POLITECNICO
MILANO 1863

based on Ulrich Schwesinger lecture on

MOTION PLANNING FOR AUTOMATED CARS

Unmanned autonomous vehicles in air land and sea

Some relevant examples from the DARPA Urban Challenge

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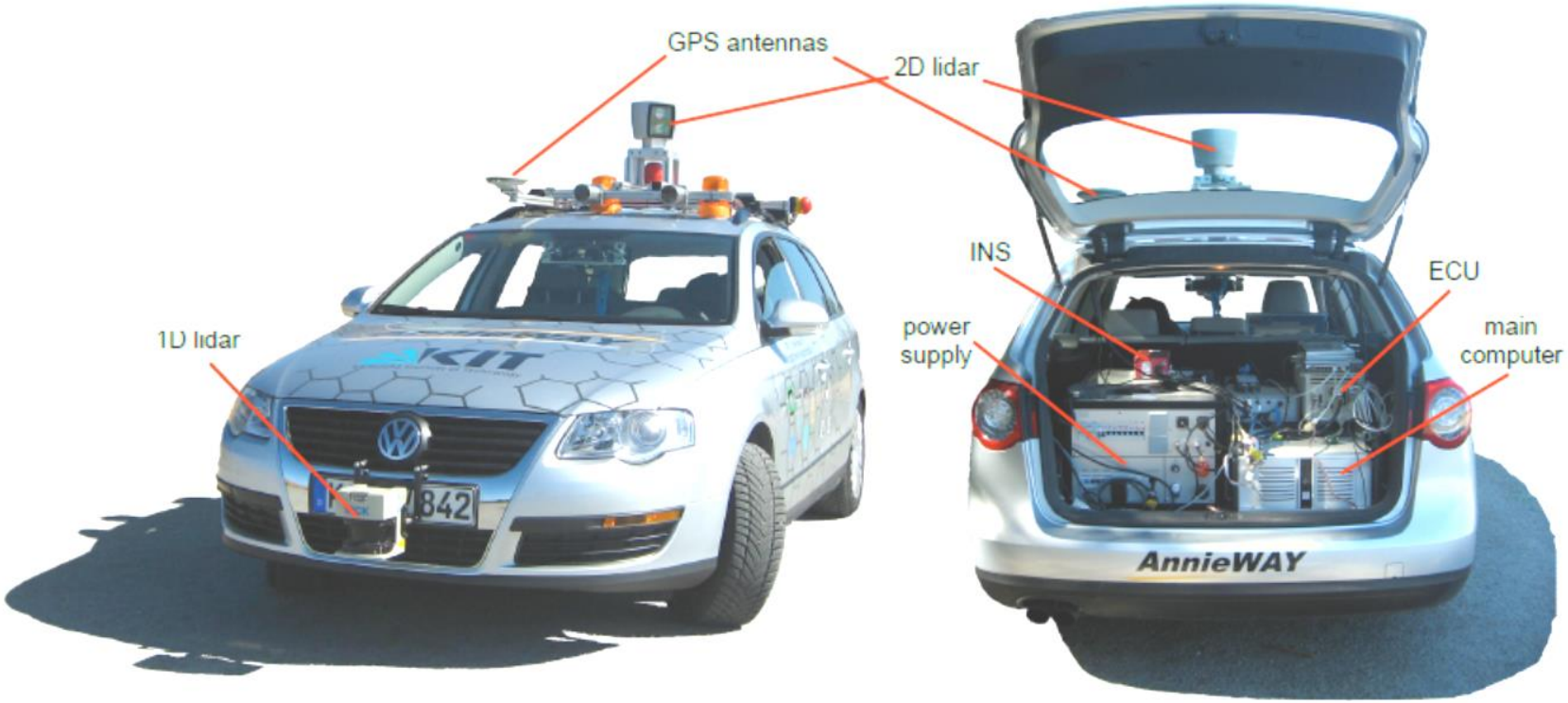
The DARBA Urban Challenge 2007

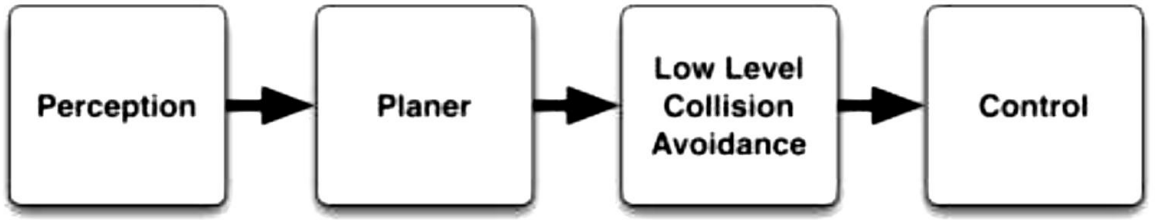
Annieway
Karlsruhe/Munich
not finished

Boss
Carnegie Mellon
1st place

Junior
Stanford
2nd place

Team Annieway (Karlsruhe/Munich)



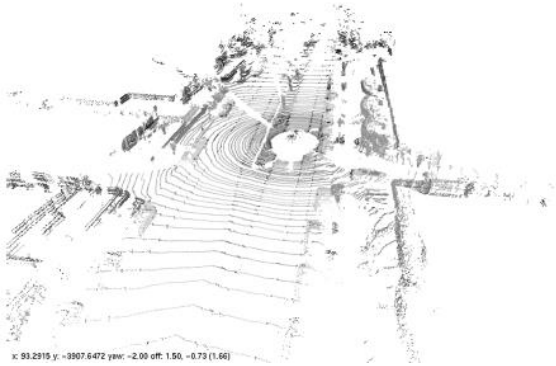


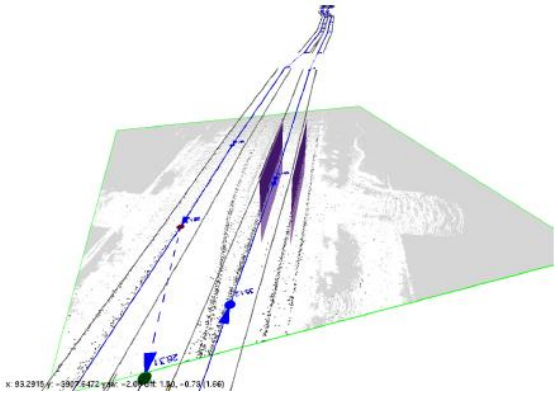
T. Gindele and D. Jagszent, "Design of the planner of Team AnnieWAY's autonomous vehicle used in the DARPA Urban Challenge 2007," *Intelligent Vehicle Symposium*, 2008

