# LiDAR-Based Cooperative Scan Matching for Relative Pose Estimation of Multiple Vehicles in GNSS-Denied Environments

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# Resume

## Education

Ryoga Takahashi

**Doshisha University, Kyoto, Japan**

**Apr. 2017 – Mar. 2021**

- **Major: Science and Engineering**
- **Dissertation title: “Cooperative Scan Matching using by Ground and Onboard LiDARs”**

**Graduate school of Doshisha University, Kyoto, Japan**

**Apr. 2021 – present**

- **Major: Science and Engineering**

# Agenda

1. Introduction
2. Experimental System
3. Cooperative Moving Object Tracking
4. Feature Extraction
5. Relative pose estimation
6. Experimental Results
7. Conclusions & Future works

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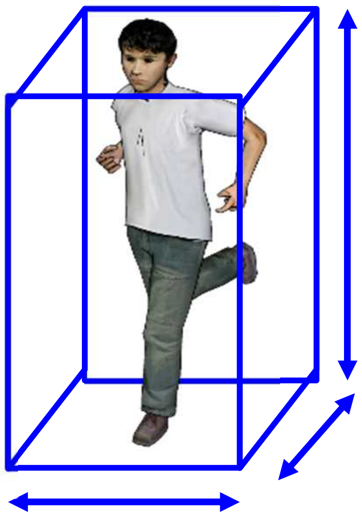
# Introduction

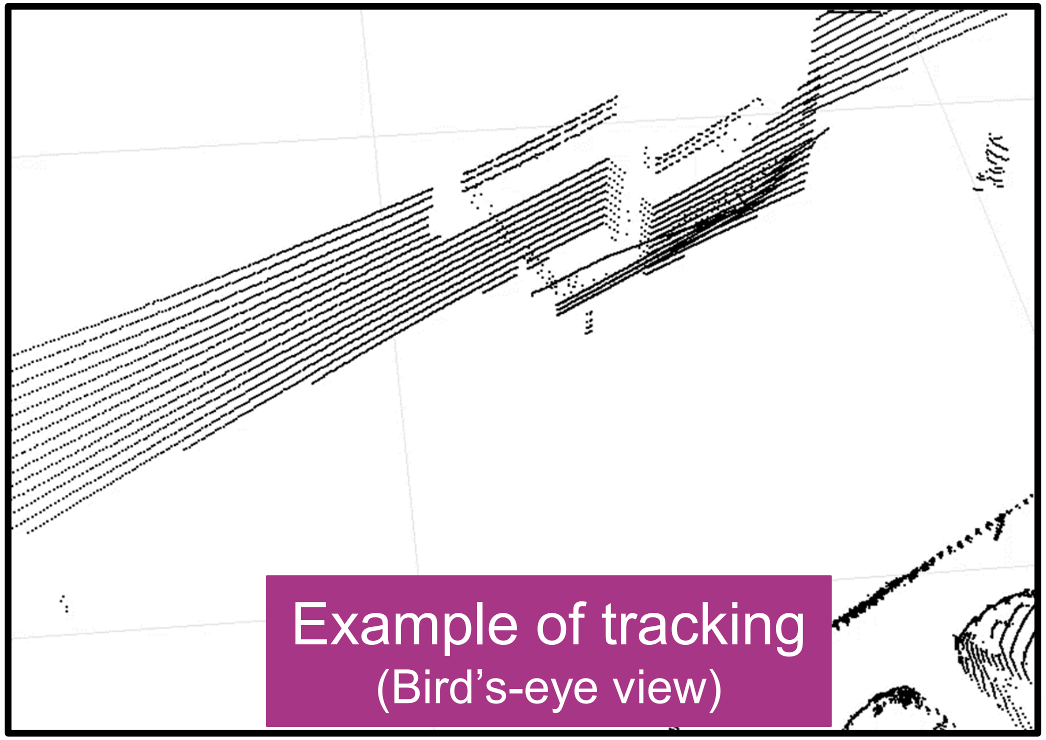
- **Tracking (estimation of position, velocity and size) of moving objects, such as cars, bicycles, and pedestrians, is an important issue for the safe navigation and autonomous driving of robots and vehicles.**
- **Vehicle-mounted LiDAR is used to recognize surrounding environments.**

**[Marti et al., IEEE ITS Magazine 2019]**

LiDAR




Pedestrian



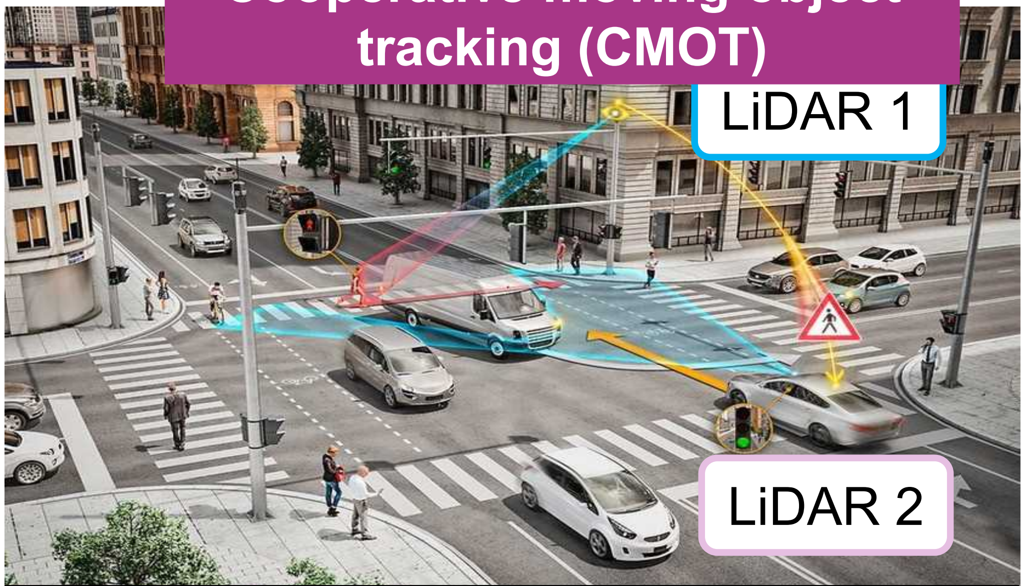
Example of tracking
(Bird's-eye view)

