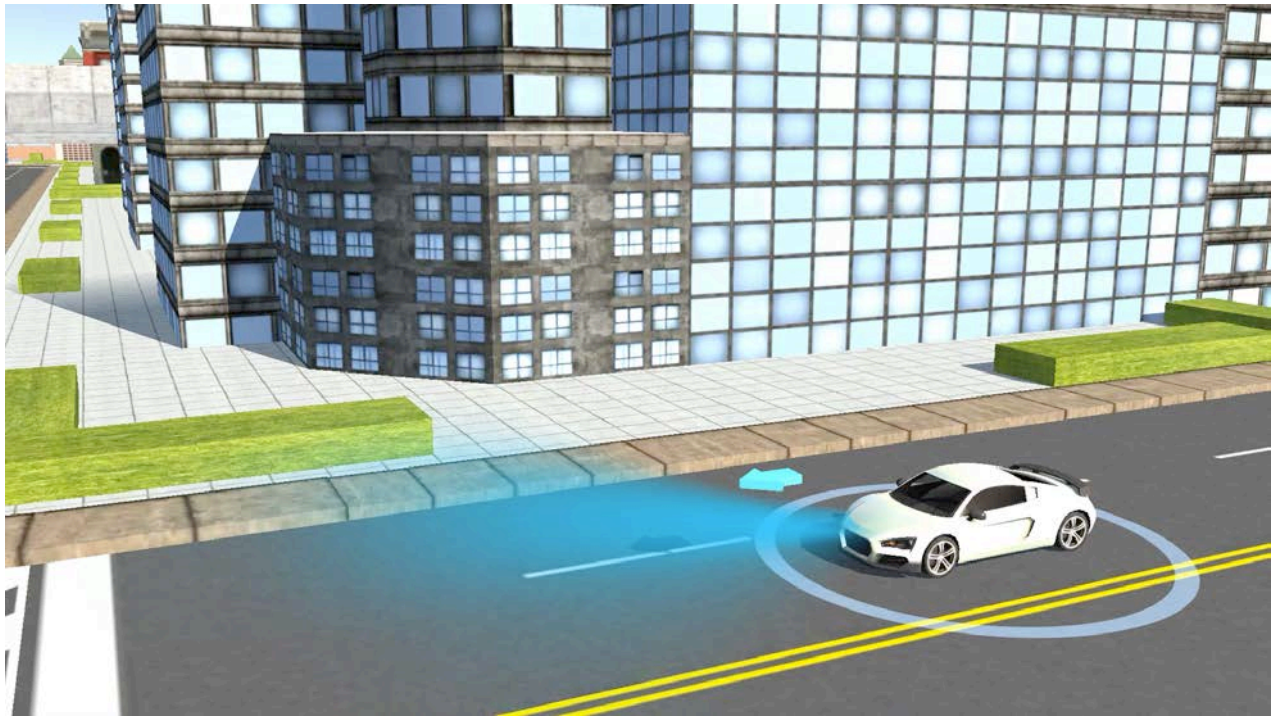
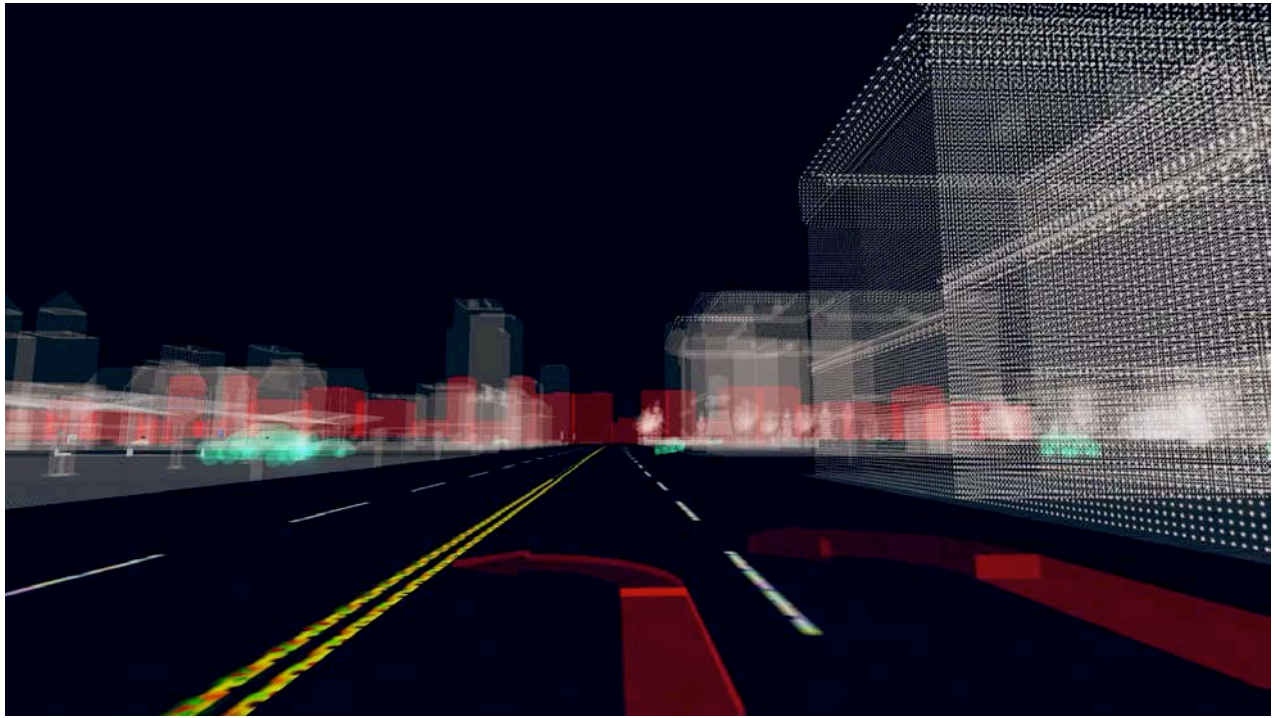
CarMap: Fast 3D Feature Map Updates for Automobiles

Fawad Ahmad, Hang Qiu, Ray Eells, Fan Bai, and Ramesh Govindan

Localization for Autonomous Vehicles



3D Maps



3D Maps

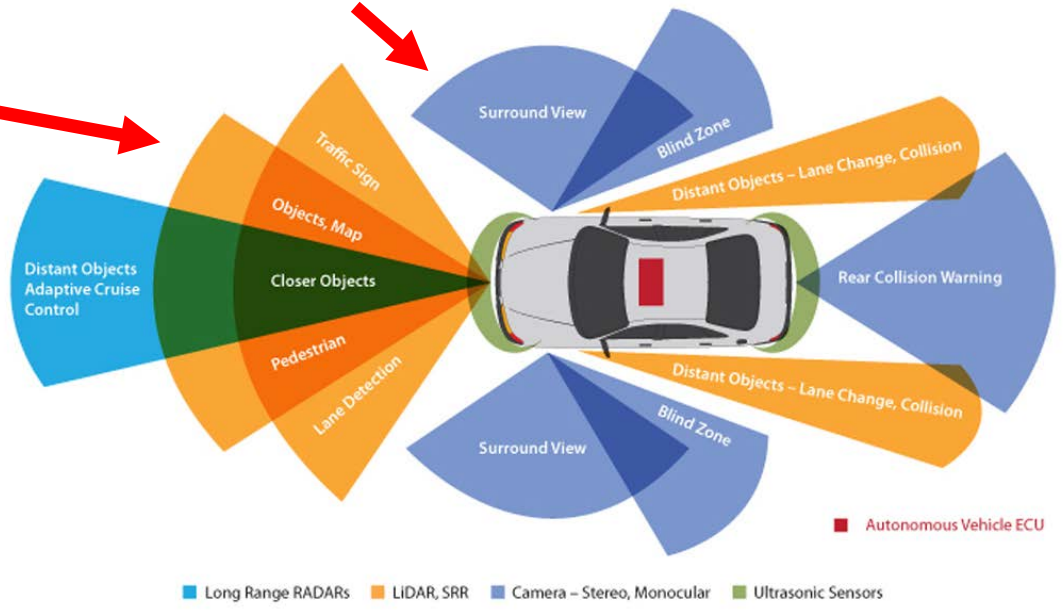
https://360.here.com/2015/07/20/here-introduces-hd-maps-for-highly-automated-vehicle-testing/

