AO-Car: Transfer of Space Technology to Autonomous Driving with the Use of WORHP

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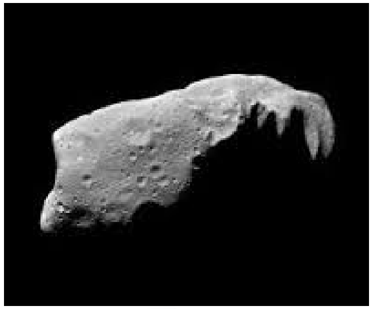
Transfer of space expertise into terrestrial applications



Transfer of space expertise into terrestrial applications

- Provide a test platform
- Increase public acceptance
- Technologies are available on earth

Research project AO-Car with terrestrial application

Autonomous and optimal navigation and control of a vehicle in urban areas

Universität Bremen

Universität der Bundeswehr München

September 2016
-
March 2018

DLR

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

09.11.2018

Research vehicle

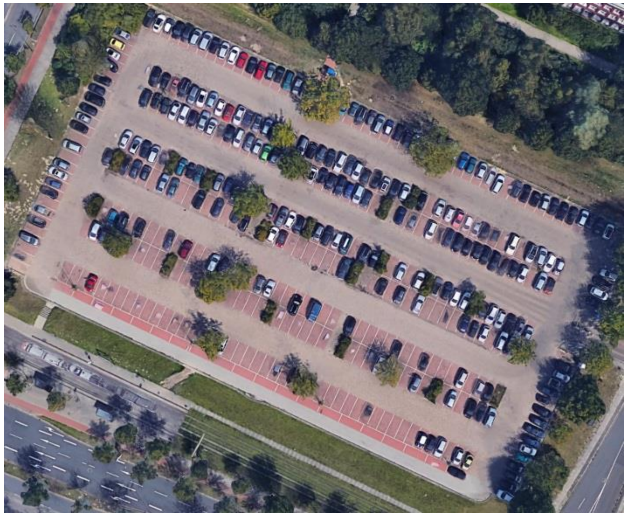
- VW Passat GTE, Plug-in-Hybrid
- Equipped with
  - Laser scanners
  - Ultrasonic sensors
  - GNSS
  - Radar
  - Camera systems
- Control loop with a frequency of 50Hz

DLR

Goals of the research project AO-Car

Autonomous exploration of a parking lot including

- lane keeping in corridors
- turning maneuvers
- obstacle avoidance
- emergency stops
- controlled stopping
- parking



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Trajectory planning and control approach

Transfer the vehicle from state A to state B

respecting its dynamics

without any collision

and minimizing an individual optimization criterion.

Trajectory planning and control approach

Transfer the ~~vehicle~~ spacecraft from state A to state B

respecting its dynamics

without any collision

and minimizing an individual optimization criterion.

Optimal control problem (OCP)

$$
\begin{aligned}
\min_{z,u,T} \quad & J(z,u,T) \\
\text{s.t. } \dot{z}(t) &= f(z(t),u(t)), \\
z(0) = z_0, \quad & z(T) = z_T, \\
z_{\min} \le\ & z(t) \le z_{\max}, \\
u_{\min} \le\ & u(t) \le u_{\max}, \\
C(z(t),u(t),t) &\le 0 \text{ for all } t \in [0,T].
\end{aligned}
$$

$$
\begin{aligned}
J &\in \mathcal{C}^1(\mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}, \mathbb{R}), \\
z &\in \mathcal{C}^1([0,T], \mathbb{R}^n), \\
u &\in \mathcal{C}^0([0,T], \mathbb{R}^m), \\
C &\in \mathcal{C}^1(\mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}, \mathbb{R}^c), \\
f &\in \mathcal{C}^1(\mathbb{R}^n \times \mathbb{R}^m, \mathbb{R}^n).
\end{aligned}
$$

Kinematic single track model

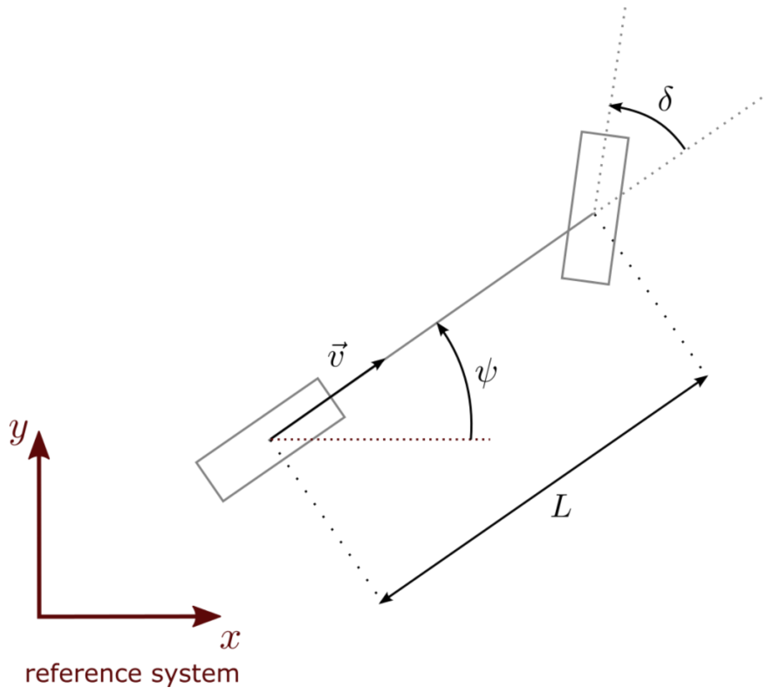
System dynamics:

