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A real-time search-based motion planning framework with risk assessment for urban environments

Kailin TONG

Senior Researcher Control Systems

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Content

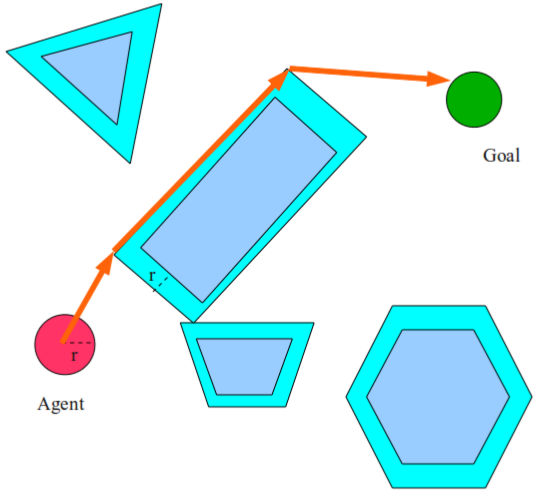
- **Background**
- **Our proposed motion planning framework**
- **Evaluation**
- **Key takeaways and outlook**

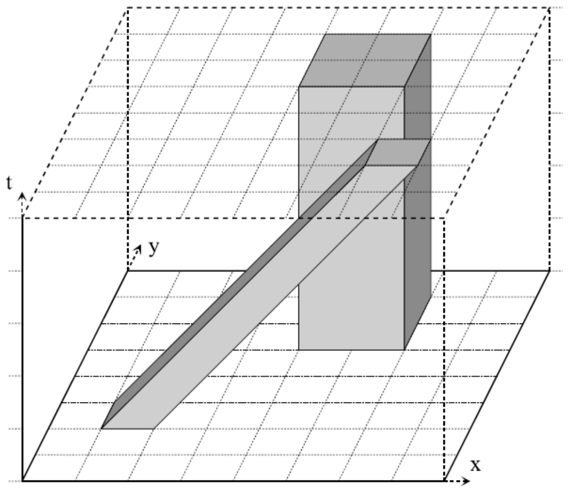
Background: Motion Planning Problem

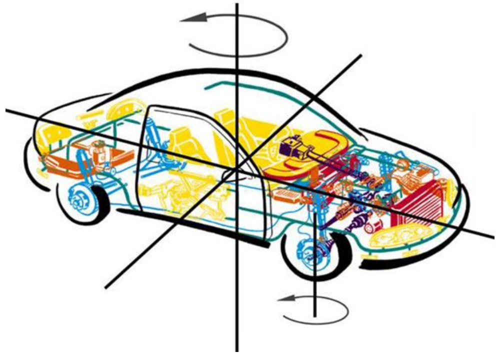
Generating a plan from A to B,

but with…

- High dimension
- Computation time limit
- Non-holonomic constraints
- Uncertainty and noises
- Scenarios: human interaction, safety critical, traffic rules, perception/prediction error, occlusion…

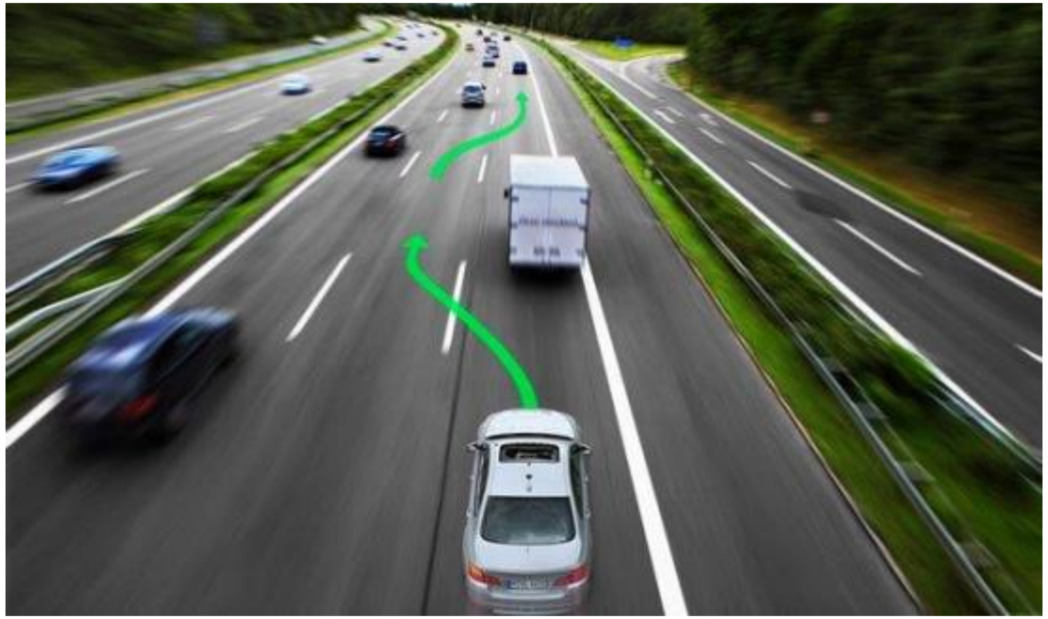






Two categories

- **Rule-based**: Graph search, Sampling-based, interpolation/roll-out, Optimization…
- **Learning-based** (end-to-end)



