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What Sensors are Needed for Autonomous Driving?

Christoph Stiller **Institut für Mess- und Regelungstechnik**

Vision-based autonomous driving

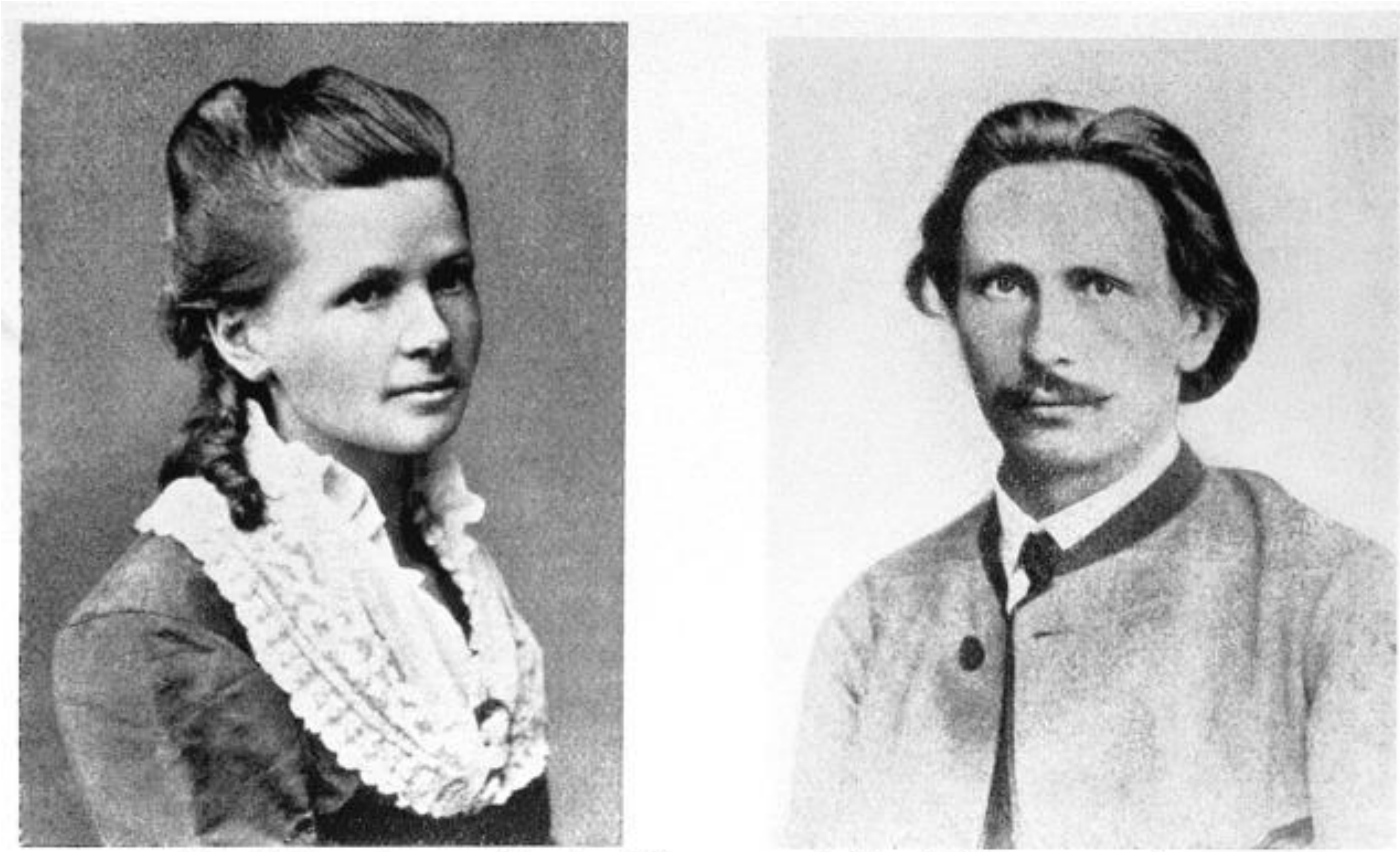
Things we wanted to leave behind:

- On-roof sensor suite
- Highly accurate DGNSS/IMU
- High-end lidars

Instead:

- Normal appearance
- Low cost cameras
- Low cost GPS/IMU
- (Pre-)series sensors
- Map-based

Bertha and Carl Benz ~ 1870



Das Brautpaar Berta Ringer und Karl Benz um 1870
Aus der Sammlung Eugen Benz, Ladenburg

1888 First long distance ride in an automobile by Bertha Benz and her two sons

Bertha Benz Memorial Route

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- first automotive long distance journey in 1888
- 104 km
- 3 large cities
- 23 smaller towns
- 18 roundabouts
- > 150 traffic lights

