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Research Presentation

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About Me

- 2020.09-2024.06

Undergraduate Student
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Main Courses: Calculus, Linear Algebra, Automobile Theory, Principles of Control Engineering, Programming Design
Awards: Outstanding Graduate

- 2024.09-2027.06

Postgraduate Student
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Beijing Institute of Technology (Project 985), Beijing, China
Research Interests: Chassis control of Distributed Drive Electric Vehicle (DDEV), Trajectory planning
Main Courses: Vehicle Dynamics, Numerical Analysis, Advanced Control, Modern Control Theory
Awards: Outstanding Freshman Scholarship

About Me

➢ Accepted Papers

1. **Chengye Wang**, Yu Zhang, Xuepeng Hu, Haipeng Qin, Guoli Wang, Yechen Qin. "Real-time multidimensional vehicle dynamic stability domain calculation and its application in intelligent vehicles", SAE 2025 Intelligent and Connected Vehicles Symposium, Chongqing, China.
2. Yu Zhang, **Chengye Wang**, Fu Du, Mingming Dong, Yechen Qin, Ming Mao. "Dynamic Region of Stability Integrated Path-tracking Control for Intelligent Vehicles". Chinese Journal of Mechanical Engineering
3. Hu, XuePeng; Zhang, Yu; **Wang, Chengye**; Shi, Shaoyang; Wang, Zhenfeng; Qin, Yechen. "MCTP: A Multi-Coupled Dynamics Trajectory Planning Scheme for Autonomous Driving in Extreme Conditions". IEEE Transactions on Automation Science and Engineering

➢ Under Review

1. **Chengye Wang**, Yu Zhang, Xuepeng Hu, Shaoyang Shi, Jingqi He, Yechen Qin. "Coordinated Tracking and Stability Control of Automated Vehicles at the Limits: A Controlled Stability Region Approach", 2026 IEEE 29th International Conference on Intelligent Transportation Systems (ITSC), Naples, Italy.
2. Shaoyang Shi, Yu Zhang, Kai Yang, **Chengye Wang**, Zhenfeng Wang, Yechen Qin. "A Risk-Aware Decision Making and Motion Planning Framework for Interactive Autonomous Driving", 2026 IEEE 29th International Conference on Intelligent Transportation Systems (ITSC), Naples, Italy.

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Coordinated Tracking and Stability Control of Automated Vehicles at the Limits: A Controlled Stability Region Approach

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Content

1 Background and Motivation

2 Current Research Status

3 Research Content and Methodology

4 Future Work

1. Background and Motivation

Challenge of Motion Control



Hierarchical Architecture

Human Driver

Perception Layer: localization, perception

Planning Layer: global-planning, decision-making, trajectory-planning

Control Layer: tracking control, stability control

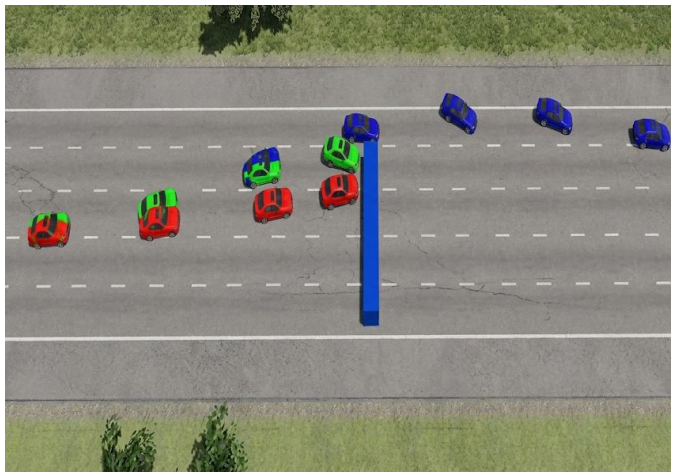
e2e



Stability Guarantee ⇄ **Tracking Accuracy Enhancement**



Safety Risk: Lack of strict stability bounds leads to loss of control.



Maneuverability Loss: Over-conservative stability criteria limit maneuverability in extreme conditions.

