Driver assistance system design A

Lane keeping part 2

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Outline

Introduction

- The goal of lane keeping systems is to maintain the vehicle within the lane through a control action on the steer.
- Indeed, lateral dynamics is unstable and control is necessary to keep the vehicle in the lane (in manual driving, controller = driver).
- The control system is not intended to replace the driver.
- The control system is aimed to improve safety:
  - help the driver in emergency situations, e.g. in the case of tiredness, lack of attention, critical road conditions, etc.
  - reduce the driver's tiredness.

1 Introduction

2 Dynamic single-track error model

3 Lane keeping

4 Simulation result

Dynamic single-track error model

- In order to design an effective state feedback controller, it is convenient to introduce a new model of the vehicle lateral dynamics, written in terms of orientation error and lateral error.
- To define these errors, we recall the variables and parameters used for the dynamic single-track models (DST and DSTP):

  X, Y: coordinates of the vehicle CoG in an inertial reference frame
  ψ: yaw angle
  $\omega_\psi \doteq \dot{\psi}$: yaw rate
  $\vec{v}$: velocity vector in the inertial frame
  v_x: longitudinal speed $= \vec{v}$ component along the longitudinal axis
  v_y: lateral speed $= \vec{v}$ component along the transverse axis
  a_x: longitudinal acceleration
  a_y: lateral acceleration
  m, J: mass and moment of inertia
  l_f, l_r: distance CoG - front/rear wheel center
  c_f, c_r: front/rear cornering stiffnesses.

Dynamic single-track error model

- The orientation error is defined as

$$e_\psi \doteq \psi - \psi_r.$$

  Note that $e_\psi = -e_h$, where e_h is the heading error. We introduced both the quantities just for the sake of coherence with the literature.
- Suppose that the vehicle has to track a given reference trajectory and let ρ be the radius of curvature of this path at a given point.
- If the vehicle is exactly tracking the reference with longitudinal speed v_x, its yaw rate is given by $\omega_{\psi r} = \dot{\psi}_r = v_x/\rho$.
  - Hence, $\omega_{\psi r}$ is the reference yaw rate.
- If the vehicle is not exactly tracking the reference, we have a yaw rate error $\omega_\psi - \omega_{\psi r}$.

Dynamic single-track error model

- From classical mechanics, we recall that $a_y = \dot{v}_y + v_x \omega_\psi$.
- If we replace ω_ψ with the yaw rate error $\omega_\psi - \omega_{\psi r}$, we obtain the following lateral acceleration error:

$$\ddot{e}_y = \dot{v}_y + v_x(\omega_\psi - \omega_{\psi r}).$$

- With $v_x \cong const$, by integration we obtain

$$\dot{e}_y = v_y + v_x(\psi - \psi_r) = v_y + v_x e_\psi.$$

  The quantity e_y is called the lateral error and quantifies the lateral deviation of the vehicle CoG from the reference trajectory.

  It is similar to the cross-track error e_{ct} but not exactly the same.
- We can now write a lateral dynamics model in terms of these two errors.

Dynamic single-track error model

- The model, called the dynamic single-track error (DSTE) model, is described by the following state equation[1]:

$$\dot{\mathbf{e}} = A_e \mathbf{e} + B_\delta \delta_f + B_\psi \dot{\psi}_r$$

$$A_e \doteq \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 2\frac{c_f + c_r}{m} & -2\frac{c_f + c_r}{m v_x} & -2\frac{c_f l_f - c_r l_r}{m v_x} \\ 0 & 2\frac{c_f l_f - c_r l_r}{J} & -2\frac{c_f l_f - c_r l_r}{J v_x} & -2\frac{c_f l_f^2 + c_r l_r^2}{J v_x} \end{bmatrix}$$

$$B_\delta \doteq \begin{bmatrix} 0 \\ 0 \\ \frac{2c_f}{m} \\ \frac{2c_f l_f}{J} \end{bmatrix}, \quad B_\psi \doteq \begin{bmatrix} 0 \\ 0 \\ -v_x - 2\frac{c_f l_f - c_r l_r}{m v_x} \\ -2\frac{c_f l_f^2 + c_r l_r^2}{J v_x} \end{bmatrix}$$

  - state: $\mathbf{e} \doteq (e_y, e_\psi, \dot{e}_y, \dot{e}_\psi)$
  - command input: δ_f (steering angle)
  - disturbance: $\dot{\psi}_r$ (reference yaw rate).

[1] Rajamani, Vehicle Dynamics and Control, Springer, 2012.

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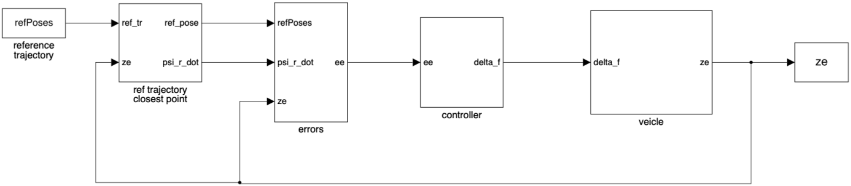
Designed controllers

- **Kraja**: State feedback controller designed from the DSTE model; closed-loop eigenvalues $\{-5+3j, -5-3j, -7, -10\}$ taken from Rajamani's book.
- **Klqr**: LQR controller designed from the DSTE model, with $R = 5$, $Q = \mathrm{diag}(1, 1, 0, 0)$.
- **Klqi**: LQI controller designed from the DSTE model, with $R = 1$, $Q = 10I$. Output: (e_y, e_ψ).
- **PIDF** (discrete-time):
  - Using $e_y + e_\psi$ as the feedback variable.
  - Designed by means of the Simulink PID tuner.
- All controllers designed assuming a constant speed $v_x = 40\,\mathrm{km/h}$.
- DSTE model used for control design. The controllers are tested using the DSTP model.