$$\dot{x} = v \cdot \cos(\psi), \qquad \dot{\psi} = v \cdot \frac{\tan(\delta)}{L},$$

$$\dot{y} = v \cdot \sin(\psi), \qquad \dot{\delta} = \omega_\delta,$$

$$\dot{v} = a, \qquad \dot{\omega}_\delta = a_\delta,$$

$$\dot{a} = j.$$



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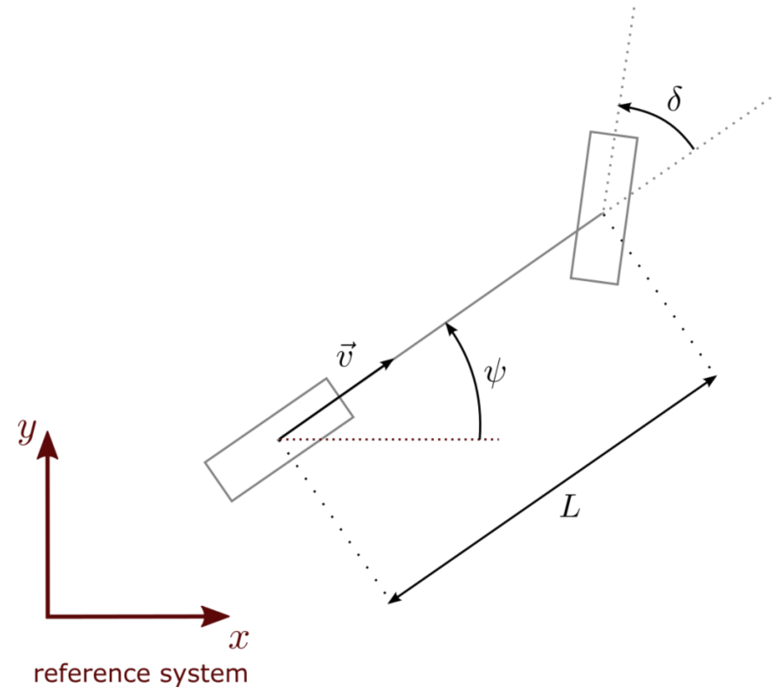


Physical limits and limitations due to comfort reasons:

$$v_{\min} \leq v \leq v_{\max}, \qquad \delta_{\min} \leq \delta \leq \delta_{\max},$$

$$a_{\min} \leq a \leq a_{\max}, \qquad \omega_{\delta_{\min}} \leq \omega_\delta \leq \omega_{\delta_{\max}}.$$

Optimization criteria

$$
\begin{aligned}
\tilde{J}(z,u,T) :=& w_0 T \\
&+ \int_0^T w_1 {\omega_\delta}^2 + w_2 a^2 + w_3 j^2 + w_4 {a_\delta}^2 \mathrm{d}t \\
&+ \int_0^T w_5 (v - v_{\mathrm{set}})^2 \mathrm{d}t.
\end{aligned}
$$

Process time

Energy & comfort

Keep desired speed

Optimization criteria

$$\begin{aligned}\tilde{J}(z,u,T) :=& w_0 T \\ &+ \int_0^T w_1 {\omega_\delta}^2 + w_2 a^2 + w_3 j^2 + w_4 {a_\delta}^2 \mathrm{d}t \\ &+ \int_0^T w_5 (v - v_{\text{set}})^2 \mathrm{d}t.\end{aligned}$$

Process time

Energy & comfort

Keep desired speed

Deviation from desired target state:

Case $v_T = 0\,{}^{\text{km}}/_{\text{h}}$:

$$\begin{aligned}J_T(z,u,T) :=& w_6 (x(T) - x_T)^2 + w_7 (y(T) - y_T)^2 \\ &+ w_8 (\psi(T) - \psi_T)^2 + w_9 (\delta(T) - \delta_T)^2.\end{aligned}$$

$$J(z,u,T) = \tilde{J}(z,u,T) + J_T(z,u,T)$$

Optimization criteria

$$\tilde{J}(z,u,T) := w_0 T$$ — Process time

$$+ \int_0^T w_1 {\omega_\delta}^2 + w_2 a^2 + w_3 j^2 + w_4 {a_\delta}^2 \mathrm{d}t$$ — Energy & comfort

$$+ \int_0^T w_5 (v - v_{\text{set}})^2 \mathrm{d}t.$$ — Keep desired speed

Deviation from desired target state:

Case $v_T = 0\, {}^{\text{km}}\!/\!{}_{\text{h}}$:

$$J_T(z,u,T) := w_6(x(T) - x_T)^2 + w_7(y(T) - y_T)^2 + w_8(\psi(T) - \psi_T)^2 + w_9(\delta(T) - \delta_T)^2.$$