# Introduction

**Individual moving object tracking (IMOT)**

https://www.forum8.co.jp/product-s/ucwin/road/road-Security.htm

**Cooperative moving object tracking (CMOT)**




https://www.tu-auto.com/continental-teams-with-3m-over-v2i/

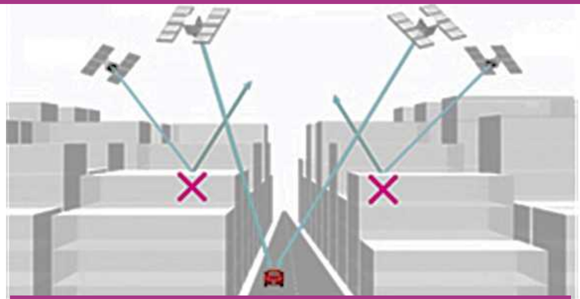
✕
- **Vehicles cannot track moving objects in blind spots or outside of sensing area of a LiDAR.**

○
- **Vehicles can track moving objects in blind spots.**
- **Improvement in tracking performance**

**IMOT** ➡ **CMOT**

# Introduction

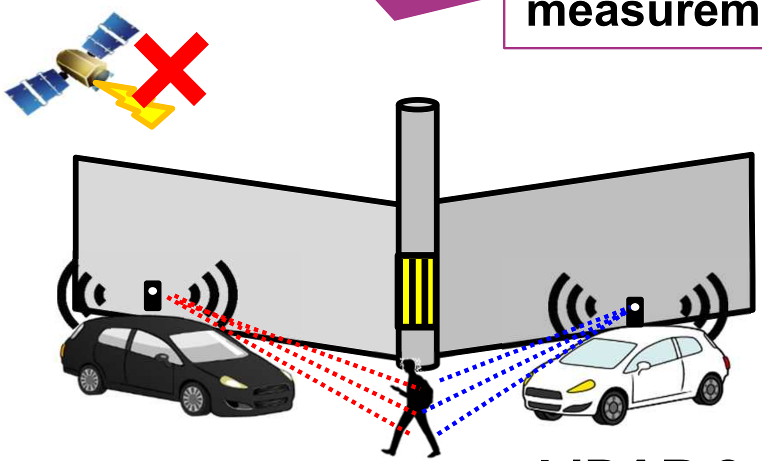
GNSS-denied environments



Urban street canyons

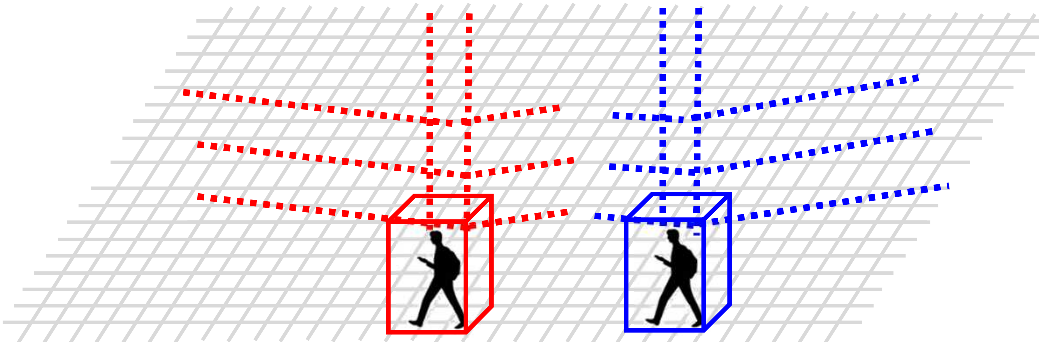
[Ozaki et al., Sensors 2012]

Mapping the LiDAR measurements onto the grid map.



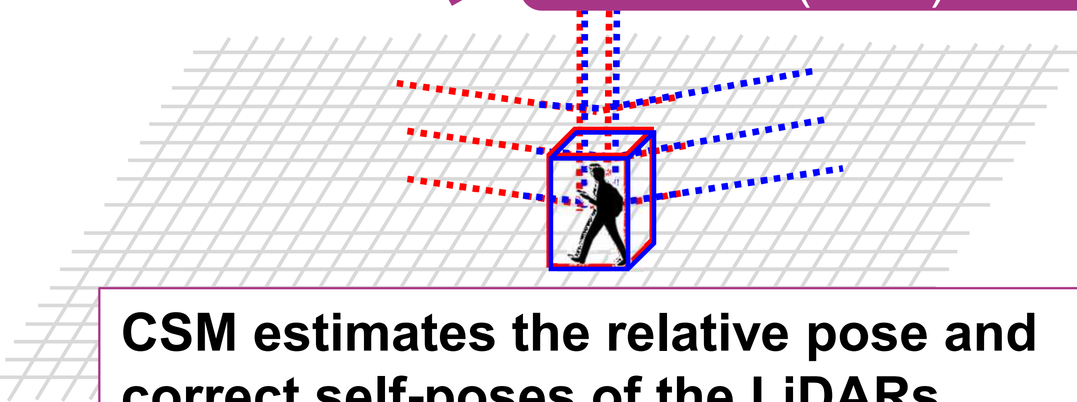

Tracking by two LiDARs

A moving object is recognized as different two objects



Measurements by LiDAR 1
Measurements by LiDAR 2

Cooperative scan matching (CSM)



CSM estimates the relative pose and correct self-poses of the LiDARs

# Topic

- Cooperative scan matching (CSM) using pole-like objects

- Pole-like objects, such as utility pole and light pole, are extracted from the LiDAR measurements.
- Pole-like objects are used as environmental features.

[Kanaki et al., IEEE AIM 2017]

- Many environments do not have such objects.
- Pole-like objects are frequently occluded by surrounding moving objects.

