Helping a driver in backward docking with N-trailer vehicles by the passive control-assistance system

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Maciej Michałek, Marcin Kiełczewski

Chair of Control and Systems Engineering
Poznan University of Technology (PUT)
Poznań, Poland

Outline

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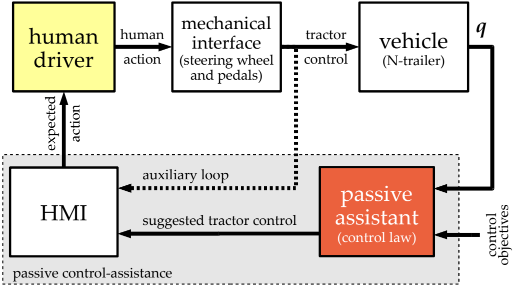
Motivation

- N-trailer vehicles – highly nonlinear kinematics hard to control
- Maneuvers *by-hand* – very difficult, nonintuitive and burdening (dangerous)
- Control-assistance for agile maneuvers – especially desirable in this case

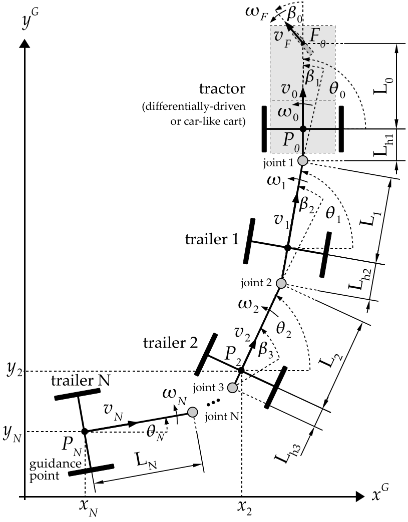
General concept of passive control-assistance



- q = measurable vehicle configuration
- Assistant suggests control action upon q and control objectives
  (human intuition NOT required)
- Control action performed entirely by a human driver
  (passive assistance $\Rightarrow$ steer-by-wire and cruise control systems NOT needed)

Outline

Kinematics of N-trailer vehicle – definitions



L_i – trailer length, L_{hi} – hitching offset

Vehicle configuration vector

$$\boldsymbol{q} \triangleq [\underbrace{\beta_1 \ \dots \ \beta_N}_{\boldsymbol{\beta}} \ \underbrace{\theta_N \ x_N \ y_N}_{\boldsymbol{q}_N}]^\top \in \mathbb{R}^{N+3} \qquad (1)$$

Kinematic control input

$$\boldsymbol{u}_0 = [\omega_0 \ v_0]^\top \in \mathbb{R}^2 \quad \text{for DDV} \qquad (2)$$

$$\boldsymbol{w}_0 = [\omega_F \ v_F]^\top \in \mathbb{R}^2 \quad \text{for CLV} \qquad (3)$$

DDV = Differentially Driven Vehicle
CLV = Car-Like Vehicle

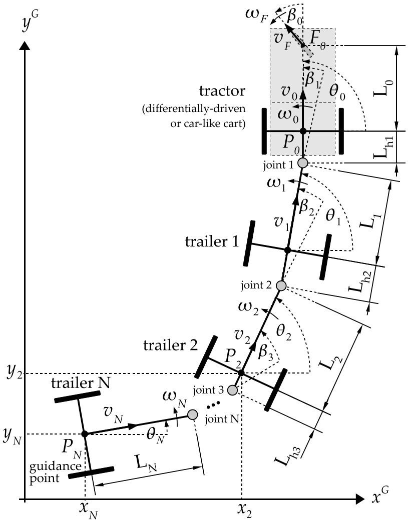
Assumptions

$$L_i > 0 \quad \forall i = 1, \dots, N$$

$$L_{hi} > 0 \quad \forall i = 1, \dots, N \text{ (nSNT)}$$

nSNT = non-Standard N-Trailer

Kinematics of N-trailer vehicle – cascaded form



Kinematics of i-th segment

$$\dot{\theta}_i = \omega_i$$
$$\dot{x}_i = v_i \cos\theta_i$$
$$\dot{y}_i = v_i \sin\theta_i$$
$$\beta_i = \theta_{i-1} - \theta_i$$