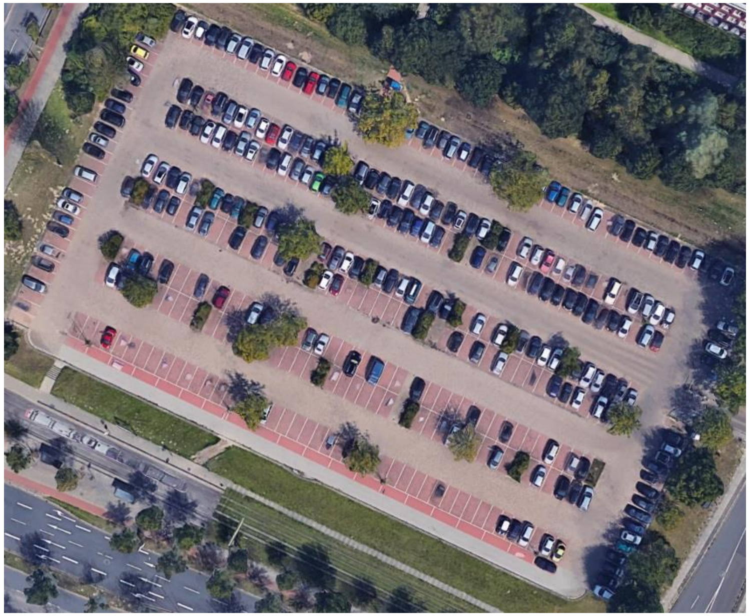
$$J(z,u,T) = \tilde{J}(z,u,T) + J_T(z,u,T)$$

Case $v_T > 0\, {}^{\text{km}}\!/\!{}_{\text{h}}$:

$$x(T) \in [x_T - \varepsilon_x, x_T + \varepsilon_x],$$
$$y(T) \in [y_T - \varepsilon_y, y_T + \varepsilon_y],$$
$$\psi(T) \in [\psi_T - \varepsilon_\psi, \psi_T + \varepsilon_\psi],$$
$$\delta(T) \in [\delta_T - \varepsilon_\delta, \delta_T + \varepsilon_\delta],$$
$$\varepsilon_x, \varepsilon_y, \varepsilon_\psi, \varepsilon_\delta > 0.$$

$$J(z,u,T) = \tilde{J}(z,u,T)$$

Predefined restrictions of the parking lot



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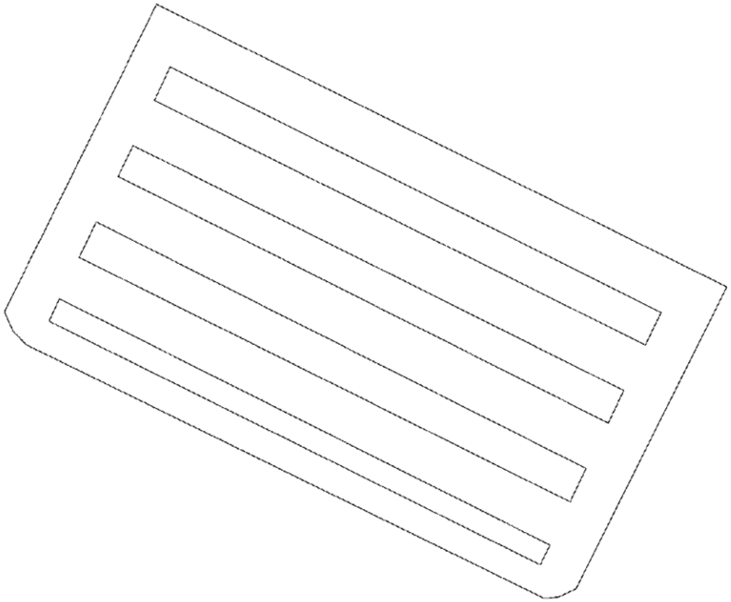
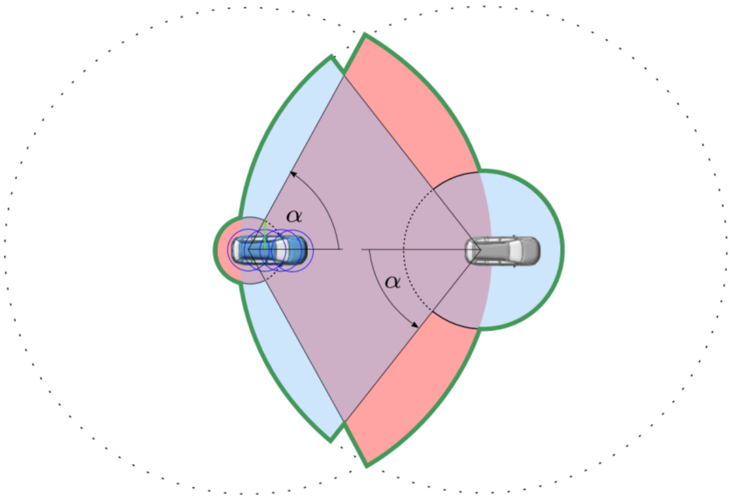