Background: Related work

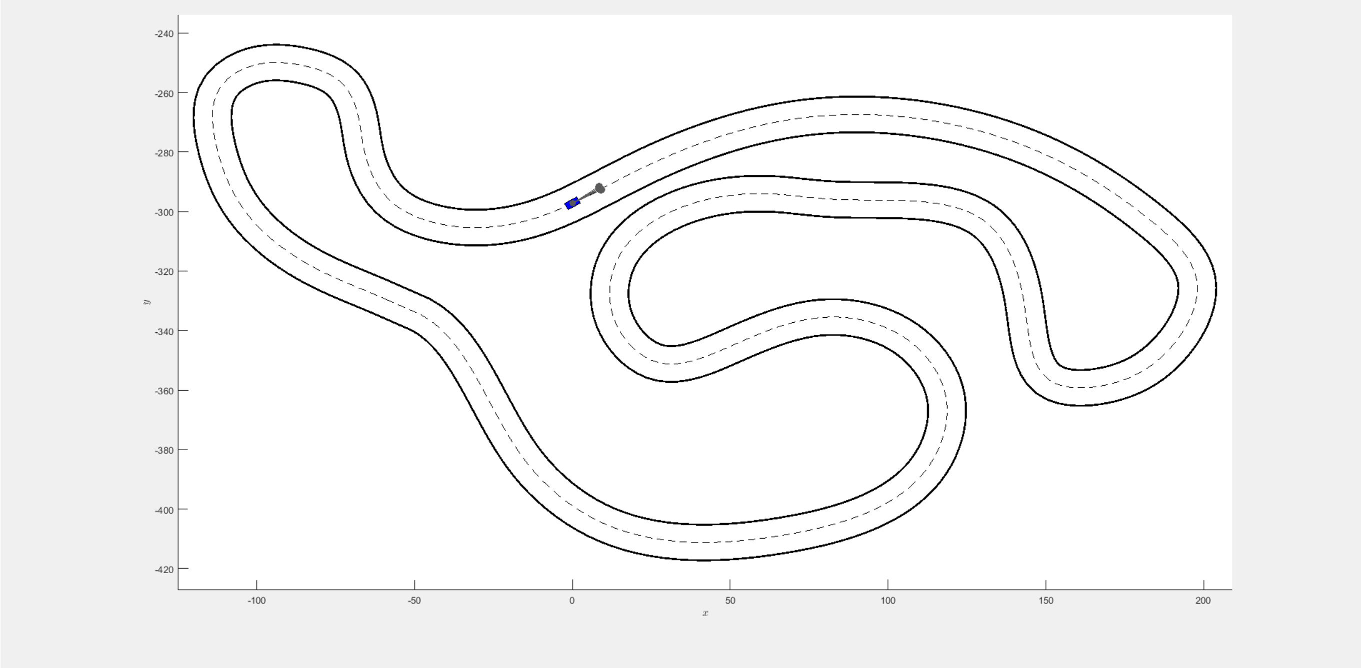
Graph search

Approach: discretize the state space into a graph

Pros: A general approach.

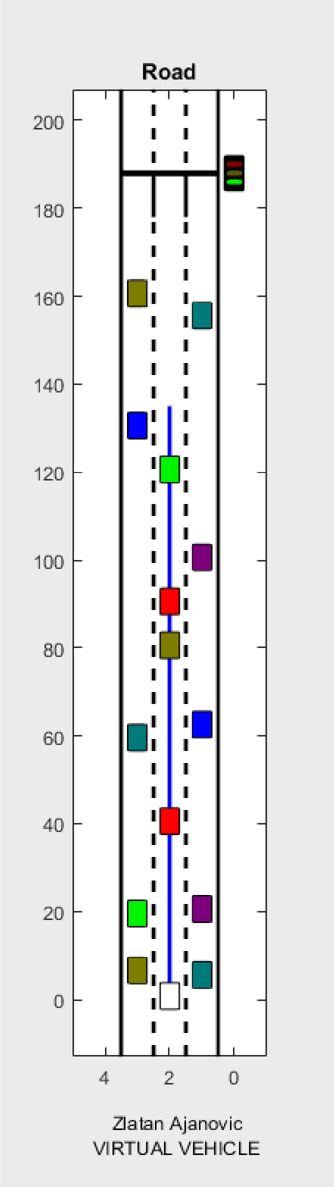
Cons: Trade-off between discretization and computation time
(typically computation time more than 100 ms)

Automated performance driving



Ajanovic, Z., Lacevic, B., Shyrokau, B., Stolz, M., Horn, M., 2018 October. Search-based optimal motion planning for automated driving. In Intelligent Robots and Systems, 2018. IROS 2018

Automated urban driving



Ajanovic, Z., Regolin, E., Stettinger, G., Horn, M., A. Ferrara, 2019. Search-Based Motion Planning for Performance Autonomous Driving. In IAVSD Vehicles on Road and Tracks 2019. IAVSD.