Depth Perception Sensors

LiDAR

Stereo Camera

Radar



3D Map Collection Today

Mapping companies

3D Map Collection Today

Mapping companies

Fleet of data collection vehicles

3D Map Collection Today

Fleet of data collection vehicles

Environmental changes render maps stale

Short Timescale Events

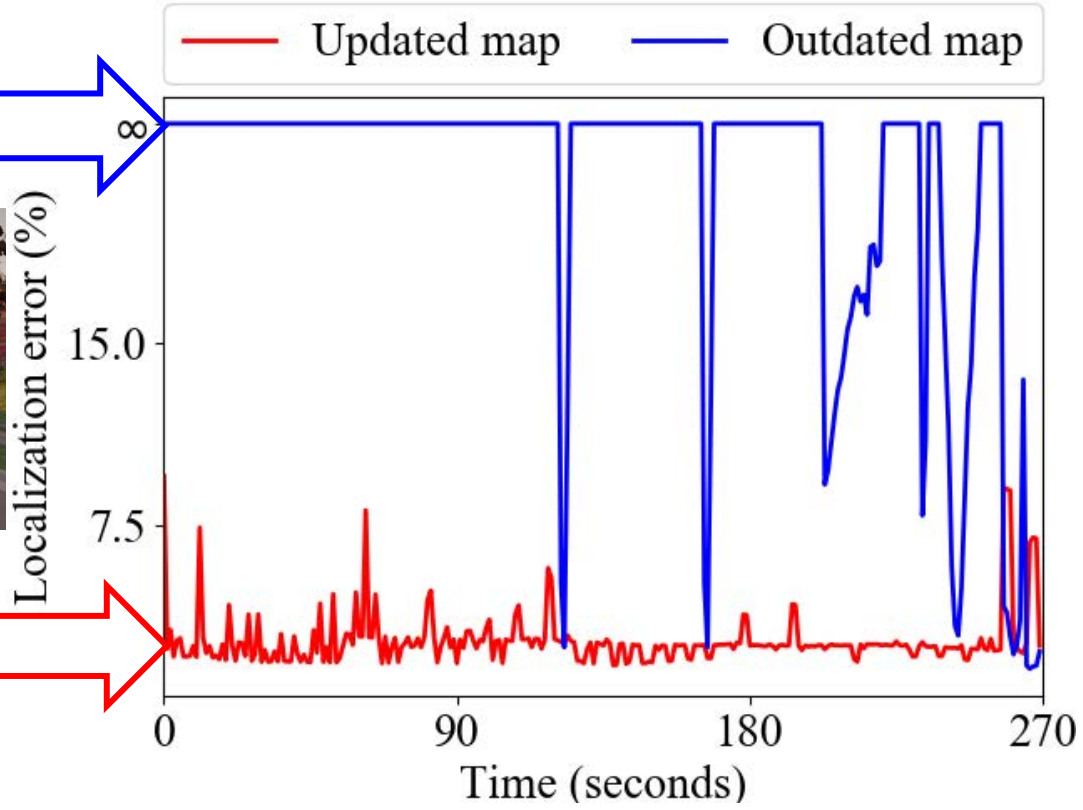
Traffic accidents

Road construction

Delivery trucks

Importance of Map Updates

Traffic accident



Cost of Map Collection

Mapping cost:
$5000 / km

The Question

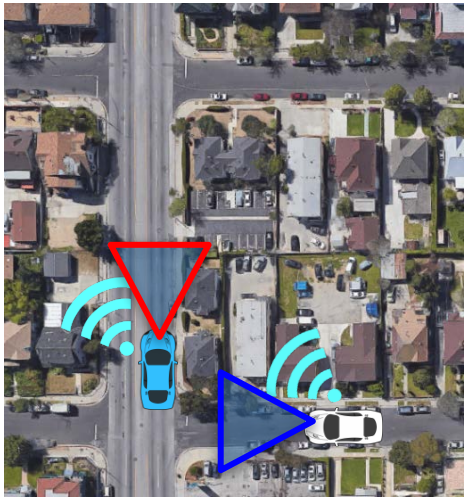
What is a scalable way to build an up-to date 3D map with near real-time updates?

Our Approach

Depth sensors and wireless radios in vehicles

Crowdsource map collection & updates

Our Approach: Crowdsourcing

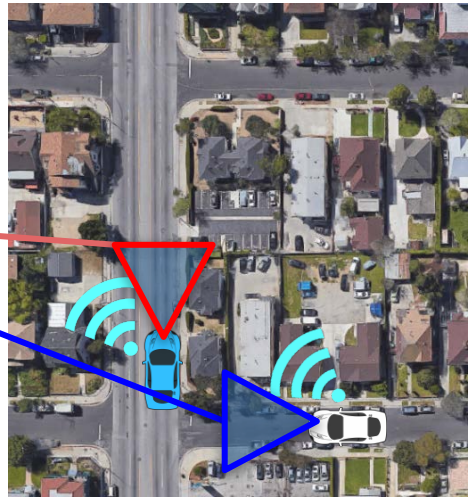


Stereo camera

Scan environment

Our Approach: Crowdsourcing

3D Map



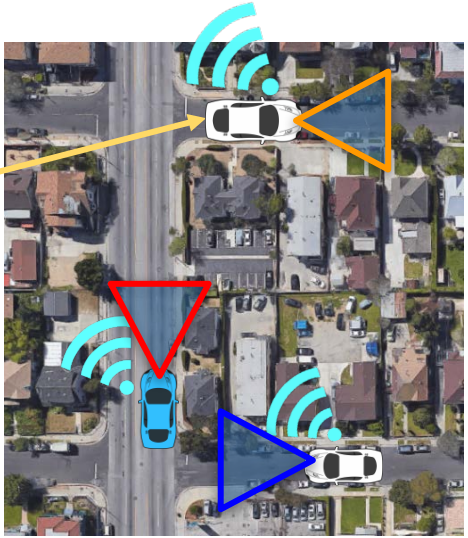
Stereo camera

Upload map data

Our Approach: Crowdsourcing

3D Map

Download map data



Stereo camera

Upload map data

Challenge: Size of 3D Maps

SLAM

Challenge: Size of 3D Maps

SLAM

3D Pose

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_1 \\ R_{21} & R_{22} & R_{23} & T_2 \\ R_{31} & R_{32} & R_{33} & T_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

3D Map

Challenge: Size of 3D Maps

SLAM

3D Pose

Feature map

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_1 \\ R_{21} & R_{22} & R_{23} & T_2 \\ R_{31} & R_{32} & R_{33} & T_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

30 kph - 100 Mbps

Challenge: Environmental Transients

Challenge: Environmental Transients

Map from rush hour

Challenge: Environmental Transients

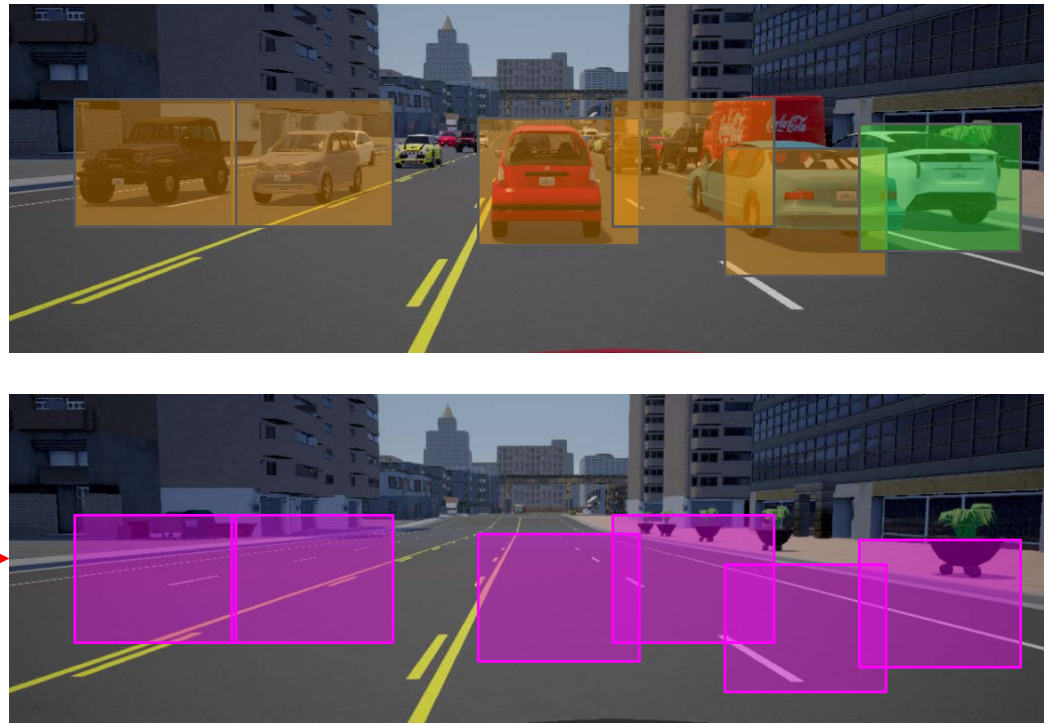
Map from rush hour

No traffic

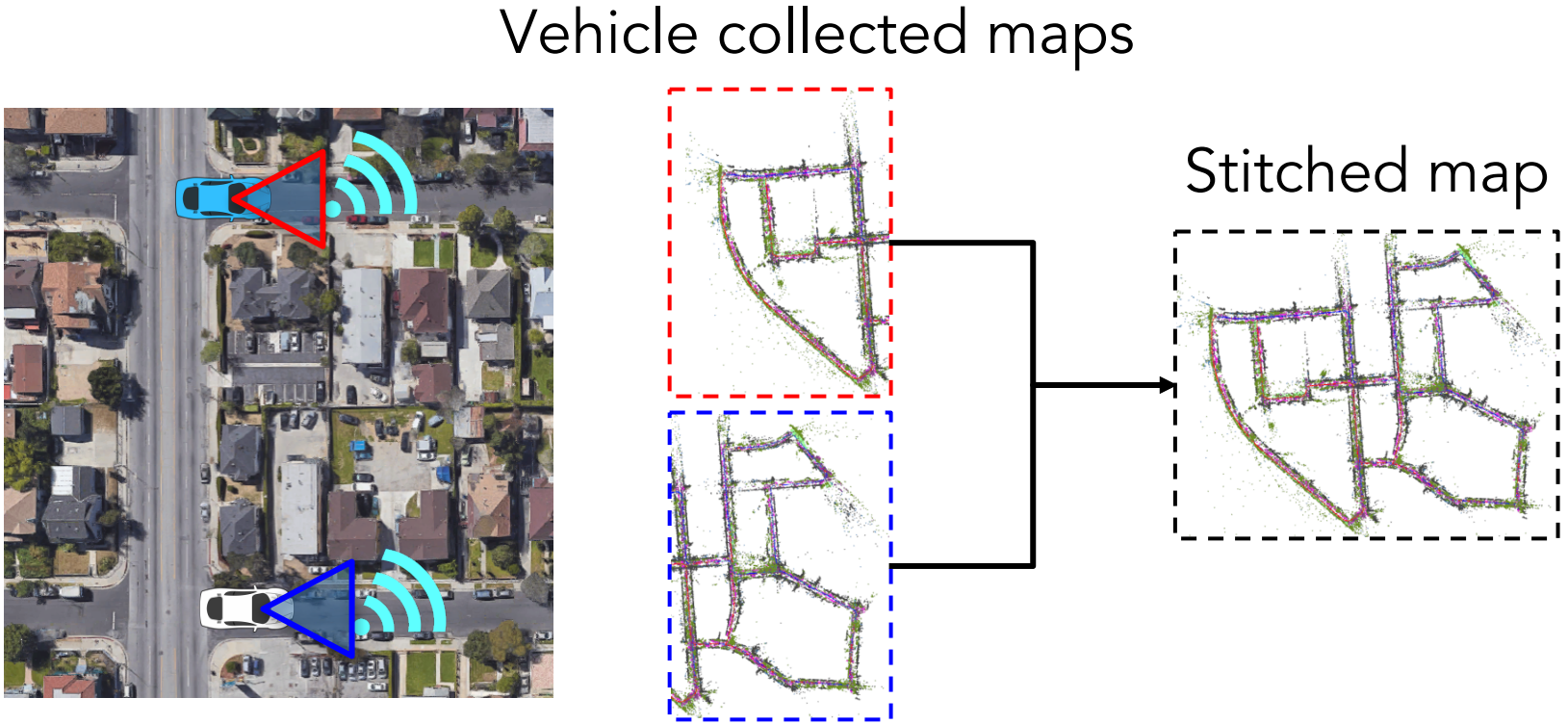
Challenge: Environmental Transients

Map from rush hour

Poor localization



Challenge: Map Updates



CarMap Contributions

Challenges

Contributions

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation
Environmental transients	Dynamic object filter