Construction of feasibility polygons



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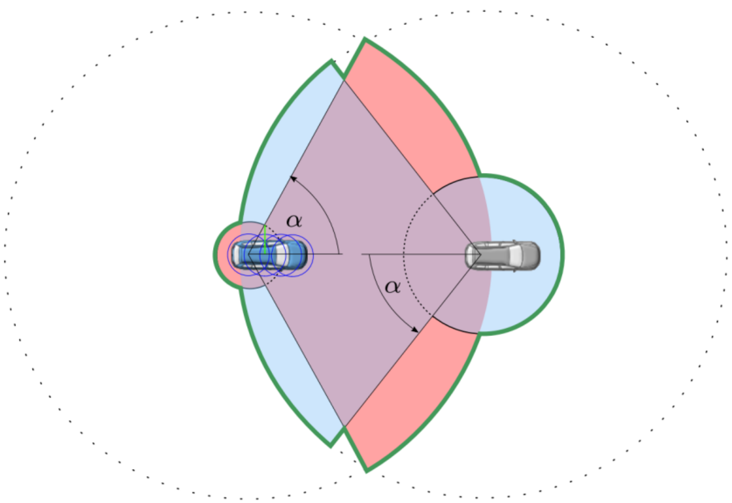
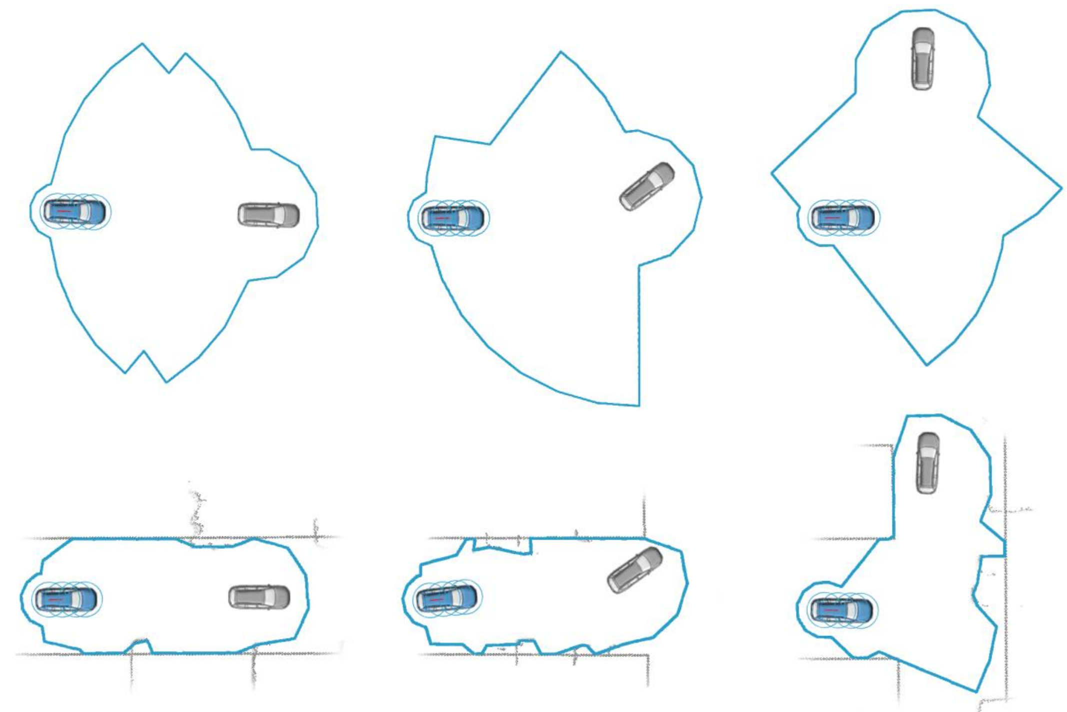
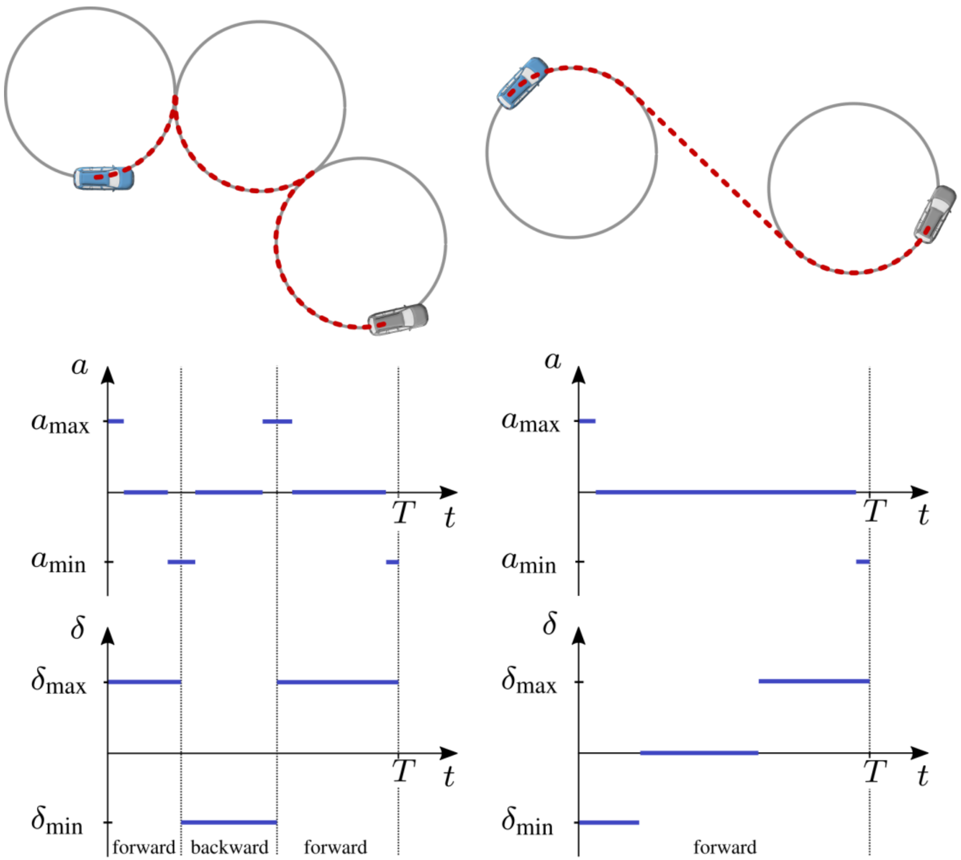
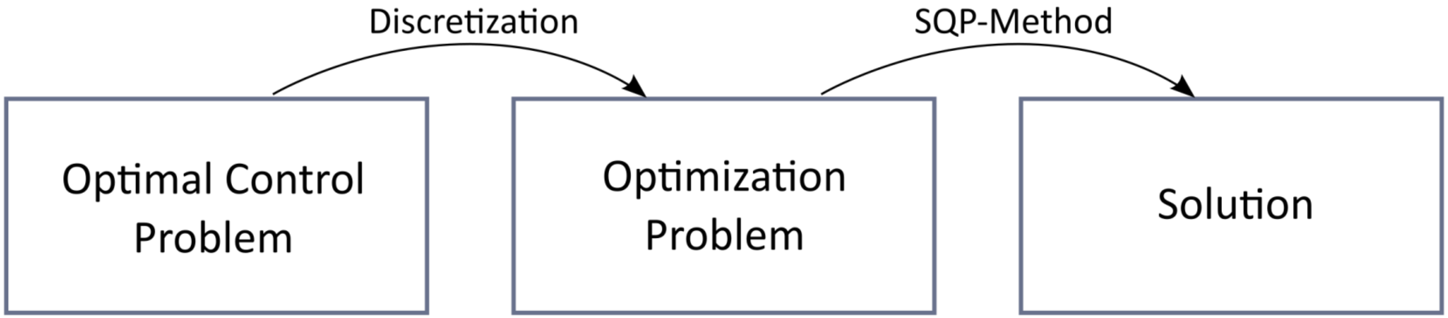