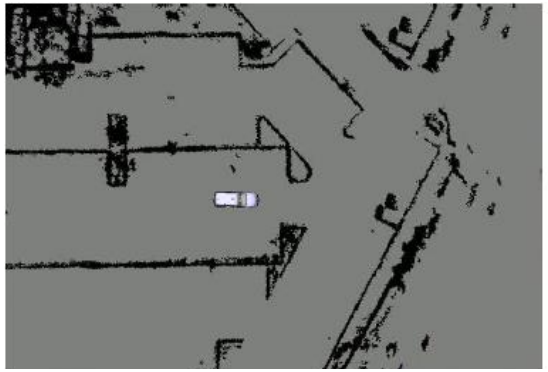
Team Annieway (Karlsruhe/Munich)

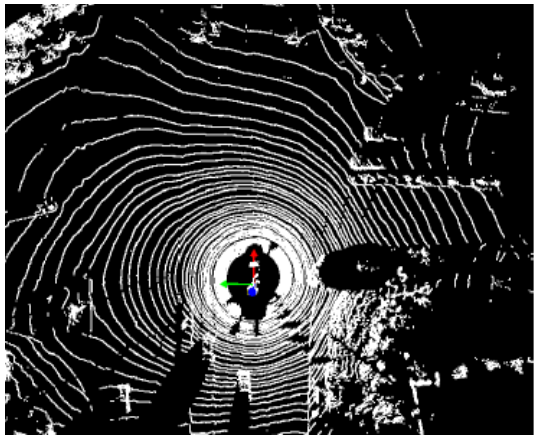
Perception performs several tasks simultaneously

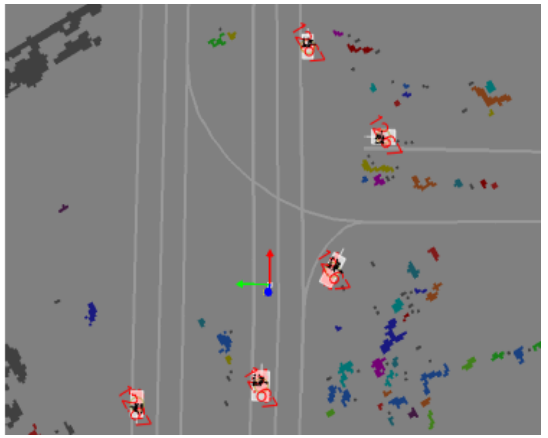
- Environment mapping through 3D lidar (Occupancy Grid mapping)
- Tracking of dynamic objects (Occupancy grid and Kalman Filter)
- Line marker detection (Combined lidar range and intensity)









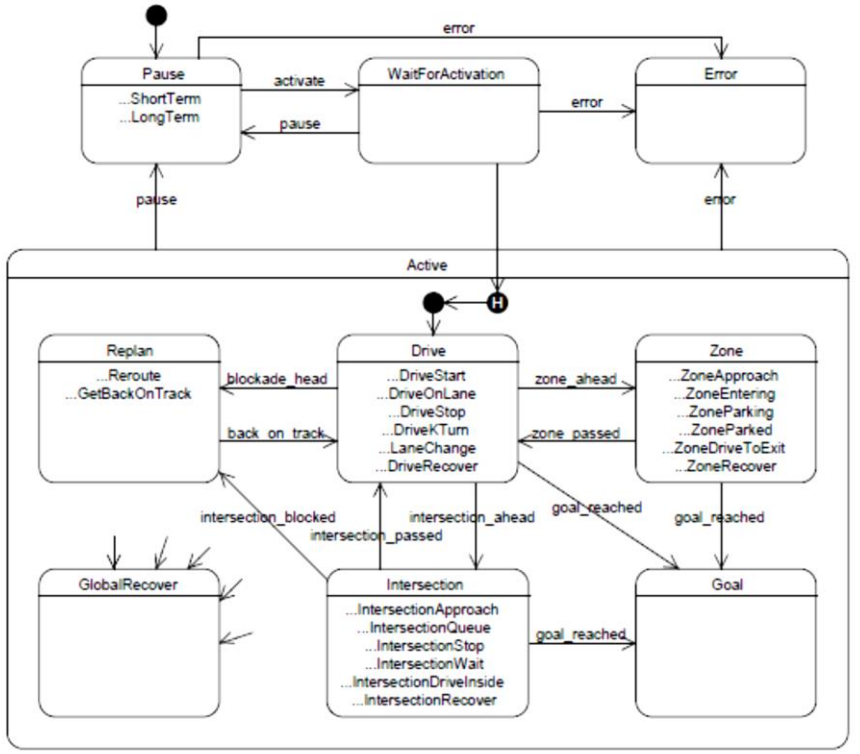


Team Annieway (Karlsruhe/Munich)

High-level state machine with several states

- Regular driving on lanes
- Turning at intersections with oncoming traffic
- Lane changing maneuvers
- Vehicle following and passing
- Following order of precedence at 4-way stops
- Merging into moving traffic

Mission planning by A* on roadgraph

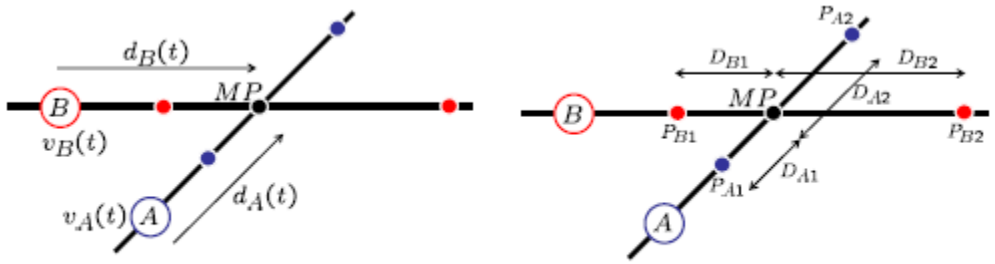


T. Gindele and D. Jagszent, "Design of the planner of Team AnnieWAY's autonomous vehicle used in the DARPA Urban Challenge 2007," *Intelligent Vehicle Symposium*, 2008

