

Map-Based Autonomous Driving

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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



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Bertha and Carl Benz ~ 1870



Das Brautpaar Bertha Ninger und Karl Benz um 1870
Aus der Sammlung Eugen von, Lebensdaten

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

Bertha Benz Memorial Route



Bertha Benz Memorial Route

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

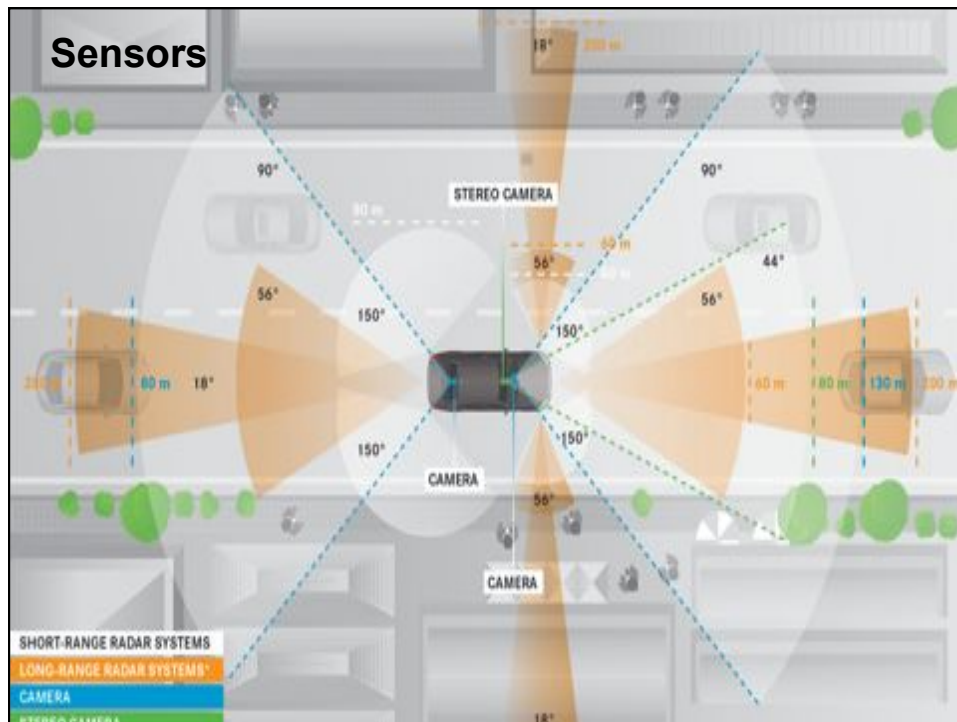
Major KIT/FZI Tasks



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



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Map Layers

KIT
Karlsruhe Institute of Technology

- **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

2014 ETH [Lategahn, Bender, Schreiber, Franke et al. 11-14]

Visual Localization from Point Feature Matches



map features

R, t

image features

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

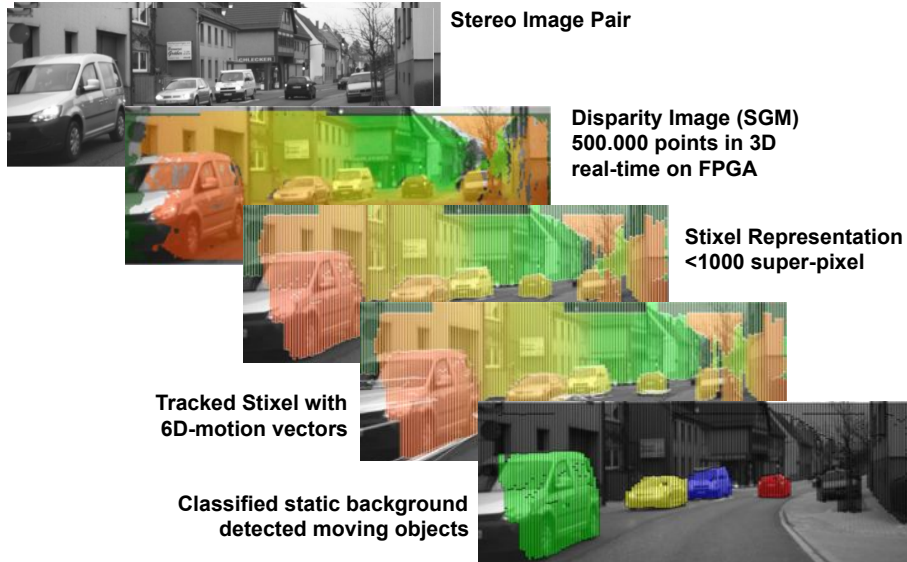
Localization



[Lategahn 2009-2013]
Now Atlatec UG

10

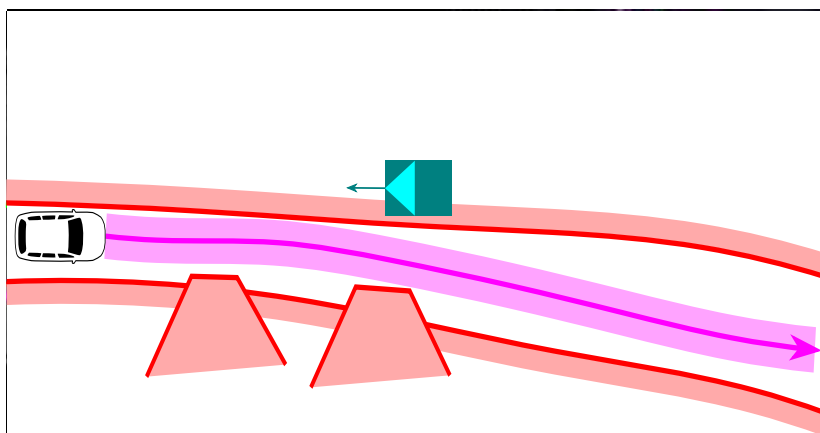