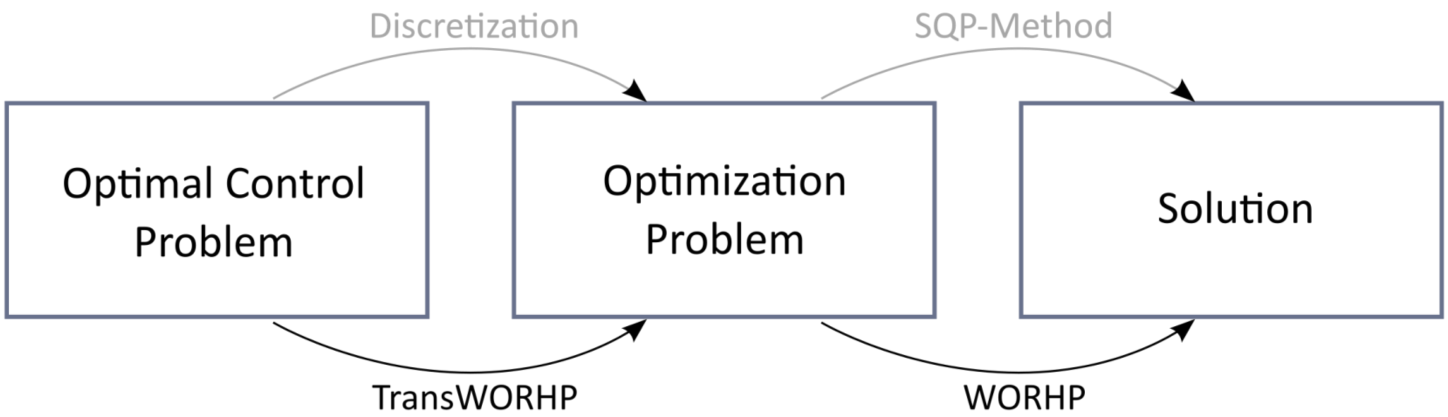
Initial guess based on Reeds-Shepp paths