- **CSM method can estimate the relative pose using any environment features including pole-like objects.**

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# Experimental System

LiDAR 1

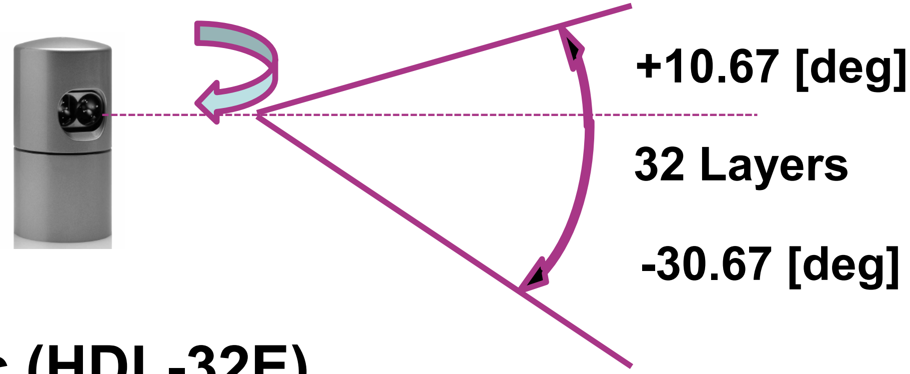
Small car
(Toyota auto body, Coms ZAD-TAK30BS)

LiDAR 2

Motorcycle
(Honda Gyro Canopy)

# Experimental System

## LiDAR (Velodyne HDL-32E)




**Spec.(HDL-32E)**

| | |
|---|---|
| Measurement range | 70 [m] |
| Horizonal viewing angle (Res.) | 360(0.16)[deg] |
| Horizonal viewing angle (Res.) | 41.3(1.33) [deg] |
| Scan period | 100 [ms] |

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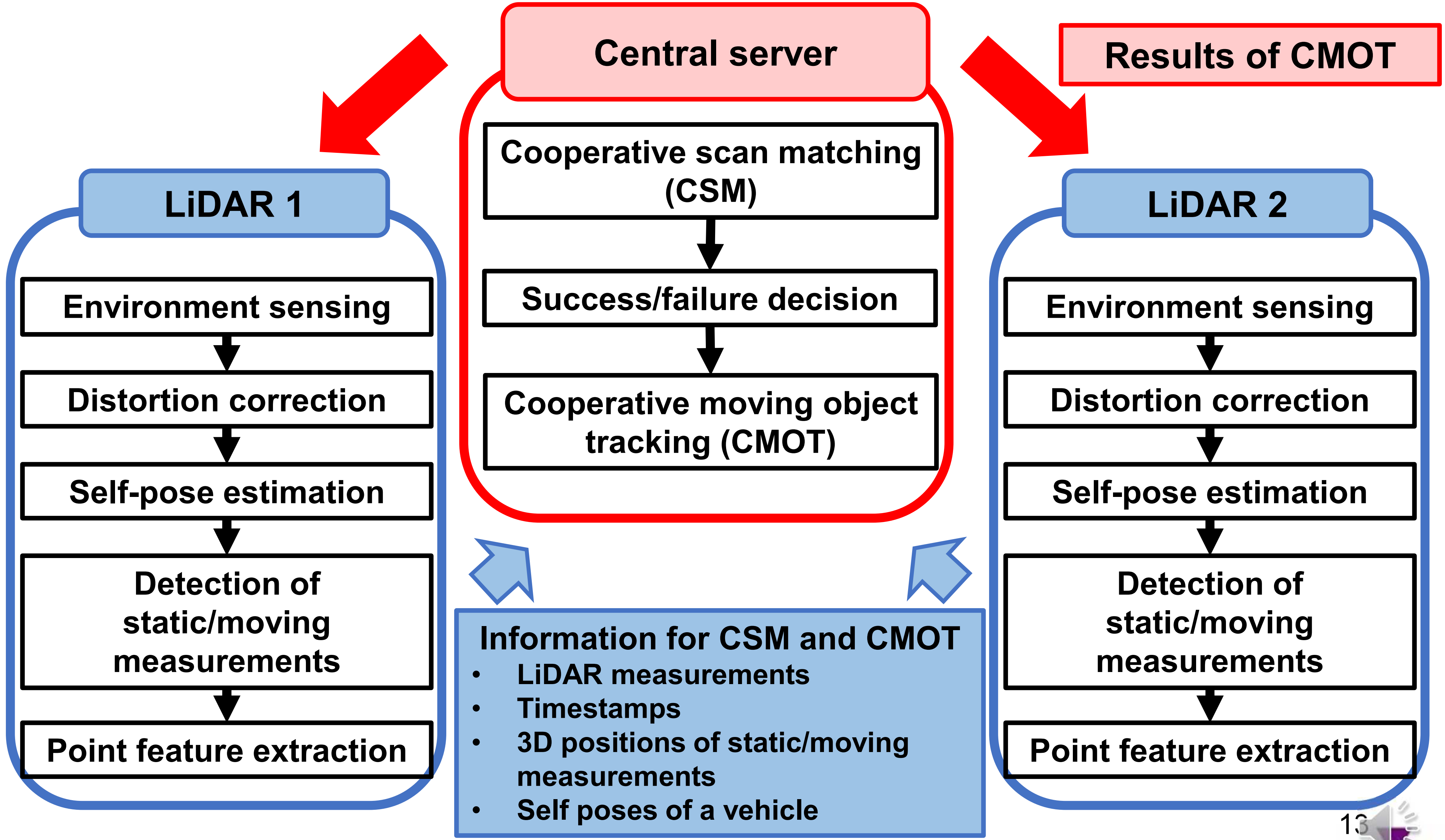
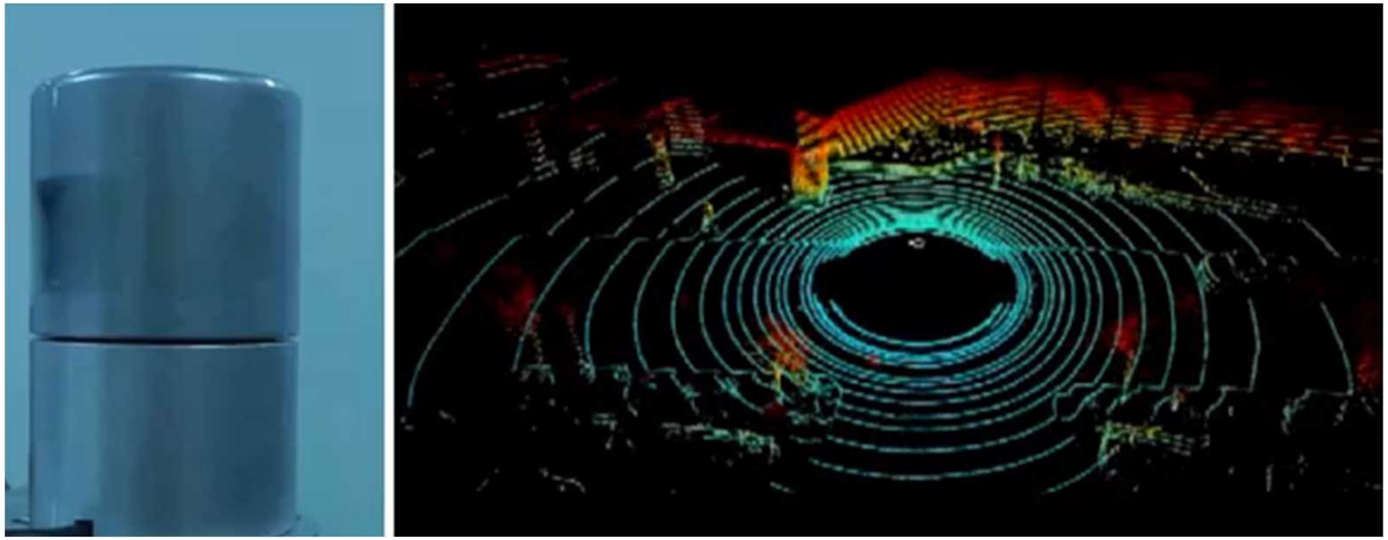
# Overview of cooperative moving object tracking (CMOT)