ω_i, v_i – virtual inputs of i-th segment

Velocity transformation

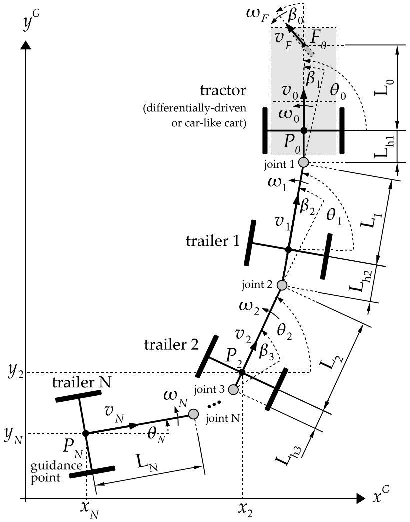
$$\underbrace{\begin{bmatrix}\omega_i \\ v_i\end{bmatrix}}_{\boldsymbol{u}_i} = \underbrace{\begin{bmatrix} -\frac{L_{hi}}{L_i}\cos\beta_i & \frac{1}{L_i}\sin\beta_i \\ L_{hi}\sin\beta_i & \cos\beta_i \end{bmatrix}}_{\boldsymbol{J}_i(\beta_i) \leftarrow \text{invertible for } L_{hi} \neq 0} \underbrace{\begin{bmatrix}\omega_{i-1} \\ v_{i-1}\end{bmatrix}}_{\boldsymbol{u}_{i-1}}$$

Velocity propagation along a vehicle chain

$$\boldsymbol{u}_i = \prod_{j=i}^{1} \boldsymbol{J}_j(\beta_j)\boldsymbol{u}_0, \quad \boldsymbol{u}_{i-1} = \prod_{j=i}^{N} \boldsymbol{J}_j^{-1}(\beta_j)\boldsymbol{u}_N$$

$i = 1, \ldots, N$

Control objective formulation (*docking task*)



Constant reference set-point

$$\boldsymbol{q}_{Nd} = [\theta_{Nd} \; x_{Nd} \; y_{Nd}]^{\top} \tag{4}$$

Weighted posture/docking error

$$\boldsymbol{e}_w(t) \triangleq \boldsymbol{W}\boldsymbol{e}(t), \quad \boldsymbol{e}(t) = \begin{bmatrix} e_\theta \\ e_x \\ e_y \end{bmatrix} \triangleq \boldsymbol{q}_{Nd} - \boldsymbol{q}_N(t)$$

where $\boldsymbol{W} = \mathrm{diag}\{w, 1, 1\}$ and $w \in [0, 1]$

Definition (Docking task)

Compute control suggestions in the form of velocities $\boldsymbol{u}_0(\boldsymbol{e}, \boldsymbol{\beta})$ and desired steering angle $\beta_{0c}(\boldsymbol{u}_0(\boldsymbol{e}, \boldsymbol{\beta}))$ which guide the N-th trailer to set-point $\boldsymbol{q}_{Nd}$ with prescribed accuracy $\delta > 0$ guaranteeing that

$$\forall t \geq T \; \|\boldsymbol{e}_w(t)\| < \delta,$$

where $T \in (0, \infty)$ is a control time-horizon.