Team Annieway (Karlsruhe/Munich)

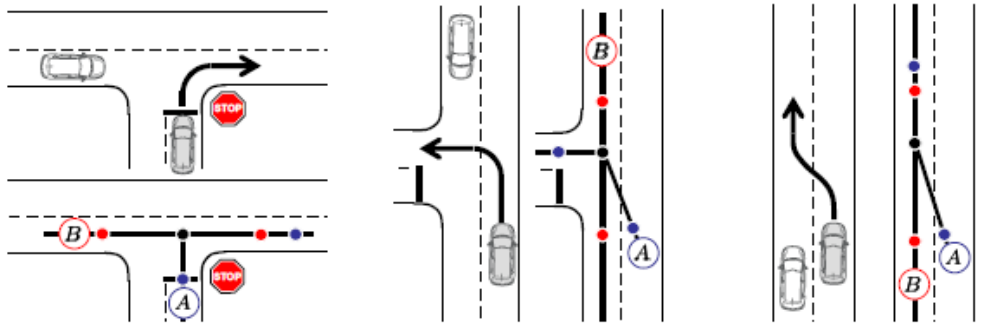
Situational awareness module enhances capabilities of the state-machine

- Enforce spatial and temporal gap to moving objects along lanes
- Simple feasibility check of maneuver



Assumptions:

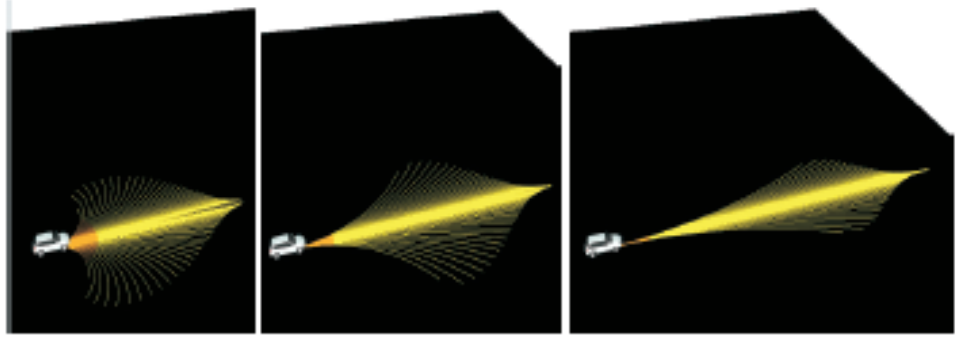
- Constant velocity of other traffic participants
- Constant acceleration of ego vehicle until desired velocity



Team Annieway (Karlsruhe/Munich)

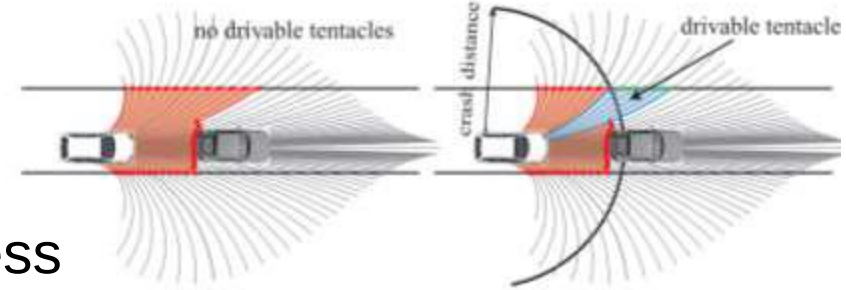
Pre-computed sets of motion primitives for different initial velocities

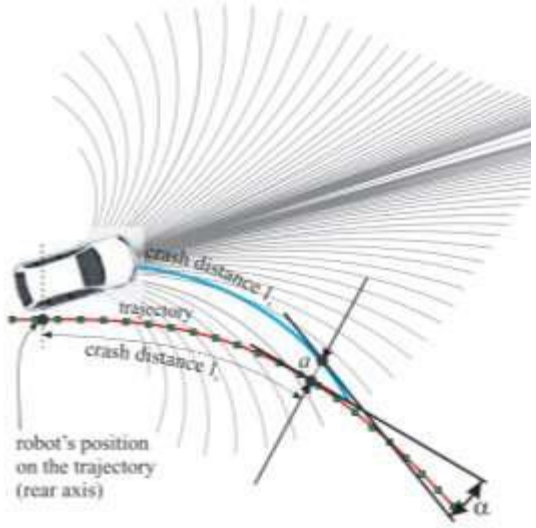
- Constant steering angles circular arcs (Dynamic Window Approach)
- Arc lengths shorter for high curvatures to avoid endpoints behind vehicle



Cost Function:

- Clearance: distance to closest obstacle along trajectory
- Flatness: averaged terrain flatness over support area
- Trajectory: alignment of trajectory with a reference path



