Trajectory Optimization for Car-Like Vehicles in Structured and Semi-Structured Environments

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Trajectory Optimization

- OCP with an objective function which should be minimized for the prediction horizon *tf*
- Problem is discretized with the direct multiple shooting approach
- Quadratic cost function
- Kinematic single track model is used as system model

Objective Function

$$\min_{\substack{\mathbf{x}_0,\dots,\mathbf{x}_N \\ \mathbf{u}_0,\dots,\mathbf{u}_{N-1}}} \sum_{k=1}^{N} [w_v c_{v,k}^2 + w_p c_{p,k}^2 + w_a c_{a,k}^2 + w_j c_{j_{lat},k}^2 + w_j c_{j,k}^2 + w_\alpha c_{\alpha,k}^2 + w_{stat} c_{stat,k}^2 + w_{dyn} c_{dyn,k}^2] + w_\psi c_{\psi,N}^2.$$

$$c_{stat,k} = c_{s,left,k} + c_{s,right,k}$$

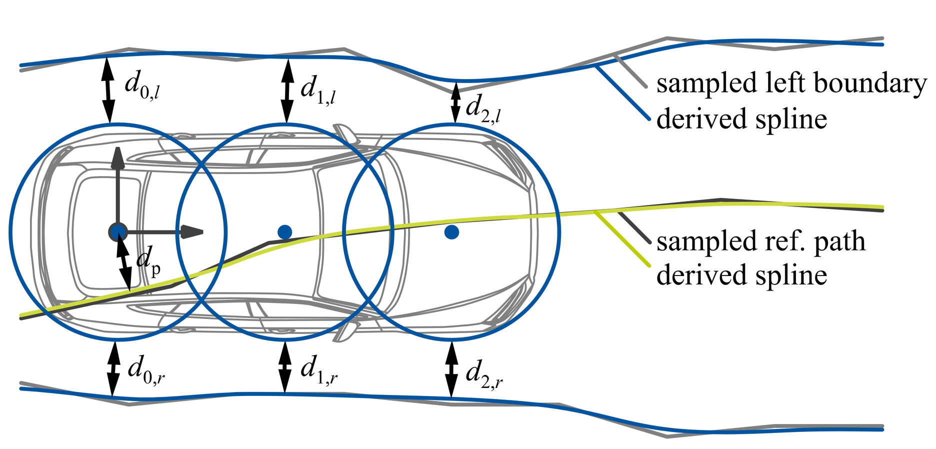
$$c_{s,left,k} = \sum_{n=0}^{2} \begin{cases} 0 & d_{n,left,k} > p_{d,stat} \\ \frac{1+0.1\,v_k}{3\,p_{d,stat}} \left(1 - \frac{d_{n,left,k}}{p_{d,stat}}\right) & d_{n,left,k} \le p_{d,stat} \end{cases}$$

$$c_{v,k} = \frac{v_{ref} - v_k}{\max(v_{ref}, 2.78)} \qquad c_{p,k} = \frac{d_{p,k}}{p_{p,ref}} \qquad c_{a,k} = \frac{\|\mathbf{a}_k\|_2^2}{p_{a,ref}^2}$$

$$c_{j_{lat},k} = \frac{j_{lat,k}}{p_{j,ref}} \qquad c_{j,k} = \frac{j_k}{p_{j,ref}} \qquad c_{\alpha,k} = \frac{\alpha_k}{p_{\alpha,ref}}$$