Major KIT/FZI Tasks

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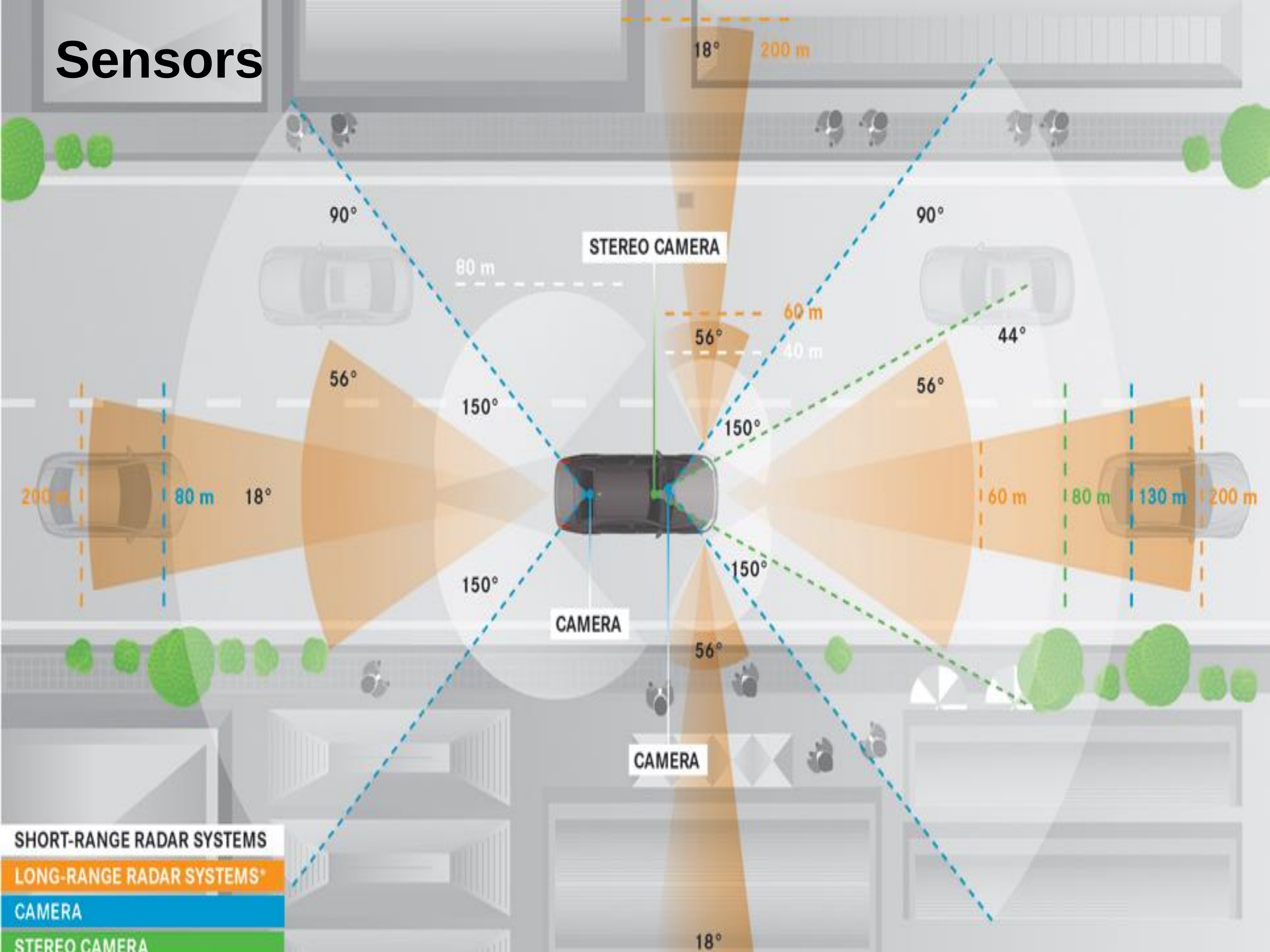
- Map generation
- Visual localization (KIT/FZI & Daimler)
- Behaviour decision
- Trajectory planning

Sensors



18°
200 m
90°
90°
STEREO CAMERA
80 m
60 m
56°
40 m
44°
56°
56°
150°
150°
200 m
80 m
18°
60 m
80 m
130 m
200 m
150°
150°
CAMERA
56°
CAMERA
SHORT-RANGE RADAR SYSTEMS
LONG-RANGE RADAR SYSTEMS*
CAMERA
STEREO CAMERA
18°

Map Layers

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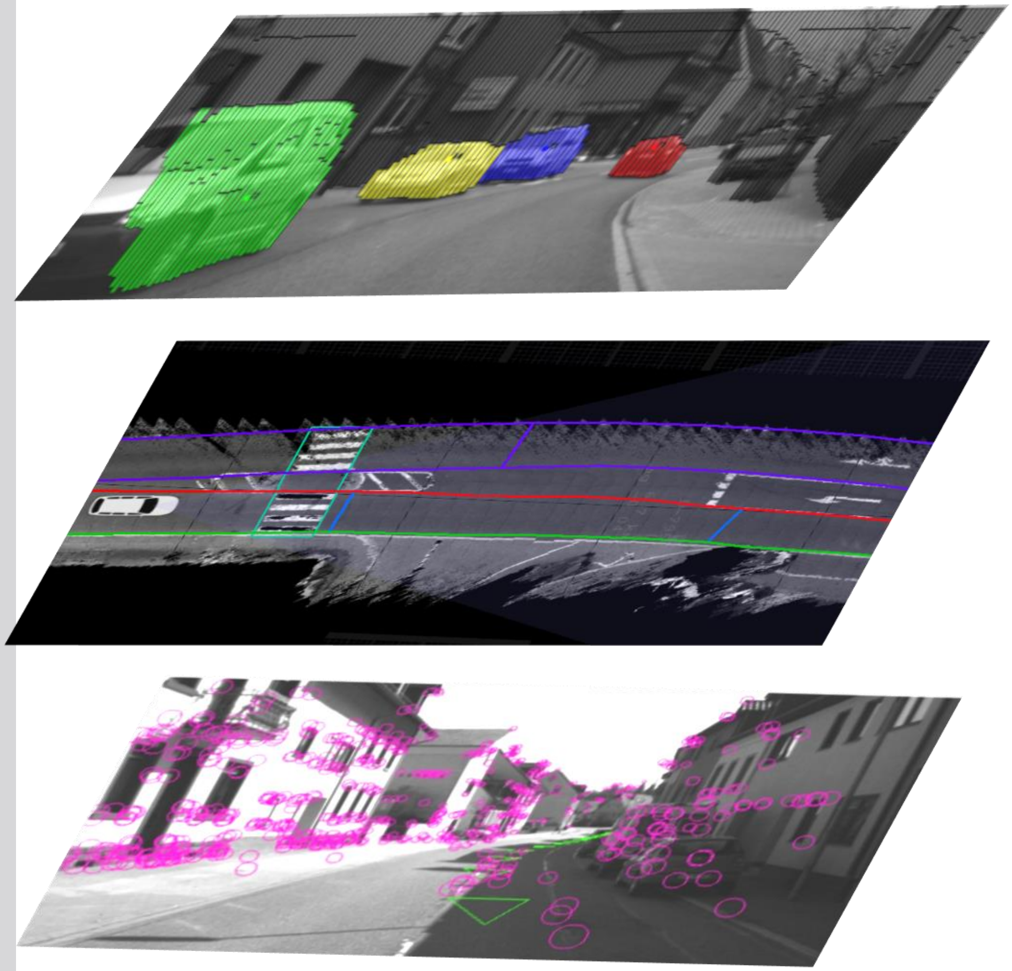

- Dynamic layer
  - dynamic objects
  - new static objects
- Static planning layer
  - 3d geometry, lanelets
  - traffic lights/rules
  - tactical information
- Localization layer
  - 3d landmarks
  - lane markers
  - 6d camera poses