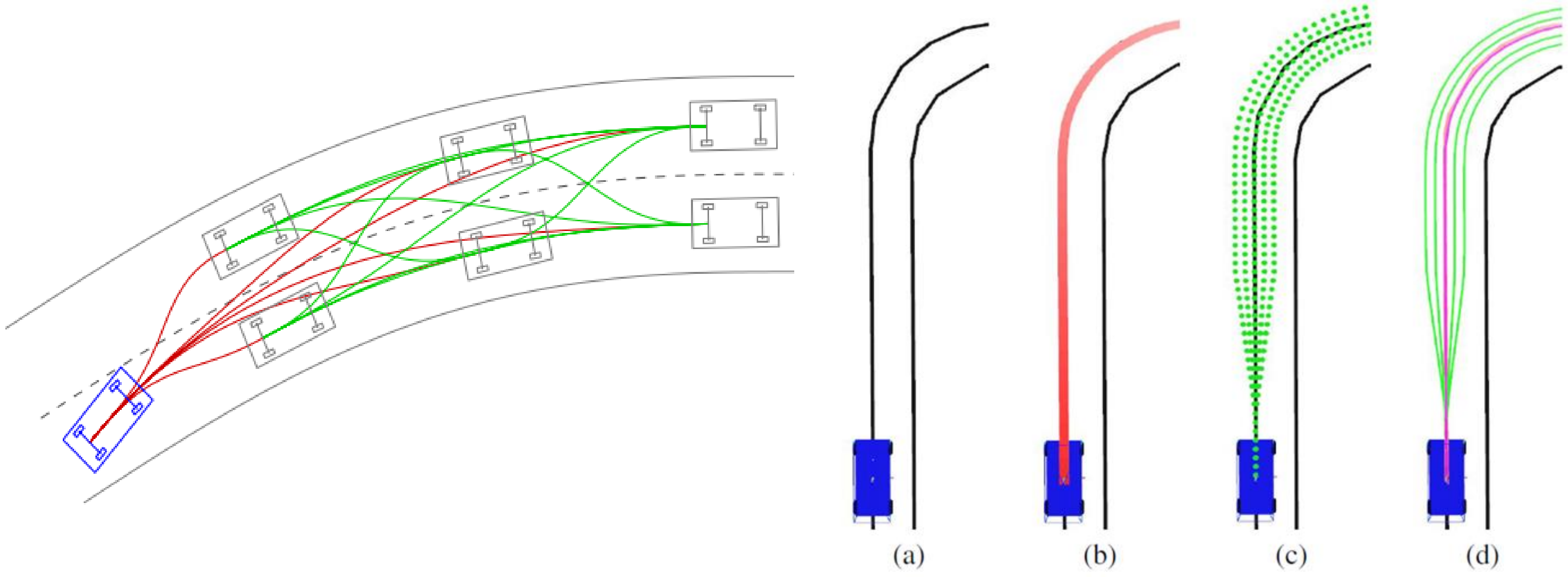
Background: Related work

Interpolation / roll-out

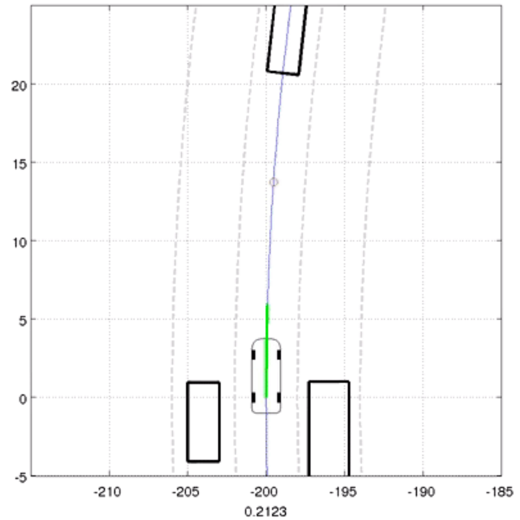
Approach: use geometric curves to represent vehicle motion