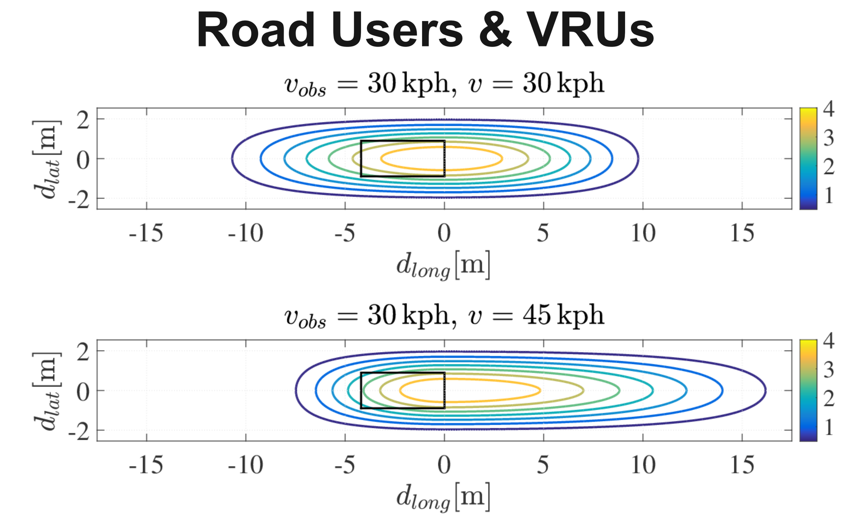
Environment Representation

Static Environment



- Generic interface by using ordered sampled points
- All static obstacles need to be included in the boundaries
- Smoothed cubic spline interpolation
- Vehicle shape approximated by circles

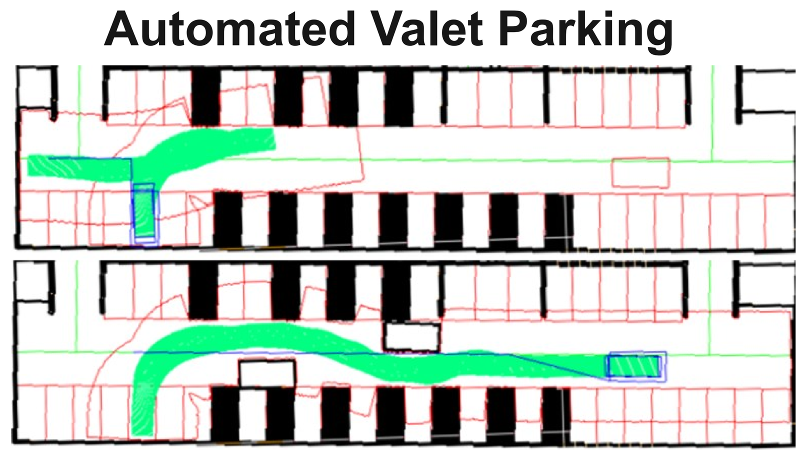
Road Users & VRUs



- Road Users & VRUs are modeled as scalar potentials
- Prediction assuming a constant velocity and is matched to lanes (wherever possible)

Trajectory Reference Information

Automated Valet Parking



- Hybrid A* for path planning (parking & retrieving the vehicle)
- Boundary extraction from grid map
- Path & Boundaries are used as input for the trajectory optimization