[Lategahn, Bender, Schreiber, Franke et al. 11-14]

Visual Localization from Point Feature Matches

map features

R, t

image features

[Lategahn et al. 11-14]
start up company Atlatec UG

Localization

[Lategahn 2009-2013]
Now Atlatec UG

Front Stereo: Stixel Representation

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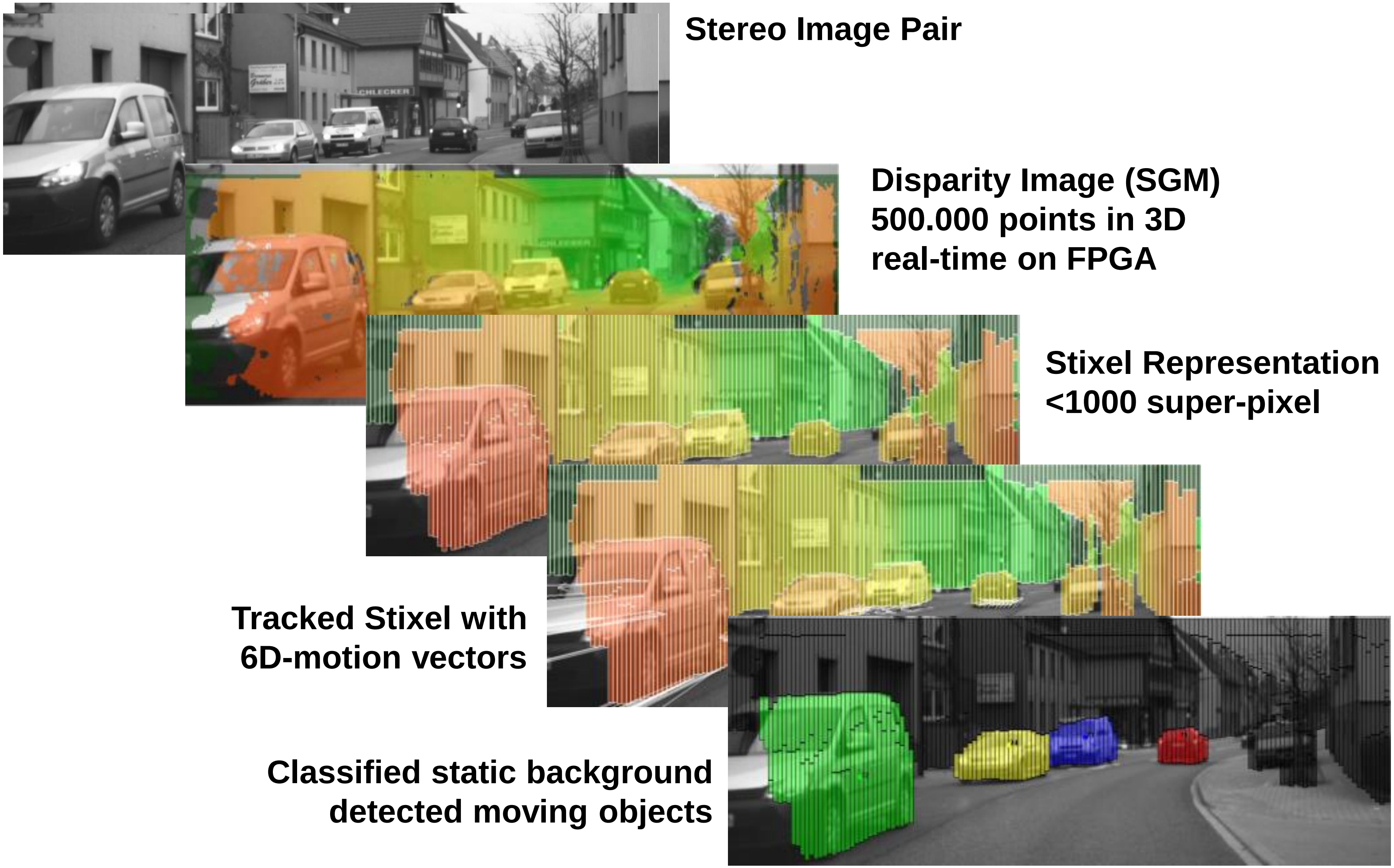