The Tracking-Stability Coordination is the Core Challenge in Motion Control

1. Background and Motivation

Wheel-End Actuation

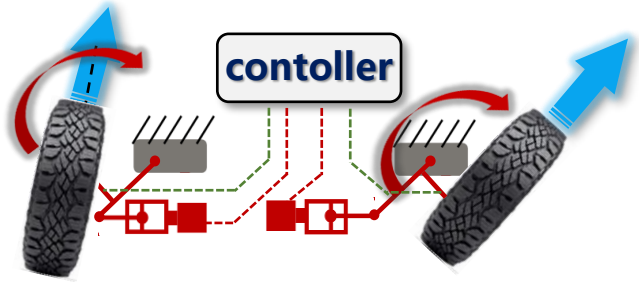


Wheel-end Driving, Braking, and Steering



Power-by-Wire
Ultimate Efficiency

Independent Wheel Control

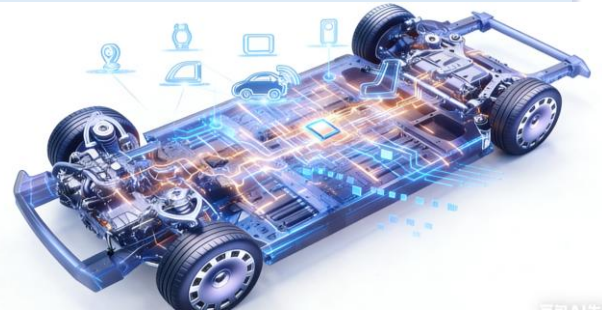


Tire-Road Adhesion → Extremum

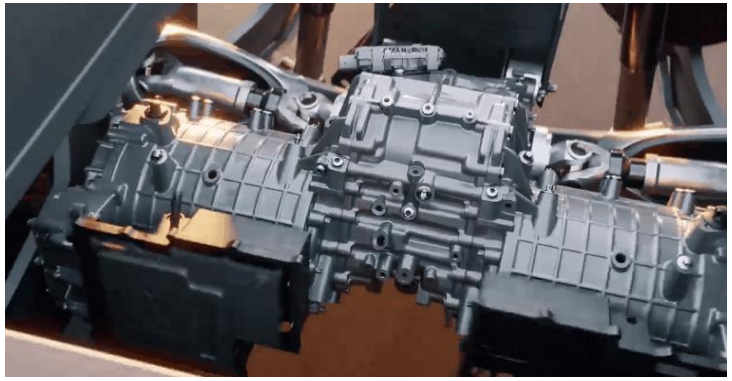


High Control DOFs
Extended Dynamic Boundaries

Software-Defined



AD-Chassis Domain Integration, Customizable Functions



The Optimal Platform for
Autonomous Driving

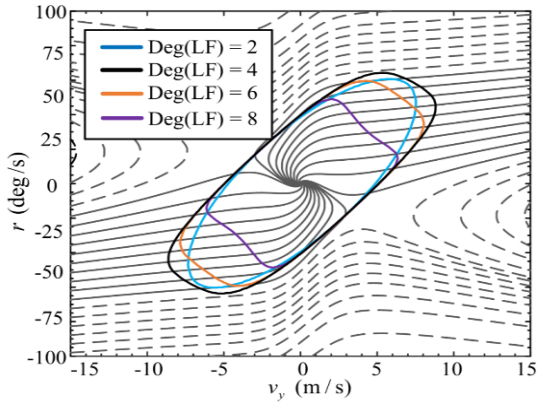
DDEV Architecture Unleashes the Potential of Vehicle Motion Control

2. Current Research Status

Current Research on Vehicle Lateral Stability Analysis

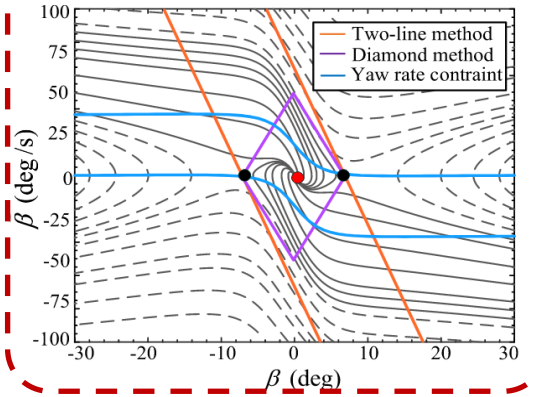
Stability Analysis Method

- Lyapunov Function Method



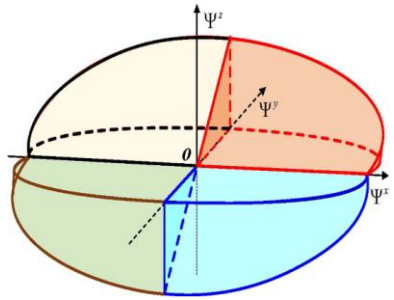
Inability to Model Complex Nonlinearities