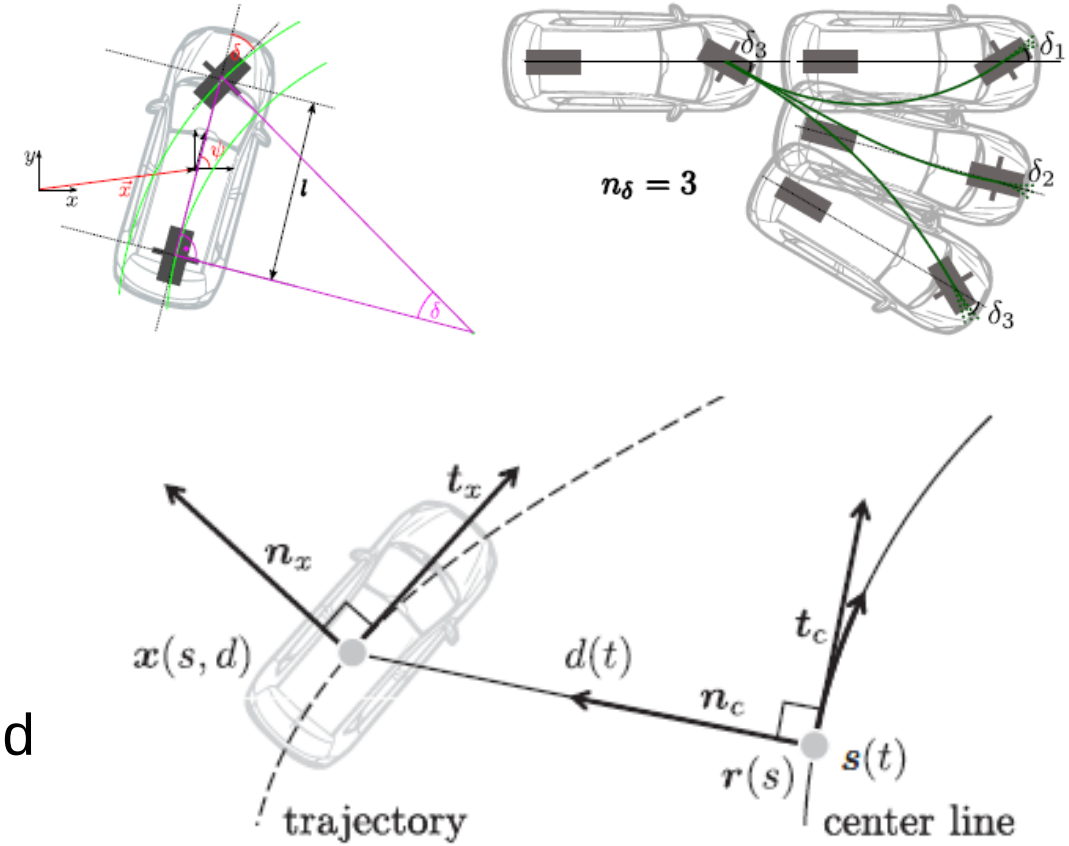


Team Annieway (Karlsruhe/Munich)

Trajectory planning is performed on a search graph

- A* search algorithm
- Single track motion primitives
- Two heuristic combined
  - Kinematic constraints (close)
  - Voronoi diagram (far)

Plannig assume two independent integrators for the longitudinal and lateral control and generates two sets of trajectories then merged



M. Werling, et al., "Optimal trajectories for time-critical street scenarios using discretized terminal manifolds", IJRR, Dec. 2011.

Team Annieway (Karlsruhe/Munich)

Team AnnieWay

2007

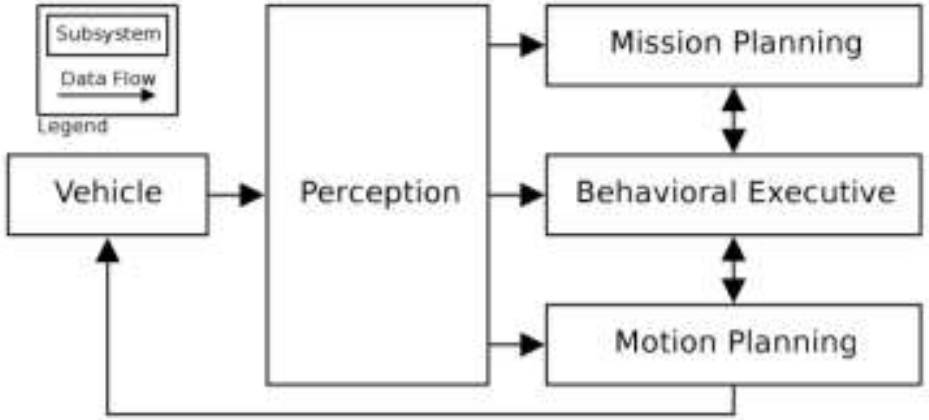
Visualization of AnnieWAY's Autonomous Run
in the DARPA Urban Challenge Final

http://his.anthropomatik.kit.edu

Team Boss (Carnegie Mellon)

Team Boss uses and hybrid architecture too

- Mission Planning
  - In charge of computing expected time to reach the waypoints
- Behavioral Executive
  - High-level management (follow lane, park)
  - Goal-assignment
  - On-road driving
  - Lane-change maneuvers
  - Intersection handling
- Motion Planning
  - On-road driving
  - Unstructured zone navigation

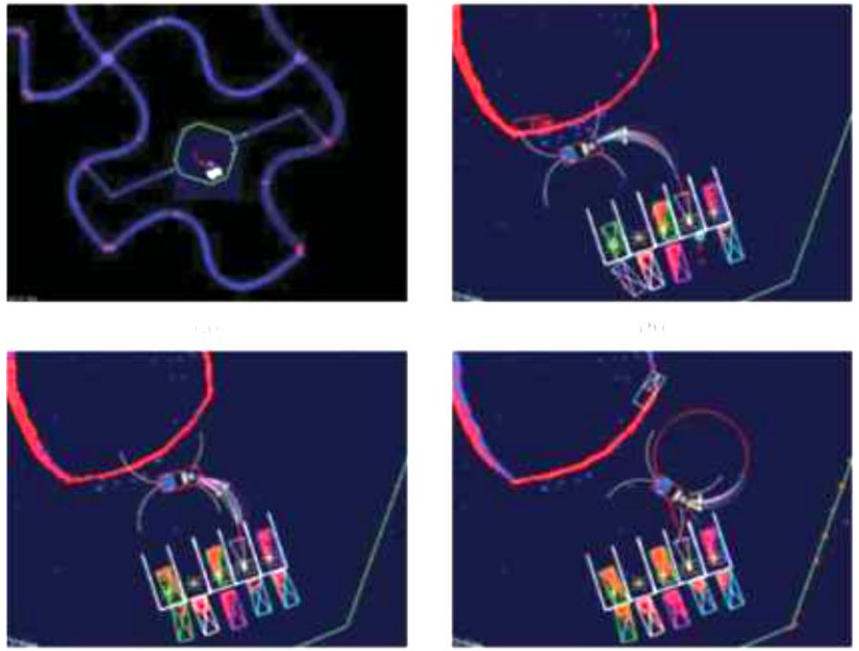


C. Baker and J. Dolan, "Traffic interaction in the urban challenge: Putting boss on its best behavior", IEEE Int. Conf. Intell. Robot. Syst., 2008.