Pros: Suitable for structured road, simple and efficient

Cons: Sub-optimal, limited choices, discretization problem



Frenet Frame Planner

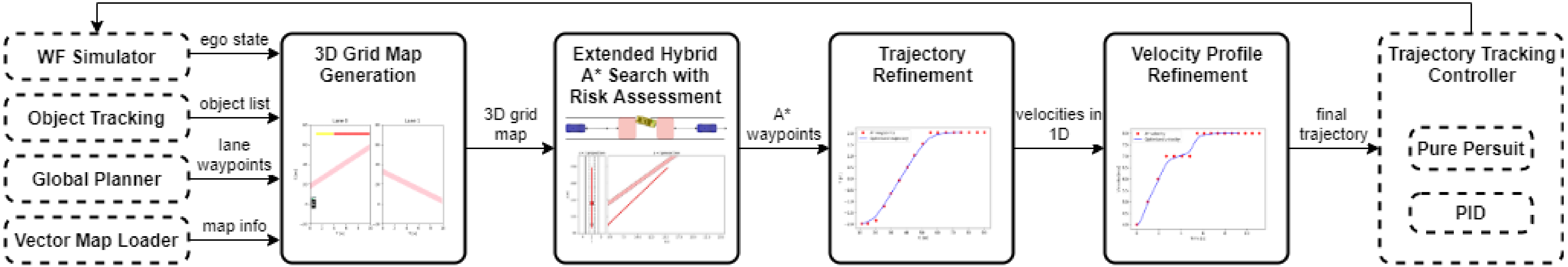


Werling, Moritz, et al. "Optimal trajectory generation for dynamic street scenarios in a frenet frame." *2010 IEEE international conference on robotics and automation*. IEEE, 2010.

Benchmark -- Open Planner (Autoware)

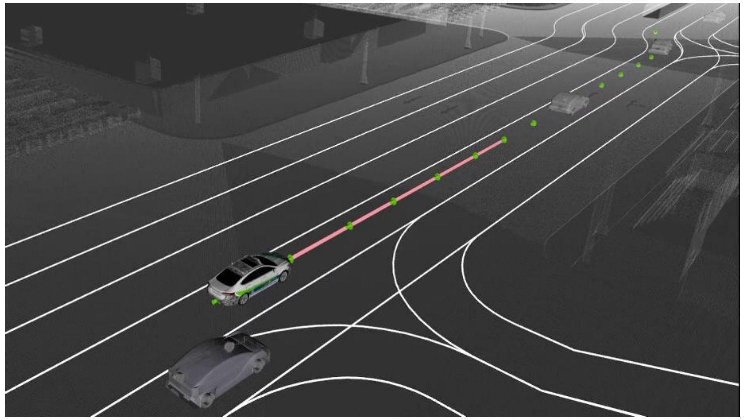
Darweesh, Hatem, et al. "Open source integrated planner for autonomous navigation in highly dynamic environments." *Journal of Robotics and Mechatronics* 29.4 (2017): 668-684.

Proposed motion planning framework



Main Contributions

- A computationally efficient framework (worst case 55 ms computation time)
- A* search which integrates risk assessment heuristics
- Validation in realistic simulated scenarios



Proposed motion planning framework

3D grid map Generation

Inputs

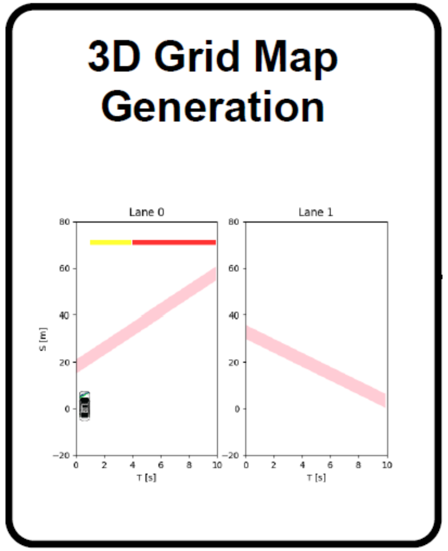
- ego state, object list, lane waypoints, map info

Outputs

- 3D grid map a triple $(s, t, l) \in [s_{min}, s_{max}] \times [0, t_{max}] \times \{0, \cdots, N_l\}$

Approach

- Adding a time dimension to a 2D space
- Projection into Frenet coordinate system
- Constant speed prediction of moving objects