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation
Environmental transients	Dynamic object filter
Map updates	Robust stitching, efficient diff

Details in the paper

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation
Environmental transients	Dynamic object filter
Map updates	Robust stitching, efficient diff

Background: Image Features

Image feature

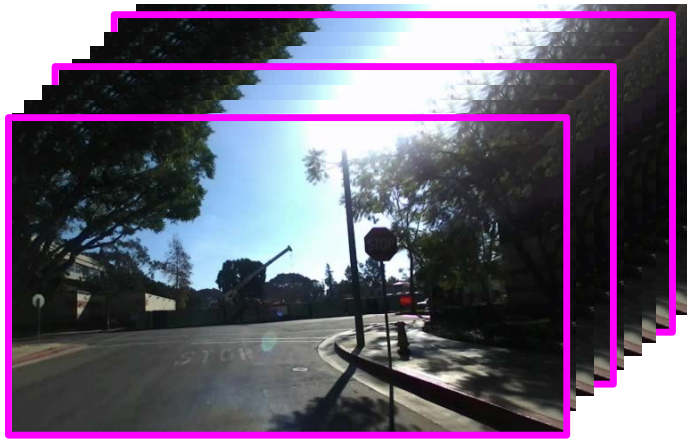
3D position
(x, y, z)

Descriptor
[23, 78, … , 71]