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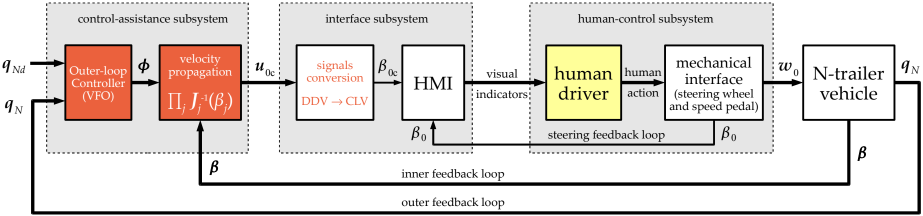
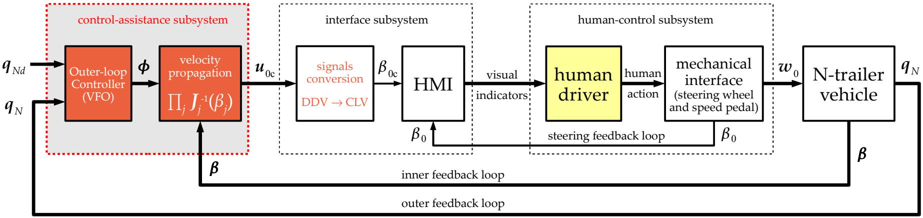
Cascaded structure of the motion control system



- N-trailer with CLV tractor ⇒ control input $\boldsymbol{w}_0 = [\omega_F \ v_F]^\top$
- Human driver as a feedback controller of steering-angle β_0 and governor of driving speed v_F

Control-assistant subsystem



$$u_{0c} \triangleq \begin{cases} \prod_{j=1}^{N} J_j^{-1}(\beta_j)\Phi(e) & \text{for} \quad \|e_w\| > \delta \\ 0 & \text{for} \quad \|e_w\| \le \delta \end{cases}, \qquad \Phi(e) \triangleq \begin{bmatrix} k_a(\theta_{Na} - \theta_N) + \dot{\theta}_{Na} \\ \|\bar{e}\|^{\gamma} \cos\alpha \end{bmatrix}$$

$$\|\bar{e}\| \triangleq \sqrt{e_x^2 + e_y^2}$$

$$h_x \triangleq k_p e_x - \eta\sigma \|\bar{e}\| \cos\theta_{Nd}$$

$$h_y \triangleq k_p e_y - \eta\sigma \|\bar{e}\| \sin\theta_{Nd}$$

$$k_a > 0, \quad k_p \in (0, k_a), \quad \eta \in (0, k_p)$$

$$\theta_{Na} \triangleq \mathrm{Atan2c}\,(\sigma \cdot h_y, \sigma \cdot h_x) \in \mathbb{R}$$

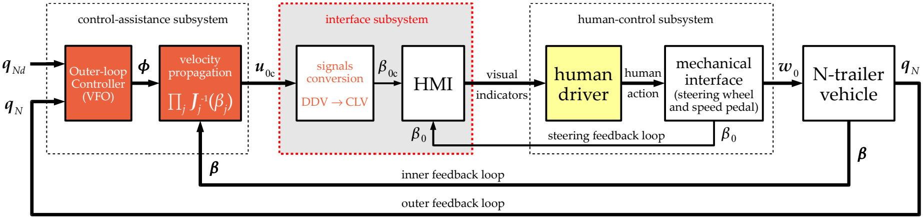
$$\dot{\theta}_{Na} = (\dot{h}_y h_x - h_y \dot{h}_x)/(h_x^2 + h_y^2)$$

$$\cos\alpha \triangleq (h_x \cos\theta_N + h_y \sin\theta_N)/\sqrt{h_x^2 + h_y^2}$$

$$\sigma \in \{-1, +1\}, \quad \gamma \in [0, 1)$$

M. Michałek, K. Kozłowski: Vector-Field-Orientation feedback control method for a differentially driven vehicle. IEEE Trans. Cont. Sys. Techn., 18(1), 2010
M. Michałek: Application of the VFO method to set-point control for the N-trailer vehicle with off-axle hitching, Int. Journal of Control, 85(5), 2012