- Phase Plane Method



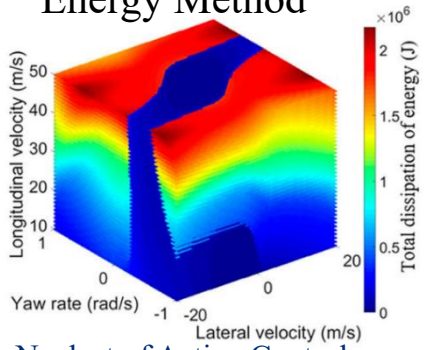
Based on open-loop assumptions

- Tire Force Analysis Method



Impractical for Real-vehicle Application

- Energy Method

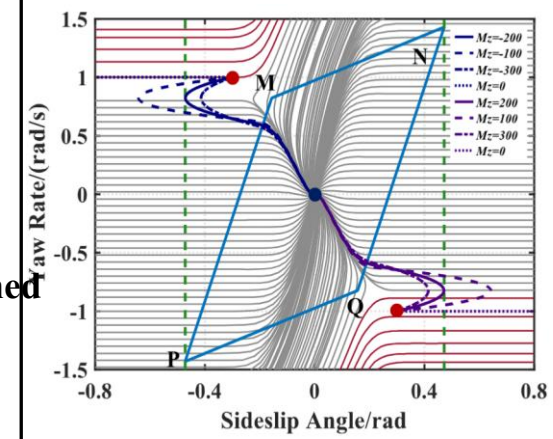


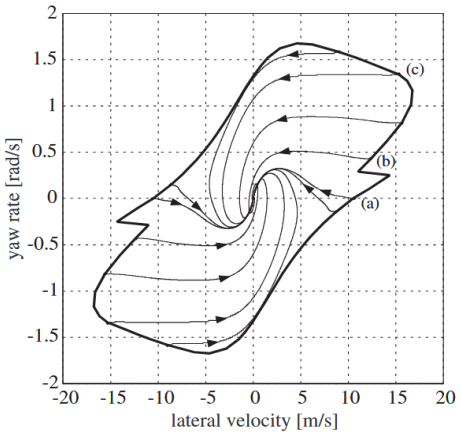
Neglect of Active Control

predetermined control sequences

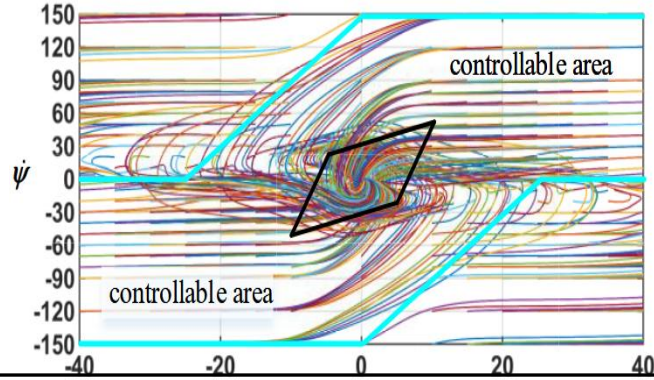
Phase Plane Considering Active Control Inputs

- Phase Trajectory Convergence via DYC:





- Phase Trajectory Convergence via AFS:

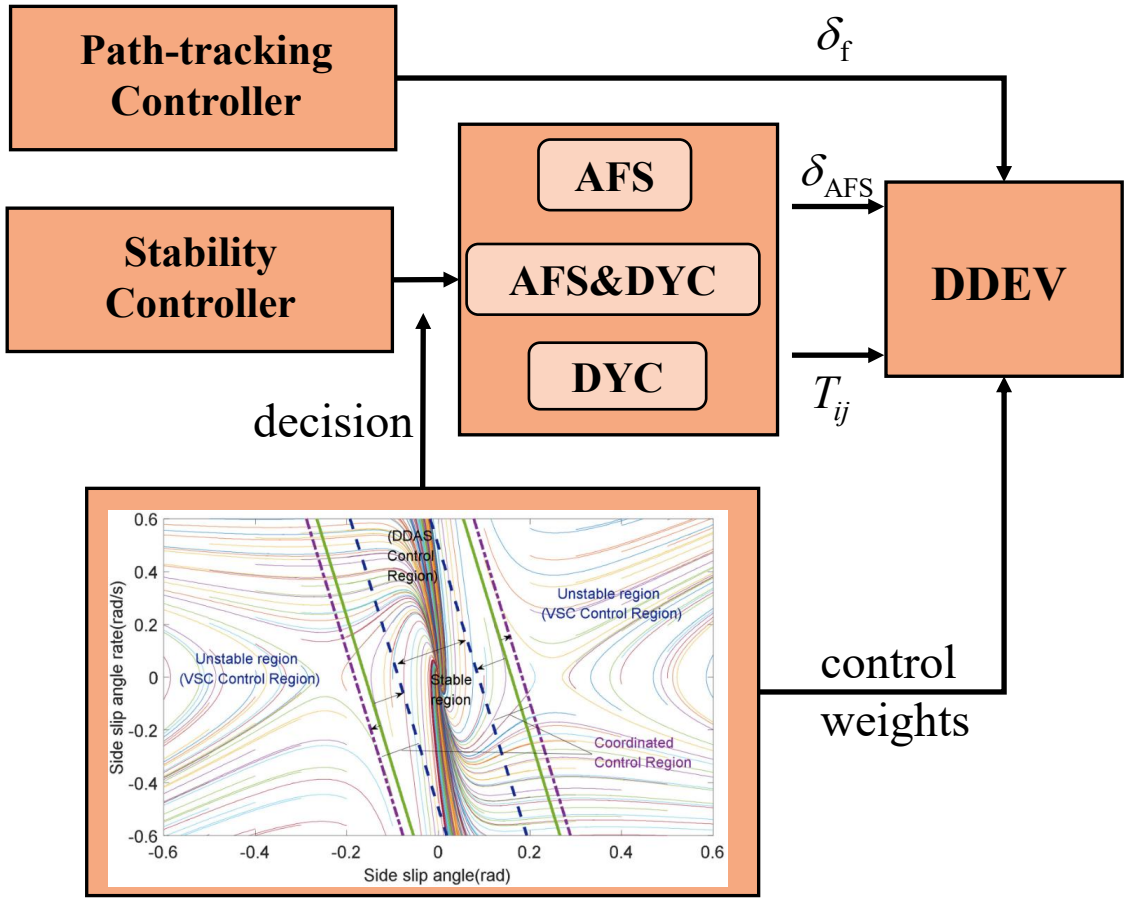


Need to Quantify Stability Characteristics Under Actual Closed-loop Control

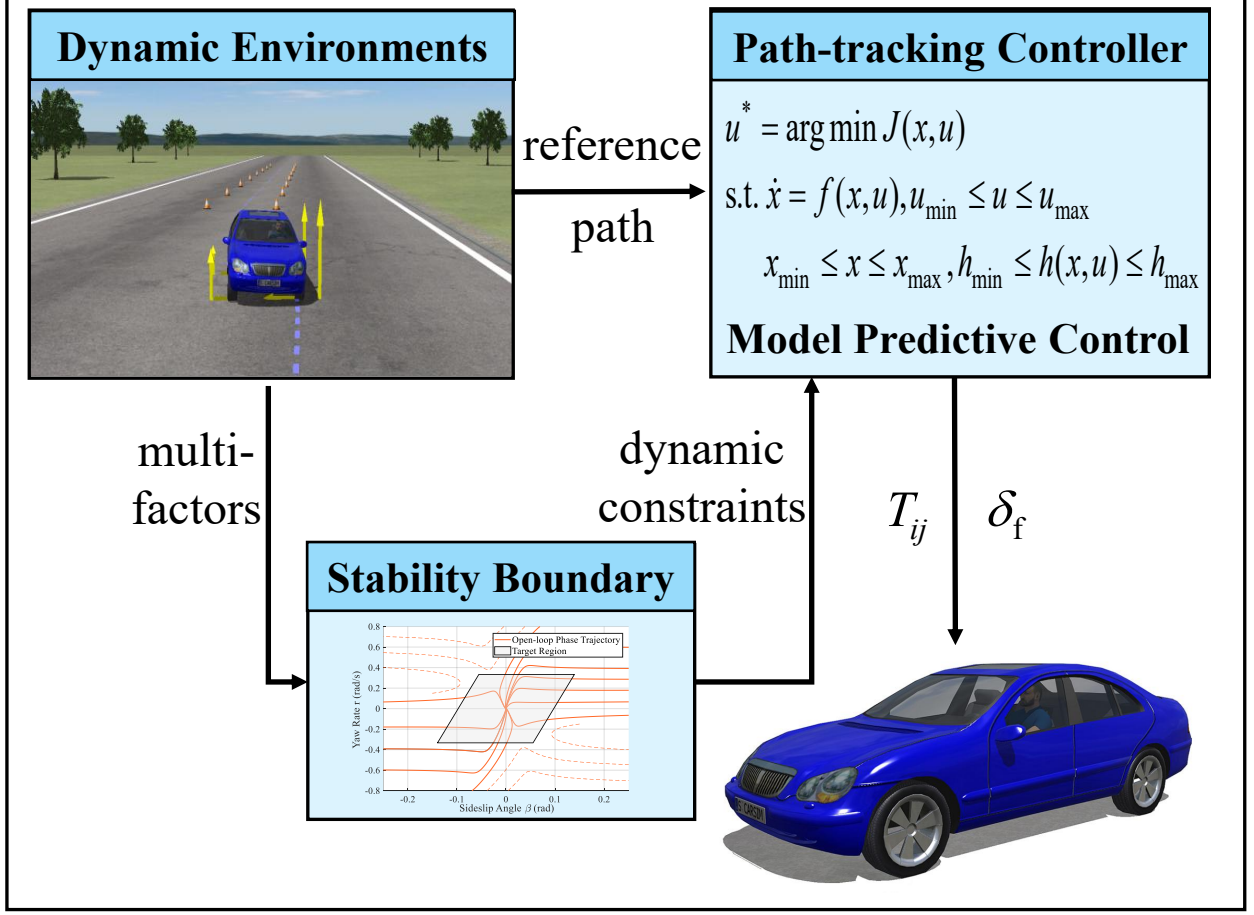
2. Current Research Status

Current Research on Coordinated Tracking and Stability Control

Coordination of Control Weights



Constraints for Optimization Framework



How to Integrate Dynamic Stability Region into Motion Control is Crucial

3. Research Content and Methodology

Targeted Problems and Main Contributions

Neglect of Closed-Loop Active Control Capabilities in Existing Stability Analysis

- Severe **load transfer and combined slip** characteristics **at the limits**.
- Existing stability analyses overlook the **stabilizing potential of active control**.

Severe Restriction of Path-Tracking Potential by Open-loop Stability Criteria

- Conservative stability region **constrains the vehicle dynamic capabilities** at the limits.
- Ensure the lateral stability of the vehicle **near the stability boundary**

A closed-loop Controlled Stability Region (CSR) Quantification Method

- Analyze phase trajectory convergence by **embedding control laws into nonlinear dynamics.**
- **Quantify the active stabilization capacity** by computing the maximal recoverable state set over a finite time horizon.

A Controlled Stability Region based Hierarchical Motion Controller (CSR-HMC)

- Constructing an offline CSR database with **multi-dimensional time-varying factors** to parameterize CSR boundaries.
- Utilize the CSR to **constrain path tracking** and quantify stability margins for **dynamic weight adjustment between tracking and stability control.**

3. Framework of the Work

Real-time Driving Environments

Construction of Controlled Stability Region (CSR)

Target Region SE

$x_{\text{ref}} = [\beta_{\text{ref}}, r_{\text{ref}}]^\top$

Initial Point

x_0

e

Stability Controller

$u^* = \arg\min J_{\text{stab}}$

$u = [T_{ij}]^\top$

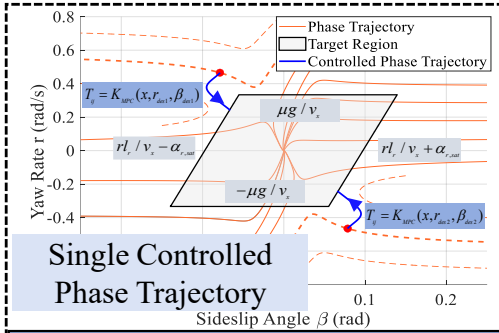
7DOF Phase Plane

$\dot{x} = f(x,u)$

$x = [\beta, r]^\top$

$x(t) = x_0 + \int_0^t f(x(\tau), u(\tau))\mathrm{d}\tau$

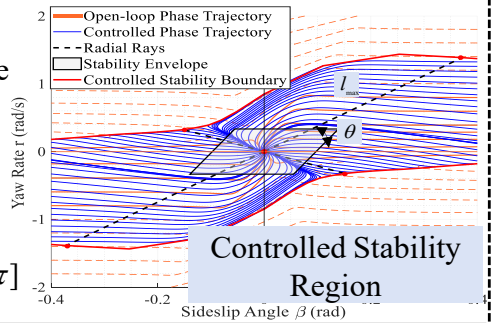
Definition of Closed-Loop Controlled Phase Trajectory