Stereo Image Pair

Disparity Image (SGM)
500.000 points in 3D
real-time on FPGA

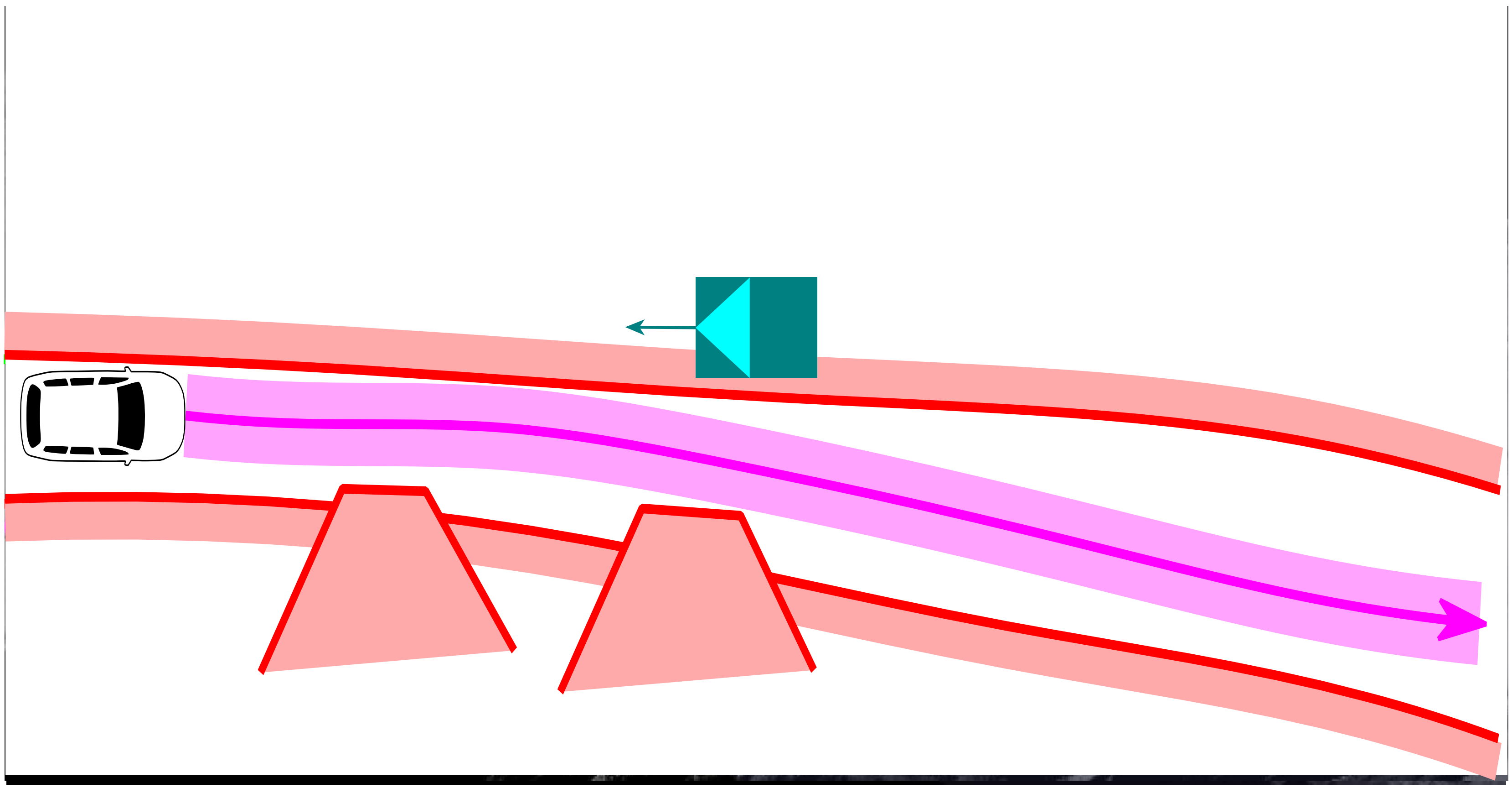
Stixel Representation
<1000 super-pixel

Tracked Stixel with
6D-motion vectors

Classified static background
detected moving objects

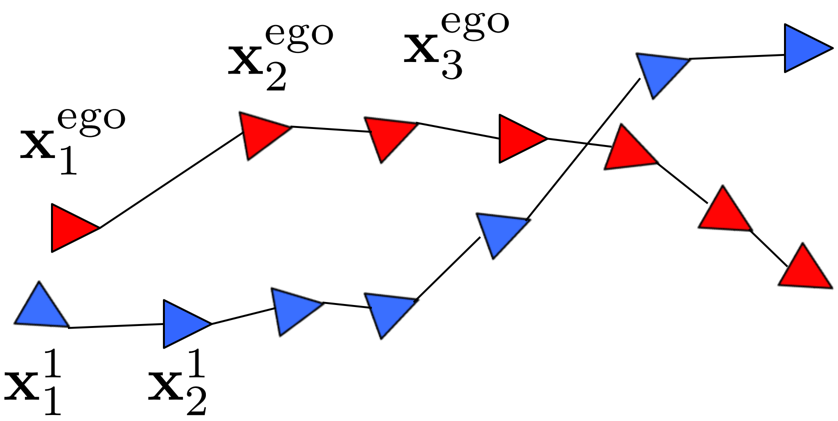
[Franke, Pfeiffer, Rabe, Knoeppel, Enzweiler, Stein, Herrtwich, ICCV Workshop 13]
Courtesy Daimler AG

Bertha's Driving Corridor



[Ziegler et al.2009-2013]

Cooperative Trajectory Planning



pose = (position, orientation)

$$\mathbf{x}_k = (\mathbf{X}_k, \mathbf{R}_k)$$

trajectory

$$\mathbf{x}_{j:l} = (\mathbf{x}_j, \mathbf{x}_{j+1}, \cdots, \mathbf{x}_l)$$

past

$$\mathbf{x}_{j:k} = (\mathbf{x}_j, \mathbf{x}_{j+1}, \cdots, \mathbf{x}_k)$$

future

$$\mathbf{x}_{k+1:l} = (\mathbf{x}_{k+1}, \mathbf{x}_{k+2}, \cdots, \mathbf{x}_l)$$

$$p(\mathbf{x}_{k+1:l}^{\text{ego}} | \mathbf{x}_{j:k}^1, \mathbf{x}_{j:k}^2, \cdots, \mathbf{x}_{j:k}^{\text{ego}}) =$$

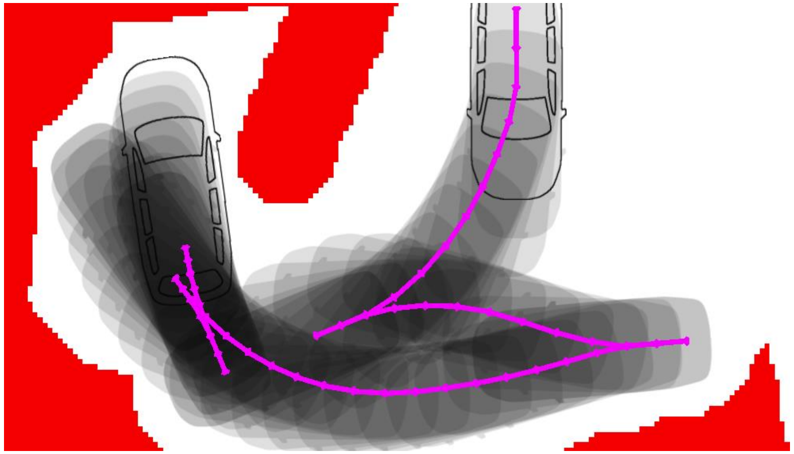
$$\int p(\mathbf{x}_{k+1:l}^{\text{ego}} | \mathbf{x}_{j:l}^1, \mathbf{x}_{j:l}^2, \cdots, \mathbf{x}_{j:k}^{\text{ego}}) p(\mathbf{x}_{k+1:l}^1, \mathbf{x}_{k+1:l}^2, \cdots | \mathbf{x}_{j:k}^1, \mathbf{x}_{j:k}^2, \cdots, \mathbf{x}_{j:k}^{\text{ego}}) d\mathbf{x}_{k+1:l}^i$$