Solution of the OCP



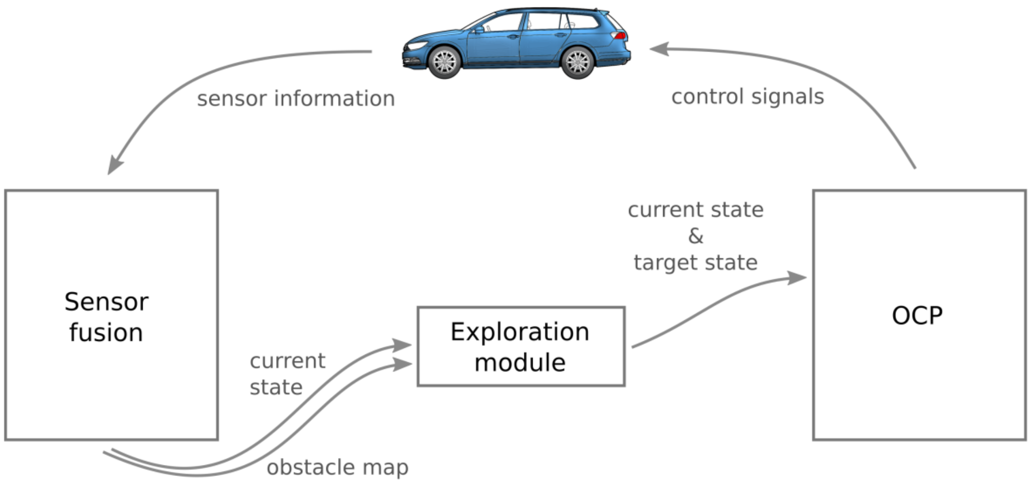
Solution of the OCP



WORHP
We Optimize Really Huge Problems

Control loop (simplified)

Nonlinear model predictive control



