TRAJECTORY PLANNING FOR AUTOMATED YIELDING MANEUVERS

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Why automated maneuvers?

Safety and convenience

- Your life
- Your time
- Your choice
Why trajectory planning?

An automated vehicle must know what to do.
Agenda

- Problem description
- Contribution
- Short introduction to convex optimization and model predictive control
- Trajectory planning algorithm
- Summary
- Questions
Problem description

If the ego vehicle should perform an automated yielding maneuver, determine:

1. in which gap between some traffic participants or objects and at what time instance the maneuver should be performed, and

2. calculate a feasible maneuver (if such exists) in terms of a longitudinal and a lateral trajectory, i.e., the control signals, which allow the ego vehicle to position itself in the selected gap at the desired time instance.

Furthermore, the maneuver should be planned such that the ego vehicle maintains safety margins to all surrounding traffic participants and objects, respects traffic rules and regulations, as well as satisfies physical and design limitations.
What is the challenge?

To develop a trajectory planning algorithm which is applicable to passenger vehicle ADAS or highly automated vehicles, the algorithm must have the ability to deal with the demands of

- limited computational resources,
- planning in a dynamic and uncertain environment,
- generating safe collision-free trajectories,
- satisfying physical and design limitations, as well as
- abiding traffic rules and regulations.
Contribution

Trajectory planning algorithms for automated yielding maneuvers formulated as convex Quadratic Programs (QP) within the Model Predictive Control (MPC) framework which provides a structured approach to express system objectives and constraints to allow for reliable, predictable, and robust, real-time implementation without the assumption of a reference trajectory.
Convex QP

\[
\begin{align*}
\min_{\text{trajectory}} & \quad \text{cost function}, \\
\text{subject to} & \quad \text{vehicle dynamics,}
\phantom{\text{subject to}} \\
& \quad \text{physical and design constraints,}
\phantom{\text{subject to}} \\
& \quad \text{collision avoidance constraints.}
\end{align*}
\]

\[
\begin{align*}
\leftrightarrow \\
\min_w J(w) &= \frac{1}{2} w^T H w + d^T w \\
\text{subject to} & \quad H_{in} w \leq k_{in}, \\
& \quad H_{eq} w = k_{eq}.
\end{align*}
\]
MPC

1. Measure the state $x$ at the current time instance $t$.
2. Solve the optimal control QP problem to obtain the control sequence $U$.
3. Apply the first element of $U$ to the system.
4. Repeat Step 1-3 at time instance $t+1$. 

\[ x(t) = x(t+1) \]

\[ u(t) = u^*(t) \]

\[ u(t+1) = u^*(t+1) \]
Trajectory planning for automated yielding maneuvers

Problem: Find a longitudinal and a lateral trajectory, i.e. the control signals, which allows the ego vehicle, $E$, to perform a safe and smooth yielding maneuver e.g. a lane change maneuver.

Solution: Loosely coupled longitudinal and lateral optimal control problems in the form of convex QPs which are solved within the MPC framework.
Trajectory planning algorithm

I. Determine an appropriate inter-vehicle traffic gap in the target lane and a time instance to initialize the lateral motion of the maneuver.

II. Determine the longitudinal safety corridor.

III. Determine the longitudinal trajectory (QP optimization).

IV. Determine the lateral safety corridor.

V. Determine the lateral trajectory (QP optimization).
Simulation results

Simulation scenario: decelerate into the lane change gap.
Real-time experiments

$S_2 \sim 14 m/s$

$E \sim 14 m/s$

$S_1 \sim 14 m/s$

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Automated Yielding Maneuvers
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Real-time experiments
Summary

\[
\min \text{ cost function, trajectory,}
\]

subject to

\text{vehicle dynamics, physical and design constraints, collision avoidance constraints.}
Further information


Questions
I. Traffic gap and initiation time selection

1. Approximate the reachable set of $E$ by e.g. a set of ACC trajectories $\Rightarrow T \in T$

2. For each inter-vehicle traffic gap and discrete time instance to initialize the lateral motion of the maneuver, determine if there exists a trajectory within the set, $T$, which allows $E$ to be safely positioned in its current lane, enter the lane change region of the inter-vehicle traffic gap at the specified time instance, remain in that region for $n_{min}$, and thereafter safely be positioned in the target lane until the end of the prediction horizon $\Rightarrow T_F \in T \in T$