# Overview of cooperative moving object tracking (CMOT)

**LiDARs 1 & 2**

- Environment sensing
- ↓
- Distortion correction
- ↓
- Self-pose estimation
- ↓
- Detection of static/moving measurements
- ↓
- Point feature extraction

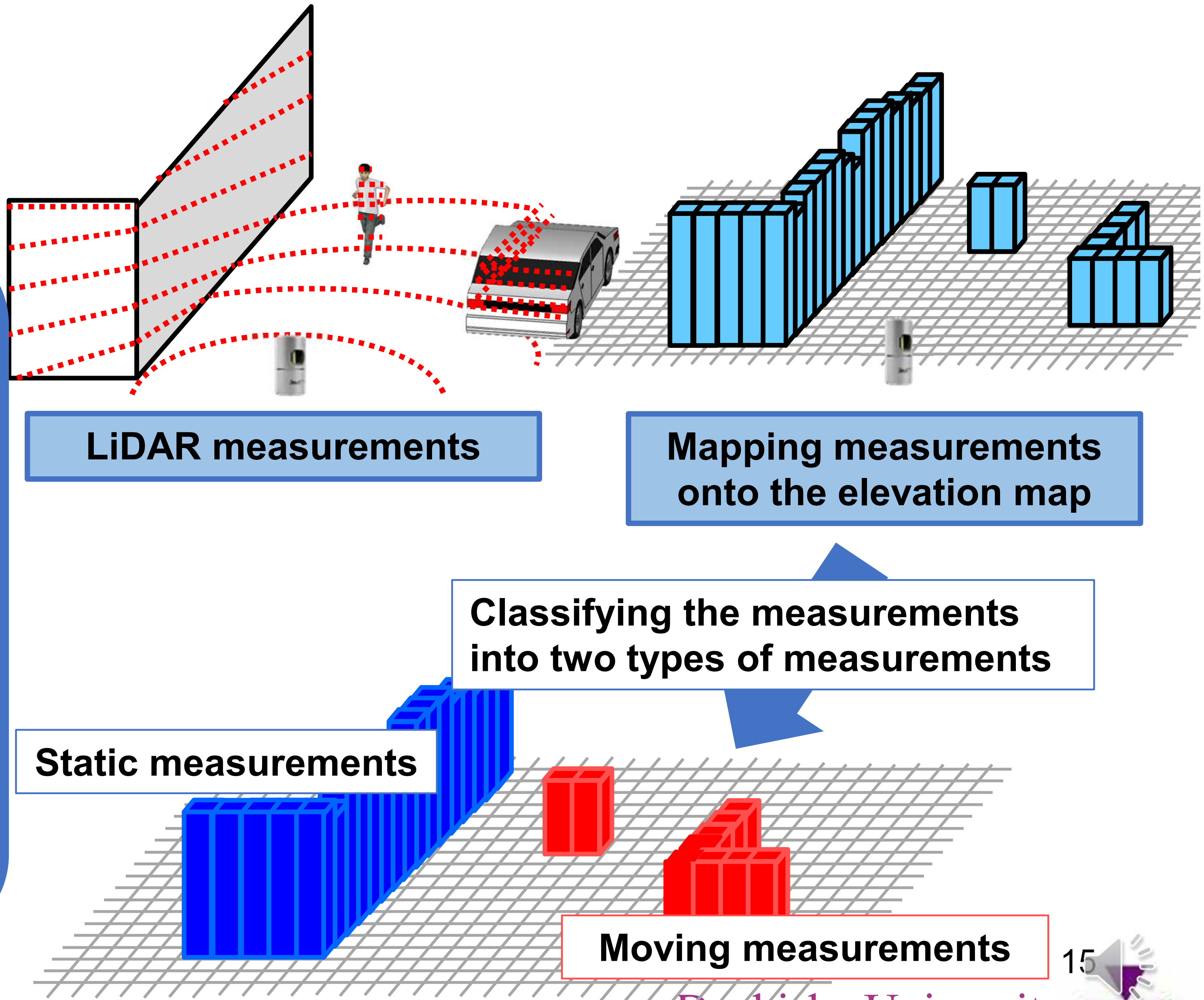


Environment sensing using a LiDAR

# Overview of cooperative moving object tracking (CMOT)

**LiDARs 1 & 2**

- Environment sensing
- ↓
- Distortion correction
- ↓
- Self-pose estimation
- ↓
- Detection of static/moving measurements
- ↓
- Point feature extraction



# Overview of cooperative moving object tracking (CMOT)

**Central server**

- Cooperative scan matching (CSM)
- ↓
- Success/failure decision
- ↓
- Cooperative moving object tracking (CMOT)

**Results of CMOT**

**LiDAR 1**

- Environment sensing
- ↓
- Distortion correction
- ↓
- Self-pose estimation
- ↓
- Detection of static/moving measurements
- ↓
- Point feature extraction

**LiDAR 2**

- Environment sensing
- ↓
- Distortion correction
- ↓
- Self-pose estimation
- ↓
- Detection of static/moving measurements
- ↓
- Point feature extraction