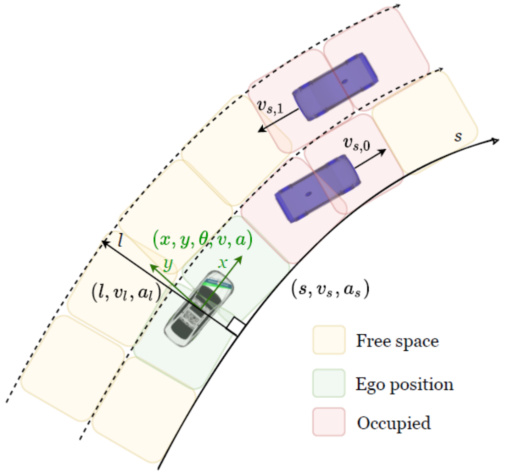
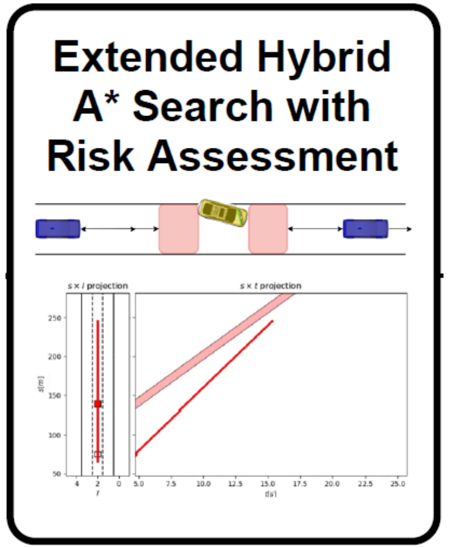


Fig. 3: Illustration of motion planning in a Frenet frame. The vehicle states in a Cartesian frame include (x, y, θ, v, a) , which denote vehicle position, heading, velocity, and acceleration respectively. They are projected onto the driving reference line for motion decoupling. (l, v_l, a_l) represent lateral distance, velocity and acceleration respectively, while (s, v_s, a_s) represent longitudinal quantities. $v_{s,0}$ and $v_{s,1}$ are the longitudinal velocity of tracked object 0 and 1 respectively.

Proposed motion planning framework



Risk Assessment

Time-to-collision is used to model collision possibilities.

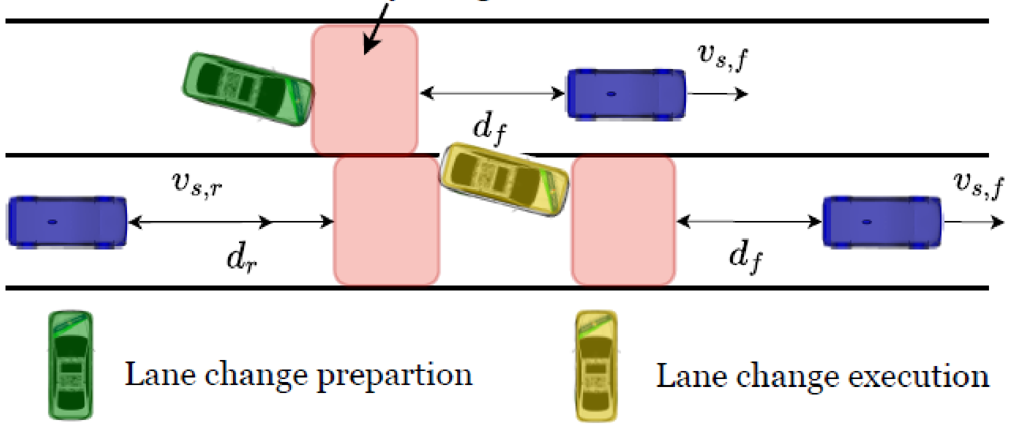
$$TTC_i = \begin{cases} \frac{d_{s,i}-MSM}{v_{s,i}-v_{s,j}} & \frac{d_{s,i}-MSM}{v_{s,i}-v_{s,j}} > 0 \\ +\infty & \text{otherwise} \end{cases}$$

Collision risk is defined as

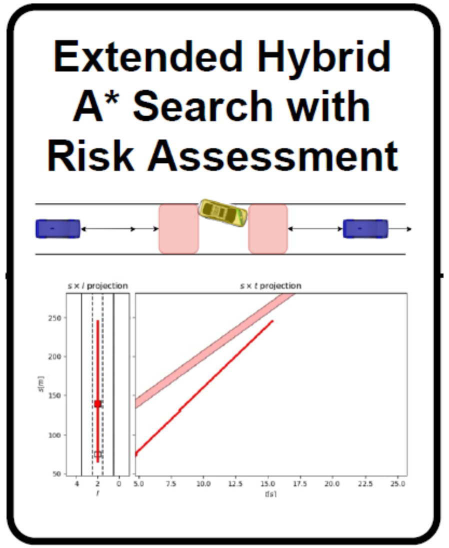
$$R(i) = e^{-w(TTC_i - TTC_{safe})}$$

Collision risk is used as heuristics in A* search

Risk assessment for lane change



Proposed motion planning framework



Extended Hybrid A* Search with Risk Assessment

Inputs; 3D grid map

Outputs: A* waypoints

Approach

- Search space: (t, s, l, v_s, dir) dir ∈ {left, right, forward}.
- Cost function: $cost = w_1(v_s - v_d)^2 \Delta T + w_2 \bar{a}_s{}^2 \Delta T$

$$v_d = min\{v_c, \sqrt{a_{lat}^{des}/k(s)}\}$$

- Heuristic value function:

Admissible heuristics

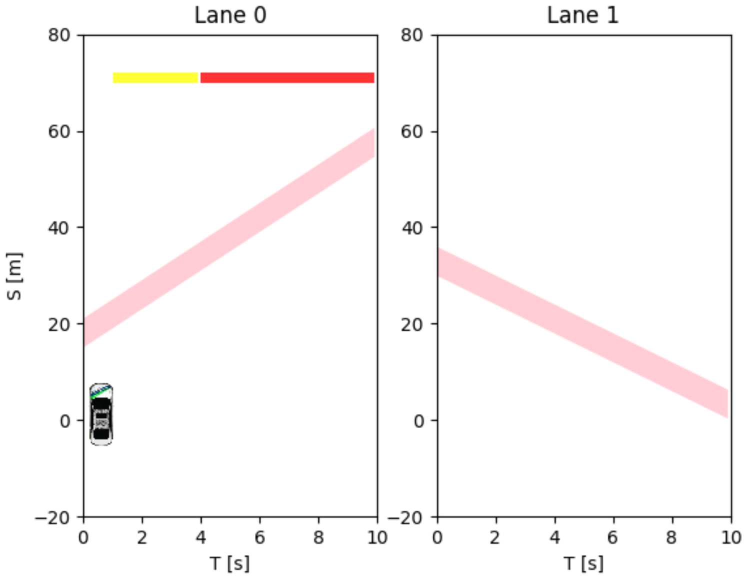
$$h_a(n) = \frac{2w_1(v_s - v_d)^2}{\sqrt{12w_1/w_2}} + \frac{\sqrt{3}w_1^2(v_s - v_d)^2}{3w_2(w_1/w_2)^{\frac{3}{2}}} \quad (w_1, w_2 \neq 0)$$

Ego Collision risk — Follower Collision risk

Risk heuristics

$$h_t(n) = \begin{cases} R(e) + R(i) + \varepsilon\,|l - l_d| & \text{LC execution} \\ R(e) + \varepsilon\,|l - l_d| & \text{otherwise} \end{cases}$$

Lane change cost



3D grid map

Trajectory Refinement

Inputs

- A* waypoints

Outputs

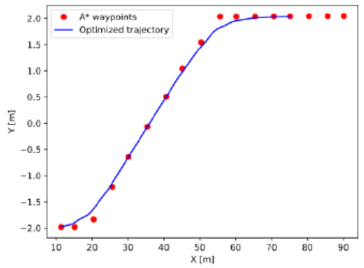
- Refined waypoints

Approach

- minimal jerk trajectory generation
- Closed-form solution

$$\mathbf{d_P}^* = -R_{PP}^{-1} R_{FP}^{T} \mathbf{d_F}$$

Trajectory Refinement



Minimal jerk trajectory optimization

$$\min_{\mathbf{p}_1,\dots,\mathbf{p}_M} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix}^T \begin{bmatrix} Q_1(T_0) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & Q_M(T_M) \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix}$$

$$s.t. \quad A_{eq} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix} = \begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_M \end{bmatrix}$$

Proposed motion planning framework

Velocity Profile Refinement

Inputs

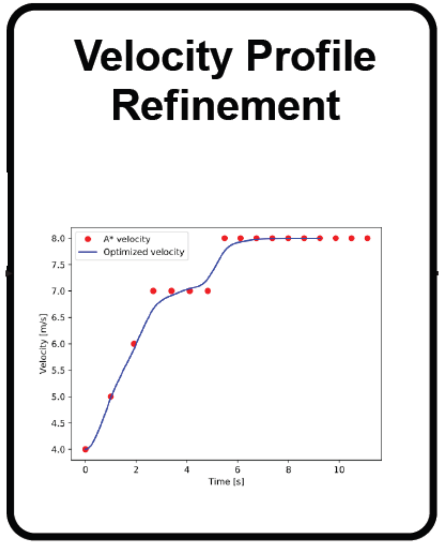
- velocities in1D

Outputs

- final trajectory

Approach

- minimal jerk velocity profile generation
- only the number of coefficients and derivatives are different