3. Select the gap and time instance for which the trajectory, $T_F \in T$, minimizes

$$J_x = \sum_{k=1}^{N} \vartheta \left( v_{x_k} - v_{x_{des_k}} \right)^2 + \kappa (a_{x_k})^2 + \varphi (\Delta a_{x_k})^2$$
II. Longitudinal safety corridor

\[ x_{\text{max}_k} = x_{1k} - s_d, \forall k = 0, ..., N_{\text{peri}}, \]

\[ x_{\text{max}_k} = \min(x_{1k}, x_{2k}) - s_d, \forall k = N_{\text{peri}}, ..., N_{\text{post}}, \]

\[ x_{\text{max}_k} = x_{2k} - s_d, \forall k = N_{\text{post}}, ..., N. \]

\[ N_{\text{post}} = N_{\text{peri}} + n_{\text{min}} \]
II. Longitudinal safety corridor

\[ x_{\min_k} = x_{3k} + s_d, \forall k = 0, ..., N_{\text{Peri}}, \]

\[ x_{\min_k} = \max(x_{3k}, x_{4k}) + s_d, \forall k = N_{\text{Peri}}, ..., N_{\text{Post}}, \]

\[ x_{\min_k} = x_{4k} + s_d, \forall k = N_{\text{Post}}, ..., N. \]
III. Longitudinal trajectory planning

Longitudinal motion captured by a double integrator

\[ x_{k+1} = x_k + v_{x_k} t_s + a_{x_k} \frac{t_s^2}{2}, \forall k = 0, ..., N - 1, \]

\[ v_{x_{k+1}} = v_{x_k} + a_{x_k} t_s, \forall k = 0, ..., N - 1, \]

which is subjected to the following set of constraints

\[ x_{min_k} \leq x_k \leq x_{max_k}, \forall k = 1, ..., N, \]

\[ v_{x_{min_k}} \leq v_{x_k} \leq v_{x_{max_k}}, \forall k = 1, ..., N, \]

\[ a_{x_{min_k}} \leq a_{x_k} \leq a_{x_{max_k}}, \forall k = 1, ..., N, \]

\[ \Delta a_{x_{min_k}} \leq \Delta a_{x_k} \leq \Delta a_{x_{max_k}}, \forall k = 1, ..., N. \]
III. Longitudinal trajectory planning

Trajectory planning problem is solved as a standard quadratic program

$$\min_w J_x = \frac{1}{2} w^T H w,$$

subject to

$$H_{eq} w = K_{eq},$$
$$H_{in} w \leq K_{in},$$

where $w = [x_k, v_{x_k}, a_{x_k}]$ and

$$J_x = \sum_{k=1}^{N} \vartheta \left( v_{x_k} - v_{x_{des_k}} \right)^2 + \kappa (a_{x_k})^2 + \varphi (\Delta a_{x_k})^2.$$
IV. Lateral safety corridor

\[ y_{\text{max}_k} = L_{l_i k}, \forall k = 0, ..., N_{\text{peri}}, \]

\[ y_{\text{max}_k} = L_{l_{i+1} k}, \forall k = N_{\text{peri}}, ..., N, \]

\[ y_{\text{min}_k} = L_{r_i k}, \forall k = 0, ..., N_{\text{post}}, \]

\[ y_{\text{min}_k} = L_{r_{i+1} k}, \forall k = N_{\text{post}}, ..., N. \]
V. Lateral trajectory planning

Lateral motion captured by a double integrator

\[ y_{k+1} = y_k + v_{y_k} t_s + a_{y_k} \frac{t_s^2}{2}, \quad \forall \ k = 0, \ldots, N - 1, \]

\[ v_{y_{k+1}} = v_{y_k} + a_{y_k} t_s, \quad \forall \ k = 0, \ldots, N - 1, \]

which is subjected to the following set of constraints

\[ y_{min_k} \leq y_k \leq y_{max_k}, \quad \forall \ k = 1, \ldots, N, \]

\[ v_{y_{min_k}} \leq v_{y_k} \leq v_{y_{max_k}}, \quad \forall \ k = 1, \ldots, N, \]

\[ (-0.17 v_{x_k} \leq v_{y_k} \leq 0.17 v_{x_k}) \]

\[ a_{y_{min_k}} \leq a_{y_k} \leq a_{y_{max_k}}, \quad \forall \ k = 1, \ldots, N, \]

\[ \Delta a_{y_{min_k}} \leq \Delta a_{y_k} \leq \Delta a_{y_{max_k}}, \quad \forall \ k = 1, \ldots, N. \]
V. Lateral trajectory planning

Trajectory planning problem is solved as a standard quadratic program

$$\min_w J_y = \frac{1}{2} w^T H w$$

subject to

$$H_{eq} w = K_{eq},$$

$$H_{in} w \leq K_{in},$$

where $$w = [y_k, v_{yk}, a_{yk}]$$ and

$$J_y = \sum_{k=1}^{N} \phi(v_{yk})^2 + \psi(a_{yk})^2 + \vartheta(\Delta a_{yk})^2.$$
What about dense traffic situations?

Allow the algorithm to plan trajectories which account for motion dependent safety critical zones of miscellaneous shape.
What about dense traffic situations?