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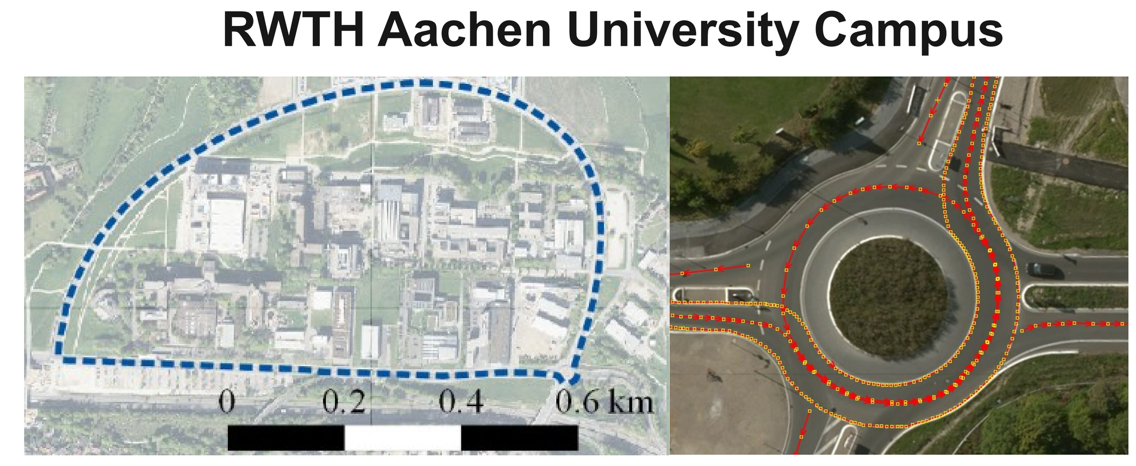
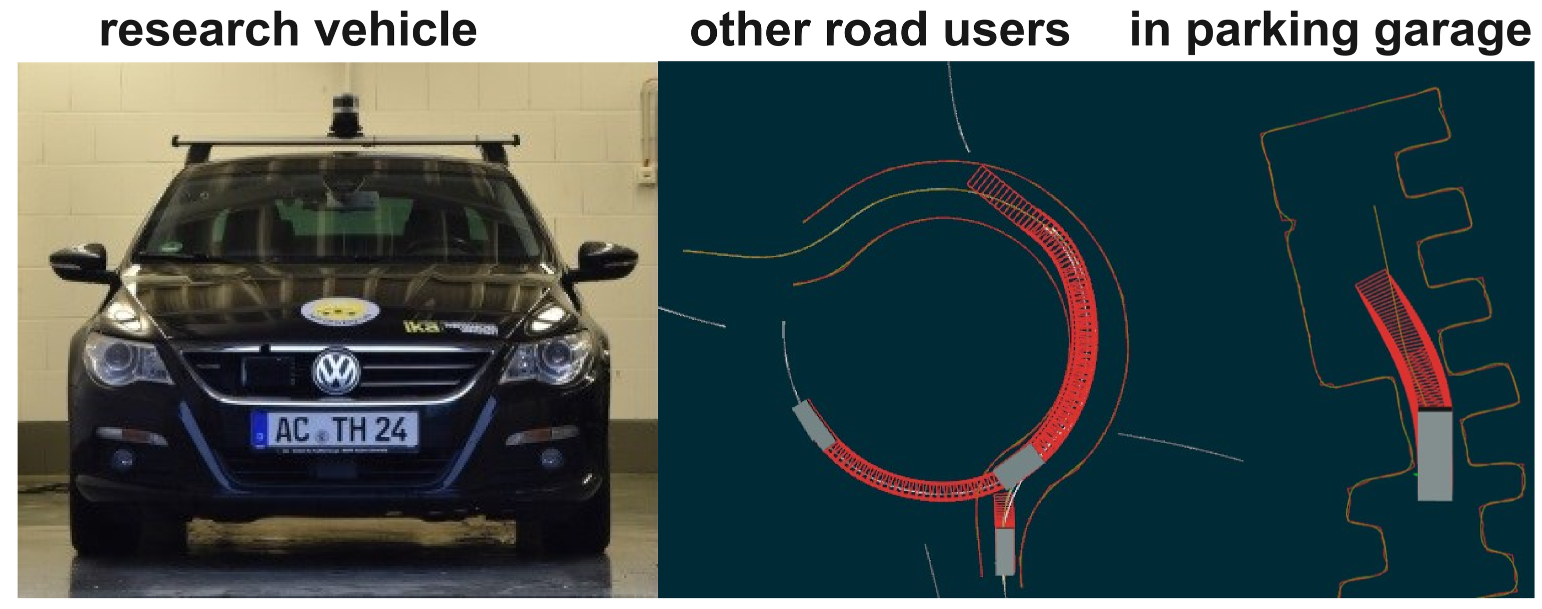


- Urban Driving Scenario on public streets with round-about and other road users
- Reference path and boundaries are derived from map data
- Map data is created with aerial imagery

Implementation & Testing

- Implementation of OCP in C++11
  - Prediction horizon *tf* up to 8.0 s with 0.1 s or 0.2 s steps
  - Single-threaded without dynamic memory allocations
  - Planning frequency set to 10 Hz
- *ACADO* Toolkit for code generation
  - *qpOases* used as solver
  - tailored C-code for integrating the system model and solving the discretized optimization problem
  - The partial derivatives of the objective function are expressed analytically and are passed as custom C-function
- Tested in ika's automated research vehicle for both scenarios

ika's automated research vehicle | **roundabout with other road users** | **narrow passage in parking garage**



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