Front Stereo: Stixel Representation



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

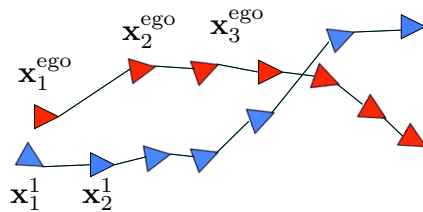
Bertha's Driving Corridor



2014 ETH

[Ziegler et al. 2009-2013]

Cooperative Trajectory Planning



pose = (position, orientation)

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

trajectory

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

past

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

future

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

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

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

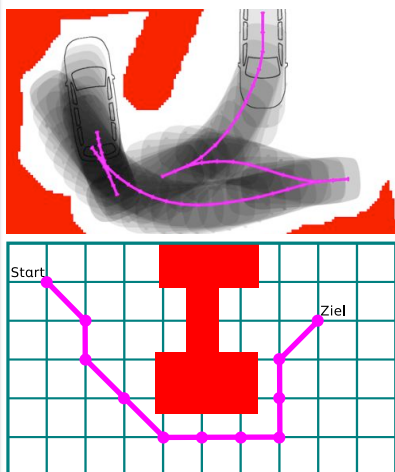
special case „certain prediction“, e.g. through v2v communication

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

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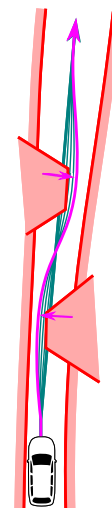
Trajectory Planning Methods

**global, discrete,
combinatoric**



[Ziegler et al.2009–2011]

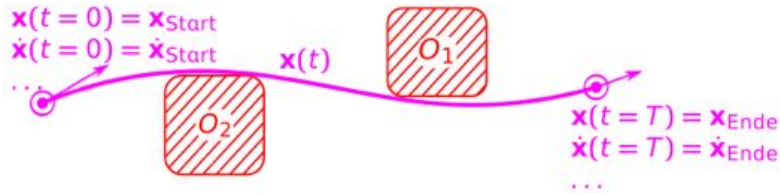
local, continuous, variational



[Ziegler et al.2011–2014]