Single Controlled Phase Trajectory

Traverse

$\theta \in [0, 2\pi]$



Controlled Stability Region

Quantification of Controlled Stability Region

CSR

Architecture of Coordinated Motion Controller

$L_{\text{CSR}} = F(v_x, \mu, \delta_f, T, \theta)$

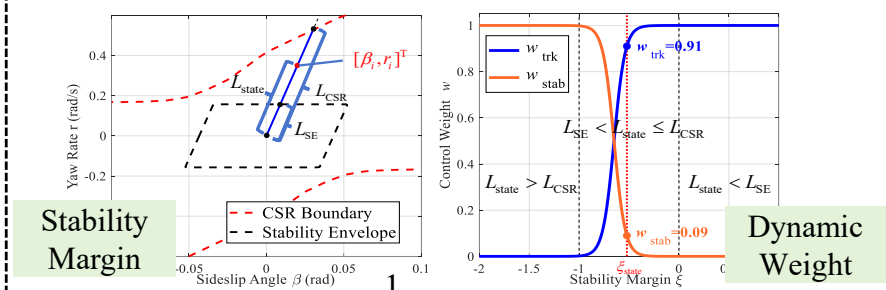
Inputs: $v_x, \mu, \delta_f, T, \theta$

CSR Dataset

Output: CSR Boundary

Controlled Stability Region Database

L_{CSR}



Stability Margin

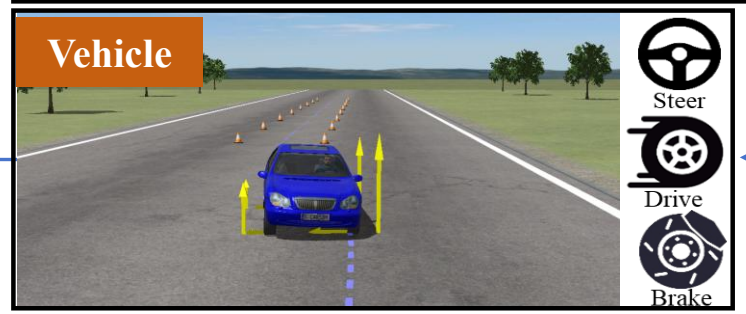
Dynamic Weight

$w_{\text{trk}} = \dfrac{1}{1+e^{a(\xi-b)}}, w_{\text{stab}} = 1 - w_{\text{trk}}$

Dynamic Weight Coordination Mechanism

$\| x_k \|_2 \le L_{\text{CSR}}(v_{x,k}, \mu_k, \delta_{fk}, T_k, \theta_k) + \rho$

$M_z = w_{\text{trk}} M_{z,\text{trk}} + w_{\text{stab}} M_{z,\text{stab}}$



δ_f

T_{ij}

QP

M_z

δ_f

Path-tracking Control Module

Stability Control Module

$u^* = \arg\min J(x,u)$

s.t. $\dot{x} = f(x,u), u_{\min} \le u \le u_{\max}$

$x_{\min} \le x \le x_{\max}, h_{\min} \le h(x,u) \le h_{\max}$

FORCESPRO

speedgoat

Controlled Stability Region based Hierarchical Motion Control (CSR-HMC)

3.1 Construction of Controlled Stability Region

Nonlinear Phase Plane Model

7 DOFs Dynamic Model

$$
\begin{cases}
\dot{v}_y = \dfrac{1}{m}\left[(F_{yfl}+F_{yfr})\cos\delta_f + (F_{xfl}+F_{xfr})\sin\delta_f + (F_{yrl}+F_{yrr})\right] - v_x r \\
\dot{v}_x = \dfrac{1}{m}\left[(F_{xfl}+F_{xfr})\cos\delta_f - (F_{yfl}+F_{yfr})\sin\delta_f + (F_{xrl}+F_{xrr})\right] + v_y r \\
\dot{r} = \dfrac{1}{I_z}\left[l_f(F_{yfl}+F_{yfr})\cos\delta_f - l_r(F_{yrl}+F_{yrr}) + M_z\right] \\
\dot{\omega}_{ij} = \dfrac{T_{ij} - F_{xij} r_w}{I_w}, (ij \in \{\text{fl, fr, rl, rr}\}), \beta = \arctan\left(\dfrac{v_y}{v_x}\right) \\
M_z = \dfrac{B_f}{2}(F_{xfr}-F_{xfl})\cos\delta_f + l_f(F_{xfl}+F_{xfr})\sin\delta_f + \dfrac{B_r}{2}(F_{xrr}-F_{xrl})
\end{cases}
$$