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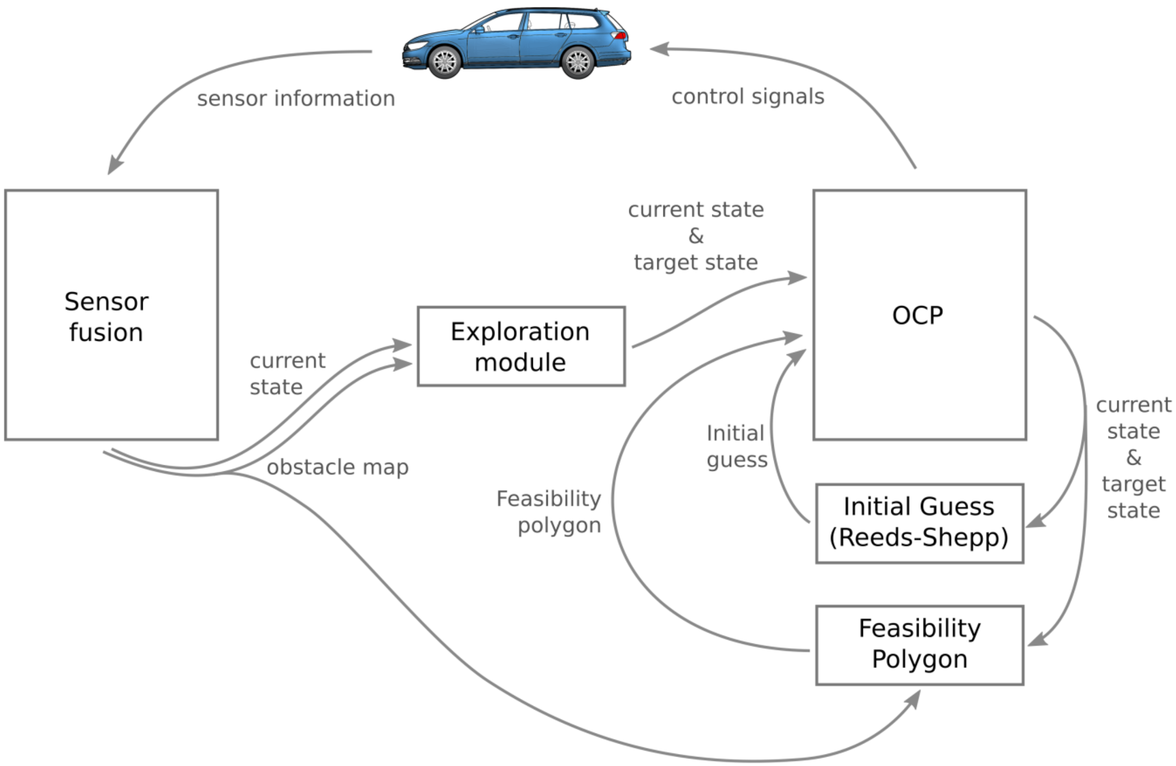
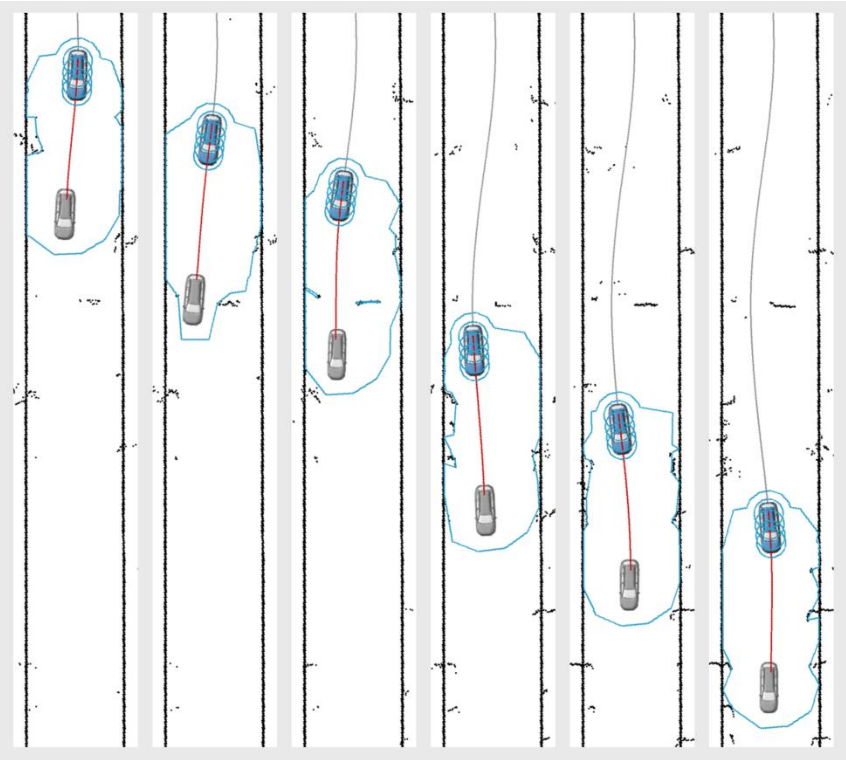
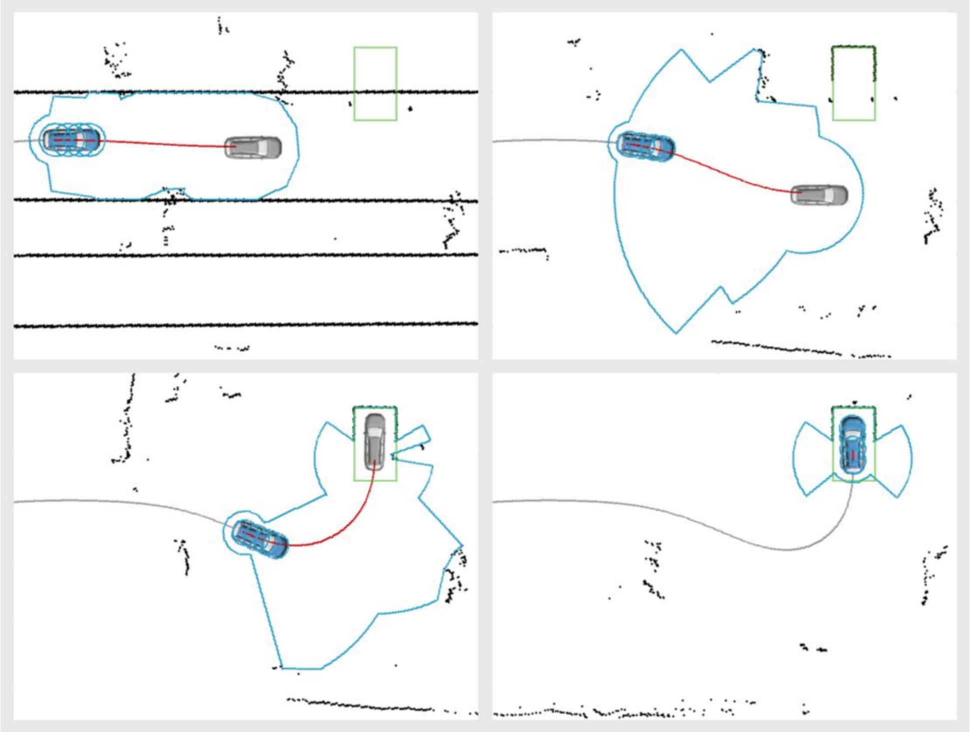