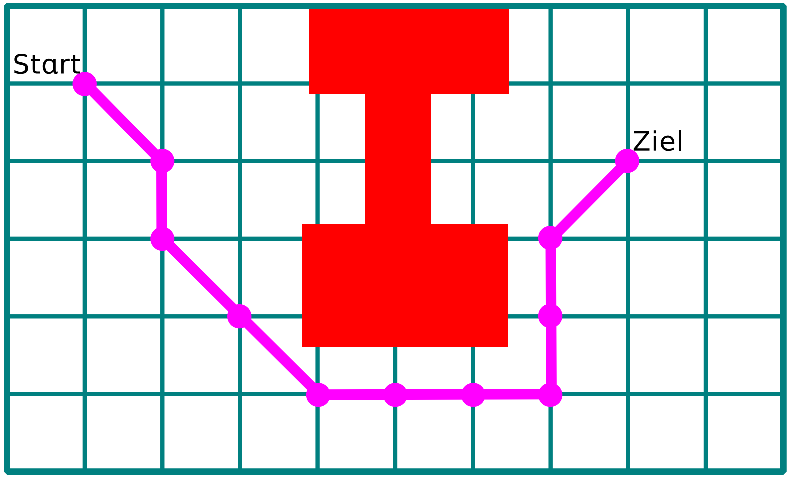
special case „certain prediction“, e.g. through v2v communication

$$= p(\mathbf{x}_{k+1:l}^{\text{ego}} | \mathbf{x}_{j:l}^1, \mathbf{x}_{j:l}^2, \cdots, \mathbf{x}_{j:k}^{\text{ego}})$$

Trajectory Planning Methods

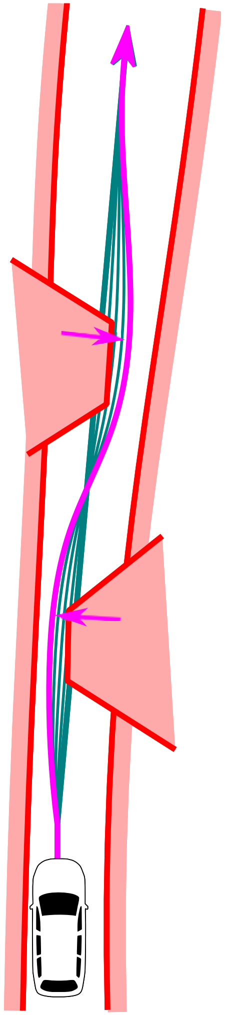
global, discrete, combinatoric





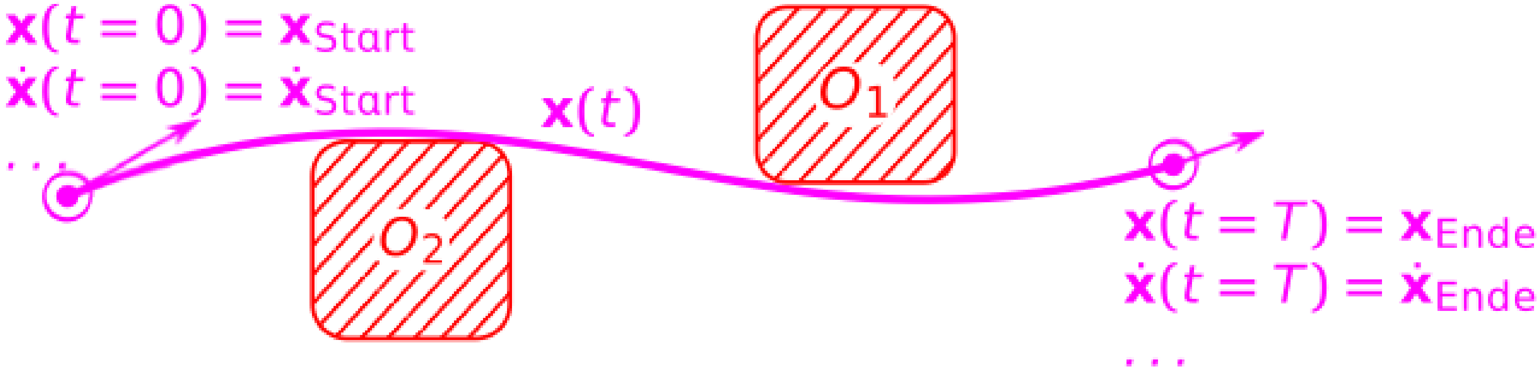
[Ziegler et al.2009–2011]

local, continuous, variational



[Ziegler et al.2011–2014]

Trajectory planning



optimize cost functional

$$E[\mathbf{x}(t)] = \int_0^T J(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \dddot{\mathbf{x}})\mathrm{d}t$$

$$\begin{aligned} J(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \dddot{\mathbf{x}}) &= w_{\text{lat}} \left| \frac{d_{\text{left}}(\mathbf{x}) - d_{\text{right}}(\mathbf{x})}{2} \right|^2 \\ &+ w_{\text{vel}} \left| (\mathbf{v}_{\text{ref}}(\mathbf{x}) - \dot{\mathbf{x}}) \right|^2 \\ &+ w_{\text{acc}} \left| \ddot{\mathbf{x}} \right|^2 \\ &+ w_{\text{jerk}} \left| \dddot{\mathbf{x}} \right|^2 \\ &+ w_{\text{jawr}} \dot{\theta}^2 \end{aligned}$$

subject to hard inner and outer conditions

inner conditions enforce drivability, e.g.:

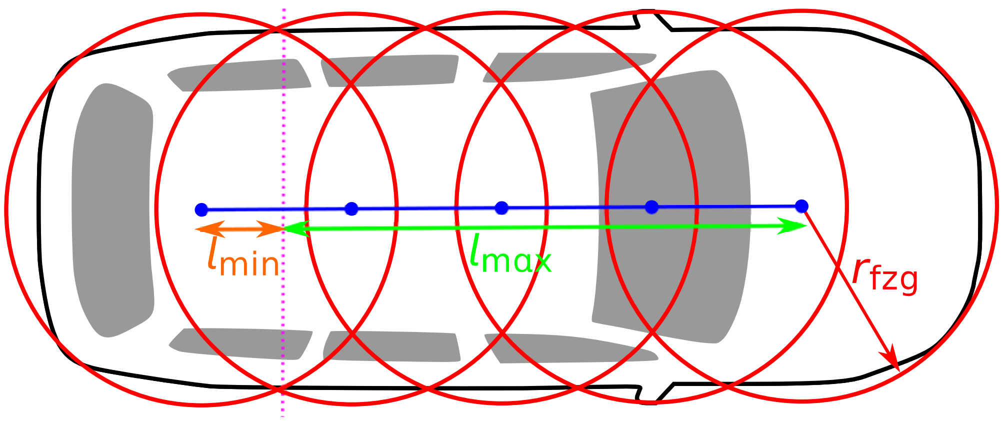
$$\|\ddot{\mathbf{x}}(t)\| < a_{\max}^2$$