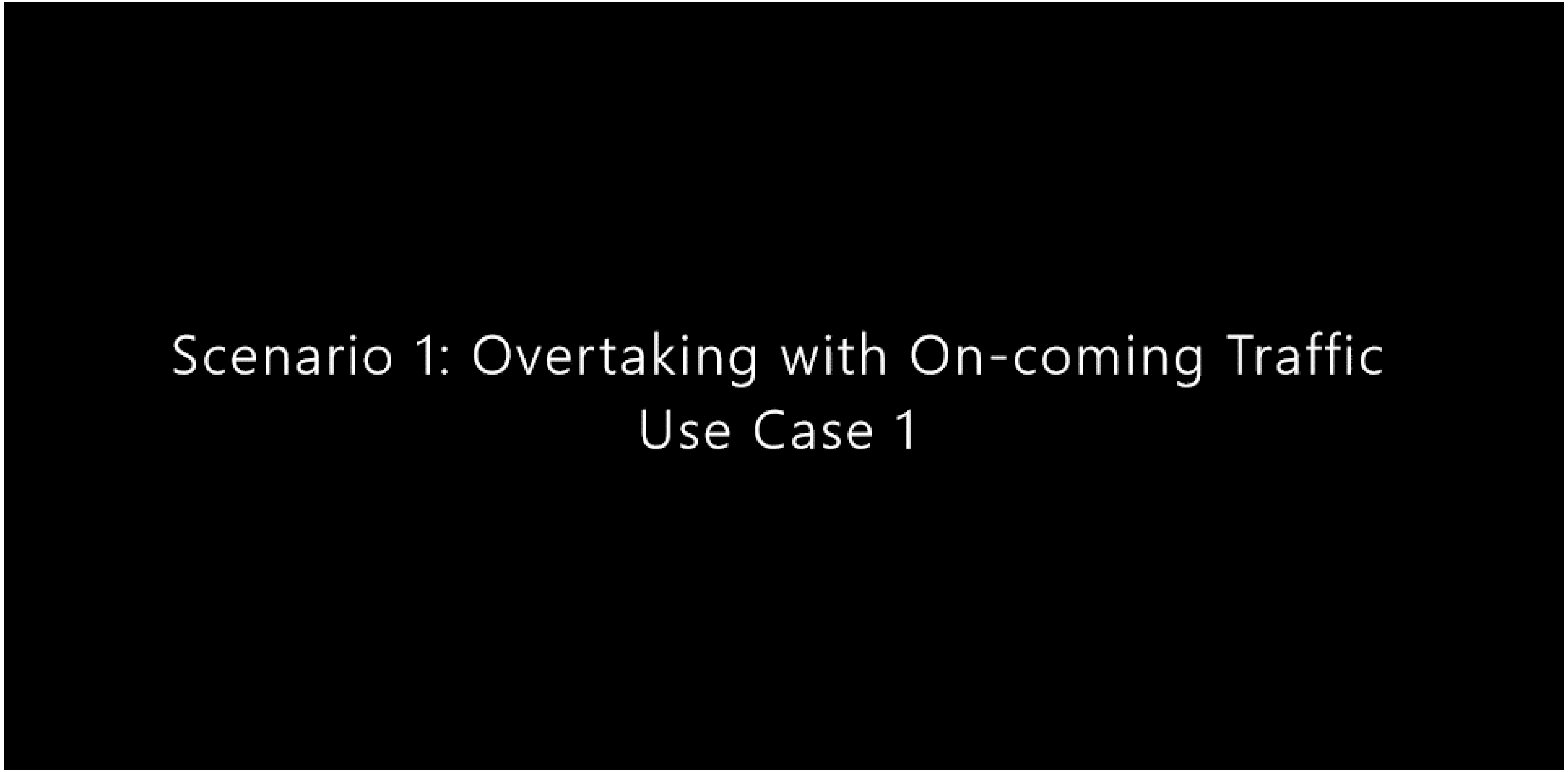
Minimal jerk velocity profile optimization

$$\min_{\mathbf{p}_1,\dots,\mathbf{p}_M} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix}^T \begin{bmatrix} Q_1(T_0) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & Q_M(T_M) \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix}$$

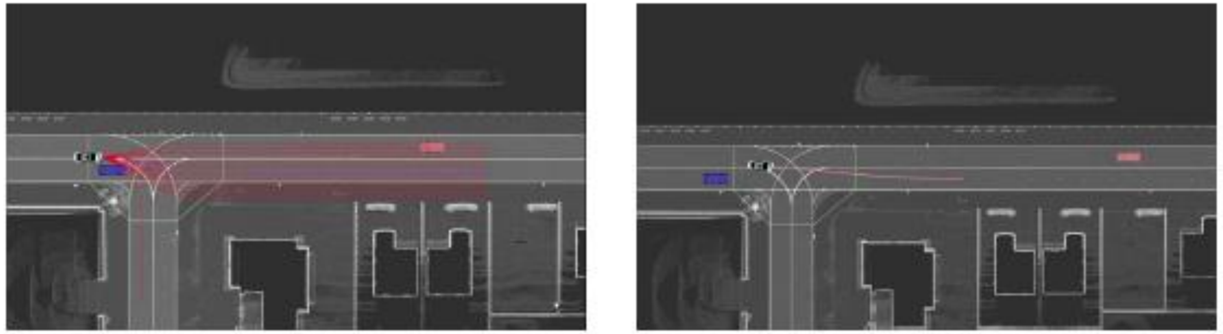
$$s.t. \quad A_{eq} \begin{bmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_M \end{bmatrix} = \begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_M \end{bmatrix}$$