Background: 3D Frames

Incoming 3D frames

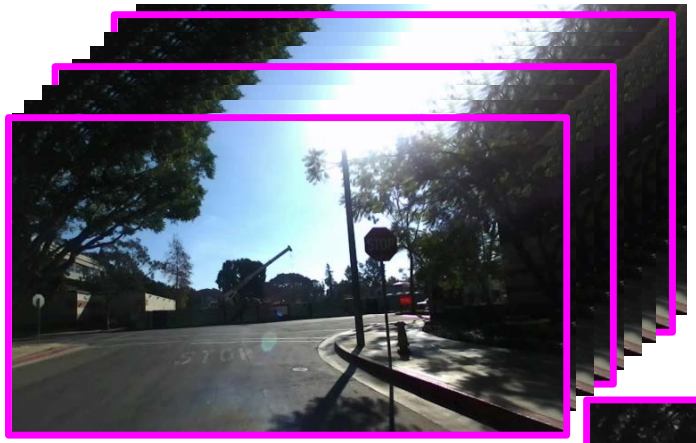
Background: Keyframe



Incoming 3D frames

Keyframes

Background: Keyframe Features

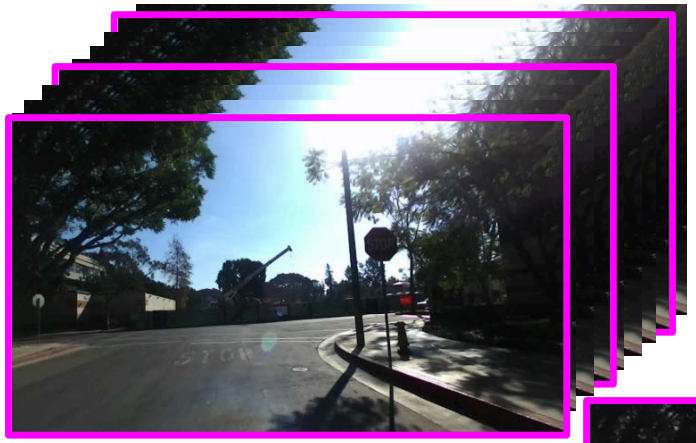


Incoming 3D frames

Keyframes

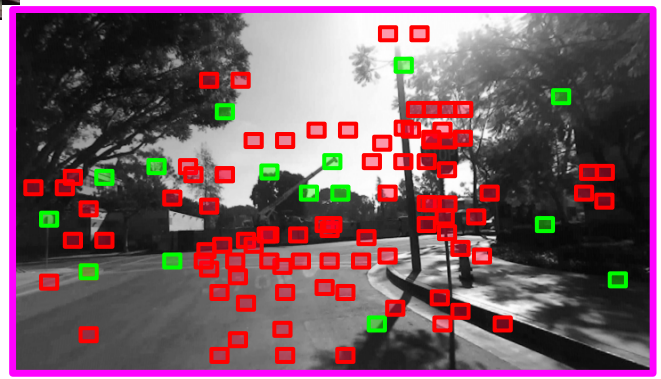
Keyframe features

Background: Map Features



Incoming 3D frames

Keyframes



Keyframe features

Map features

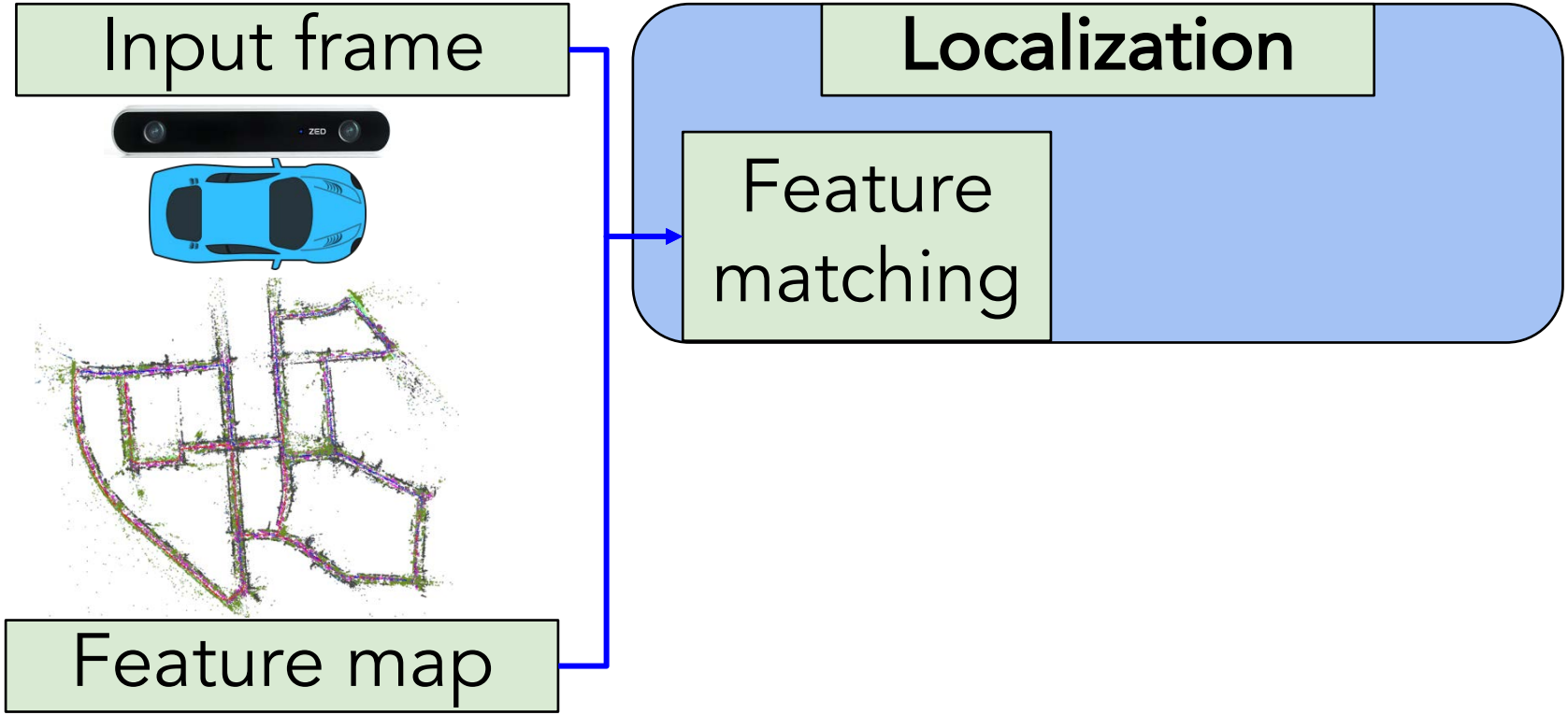
Stable across frames

Background: Feature-based SLAM

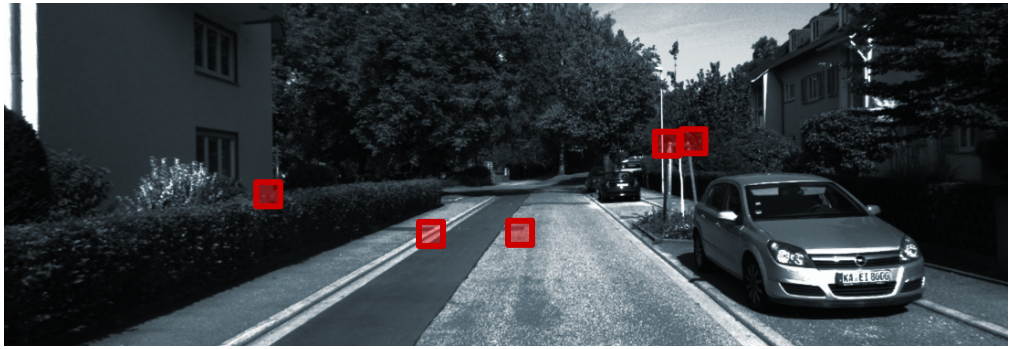
Input frame

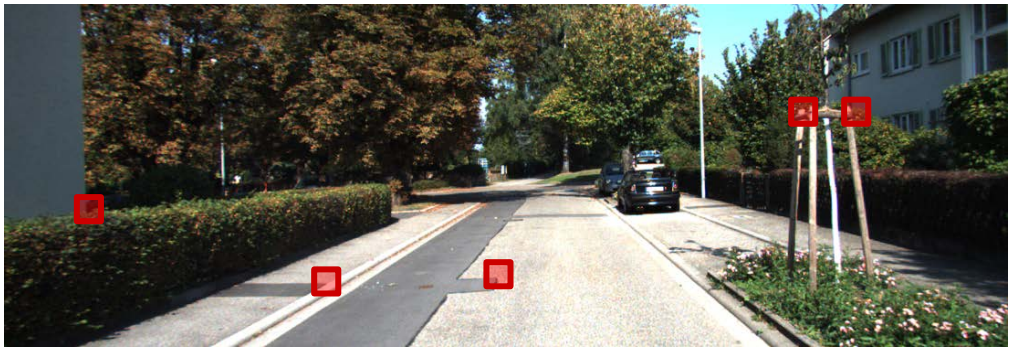
Feature map

Background: Feature-based SLAM



Background: Image Feature Matching





Background: Image Feature Matching

Features from the map

Features seen by the vehicle

Background: Image Feature Matching

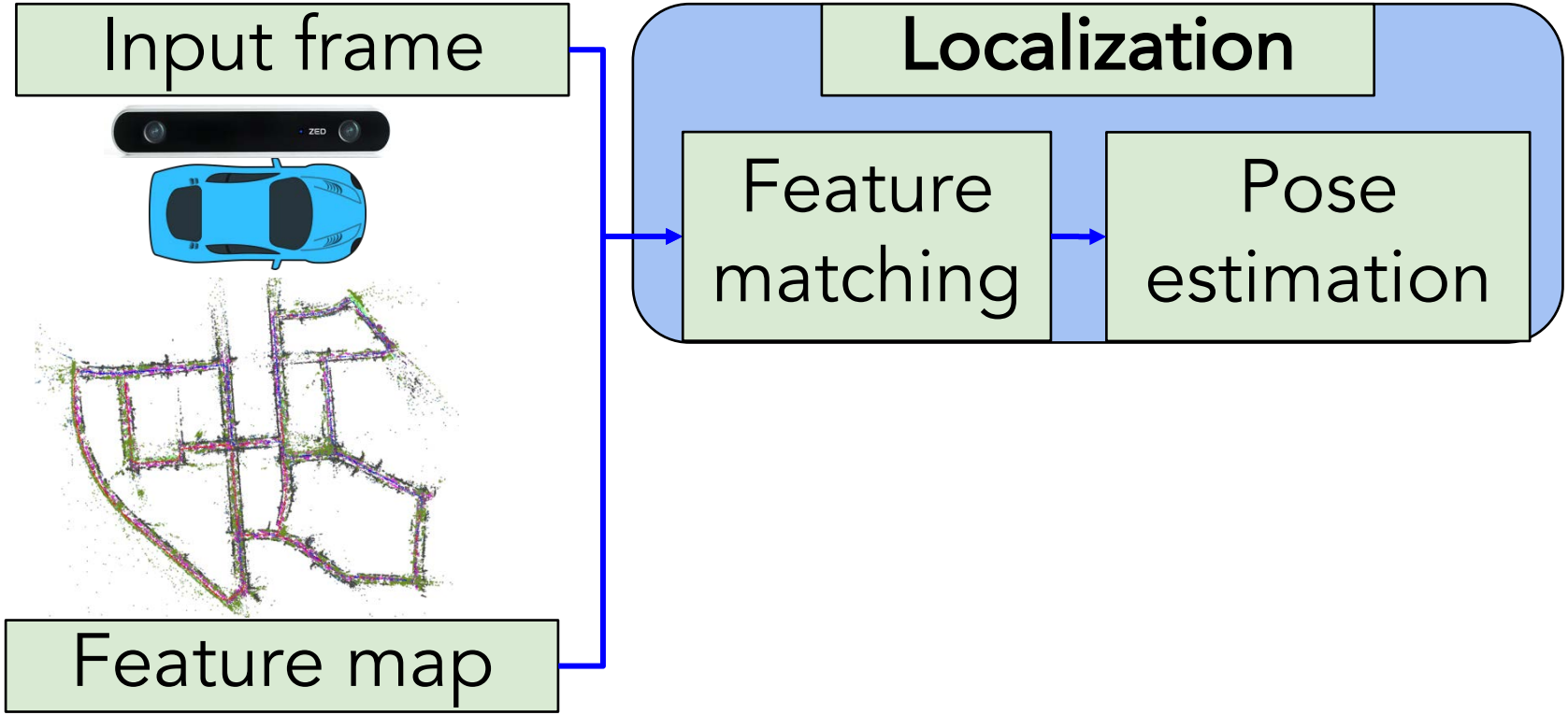
Requirements:

- Accuracy
- Speed

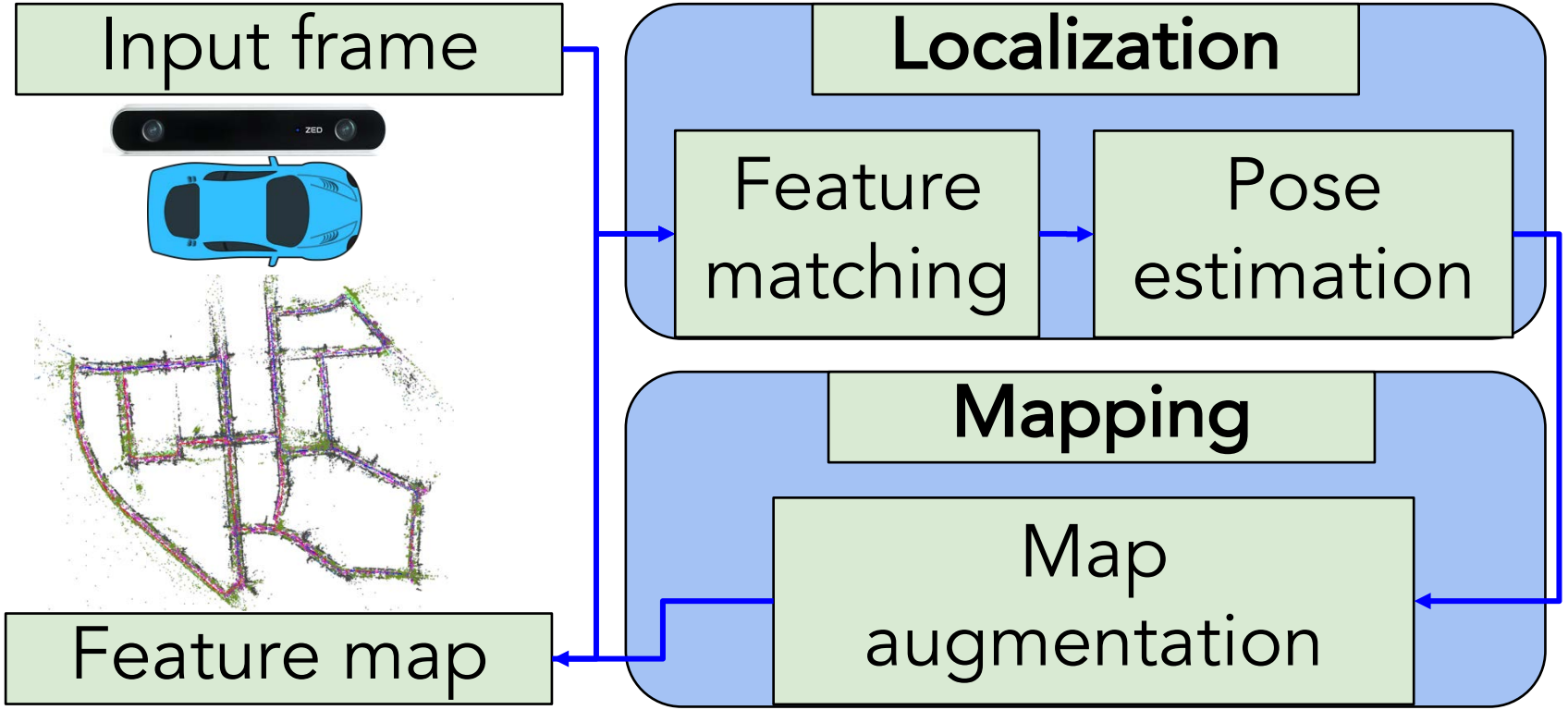
Data structures:

- Feature index
- Map feature index

Background: Feature-based SLAM

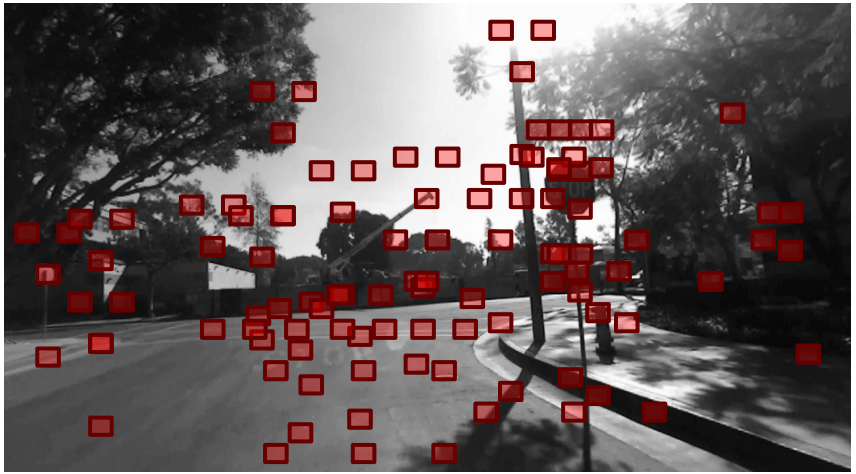


Background: Feature-based SLAM

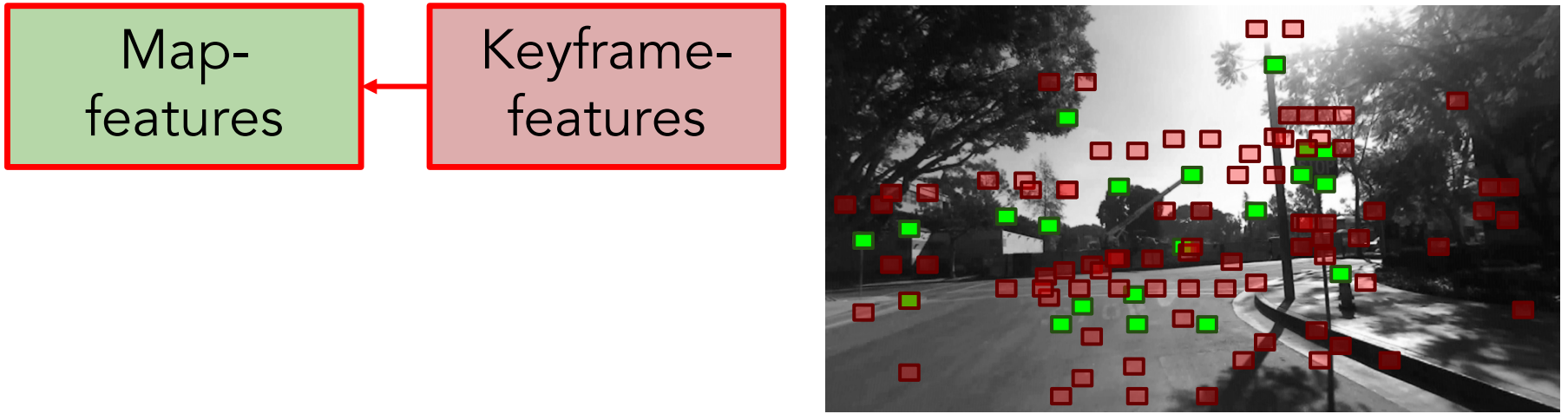


Map Elements: Keyframe-Features

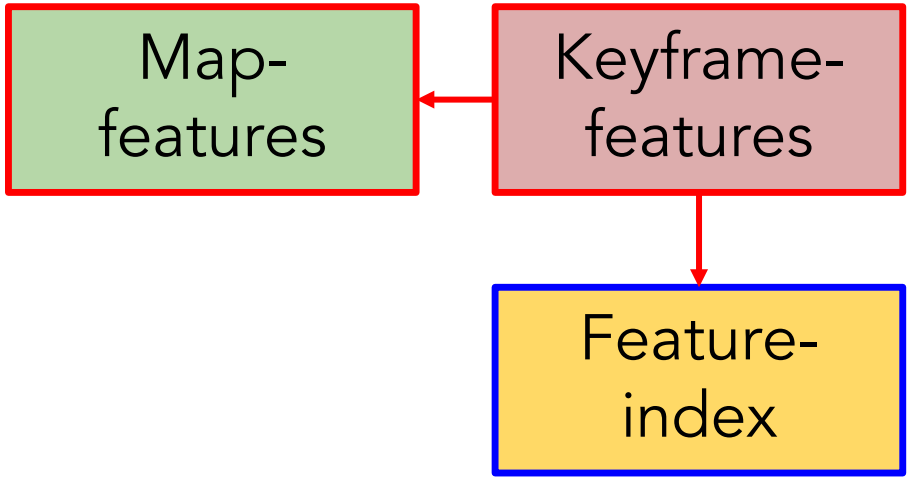
Keyframe-features

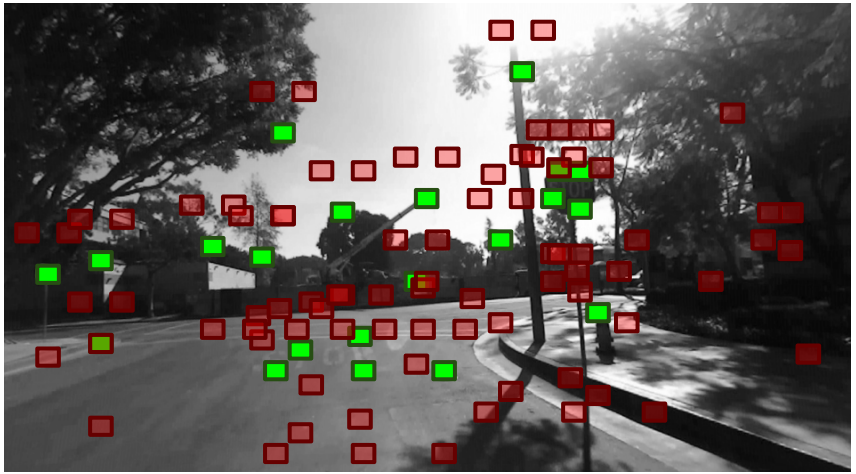


Map Elements: Map-Features

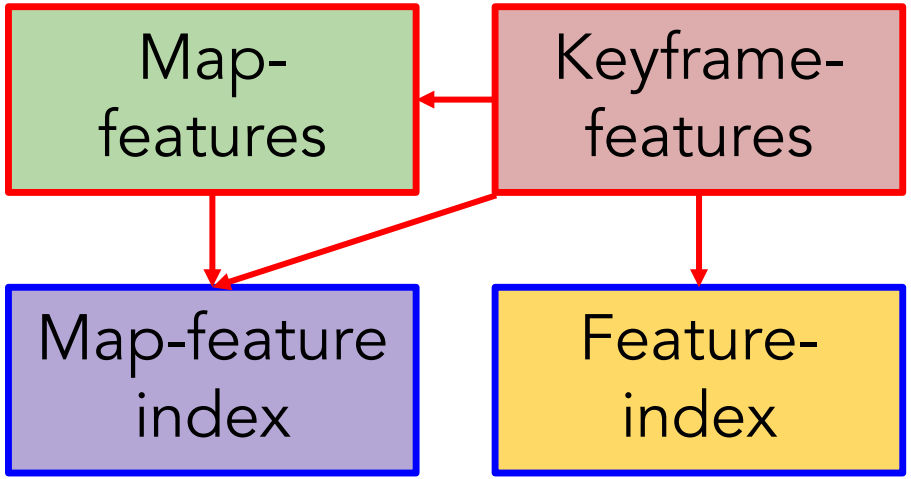


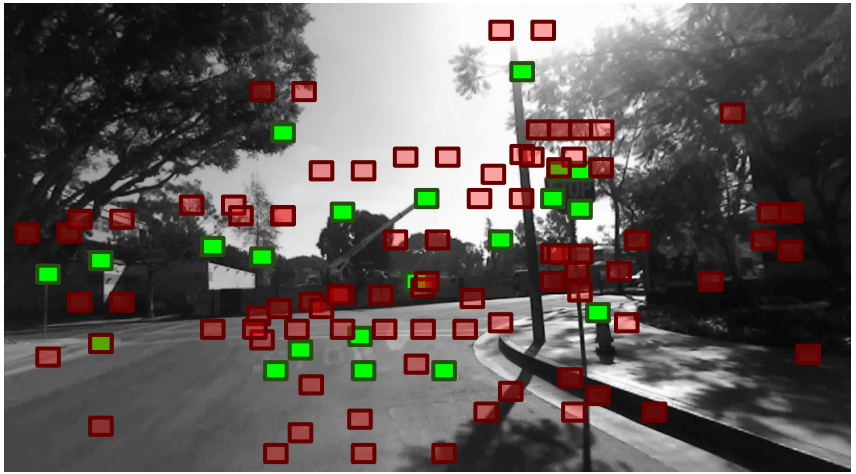
Map Elements: Feature-Index



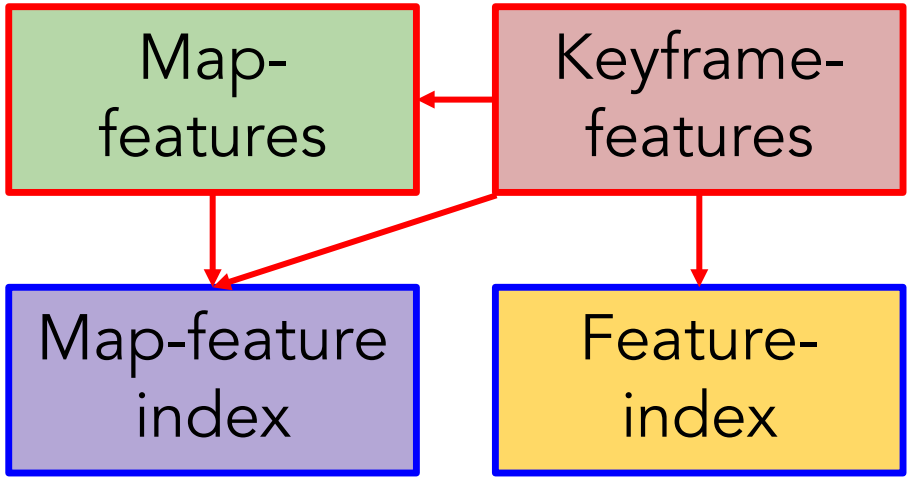


Map Elements: Map-Feature Index





Map Elements: Minimal Representation?



Feature Map Bandwidth Requirements

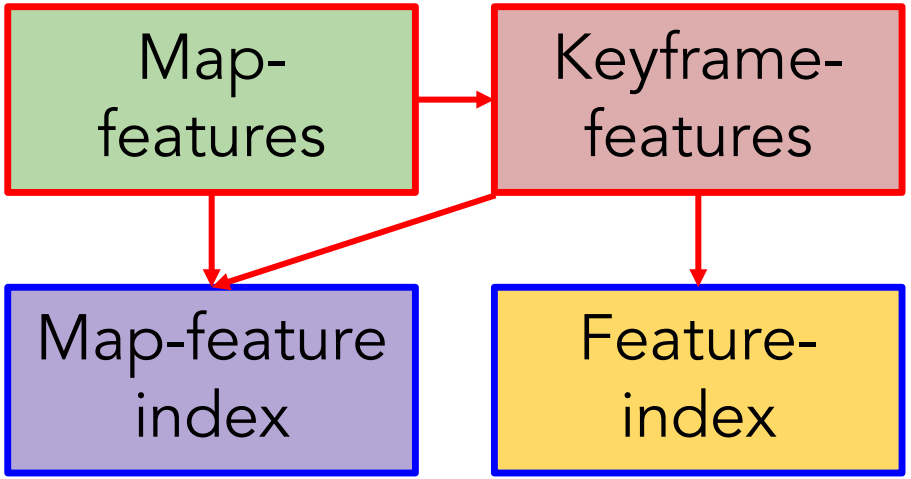
Feature-Map Scheme	**Sustained Bandwidth Requirement (Mbps)**
Full Feature-based SLAM Map	100
Keyframe-Features	27

CarMap's Lean Map Representation

Map-features

CarMap's Map Element Relationships

Map-features are only 4% of all keyframe features



Feature Map Bandwidth Requirements

Feature-Map Scheme	Sustained Bandwidth Requirement (Mbps)
Full Feature-based SLAM Map	100
Keyframe-Features	27
Map-Features	1

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation
Matching sparse features	
Environmental transients	Dynamic object filter
Map updates	Robust stitching, efficient diff

CarMap Contributions

Challenges	Contributions
Large feature maps	Lean map representation
Matching sparse features	Position hints
Environmental transients	Dynamic object filter
Map updates	Robust stitching, efficient diff

Background: Feature Matching Data Structures

Feature matching requirements:

- Accuracy
- Speed

Data structures:

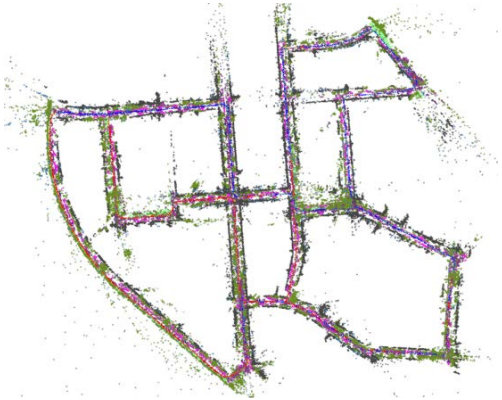
- Feature index
- Map-feature index

Background: Feature Matching Key Idea

Background: Feature Matching Key Idea

3D Frame

Feature-index



Background: Feature Matching Key Idea

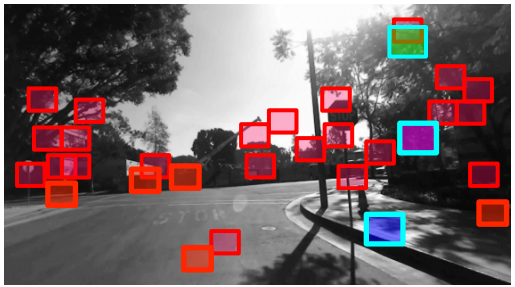
3D Frame

Image feature similarity

Feature-index

Identical keyframes

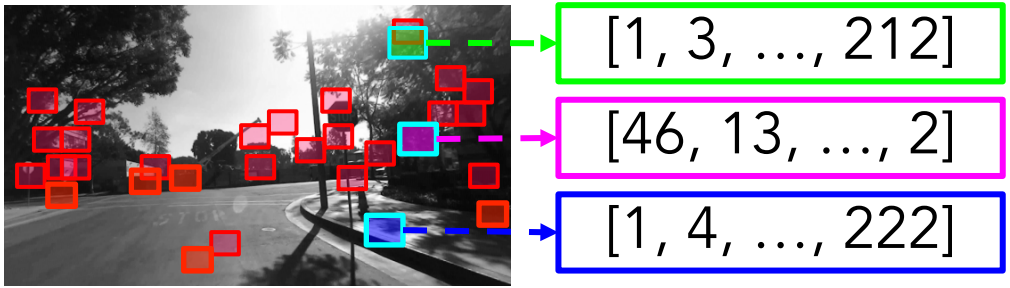
Background: Histogram-based Matching



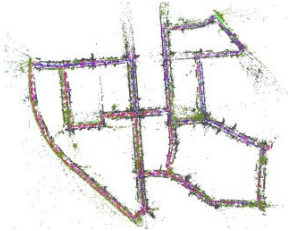
3D Frame

Feature map

Background: Histogram-based Matching

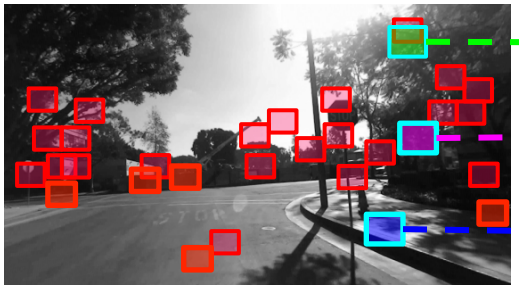


3D Frame Feature descriptors

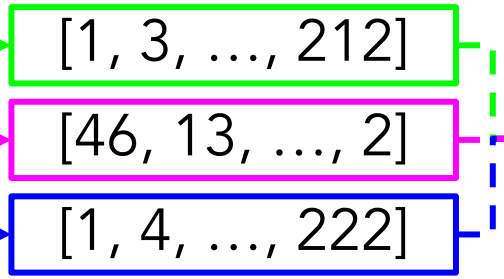


Feature map

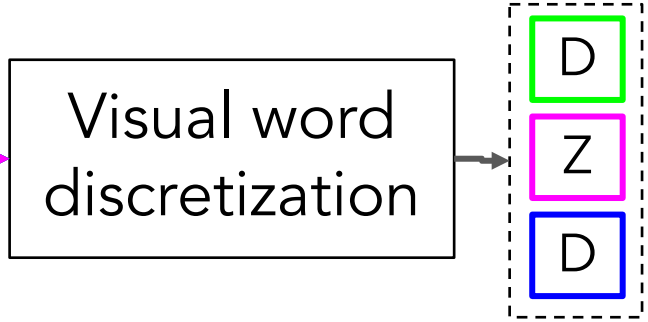
Background: Histogram-based Matching



3D Frame

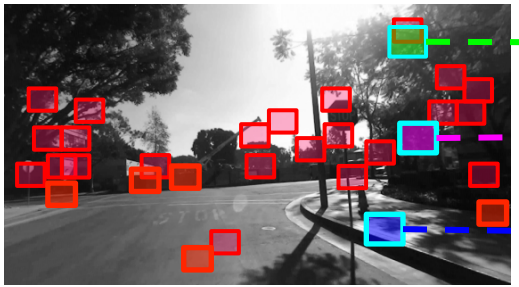


Feature descriptors



Feature map

Background: Histogram-based Matching



3D Frame

[1, 3, …, 212]

[46, 13, …, 2]

[1, 4, …, 222]

Feature descriptors

Visual word discretization

D

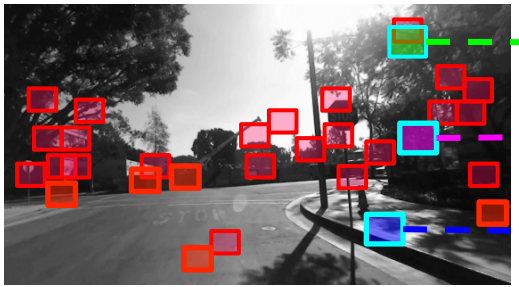
Z

D

Word histogram

Feature map

Background: Histogram-based Matching



3D Frame

[1, 3, …, 212]

[46, 13, …, 2]

[1, 4, …, 222]

Feature descriptors

Visual word discretization

D

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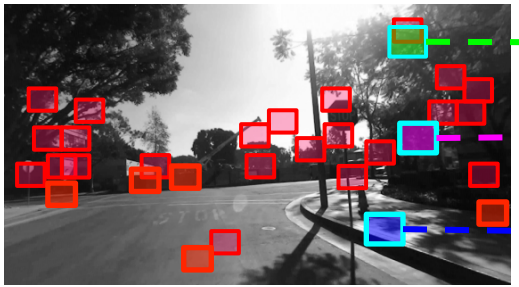
Feature map

Word histogram matching

Background: Histogram-based Matching



3D Frame

[1, 3, …, 212]

[46, 13, …, 2]

[1, 4, …, 222]