$+$

Combined-slip Magic Formula Tire Model

$$
\begin{cases}
F_{x0/y0} = D\sin\left\{C\arctan\left[Bx - E(Bx - \arctan(Bx))\right]\right\} \\
\lambda_{ij} = \dfrac{v_{xij} - r_w\omega_{ij}}{v_{xij}} \\
\alpha_{fl/r} = \arctan\left(\dfrac{v_y + l_f r}{v_x \mp \dfrac{B_f}{2} r}\right) - \delta_f, \alpha_{rl/r} = \arctan\left(\dfrac{v_y - l_r r}{v_x \mp \dfrac{B_r}{2} r}\right) \\
\sigma_x = -\dfrac{\lambda}{1+\lambda}, \sigma_y = -\dfrac{\tan\alpha}{1+\lambda}, \sigma = \sqrt{\sigma_x^2 + \sigma_y^2} \\
F_x = \dfrac{\sigma_x}{\sigma} F_{x0}, F_y = \dfrac{\sigma_y}{\sigma} F_{y0}
\end{cases}
$$

$$x = [v_y, v_x, r, \omega_{ij}]^\top \qquad u = [T_{ij}]^\top = K(x)$$

$$\dot{x} = f(x, u)$$

$$x_0 = [v_{y0}, v_{x0}, r_0, \omega_{ij0}]^\top$$

$$x(t) = x_0 + \int_0^t f(x(\tau), u(\tau))\,\mathrm{d}\tau = \phi(t; x_0, u(\cdot))$$

3.1 Construction of Controlled Stability Region

Definition of Controlled Stability Region

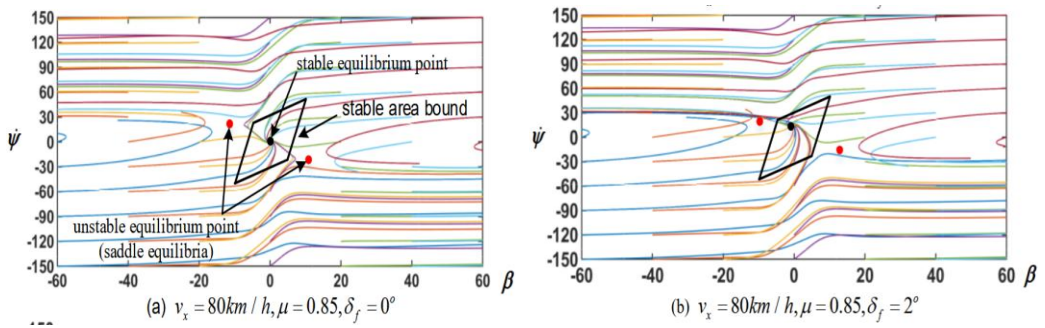
Backward Reachable Set (BRS) $R_b(T,\Omega_{\text{target}})$ denotes the set of all initial states capable of reaching a specified target set within a defined time horizon T under admissible control inputs U:

$$R_b(T,\Omega_{\text{target}}) = \left\{x_0 \in \mathcal{X} \mid \exists u \in U, \phi(T;x_0,u) \in \Omega_{\text{target}}\right\}$$

Theorem 1: If the target set Ω_{target} is a subset of the stability region containing stable equilibrium points, the BRS $R_b(T,\Omega_{\text{target}})$ constitutes the CSR of the nonlinear system $\dot{x} = f(x,u)$

The Stability Envelope (SE) is used as the target set:

$$\begin{cases} -\dfrac{\mu g}{v_x} \le r \le \dfrac{\mu g}{v_x} \\ \dfrac{rl_r}{v_x} - \alpha_{r,\text{sat}} \le \beta \le \dfrac{rl_r}{v_x} + \alpha_{r,\text{sat}} \\ \delta_{\max} = \arctan\left(\dfrac{(l_f + l_r)\mu g}{v_x^2} - \tan(\alpha_{r,\text{sat}})\right) + \alpha_{f,\text{sat}} \end{cases}$$



(a) $v_x = 80km/h, \mu = 0.85, \delta_f = 0°$ (b) $v_x = 80km/h, \mu = 0.85, \delta_f = 2°$

Target Region

$x_{\text{stab,ref}} = [\beta_{\text{ref}}, r_{\text{ref}}]^\top$

$u^*_{\text{stab}} = \arg\min_{u_{\text{stab}}} J_{\text{stab}}$

MPC Control

Design of MPC-based Stability Controller

The predictive model $\dot{x}_{\text{stab}} = f(x_{\text{stab}}, u_{\text{stab}})$, the state vector is defined as $x_{\text{stab}} = [\beta, r]^\top$, the control vector is $u_{\text{stab}} = [M_{z,\text{stab}}]^\top$, the objective function is formulated as:

$$J_{\text{stab}} = \int_t^{t+T_p} w_{\text{stab-ref}} (x_{\text{stab}} - x_{\text{stab,ref}})^2 \,\mathrm{d}t + \int_t^{t+T_p} w_{\text{stab-u}} (u_{\text{trk}})^2 \,\mathrm{d}t + \int_t^{t+T_p} w_{\text{stab-}\Delta u} (\Delta u_{\text{trk}})^2 \,\mathrm{d}t$$

the reference state vector is $x_{\text{stab,ref}} = [\beta_{\text{ref}}, r_{\text{ref}}]^\top$ which is the boundary of Stability Envelope (SE).

$$u^*_{\text{stab}} = \arg\min_{u_{\text{stab}}} J_{\text{stab}}$$
$$\text{s.t. } \dot{x}_{\text{stab}} = f(x_{\text{stab}}, u_{\text{stab}})$$
$$u_{\text{stab,min}} \le u_{\text{stab}} \le u_{\text{stab,max}}$$

the $u_{\text{stab,min}}$ and $u_{\text{stab,max}}$ are governed by the tire adhesion limits. The direct yaw moment is allocated to the four-wheel torques via a quadratic programming (QP) optimization problem:

$$\min_z \frac{1}{2} z^\top W z$$
$$\text{s.t. } A_{\text{eq}} z = b_{\text{eq}}, \quad z_l \le z \le z_u$$

where $z = [F_{x\text{fl}}, F_{x\text{fr}}, F_{x\text{rl}}, F_{x\text{rr}}]^\top$, $W = \text{diag}(w_f, w_f, w_r, w_r)$,