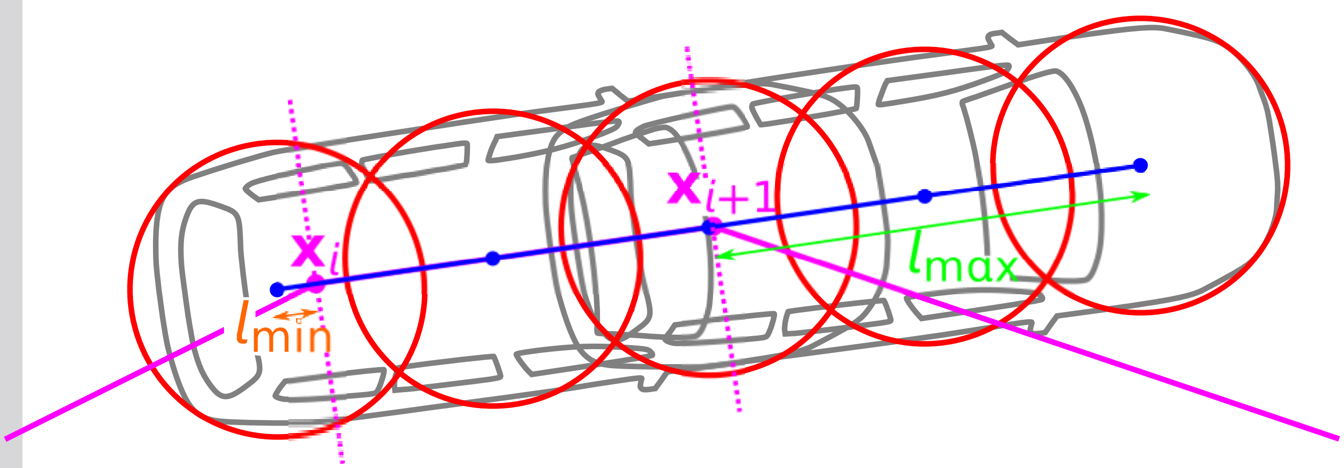
outer conditions enforce integrity, e.g.:

$$d\left(\mathbf{x}(t), O_1\right) > 0$$

Fast Collision Checking

Approximation of vehicle shape by a set of circles



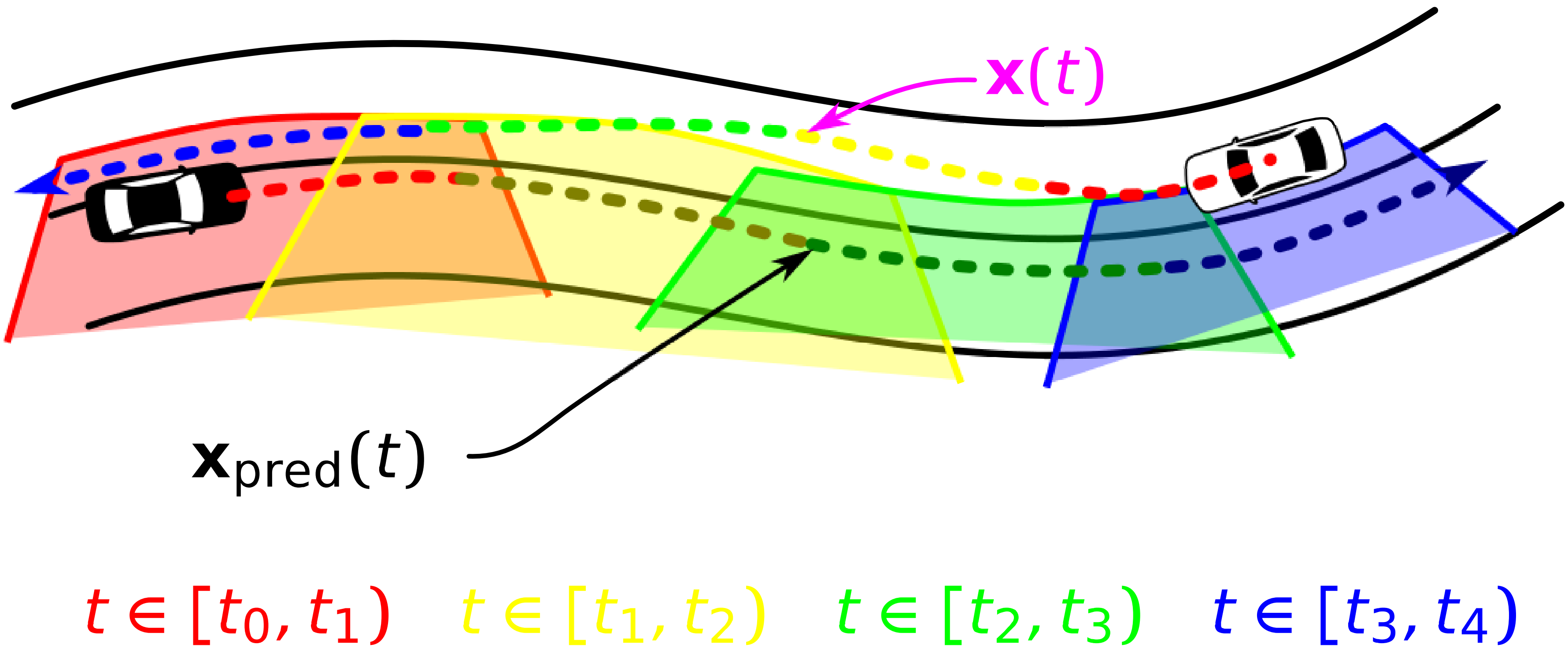


[Ziegler et al. 2011]