Experiments – Narrowing of the lane



Experiments – Parking



Impressions

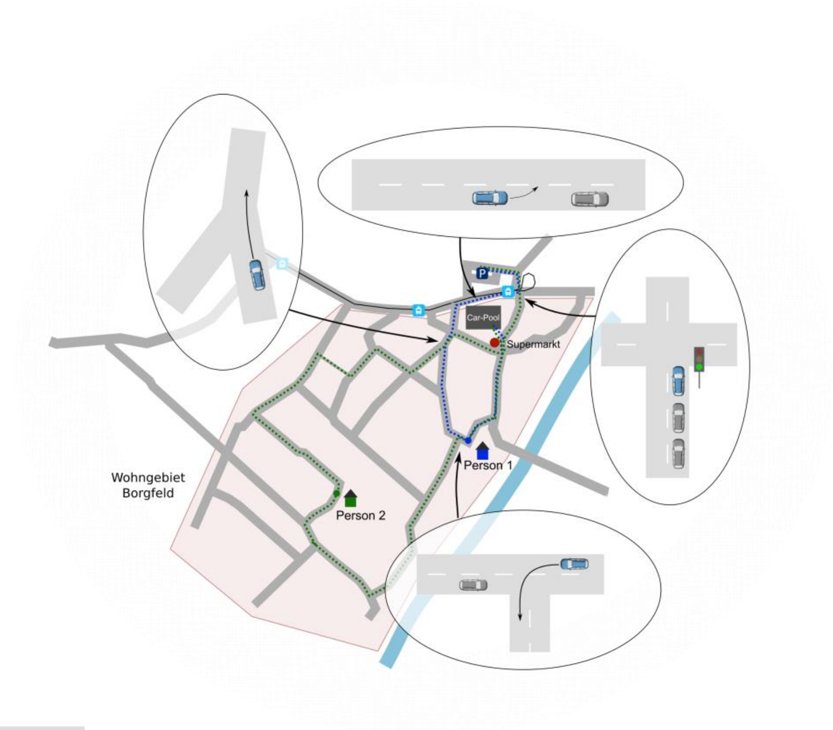
Outlook and future research

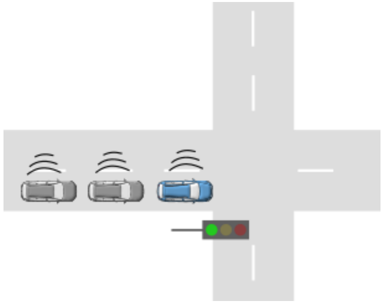
Project AO-Car

Proposal for OPA^{3}L

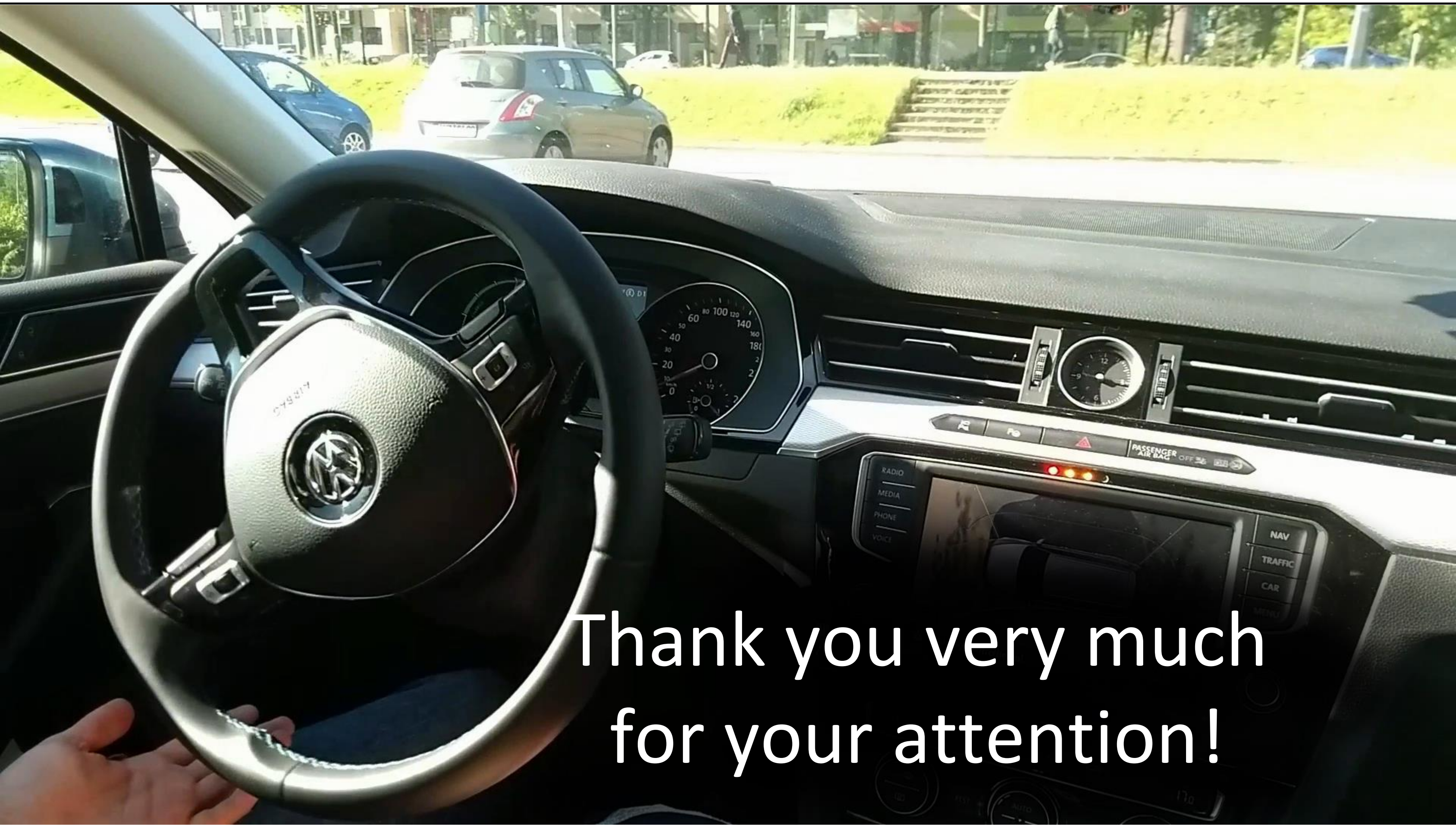
Follow-up project OPA^{3}L

- September 2016
  Start of research project AO-Car
- April 2017
  Completion of vehicle modification
- March 2018
  Final demonstration of AO-Car
- Middle of February 2019
  Start of reasearch project OPA^{3}L
- Beginning of 2023
  Final demonstration of OPA^{3}L





Vehicle on demand concept and cooperative maneuvers



Thank you very much for your attention!

Performance

	Exploration	Narrowing	Parking
Mean computing time			
optimal	33 ms	35 ms	70 ms
non-optimal	104 ms	251 ms	-
total	33 ms	41 ms	70 ms
Standard deviation			
optimal	11 ms	19 ms	49 ms
non-optimal	121 ms	169 ms	-
total	17 ms	49 ms	49 ms
# Computations	2 486	750	480
# Optimal	2 462	725	468
# Not optimal (feasible)	18	9	12
# Not optimal (unacc.)	6	16	0
Rate of unacc. solutions	0.24 %	2.13 %	0 %
# Relax	2	4	12