Team Boss (Carnegie Mellon)

Motion Planning in unstructured areas

- Anytime D* graph-search
- Multires 4D state-lattice (x, y , θ, v)
- Maximum-of-two heuristic
- Set of concatenations of two motion primitives (diverging / returning to path) for control



Motion Planning on road

- Take the lane center
- Motion primitives with final lateral offset to reference path

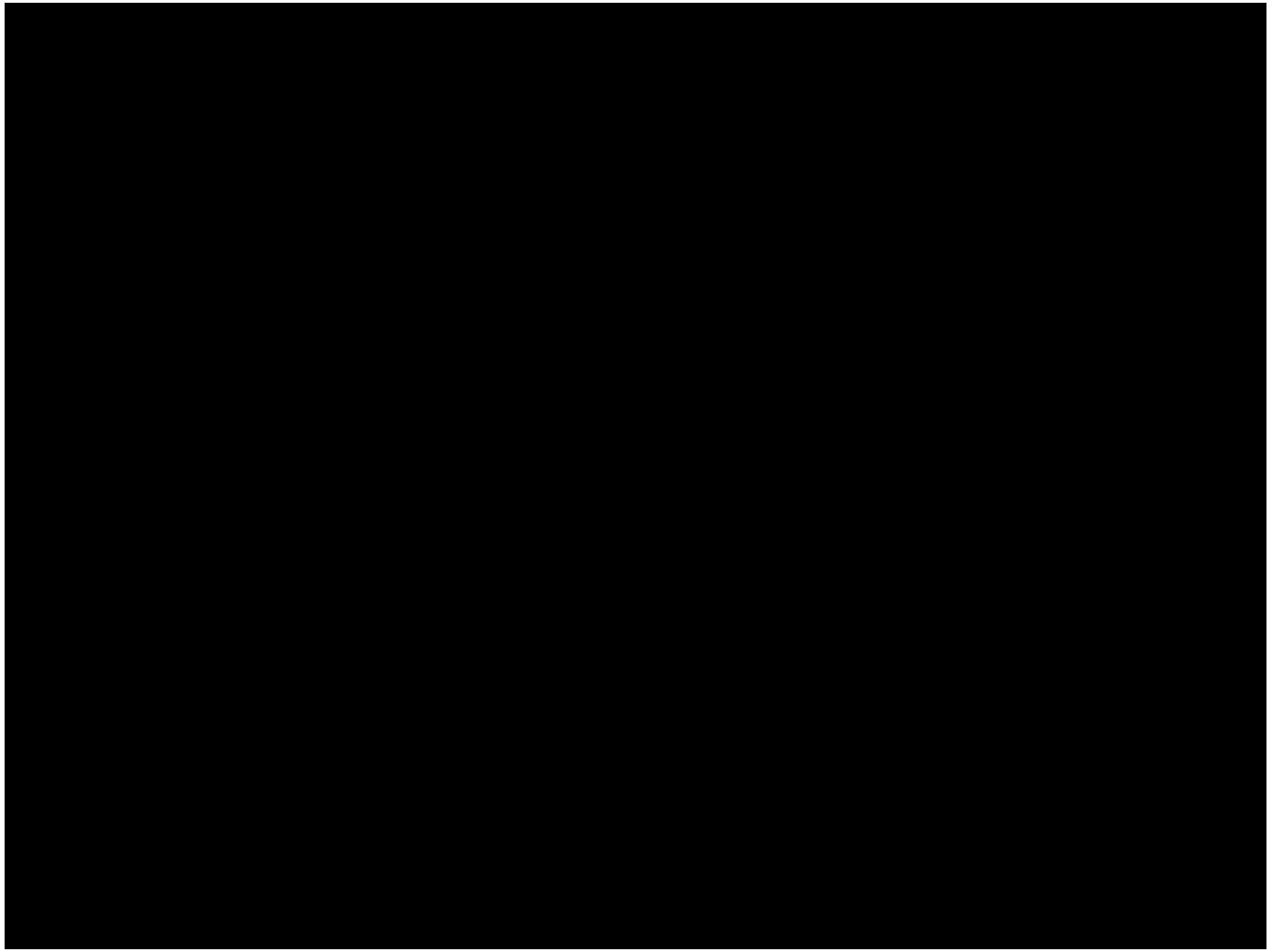
D. Ferguson, T. M. Howard, and M. Likhachev, "Motion planning in urban environments", Journal of Field Robotics, vol. 25, no. 11–12, 939–960, 2008

Team Boss (Carnegie Mellon)

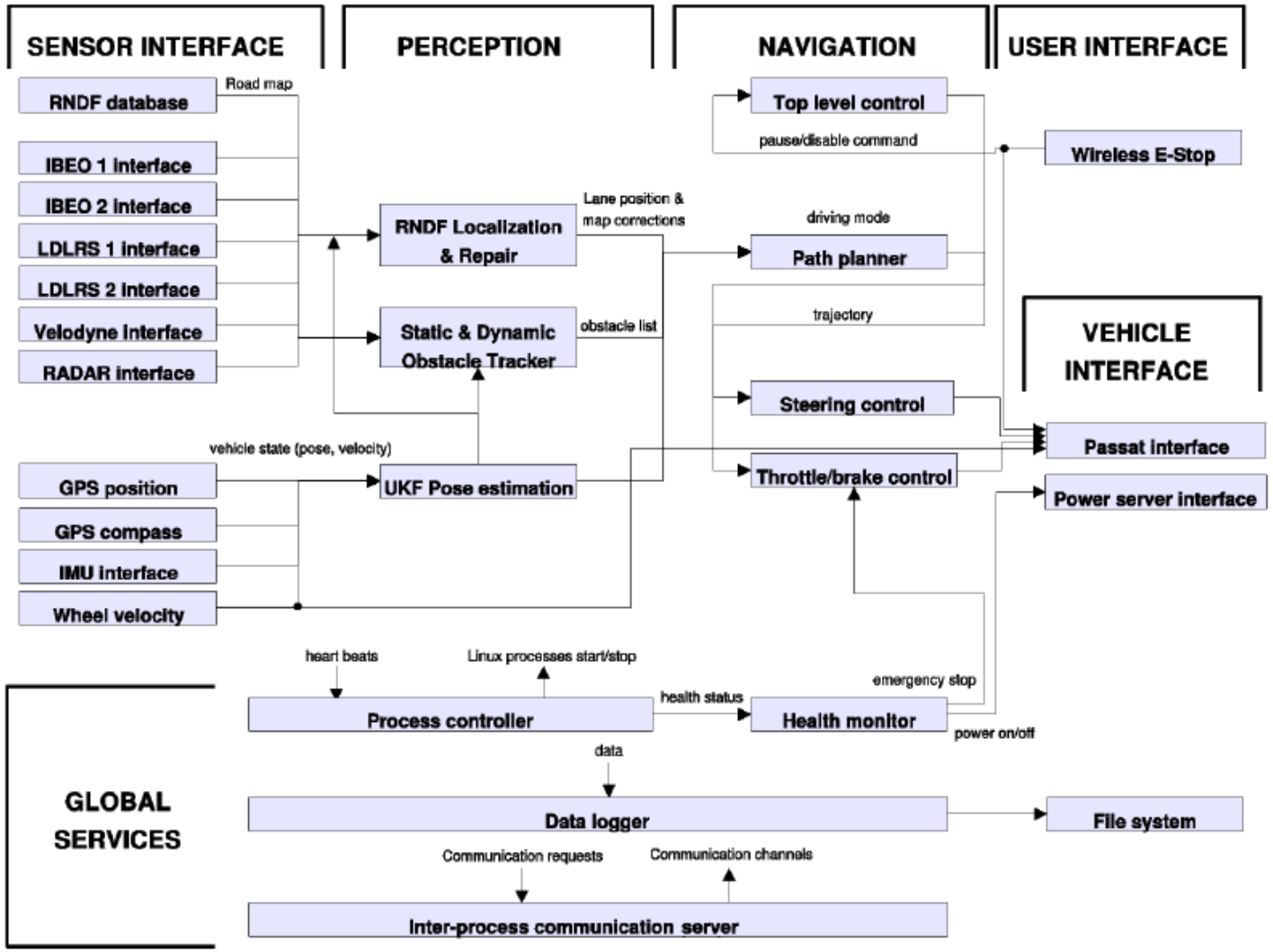
Success recipies:

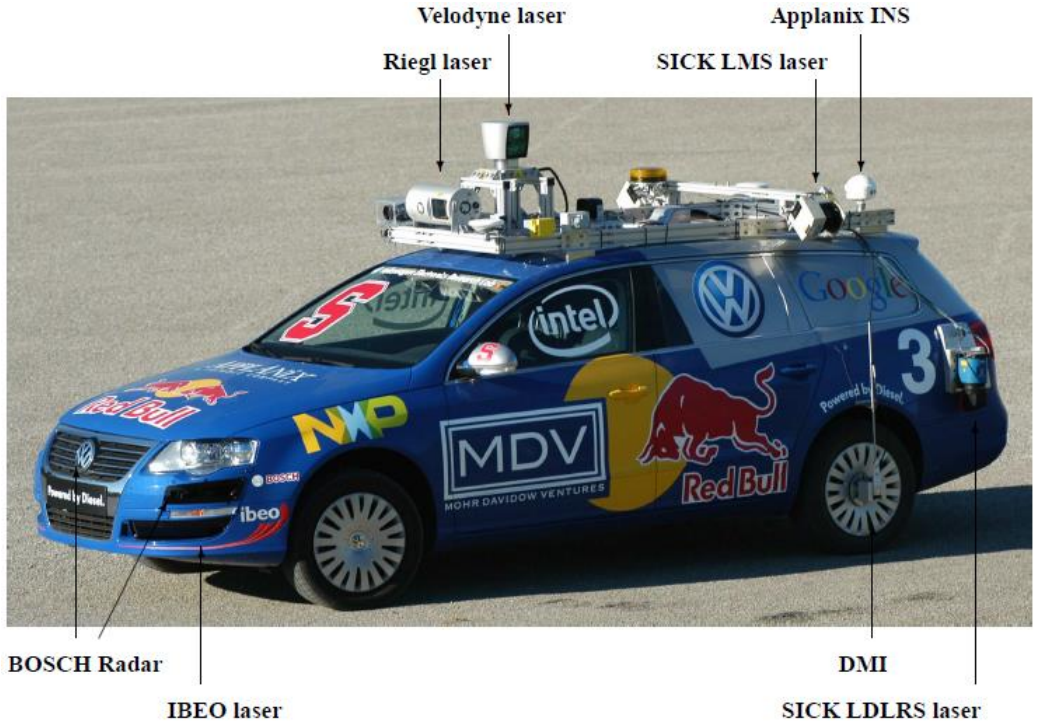
- Fast computation ensure smooth behavior
  - Preprocessing suggested wherever possible
- Detailed global planning stage increases system performance
  - Minimize divergence between planning stages
- Accurate vehicle modeling minimizes divergence between planning & execution
  - Higher speeds become safely driveable

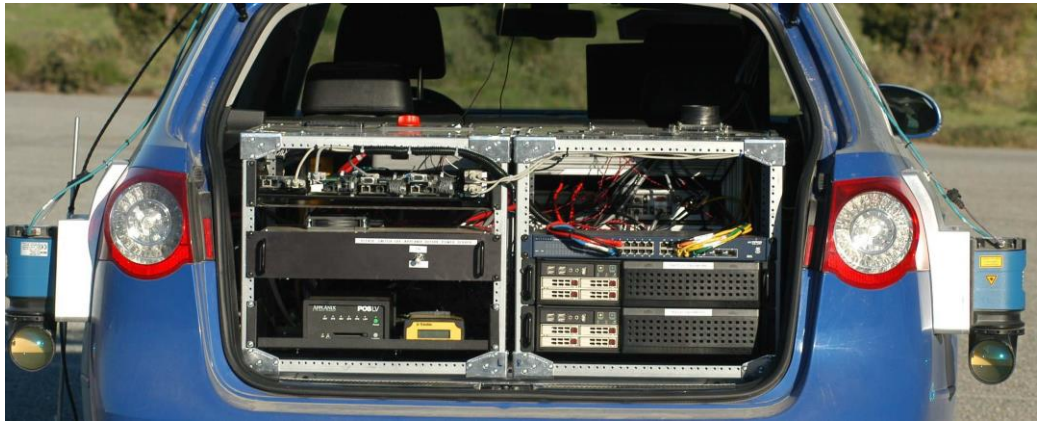
Team Boss (Carnegie Mellon)



Team Junior (Stanford)