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Trajectory planning



optimize cost functional

$$E[x(t)] = \int_0^T J(x, \dot{x}, \ddot{x}, \ddot{\ddot{x}}) dt$$

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

inner conditions
enforce drivability,

e.g.:

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

outer conditions
enforce integrity,

e.g.:

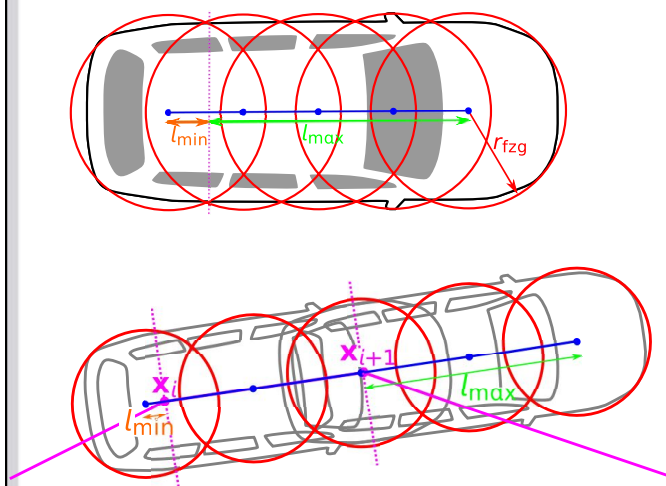
$$d(x(t), O_1) > 0$$

subject to hard inner and outer conditions

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Fast Collision Checking

Approximation of vehicle shape by a set of circles

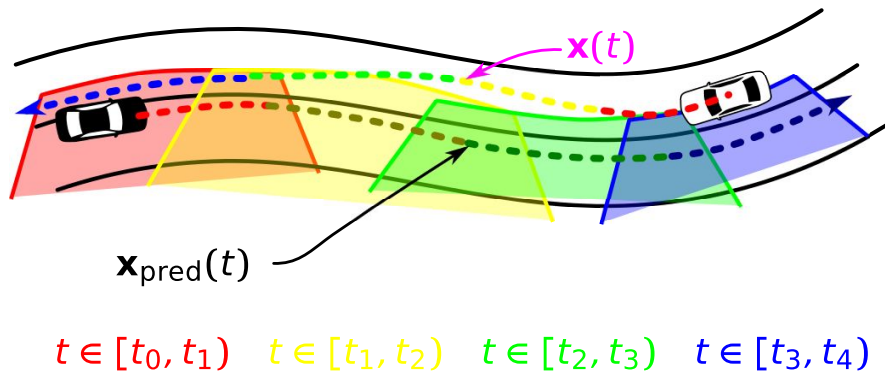


[Ziegler et al. 2011]

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Dynamic Objects

We need to plan for ourselves ...
... and for others



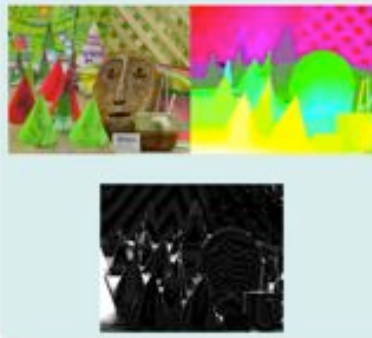
Results

KITTI Vision Benchmark

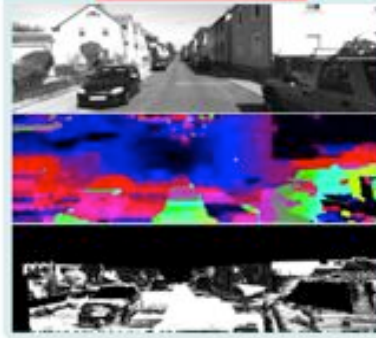


Fast guided cost-volume filtering (Rhemann et al., CVPR 2011)