**Information for CSM and CMOT**

- LiDAR measurements
- Timestamps
- 3D positions of static/moving measurements
- Self poses of a vehicle

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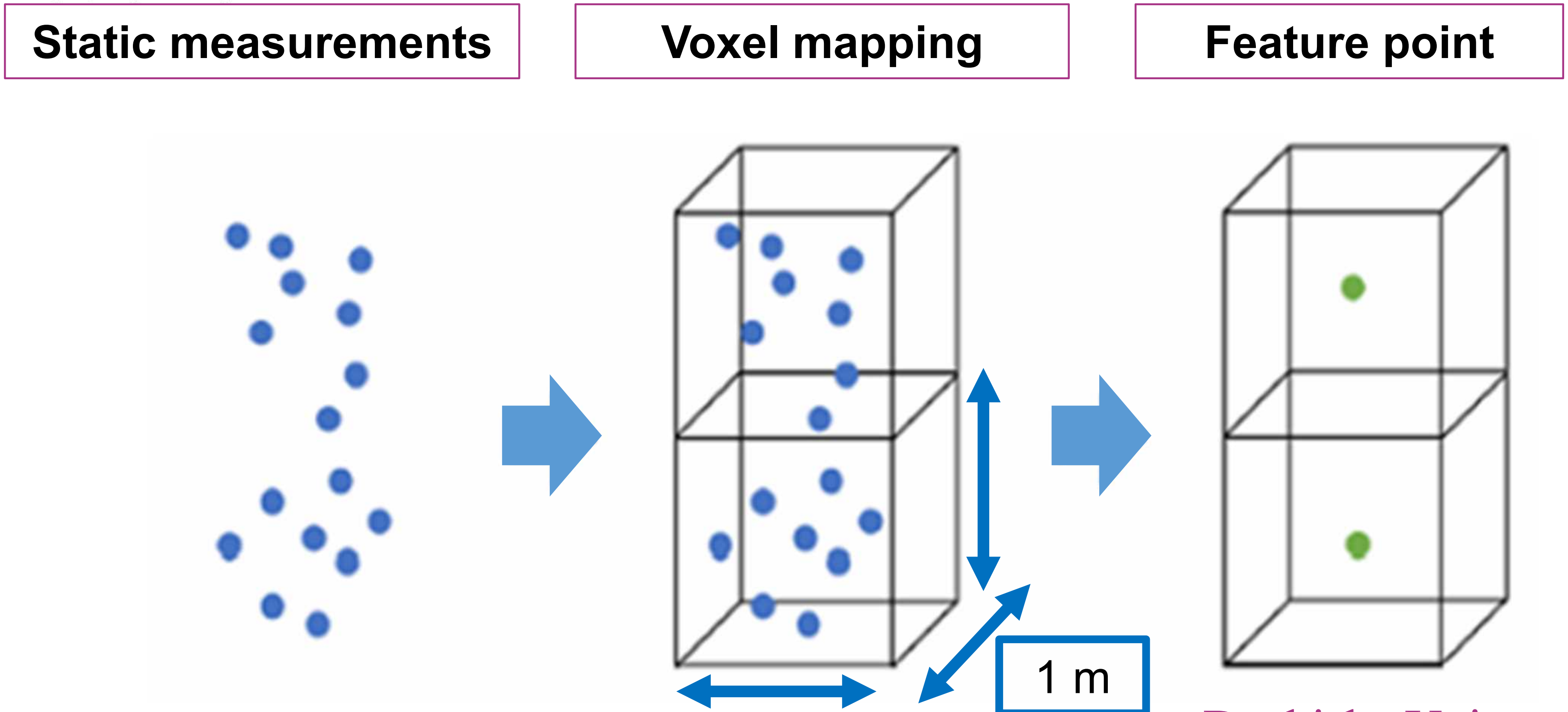
# Feature extraction

## Voxel grid filter

- **The measurements obtained by LiDARs are mapped onto a voxel map (grid size of 1 m)**
- **The centroid of the measurements (feature point) in each voxel is**