$A_{\text{eq}} = [-\frac{B_f}{2}\cos\delta_f + l_f \sin\delta_f, \frac{B_f}{2}\cos\delta_f + l_f \sin\delta_f, -\frac{B_r}{2}, \frac{B_r}{2}]$

$b_{\text{eq}} = M_{z,\text{stab}}, z_l = -\mu F_{zij}, z_u = \mu F_{zij}$ $\quad u = r_w z$

3.2 Construction of Controlled Stability Region

Quantification of Controlled Stability Region

Target Region SE

$x_{ref} = [\beta_{ref}, r_{ref}]^\top$

Initial Point

x_0

Stability Controller

$u^* = \arg\min J_{stab}$

$u = [T_{ij}]^\top$

7DOF Phase Plane

$\dot{x} = f(x,u)$

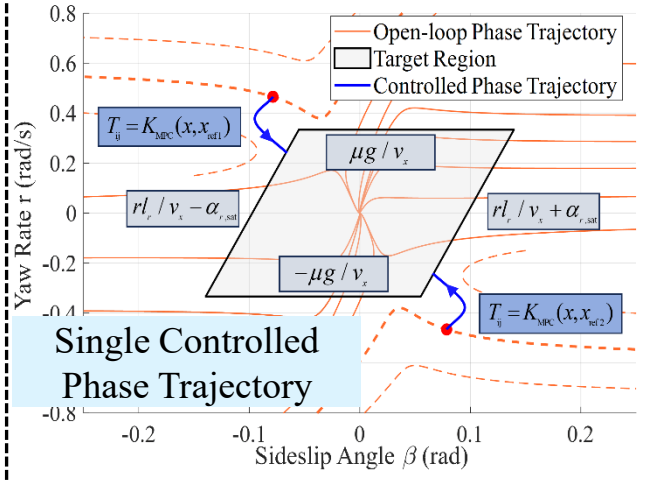
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$x = [\beta, r]^\top$

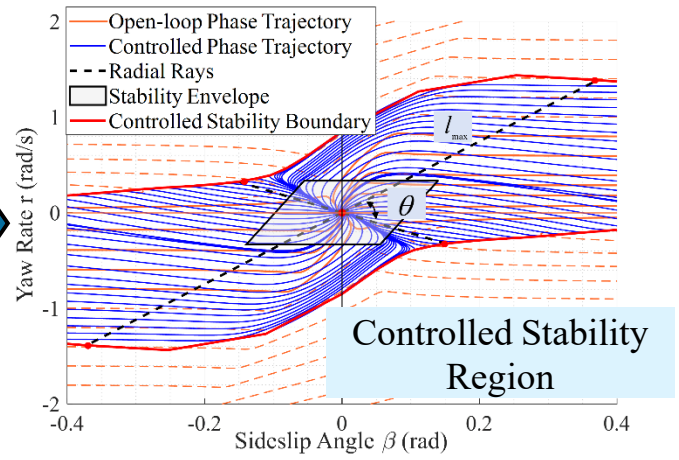
$x(t) = x_0 + \int_0^t f(x(\tau),u(\tau))\mathrm{d}\tau$

Theorem 1

$x(t) = x_0 + \int_0^T f(x(\tau),u(\tau))\mathrm{d}\tau \xrightarrow[\text{traverse}]{\theta \in [0,2\pi]} \mathcal{L}_{CSR} = \{l_{max}(\theta;T) \mid \theta \in [0,2\pi]\}$