Interface subsystem



Signals conversion for backward maneuvers:

$$\beta_{0c}(\boldsymbol{u}_{0c}(\boldsymbol{e},\boldsymbol{\beta})) \triangleq \begin{cases} \text{Atan2}\left(-L_0\omega_{0c}(\boldsymbol{e},\boldsymbol{\beta}), -v_{0c}(\boldsymbol{e},\boldsymbol{\beta})\right) & \text{for} \quad \|\boldsymbol{u}_{0c}\| > 0 \\ 0 & \text{for} \quad \|\boldsymbol{u}_{0c}\| = 0 \end{cases}$$

where

$$\boldsymbol{u}_{0c}(\boldsymbol{e},\boldsymbol{\beta}) = [\omega_0(\boldsymbol{e},\boldsymbol{\beta}) \quad v_0(\boldsymbol{e},\boldsymbol{\beta})]^\top \quad \text{(control suggestion for DDV kinematics)}$$

Note: Driving velocity $v_F < 0$ can be freely governed by a driver with a speed-pedal

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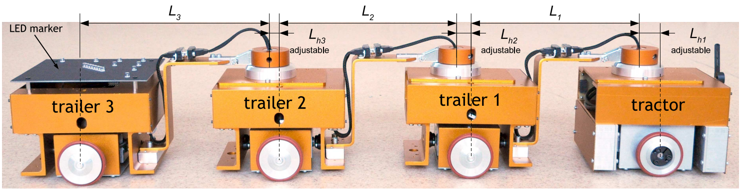
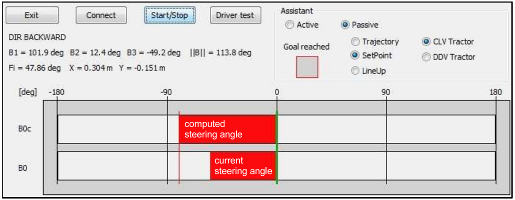
Experimental testbed – selected details

Laboratory-scale N-trailer vehicle



Selected for experiments: $L_{1,2,3} = 0.229\,\text{m}$, $L_{h1,2,3} = 0.048\,\text{m}$, $L_0 = 0.17\,\text{m}$ (for emulation of CLV tractor)

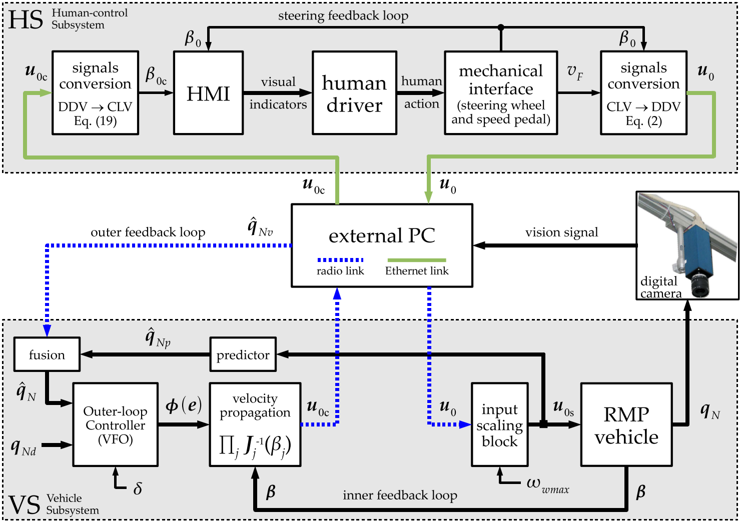
Human-Machine Interface (minimalist HMI)



Only single suggested variable β_{0c} has to be tracked by a driver

(steering angle β_{0c} determines motion curvature; driving velocity is secondary)

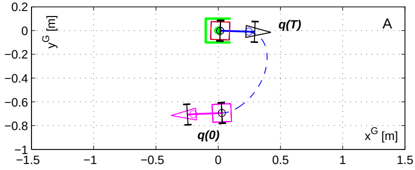
Experimental testbed – implementation scheme