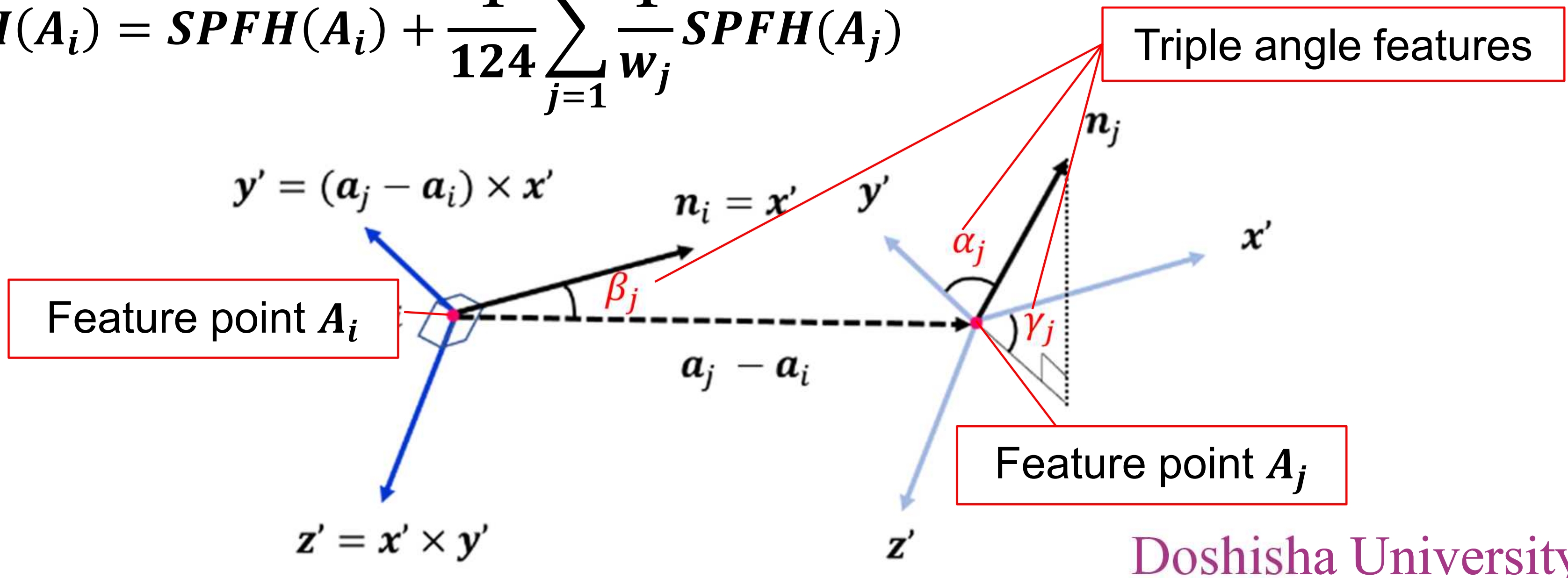
# Feature extraction

## Calculating the point feature histograms

- **The triple angle features $(\alpha, \beta, \gamma)$ are defined every feature points.**
- **The point features $SPFH(A_j)$ of 3*124-dimentsional vector are obtained by calculating the triple features for the 124 feature points $A_j$ around the point feature $A_i$.**
- **The final point feature histograms related to the feature point $A_i$ is calculated by**

**[Rusu et al., IEEE ICRA 2009]**

$$FPFH(A_i) = SPFH(A_i) + \frac{1}{124}\sum_{j=1}^{124}\frac{1}{w_j}SPFH(A_j)$$



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# Relative pose estimation using cooperative scan matching (CSM)

**Central server**

Coarse Registration
↓
Fine Registration
↓
Success/failure decision
↓
Cooperative moving-object tracking (CMOT)

## Coarse registration

[Aldoma et al., IEEE RA Magazine 2012]

- **RANdom SAmple Consensus (RANSAC)-based algorithm**

**A method estimates a coarse relative pose using the result of feature extraction.**

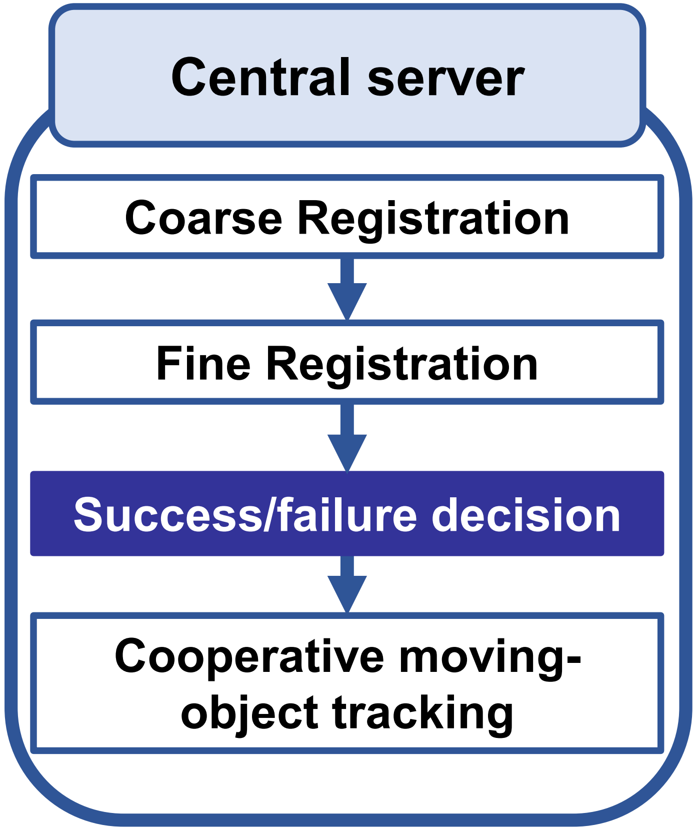
## Fine registration

[Biber et al., IEEE/RSJ IROS 2003]

- **Normal Distributions Transform (NDT)-based algorithm**

**A method estimates a fine relative pose using the initial value of the relative pose calculated by the coarse registration.**

# Success/failure decision




- The rate of matching measurements of LiDAR 1 with those of LiDAR 2 is defined as the matching rate.
- If matching rate is equal to or greater than 33%, then Cooperative Scan Matching (CSM) is deemed successful.
- Otherwise CSM is deemed failing.
- If CSM is deemed successful…

(1) Cooperative moving objects tracking (CMOT)

(2) The result of CSM in current scan is used as an initial value of a fine registration in the next scan.

**Reduce the computational cost**

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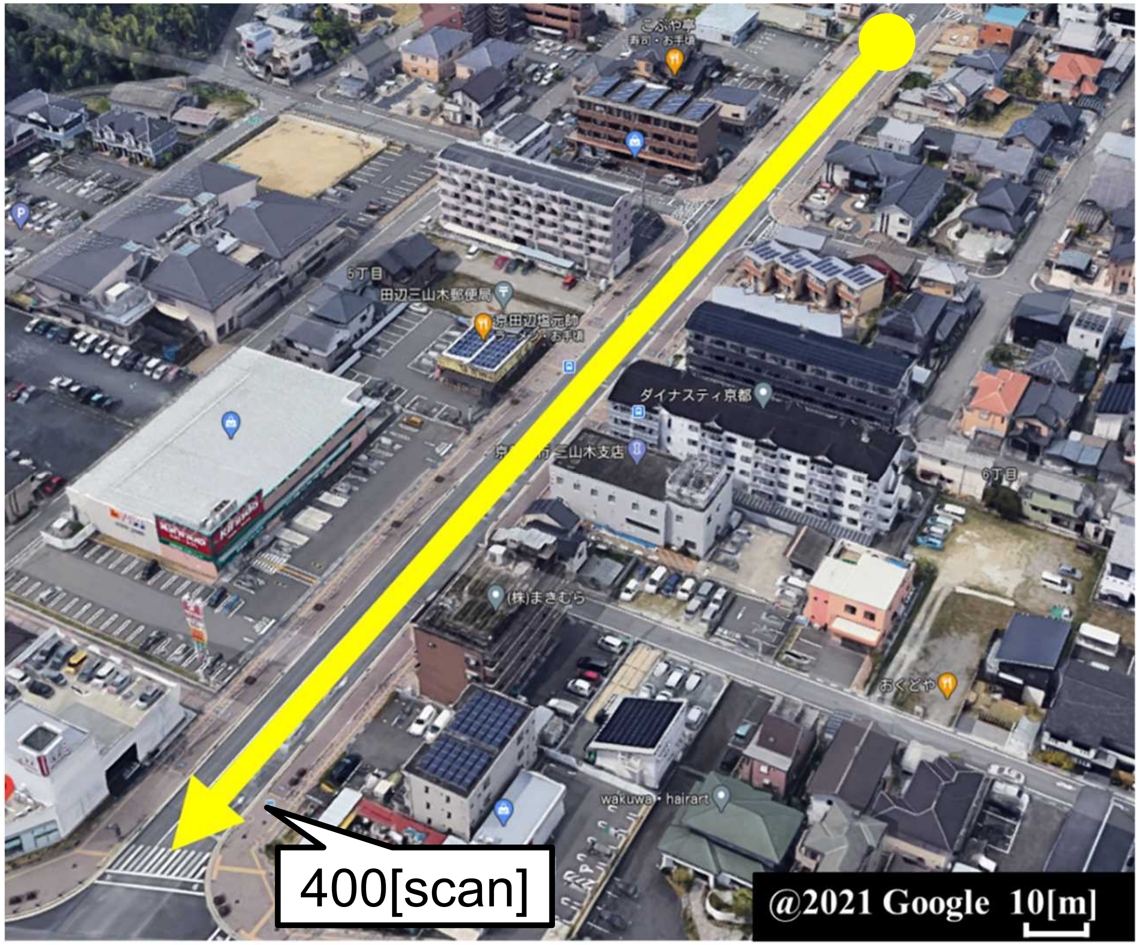
# Experimental environment