Feature descriptors

Visual word discretization

D

Z

D

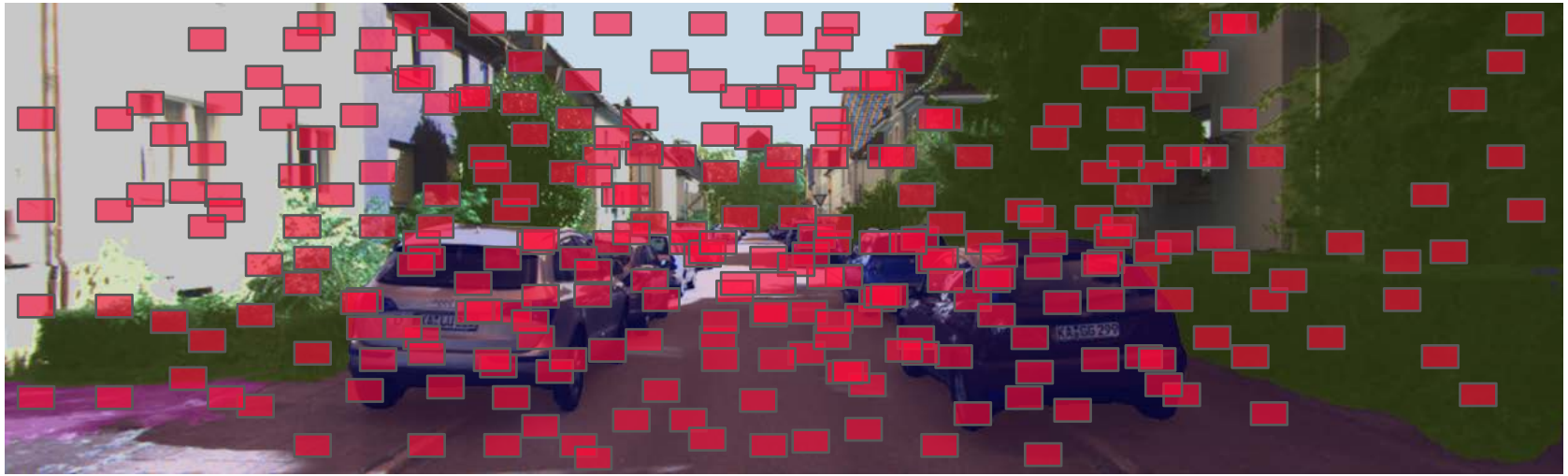
Word histogram

Feature map

Identical keyframes

Word histogram matching

In SLAM, Histograms use Keyframe Features



Keyframe features

CarMap Removes all Keyframe Features

Map features

Implications of Lean Map & Dynamic Filter

~30x fewer features in map

Feature matching with sparse features

Implications of Lean Map & Dynamic Filter

~30x fewer features in map

Feature matching with sparse features

No keyframe matches

False positives

Problem with Coarse-Grained Feature Matching

Problem: Image feature similarity not robust with sparse features

CarMap: Position Hints for Feature Matching

Problem: Image feature similarity not robust with sparse features

Solution: Use position hints

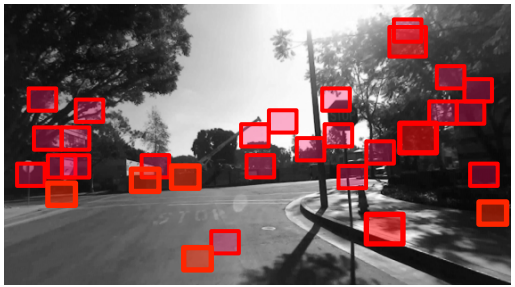
CarMap: Insight for Position Hints

Problem: Image feature similarity not robust with sparse features

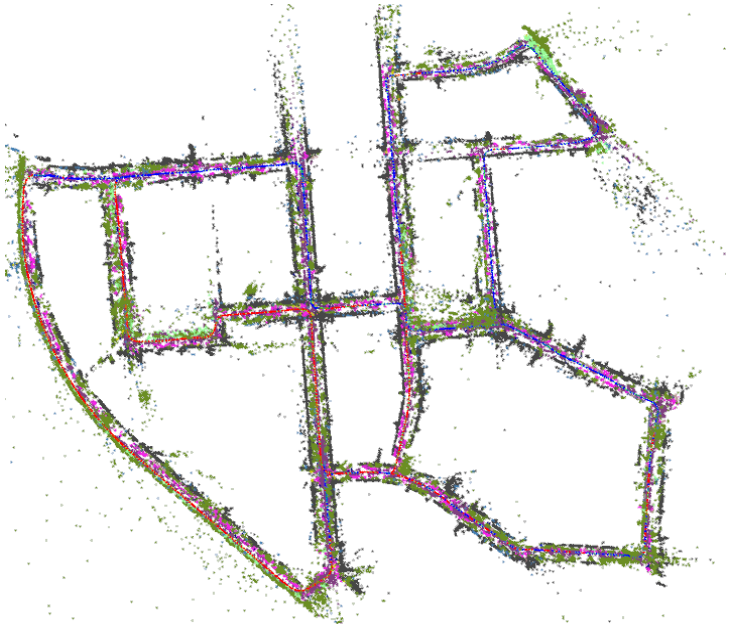
Solution: Use position hints

Insight: Vehicles will have GPS & inertial sensors

CarMap: Robust Coarse-Grained Feature Matching

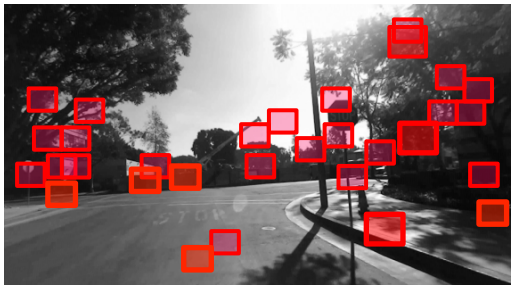


3D Frame



Feature map

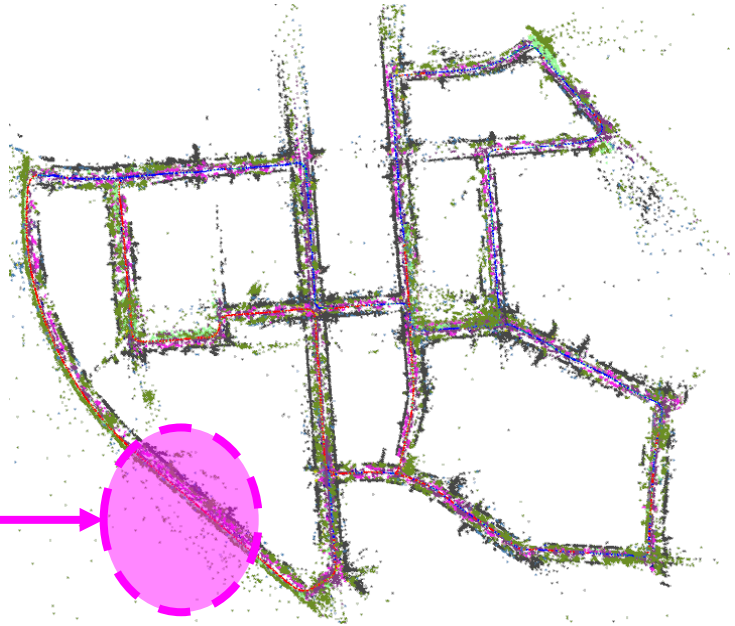
CarMap: Robust Coarse-Grained Feature Matching



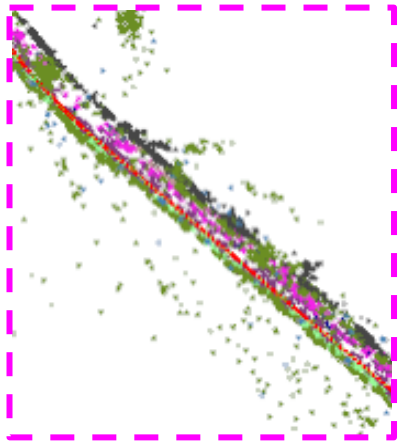
3D Frame

R

GPS

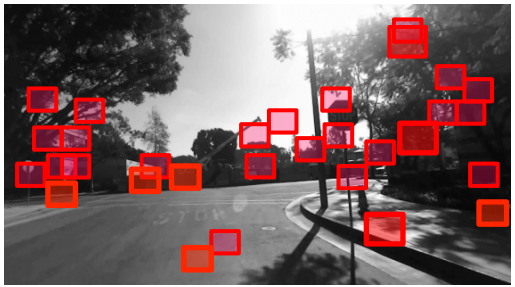


Feature map

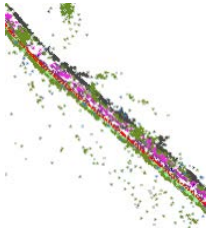


Spatially close keyframes

CarMap: Robust Coarse-Grained Feature Matching

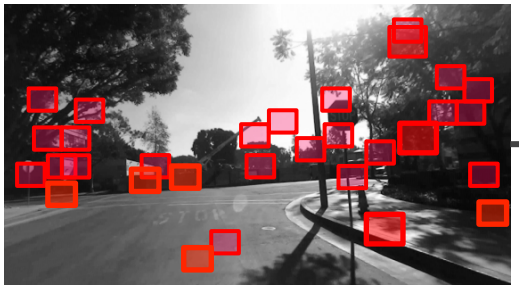


3D Frame

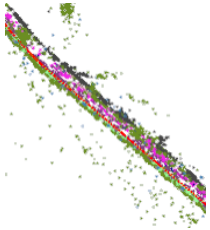


Spatially close keyframes

CarMap: Robust Coarse-Grained Feature Matching



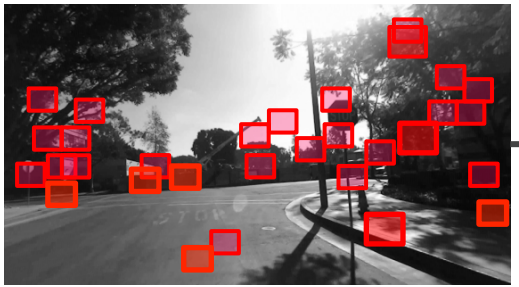
3D Frame



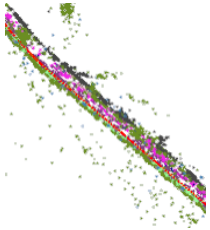
Spatially close keyframes

Word histogram matching

CarMap: Robust Coarse-Grained Feature Matching



3D Frame



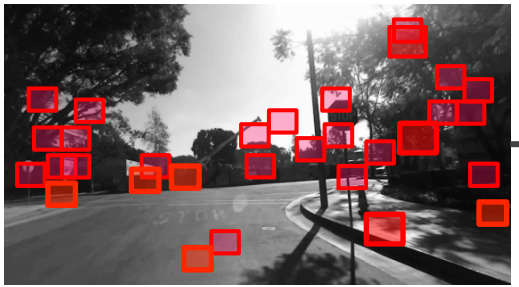
Spatially close keyframes

Word histogram matching

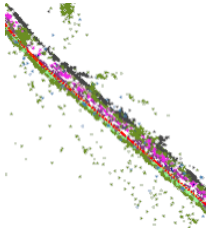
Spatial neighbors

Candidate keyframes

CarMap: Robust Coarse-Grained Feature Matching



3D Frame



Spatially close keyframes

Word histogram matching

Spatial neighbors

Candidate keyframes

Transform 3D frame and perform fine-grained feature matching

Problem with Fine-Grained Feature Matching

Problem: Image feature similarity and single keyframe matching are not robust

CarMap: Robust Fine-Grained Feature Matching

Problem: Image feature similarity and single keyframe matching are not robust

Solution: Spatial positions and multiple keyframe matching

CarMap: Insight for Robust Fine-Grained Matching

Problem: Image feature similarity and single keyframe matching are not robust

Solution: Spatial position, and multiple keyframe matching

Insight: Feature 3D positions are robust & on-board GPS

Details in the paper

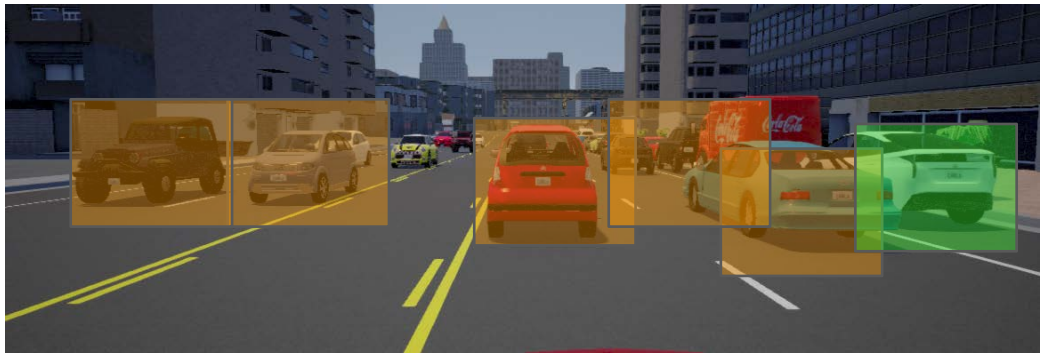
CarMap Contributions

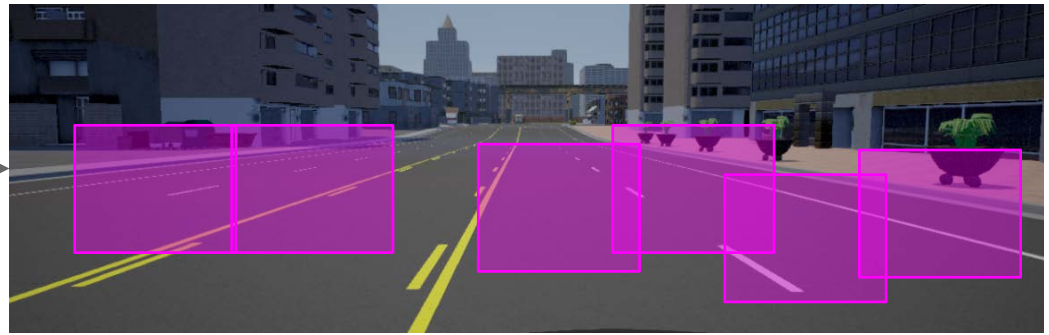
Challenges	Contributions
Large feature maps	Lean map representation
Matching sparse features	Position hints
Environmental transients	Dynamic object filter
Map updates	Robust stitching, efficient diff