Dynamic Objects

We need to plan for ourselves …

… and for others

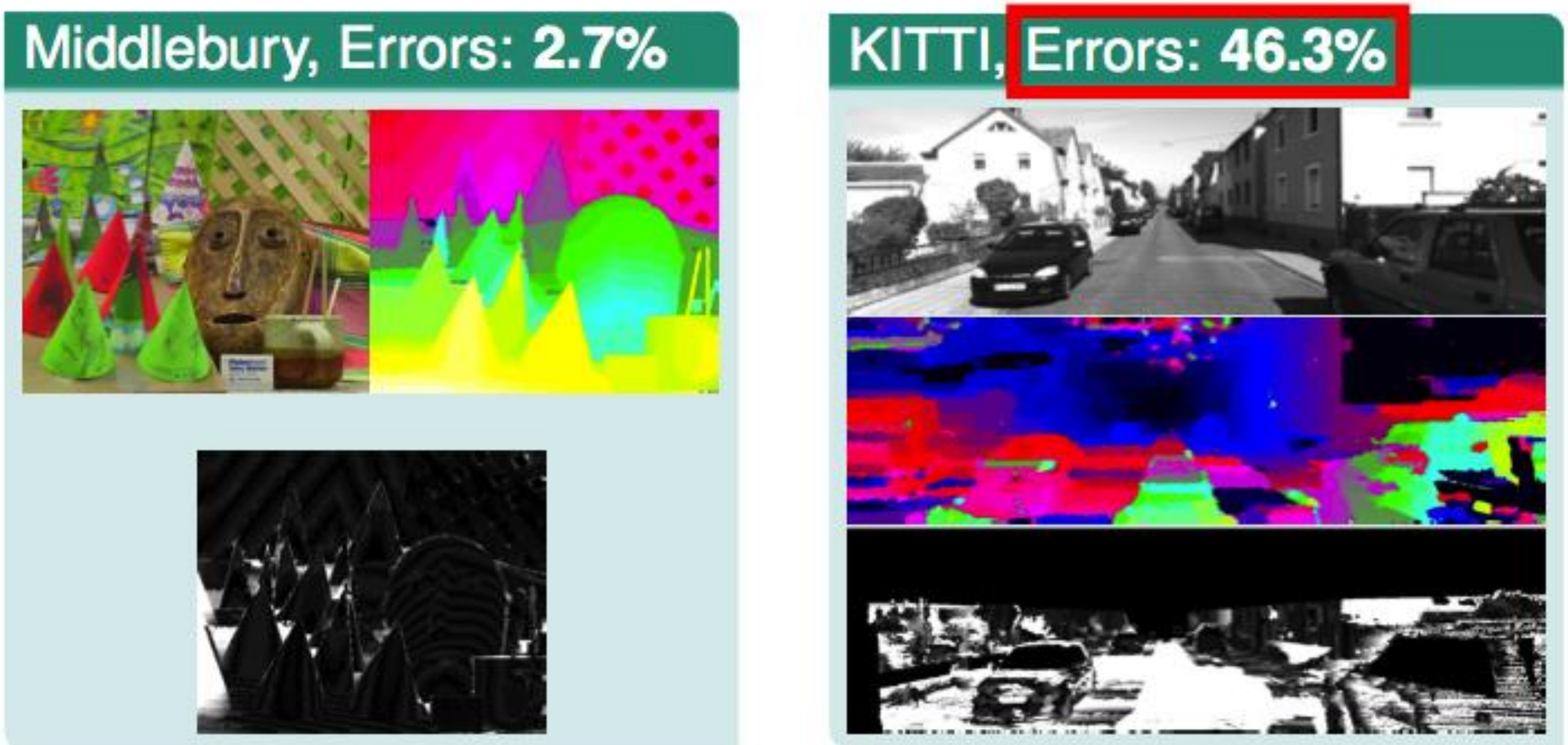


Results


Karlsruher Institut für Technologie
FZI
mrt
on behalf of
Mercedes-Benz

KITTI Vision Benchmark

Fast guided cost-volume filtering (Rhemann et al., CVPR 2011)



- Error threshold: 1 px (Middlebury) / 3 px (KITTI)

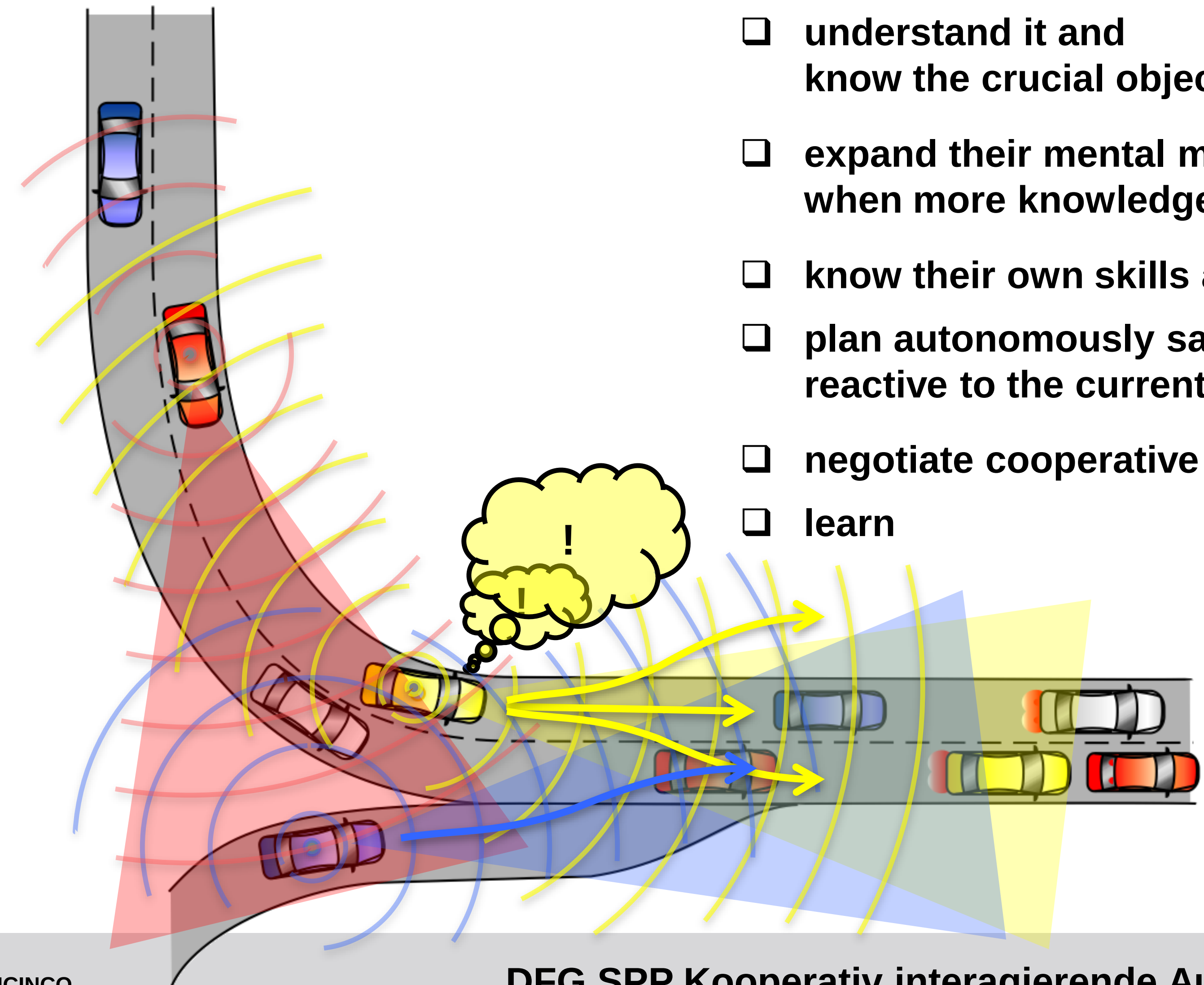
[Geiger, et al., International Journal of Robotics Research 32, 2013]