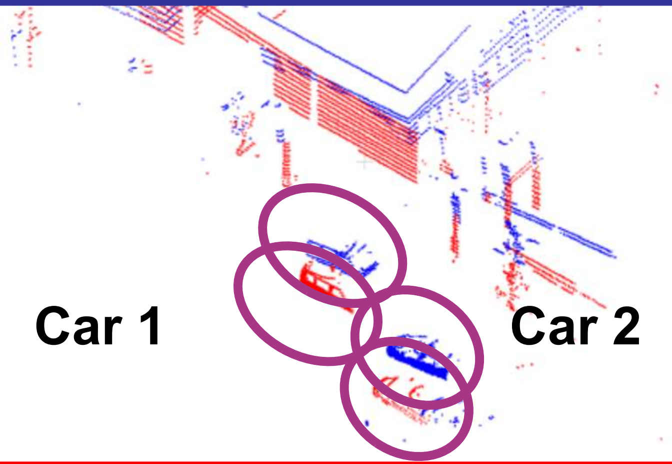
## Environment 1
## (Urban road)



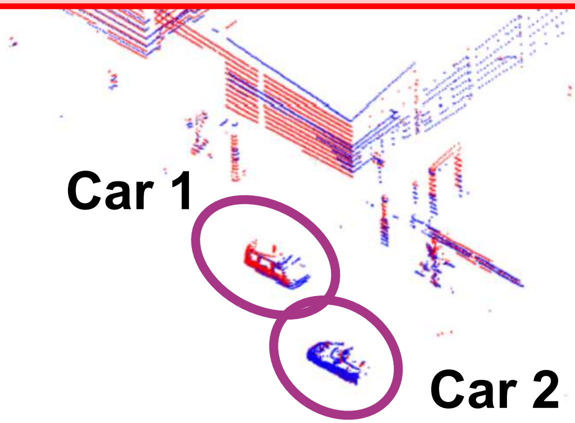

- Vehicles moving at maximum speed 40 [km/h]
- 20 cars and 5 pedestrians

# Experimental results (Mapping results)

**Using standard GNSS (Bird's-eye view)**




**Using Cooperative Scan Matching (Bird's-eye view)**

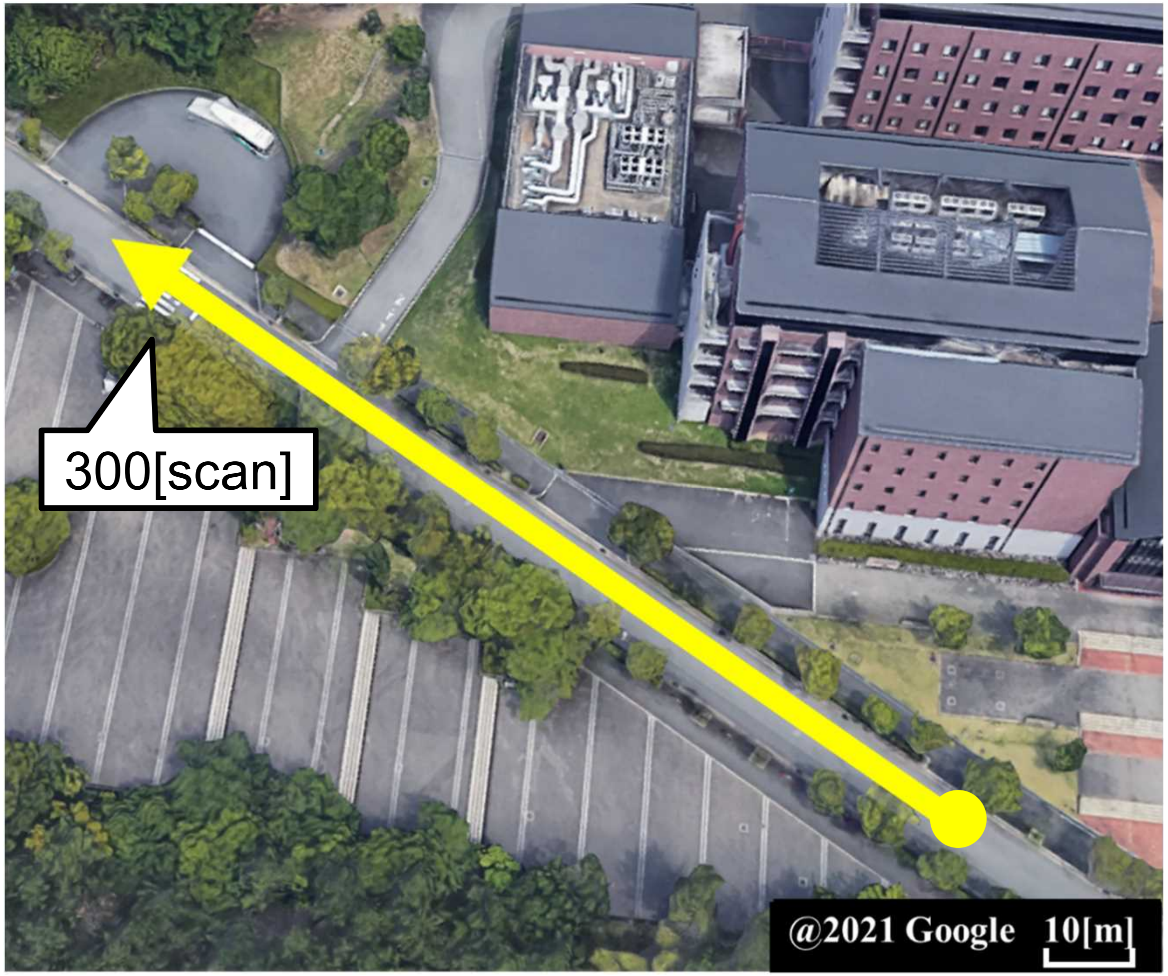



**Environment 1**


Measurements by LiDAR 1    Measurements by LiDAR 2

# Experimental environment

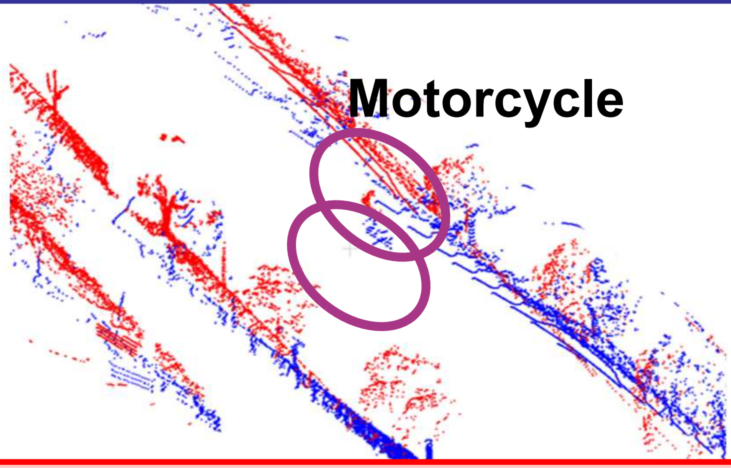
## Environment 2 (University-campus road)



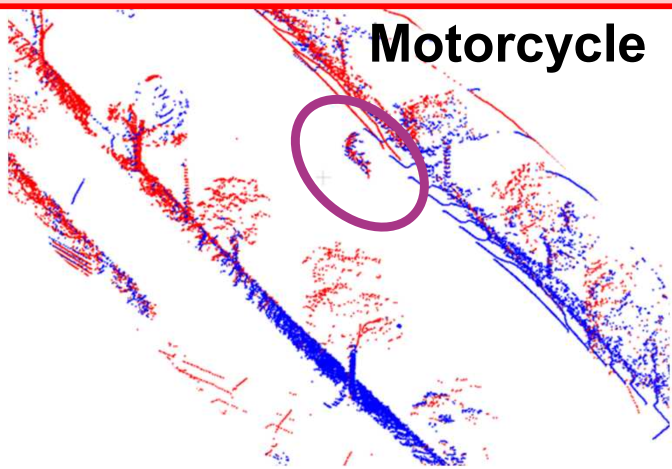

- Vehicles moving at maximum speed 30 [km/h]
- 3 cars and 10 pedestrians

# Experimental results (Mapping results)

**Using standard GNSS (Bird's-eye view)**




**Using Cooperative Scan Matching (Bird's-eye view)**



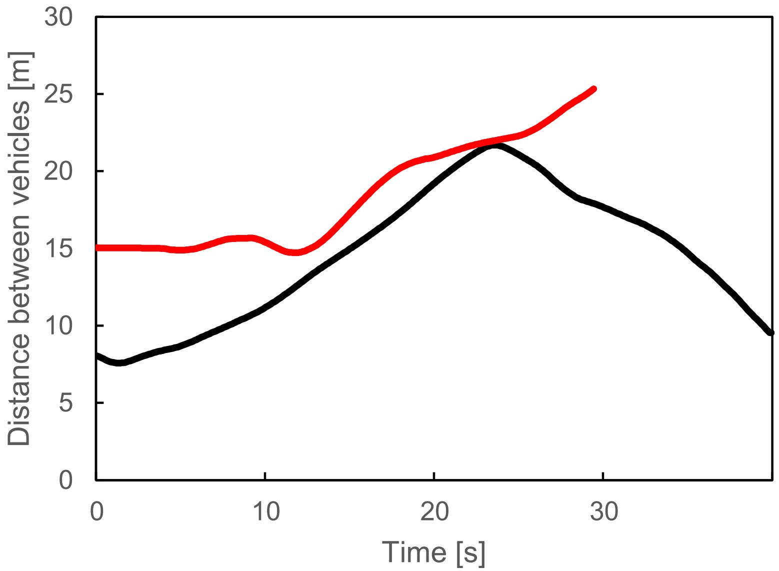

**Environment 2**

Measurements by LiDAR 1 Measurements by LiDAR 2

# Experimental Results

| | | Environment 1 | Environment 2 |
|---|---|---|---|
| Success rate of Cooperative scan matching [%] | | 78.9 | 64.3 |
| Performance of success/ failure decision | Accuracy [%] | 95.5 | 87.4 |
| | Precision [%] | 97.8 | 86.1 |
| | Recall [%] | 96.6 | 99.0 |
| | F-measure [%] | 97.2 | 92.1 |

Environment 1




Environment 2

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# Conclusion

## LiDAR-Based Cooperative Scan Matching in GNSS-Denied Environments

- **The proposed method of relative pose estimation was performed using FPFH and RANSAC-based coarse registration and NDT-based fine registration.**
  - **The mapping performance of the proposed method is better than that of using regular GNSS.**
- **The performance of proposed method was evaluated by experimental results obtained in two road environments.**
  - **The proposed CSM has better applicability in urban environments with a higher number of streets.**

# Future works

- Since the spatial resolution of LiDAR is low in the vertical direction, the distance between vehicles where cooperative scan matching (CSM) can be achieved short.
  - Our current research effort aims to improve the CSM algorithm so that the relative pose can be estimated accurately even at long inter-vehicle distances.
- CSM will be implemented to cooperative moving object tracking and cooperative positioning.

# Thank you for your attention