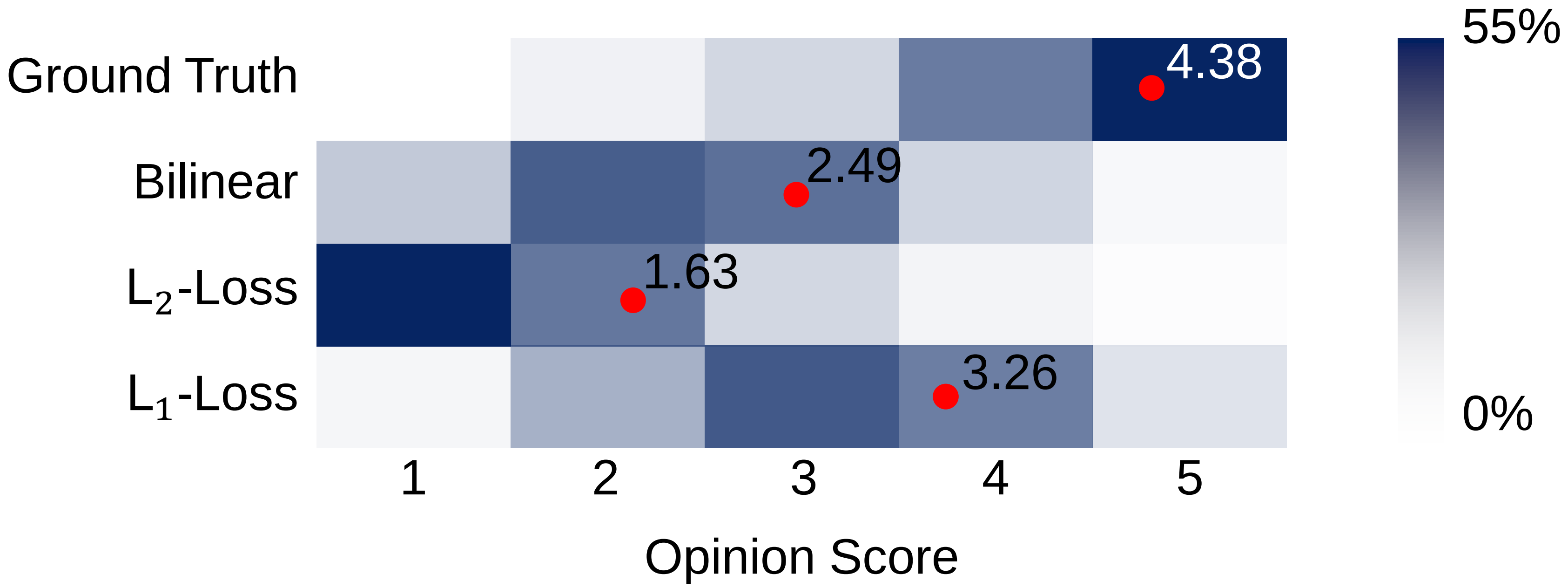

* Survey among 18 human raters with 9 scenes for each of the 4 shown categories
(9 images times 18 raters = 162 samples per method have been assessed)

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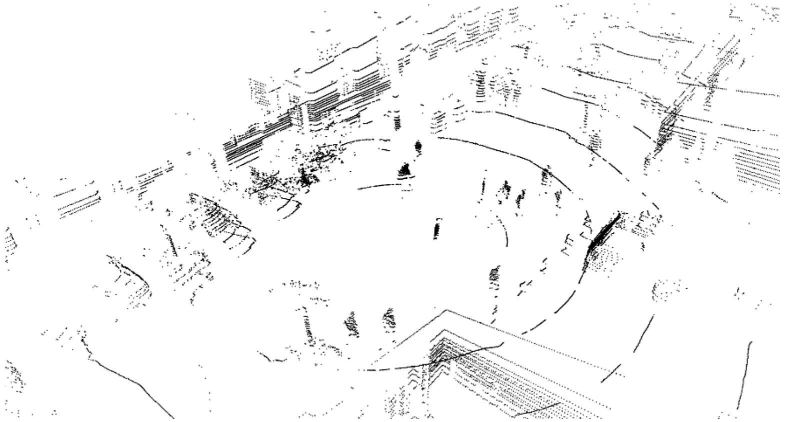
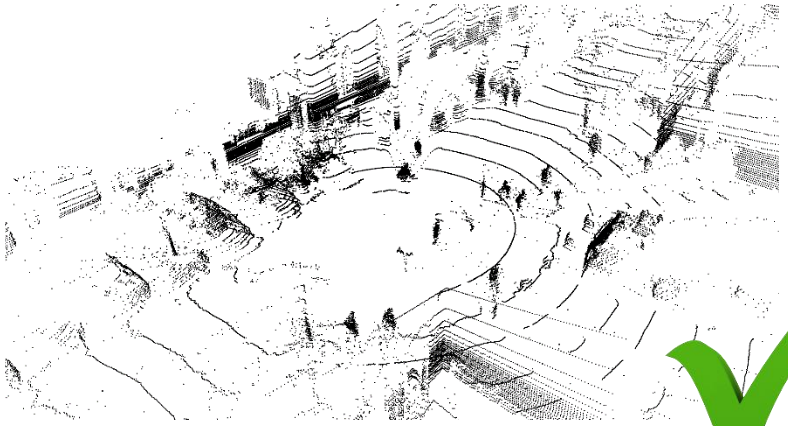
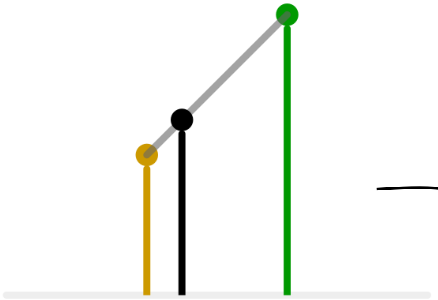
Summary