Lane keeping
Closed-loop scheme



- vehicle: DSTP model and steering actuator dynamics.
- controller: one of the controllers described above.
- errors: computation of lateral and orientation errors.
- reference trajectory: set of points giving the reference trajectory.
- ref trajectory closest point: on-line computation of the closest point to the vehicle.

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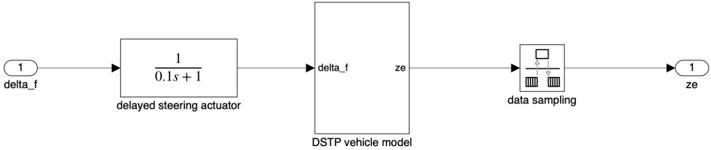
Vehicle model



- DSTP: dynamic single-track vehicle model with Pacejka's tire formula.
  - Vehicle parameters: $l_f = 1.2\,\mathrm{m}$, $l_r = 1.6\,\mathrm{m}$, $m = 1575\,\mathrm{kg}$, $J = 4000\,\mathrm{kg\,m}^2$, $c_f = c_r = 27e3\,\mathrm{N/rad}$.
  - Tire parameters: $p_1 = 3863\,\mathrm{N}$, $p_2 = 1.5$, $p_4 = -0.5$, and $p_3 = c_f/p_1/p_2$ (front tire) or $p_3 = c_r/p_1/p_2$ (rear tire).
  - A constant speed v_x is directly imposed in "DSTP vehicle model".
- Other blocks:
  - steering actuator dynamics
  - data sampling block.

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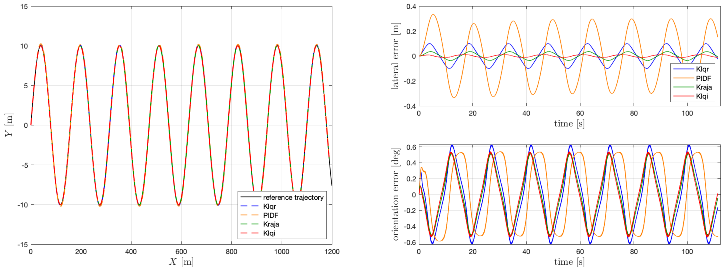
Simulation results for $v_x = 40\,\mathrm{km/h}$

- Relatively challenging reference trajectory: $Y_r = 10\sin(0.04X_r)$.



- Data sampling time $0.01\,\mathrm{s}$: All controllers work. Klqi provides an excellent performance, PIDF the worst performance.
- Data sampling time $0.05\,\mathrm{s}$: Kraja leads to an unstable behavior; Klqi works but gives rise to chattering.
- In the following, only the results of the Klqr and PIDF controllers are shown, assuming a data sampling time of $0.05\,\mathrm{s}$.

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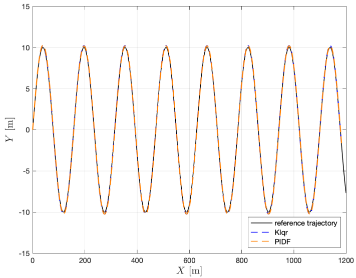
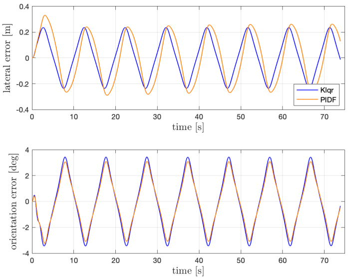
Simulation results for $v_x = 60\,\mathrm{km/h}$





- The performance of the controllers gets worse but still rather good.
- In (more realistic) scenarios with smaller curvatures, smaller errors are obtained.

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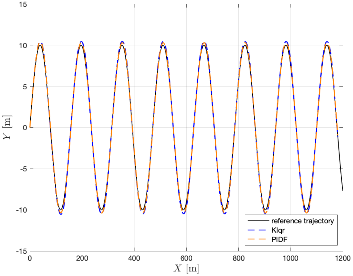
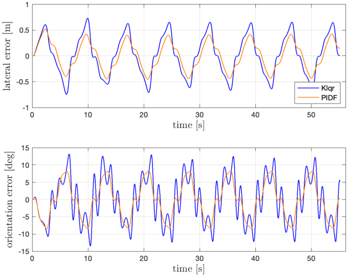
Simulation results for $v_x = 80\,\mathrm{km/h}$

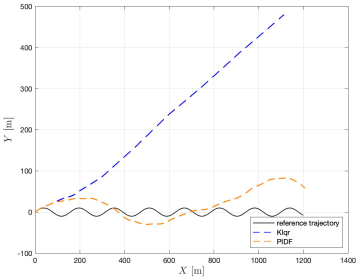


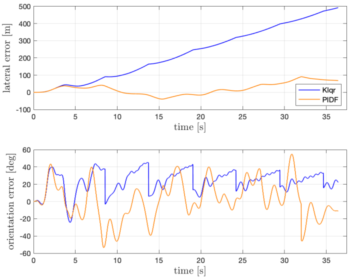


- The performance of the controllers gets worse but still not too bad.
- These controllers seem to work better than the Stanley controller and the PIDF controllers based on the cross-track error and heading error.

Lane keeping

Simulation results for $v_x = 120\,\mathrm{km/h}$





- The controllers do not work anymore.
- **Remark:** Relatively simple controllers may work for different speed ranges but not all $\rightarrow$ gain-scheduling/nonlinear control may provide better results on the whole speed range.