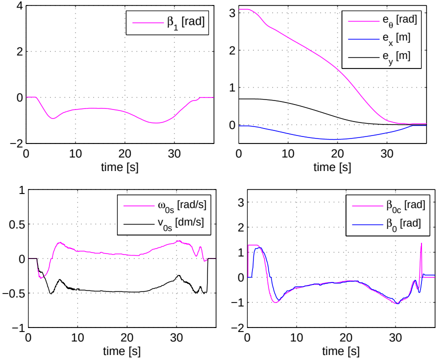
Experiment A: *U-turn docking* with 1-trailer ($N = 1$)

Selected parameters

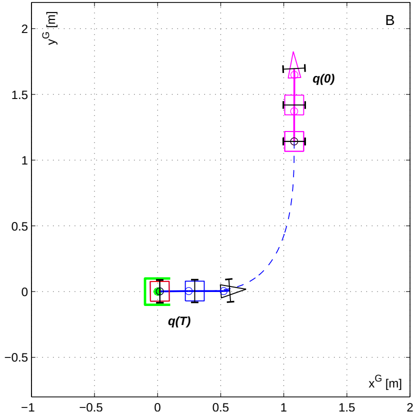
$k_a = 2, k_p = 1, \eta = 0.8, \gamma = 0.4, \sigma = -1$
$w = 0.001, \delta = 0.02$
$\boldsymbol{q}_{Nd} = \mathbf{0}$



$\boldsymbol{q}(0)$ – initial vehicle configuration
$\boldsymbol{q}(T)$ – terminal vehicle configuration



Experiment B: *perpendicular docking* with 2-trailer ($N = 2$)

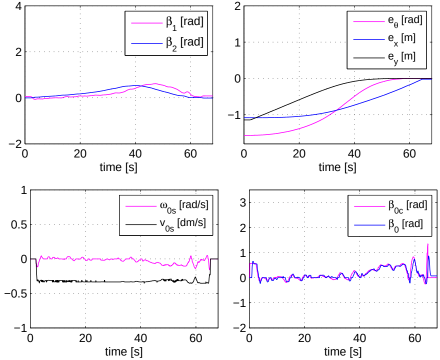


$\boldsymbol{q}(0)$ – initial vehicle configuration

$\boldsymbol{q}(T)$ – terminal vehicle configuration

Selected parameters

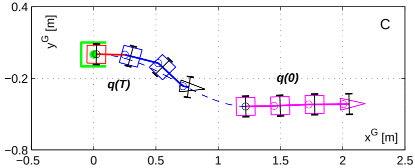
$k_a = 2,\ k_p = 1,\ \eta = 0.8,\ \gamma = 0.4,\ \sigma = -1$
$w = 0.001,\ \delta = 0.02$
$\boldsymbol{q}_{Nd} = \boldsymbol{0}$

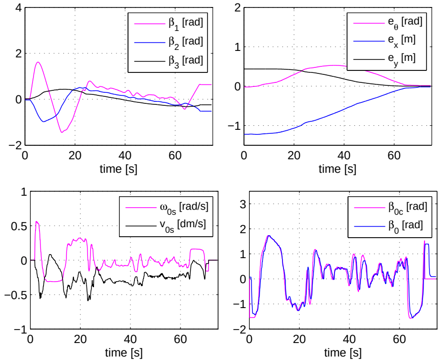


Experiment C: *parallel docking* with 3-trailer ($N = 3$)

Selected parameters

$k_a = 2,\ k_p = 1,\ \eta = 0.6,\ \gamma = 0.4,\ \sigma = -1$
$w = 0.001,\ \delta = 0.02$
$\boldsymbol{q}_{Nd} = \mathbf{0}$





$\boldsymbol{q}(0)$ – initial vehicle configuration
$\boldsymbol{q}(T)$ – terminal vehicle configuration

Outline

Summary of control-assistant properties

- Highly scalable control law (arbitrary number of trailers admissible)
- Outer-loop controller determines the task (modular approach)
- Implementation and tuning simplicity (low-cost embedded solution)
- Minimalist HMI complies perception limitations (single bar-like indicator)

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Thank you for attention