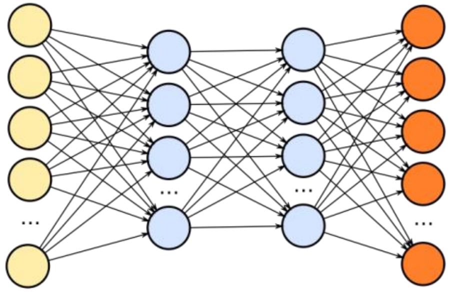
Up-Sampling



Successful up-sampling



Networks outperform traditional interpolation



$\mathcal{L}_1$ vs. $\mathcal{L}_2$

$\mathcal{L}_1$ yields more realistic output than $\mathcal{L}_2$

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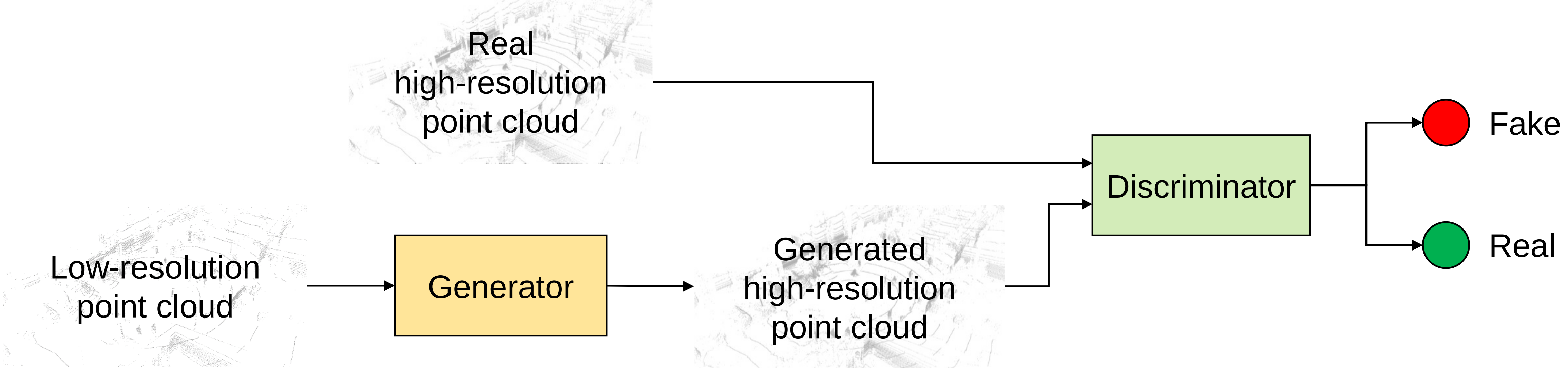
Outlook

- Test using additional camera input information or data accumulation over time

- Use a generative model for more realistic LiDAR up-sampling, for example a Cycle GAN