Automotive Vision Bechmark: www.mrt.kit.edu

Grand Cooperative Driving Challenge Holland, May 2011

Grand
Cooperative
Driving
Challenge

From Cognitive to Cooperative Automobiles



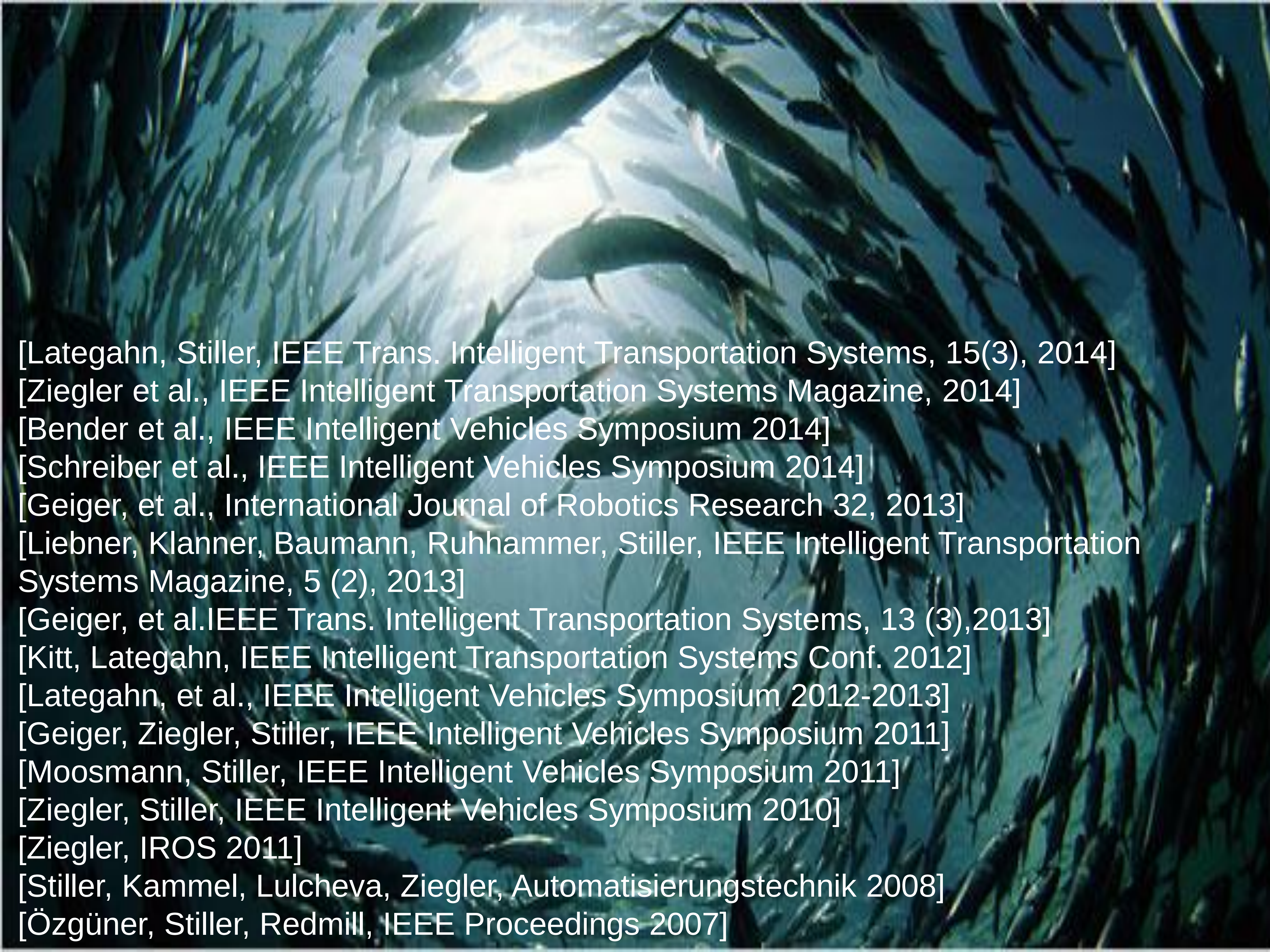
- perceive their environment,
- understand it and know the crucial objects and parameters,
- expand their mental map cooperatively when more knowledge becomes available
- know their own skills and capabilities
- plan autonomously safe behaviour reactive to the current situation
- negotiate cooperative behaviour,
- learn

DFG SPP Kooperativ interagierende Automobile 2015 - 2017

The Market: Functional Evolution

Summary & Conclusions

- Automated driving using vision, sota sensors and maps is feasible
- Maneuver decisions strongly inferred from map knowledge
- Real-time dynamic trajectory planning
- Automated driving on Bertha Benz Memorial Route
  - In normal traffic and at normal velocities
  - Safety driver still needed
- Many open issues
  - Benchmarks
  - Safety assessment
  - Handling of rare situations
  - Cooperation
- Step-by-step market introduction



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