Middlebury, Errors: 2.7%



KITTI, Errors: 46.3%



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

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

Automotive Vision Benchmark: www.mrt.kit.edu

Grand Cooperative Driving Challenge
Holland, May 2011



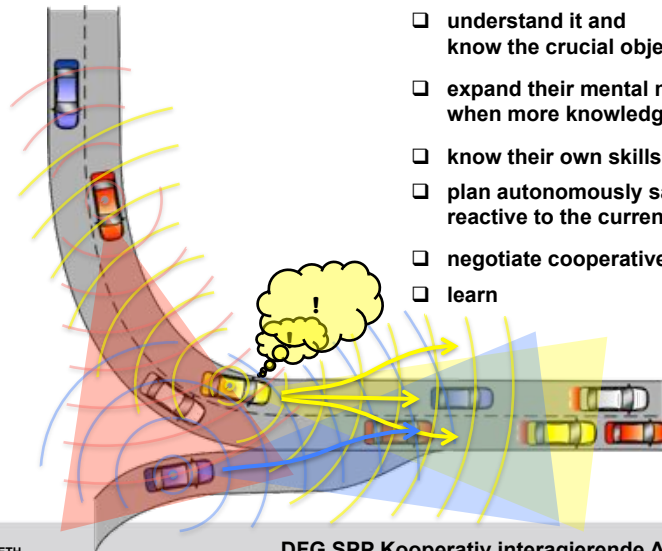
Grand
Cooperative
Driving
Challenge



Winner  KIT
Karlsruhe Institute of Technology

From Cognitive to Cooperative Automobiles

Karlsruhe Institute of Technology



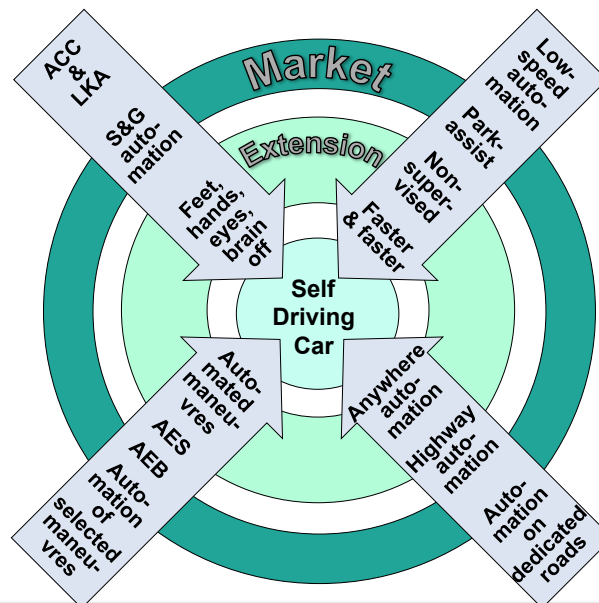
- ☐ perceive their environment,
- ☐ understand it and know the crucial objects and parameters,
- ☐ expand their mental map cooperatively when more knowledge becomes available
- ☐ know their own skills and capabilities
- ☐ plan autonomously safe behaviour reactive to the current situation
- ☐ negotiate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

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DFG SPP Kooperativ interagierende Automobile 2015 - 2017

The Market: Functional Evolution

Karlsruhe Institute of Technology



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Summary & Conclusions



- Automated driving using vision, sota sensors and maps
- 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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[Ziegler et al., IEEE Intelligent Transportation Systems Magazine, 2014]
[Bender et al., IEEE Intelligent Vehicles Symposium 2014]
[Schreiber et al., IEEE Intelligent Vehicles Symposium 2014]
[Geiger, et al., International Journal of Robotics Research 32, 2013]
[Liebner, Klanner, Baumann, Ruhhammer, Stiller, IEEE Intelligent Transportation Systems Magazine, 5 (2), 2013]
[Geiger, et al. IEEE Trans. Intelligent Transportation Systems, 13 (3), 2013]
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[Moosmann, Stiller, IEEE Intelligent Vehicles Symposium 2011]
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[Ziegler, IROS 2011]
[Stiller, Kammel, Lulcheva, Ziegler, Automatisierungstechnik 2008]
[Özgüner, Stiller, Redmill, IEEE Proceedings 2007]