Video

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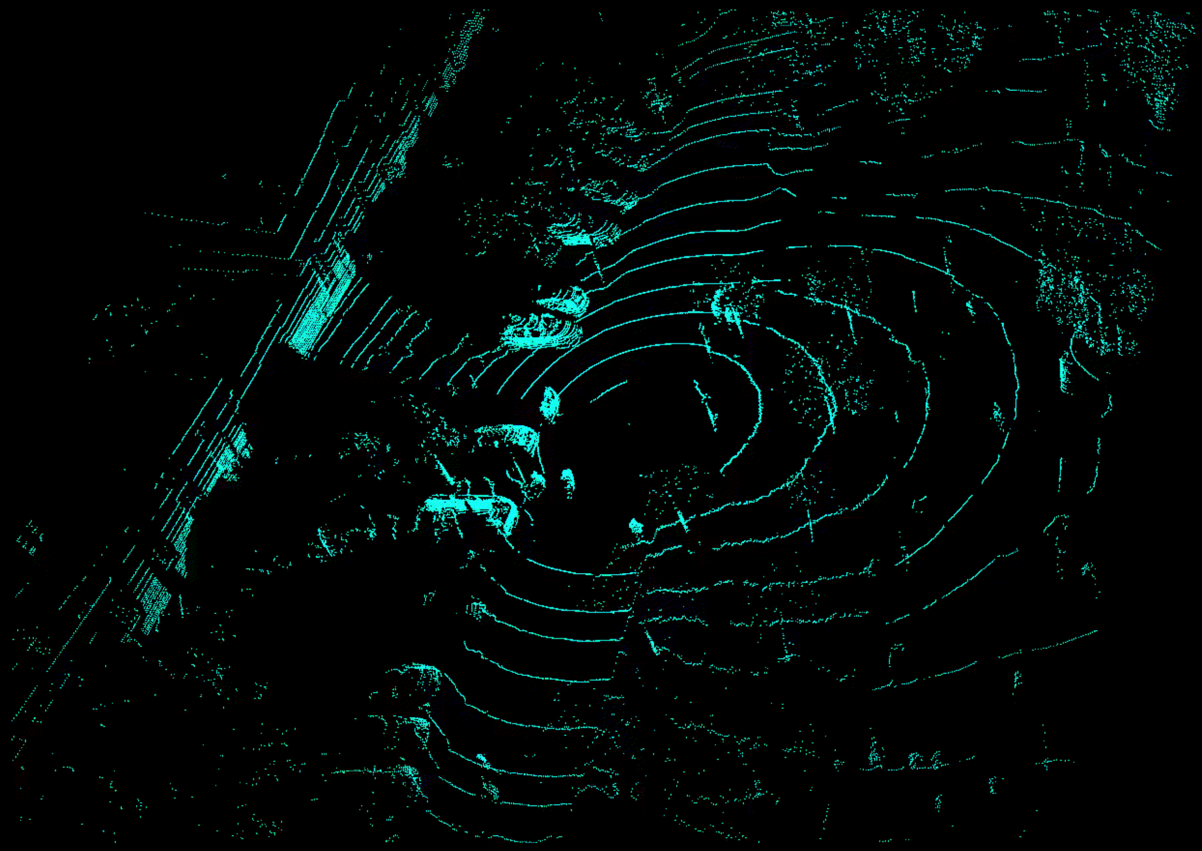
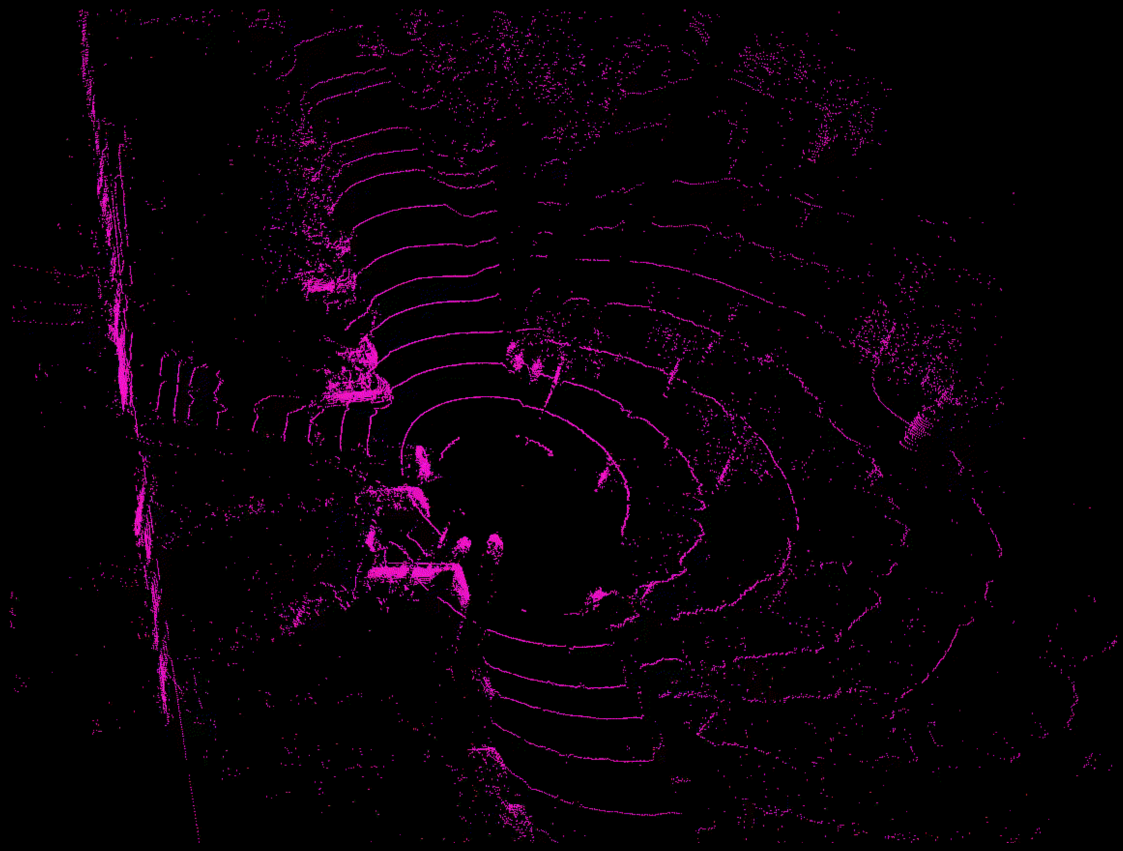


Ground Truth



Regular Network trained with L1-Loss

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Questions?