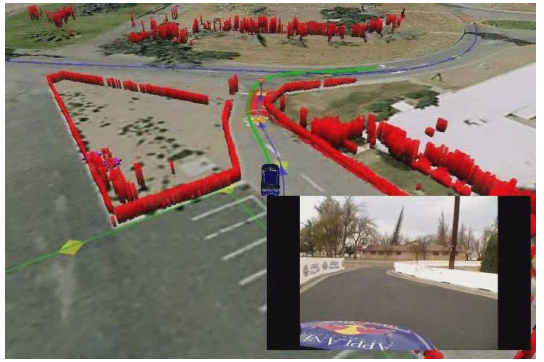


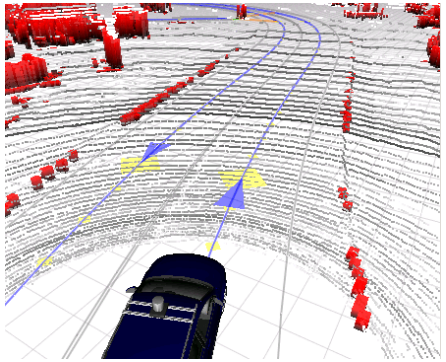


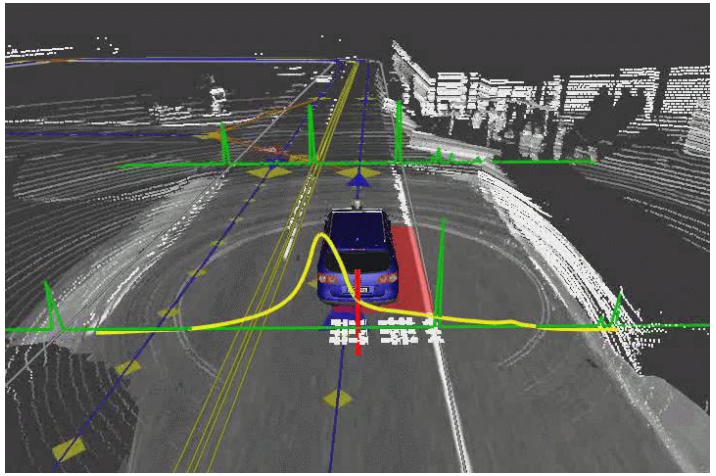
Team Junior (Stanford)

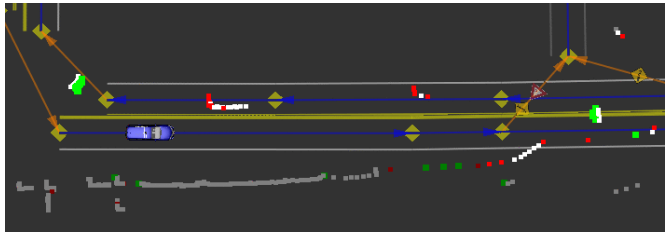
Perception performs several (usual) tasks simultaneously

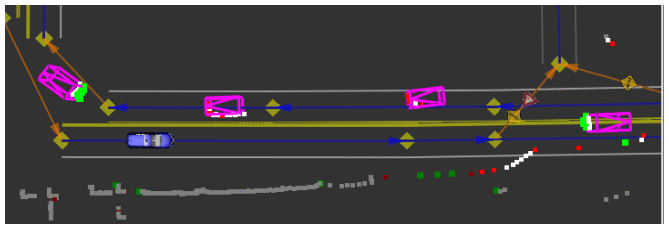
- Obstacle detection (Velodyne + IBEO)
- Grid mapping by evidence accumulation
- Object detection by scan differencing
- Localization on road network description file