Evaluation

WF Simulator of Autoware + internally developed interface – ViFWare

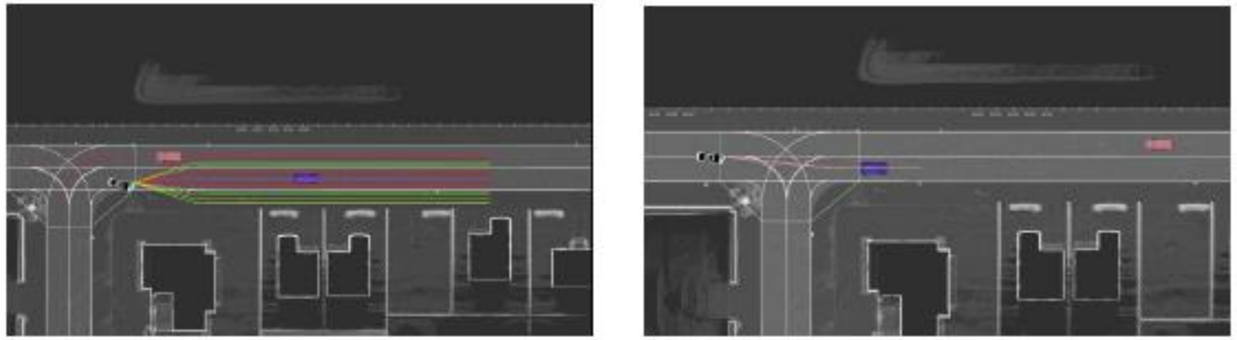


Evaluation



(a) OpenPlanner (b) Our approach

Fig. 8: Use Case 1: Overtaking with Limited Time Window



(a) OpenPlanner (b) Our approach

Fig. 9: Use Case 2: Giving Right of Way

TABLE I: Comparison of results in a 450 m route

Planner	DTC_{min} (m)	TTC_{min} (s)	$\lvert\kappa\rvert_{max}$ (m^{-1})	$\bar{v}$ (m/s)	$\bar{e}$ (m)	T_{worst} (ms)
Ours	3.97	4.90	0.04	7.22	0.12	55.0 [1]
Open Planner	5.68	4.10	0.11	4.33	0.19	< 100 [2]

[1] Time consists of: search time (54.6 ms), trajectory refinement (0.3 ms), velocity profile refinement (0.1 ms) and 3D grid map update time (0.1 ms).
[2] The estimated time is from [6].

Implementation:
C++ based on Robot Operation System (ROS)
Hardware:
a computer equipped with an Intel Core i7-9700 CPU.

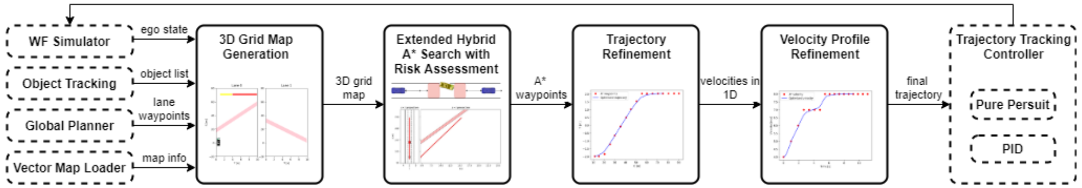
Key takeaways and outlook

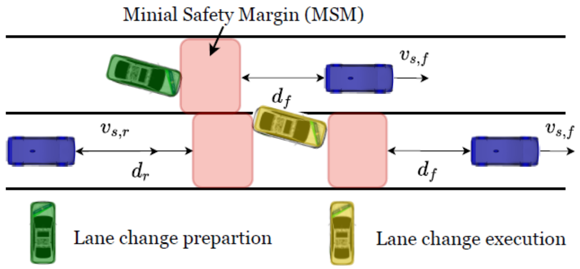
Key takeaways

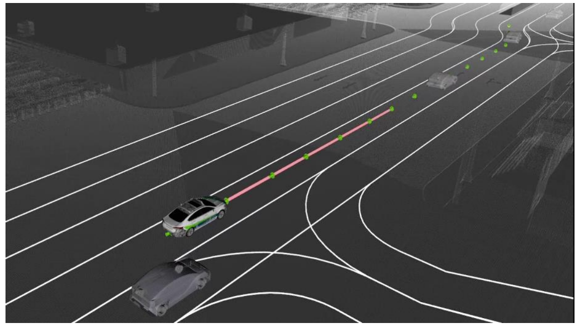
- A computationally efficient framework (worst case 55 ms computation time)
- A* search which integrates risk assessment heuristics
- Validation in realistic simulated scenarios

Outlook

- Validation with our automated driving demonstrator on public road







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Kailin Tong

kailin.tong@v2c2,at

Senior Researcher Control Systems

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