Challenge: Environmental Dynamics

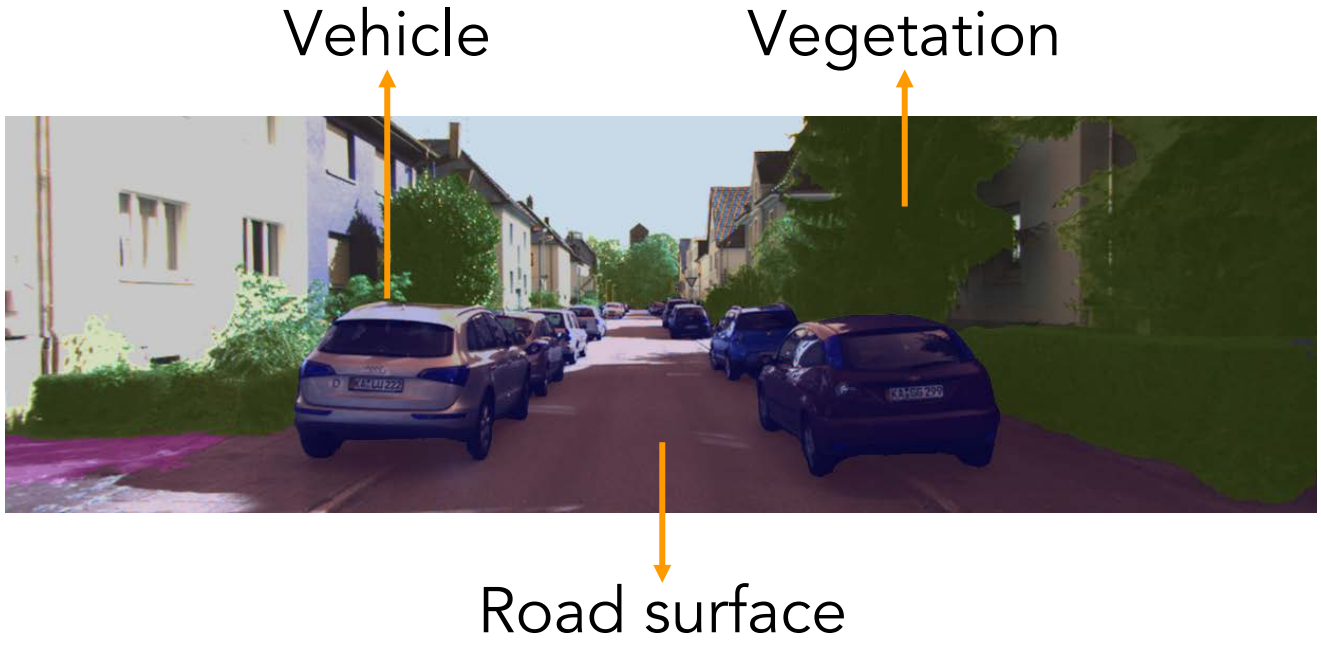
Map from rush hour

Poor localization





Semantic Segmentation



CarMap Map Features Without Dynamic Filter

Map Features

Semantic Segmentation for Feature Selection

Static object features

Environmental transient features

CarMap Map Features After Dynamic Filtering

Features in CarMap

Challenges in Semantic Segmentation

Low accuracy
62.4% iIoU

Low throughput
Less than 1 FPS

Challenges in Semantic Segmentation

Low accuracy
62.4% iIoU

Low throughput
Less than 1 FPS

- **Robust labeling**
- **Resource awareness**

Details in the paper

CarMap: Evaluation

Near real-time map updates

E2E localization accuracy

Lean map representation

Dynamic object filter

Map stitching

CarMap: Evaluation

Near real-time map updates

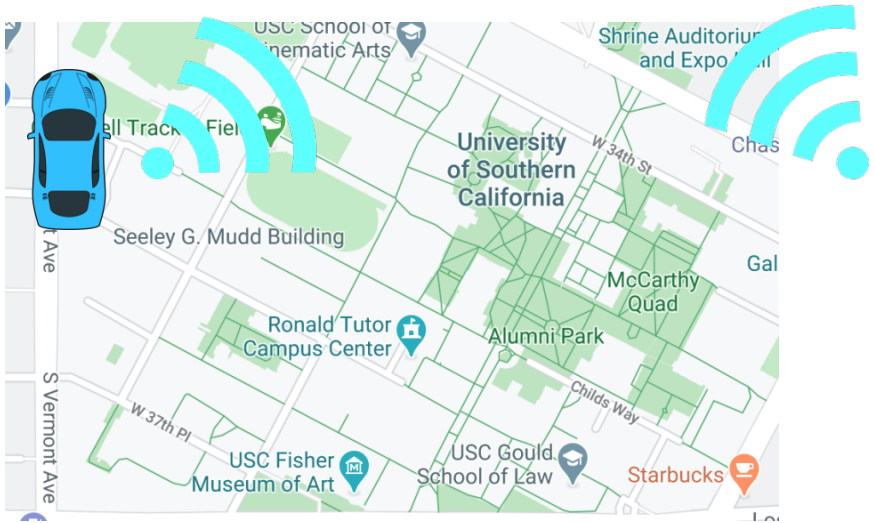
E2E localization accuracy

Lean map representation

Dynamic object filter

Map stitching

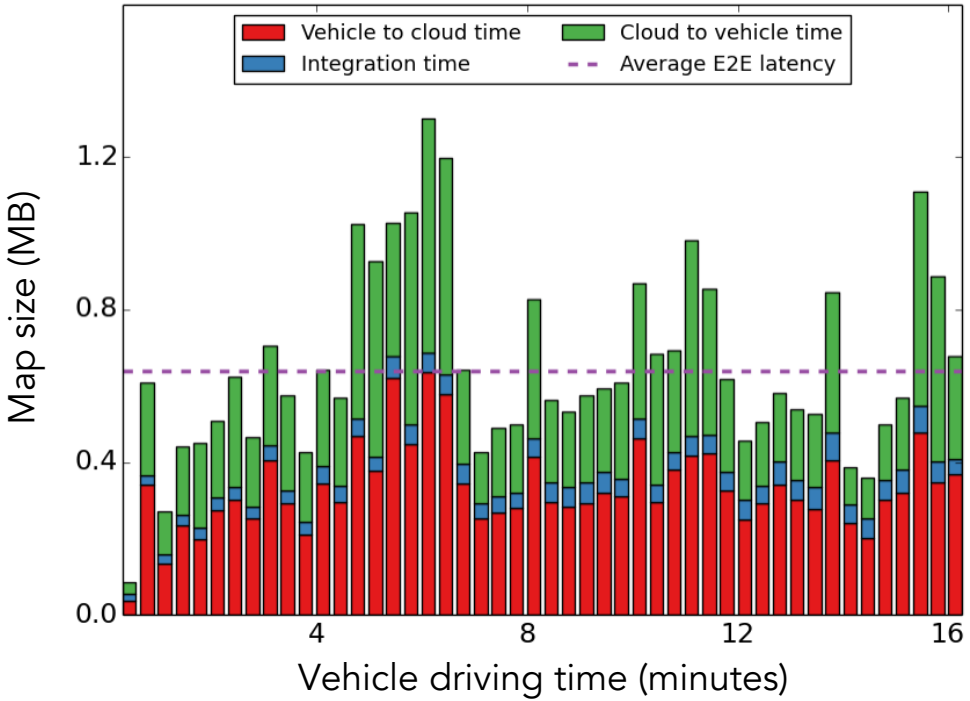
Evaluation: Near Real-Time Updates Setup



CarMap Cloud Service

Evaluation: Near Real-Time Updates Results

0.6 seconds on average for a map update



Evaluation: End-to-End Localization Setup

Build map

Use map

Dynamic scene

Static scene

Evaluation: End-to-End Localization Results

Mapping Scheme	**Suburbia**		
	Dynamic error (%)	*Static error (%)*	*Map size (MB)*
ORB-SLAM2			
QuickSketch			
CarMap			

Evaluation: End-to-End Localization Results

Mapping Scheme	**Suburbia**		
	Dynamic error (%)	*Static error (%)*	*Map size (MB)*
ORB-SLAM2	45.4		
QuickSketch	44.7		
CarMap	0.86		

~45x better

Evaluation: End-to-End Localization Results

Mapping Scheme	**Suburbia**		
	Dynamic error (%)	*Static error (%)*	*Map size (MB)*
ORB-SLAM2	45.4	∞	
QuickSketch	44.7	∞	
CarMap	0.86	1.22	
	~45x better	Robust to scene changes	

Evaluation: End-to-End Localization Results

Mapping Scheme	**Suburbia**		
	Dynamic error (%)	*Static error (%)*	*Map size (MB)*
ORB-SLAM2	45.4	∞	105.6
QuickSketch	44.7	∞	108.4
CarMap	0.86	1.22	3.94
	~45x better	Robust to scene changes	~26x smaller

Evaluation: Multi-Lane Localization Setup

Build map

Use map

Lane One

Lane Four

Evaluation: Multi-Lane Localization Results

Mapping Scheme	Static Freeway		
	Localization error (%)		
	2nd Lane	*3rd Lane*	*4th Lane*
ORB-SLAM2	3.79		
QuickSketch	4.29		
CarMap	2.26		

Better localization

Evaluation: Multi-Lane Localization Results

Mapping Scheme	Static Freeway		
	Localization error (%)		
	2nd Lane	*3rd Lane*	*4th Lane*
ORB-SLAM2	3.79	No localization	
QuickSketch	4.29	No localization	
CarMap	2.26	3.52	
	Better localization	Robust localization	

Evaluation: Multi-Lane Localization Results

Mapping Scheme	Static Freeway		
	Localization error (%)		
	2nd Lane	*3rd Lane*	*4th Lane*
ORB-SLAM2	3.79	No localization	No localization
QuickSketch	4.29	No localization	No localization
CarMap	2.26	3.52	4.85
	Better localization	Robust localization	Robust localization

Conclusion

Map updates in less than one second

Maps usable in different traffic conditions

Maps usable across multiple lanes

Thank you

https://youtu.be/SlG4QGq5ypk

GitHub https://github.com/USC-NSL/CarMap