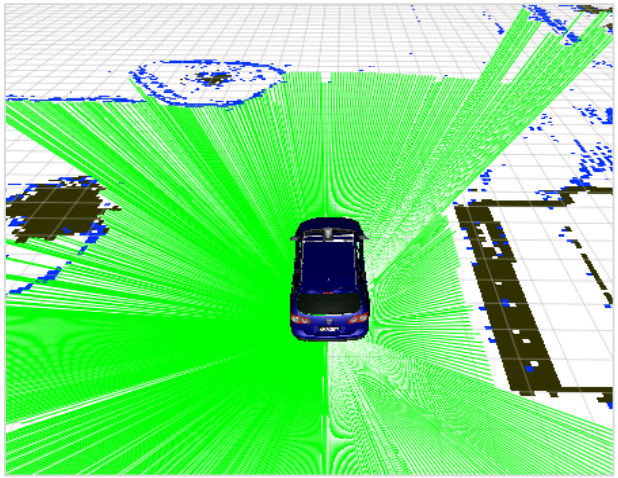


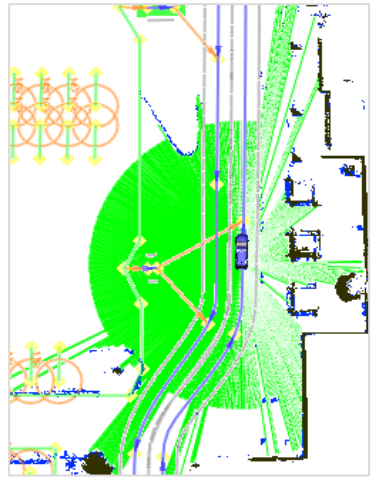








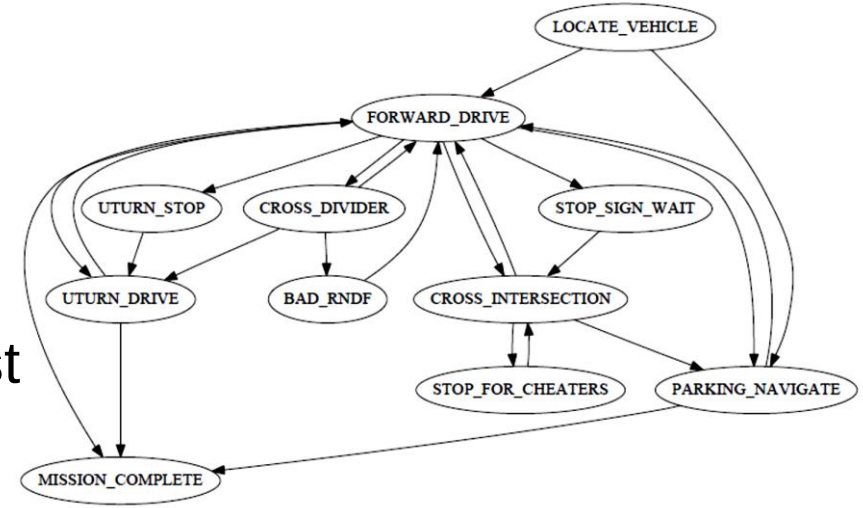


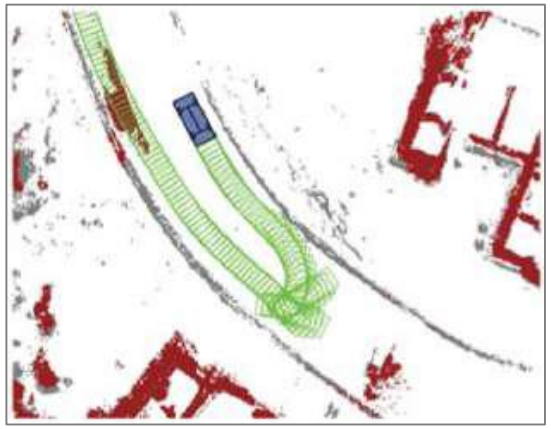


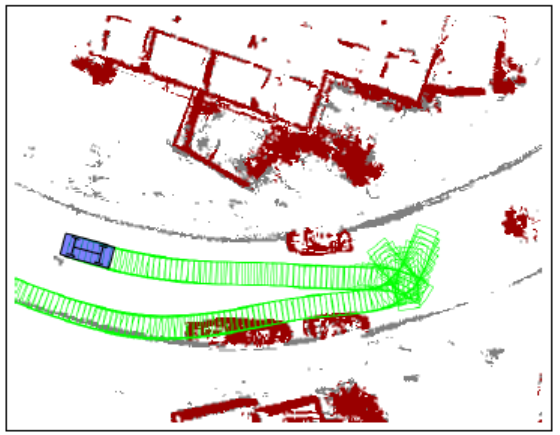
Team Junior (Stanford)

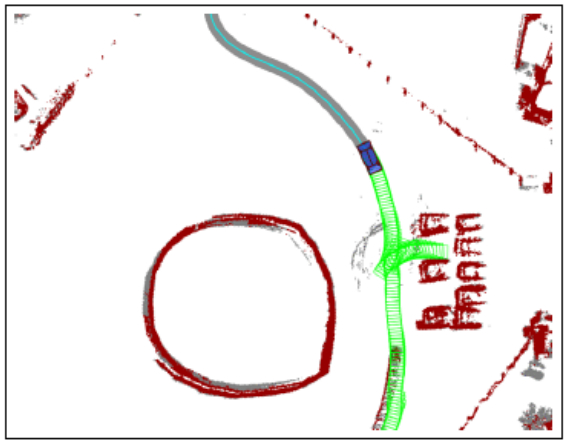
Motion planning

- Hybrid architecture based on a state machine
- Hybrid A* for navigation in unstructured space using maximum-of-two heuristic
- Graph-search on roadmap provides location cost
- Post-smoothing of paths by conjugate gradient









M. Montemerlo et al., "Junior: The Stanford entry in the Urban Challenge", Journal of Field Robotics, vol. 25, no. 9, pp. 569–597, 2008.

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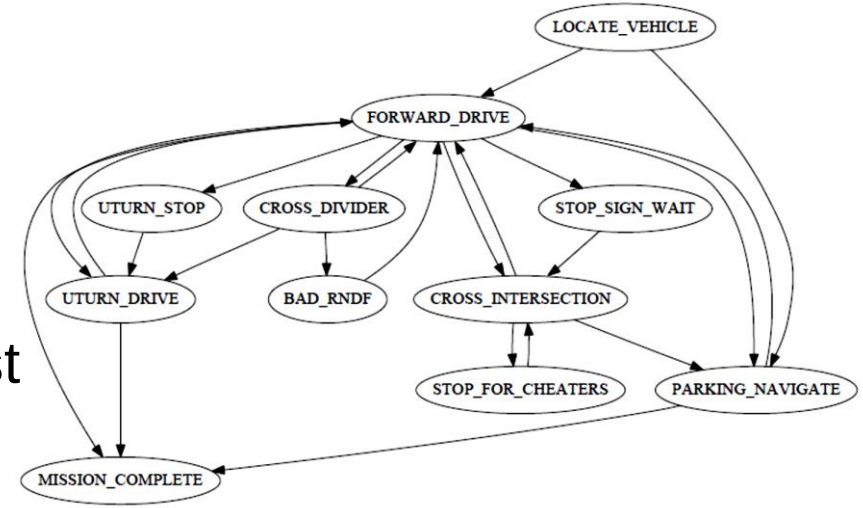
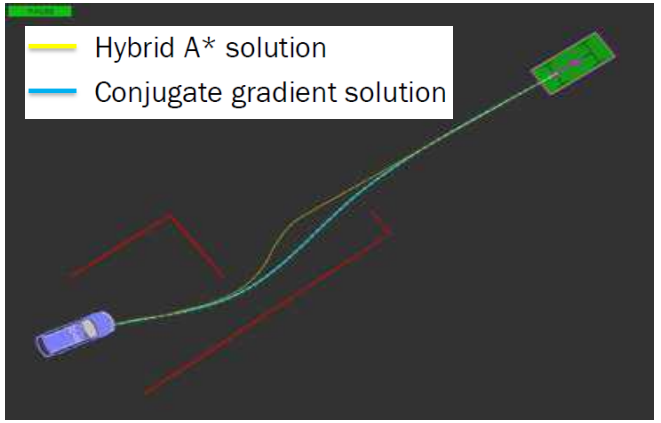


$$w_o \sum_{i=1}^{N} \sigma_o \left(|\mathbf{x}_i - \mathbf{o}_i| - d_{\max}\right) + w_\kappa \sum_{i=1}^{N-1} \sigma_\kappa \left(\frac{\Delta\phi_i}{|\Delta x_i|} - \kappa_{\max}\right) + w_s \sum_{i=1}^{N-1} (\Delta\mathbf{x}_{i+1} - \Delta\mathbf{x}_i)^2$$

Obstacle distance penalty

Maximum curvature violation penalty

Maximum acceleration violation penalty



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