Single Controlled Phase Trajectory



Controlled Stability Region

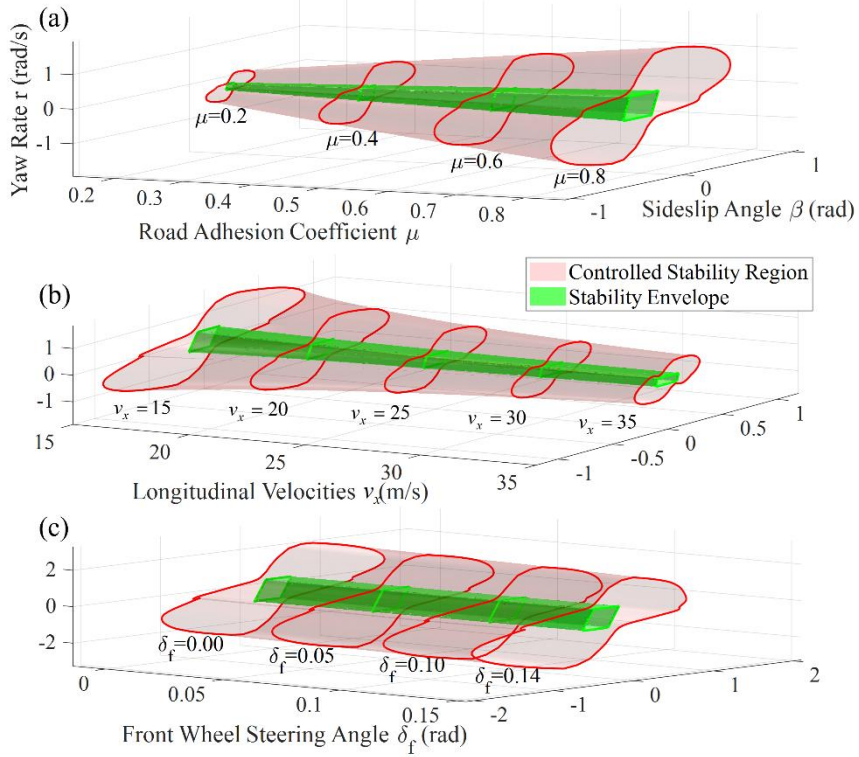
Construction of CSR Database

$L_{CSR} = F(v_x, \mu, \delta_f, T, \theta)$

Inputs: $v_x, \mu, \delta_f, T, \theta$

CSR Dataset

Output: CSR Boundary



3.2 Hierarchical Motion Control Architecture

Design of Path Tracking Controller

The predictive model $\dot{x}_{\text{trk}} = f(x_{\text{trk}}, u_{\text{trk}})$, the state vector is $x_{\text{trk}} = [\beta, r, \psi, X, Y]^{\top}$, the control vector is $u_{\text{trk}} = [M_{z,\text{trk}}, \delta_f, \rho]^{\top}$, the objective function is formulated as:

$$J_{\text{trk}} = \int_t^{t+T_p} w_{\text{trk-ref}} (x_{\text{trk-cur}} - x_{\text{trk-ref}})^2 \, \mathrm{d}t$$
$$+ \int_t^{t+T_p} w_{\text{trk-u}} (u_{\text{trk}})^2 \, \mathrm{d}t + \int_t^{t+T_p} w_{\text{trk-}\Delta u} (\Delta u_{\text{trk}})^2 \, \mathrm{d}t$$

where $x_{\text{trk-cur}} = [Y, \psi]^{\top}$ and $x_{\text{trk-ref}} = [Y_{\text{ref}}, \psi_{\text{ref}}]^{\top}$ are the current and reference state vectors, Y_{ref} and ψ_{ref} represent the reference lateral position and heading angle.

To ensure the stability of the optimization problem, the CSR is integrated into the controller as a state constraint:

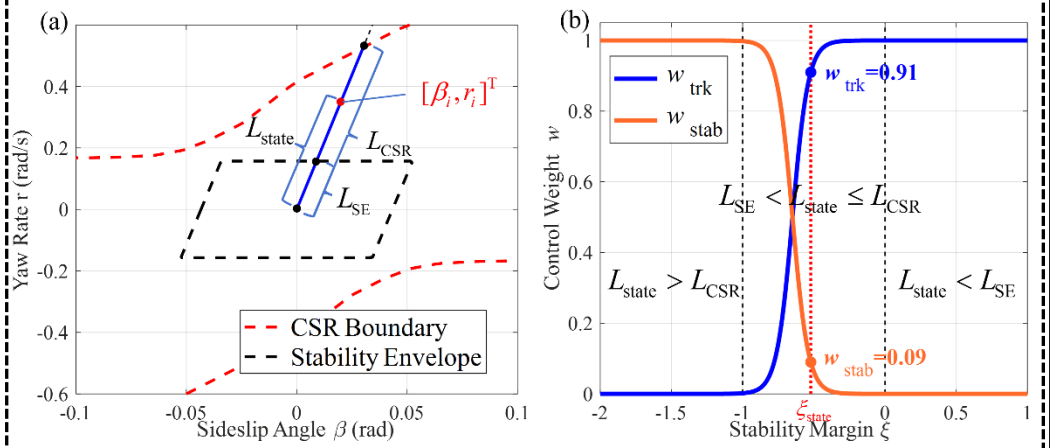
$$\| x_k \|_2 \le L_{\text{CSR}} (v_{x,k}, \mu_k, \delta_f, T_k, \theta_k) + \rho$$

The path-tracking control problem is cast as the following optimization problem:

$$u_{\text{trk}}^{*} = \arg\min_{u_{\text{trk}}} J_{\text{trk}}$$
$$\text{s.t.} \quad u_{\text{trk-min}} \le u_{\text{trk}} \le u_{\text{trk-max}}$$
$$h_{\text{trk-min}} \le h(x_{\text{trk}}) \le h_{\text{trk-max}}$$

where the upper bounds of the control variables are $u_{\text{trk-max}} = [M_{z,\max}, \delta_{\max}, \rho_{\max}]^{\top}$, and $\delta_{\max}$ is the maximum steady-state front steering angle. The constraint functions are defined as $h(x_{\text{trk}}) = \Gamma x_k - \rho$, $h_{\text{trk-min}} = -\infty$, $h_{\text{trk-max}} = L_{\text{CSR}}$.

Design of Coordinated Motion Controller



parameters $L_{\text{SE}}, L_{\text{state}} = \| x_i \|_2, L_{\text{CSR}}$ are the radial length of the SE boundary, the radial length of the current state vector $x_i = [\beta_i, r_i]^{\top}$ and the radial length of the CSR boundary at the current state.

$$\begin{cases} \dfrac{L_{\text{SE}} - L_{\text{CSR}}}{L_{\text{SE}}}, & \text{if } L_{\text{state}} \le L_{\text{SE}} \\ \dfrac{L_{\text{SE}} - L_{\text{state}}}{L_{\text{CSR}} - L_{\text{SE}}}, & \text{if } L_{\text{SE}} < L_{\text{state}} \le L_{\text{CSR}} \\ -1 - \dfrac{L_{\text{state}} - L_{\text{CSR}}}{L_{\text{CSR}}}, & \text{if } L_{\text{state}} > L_{\text{CSR}} \end{cases} \qquad w_{\text{trk}} = \frac{1}{1 + e^{a(\xi - b)}}, w_{\text{stab}} = 1 - w_{\text{trk}}$$

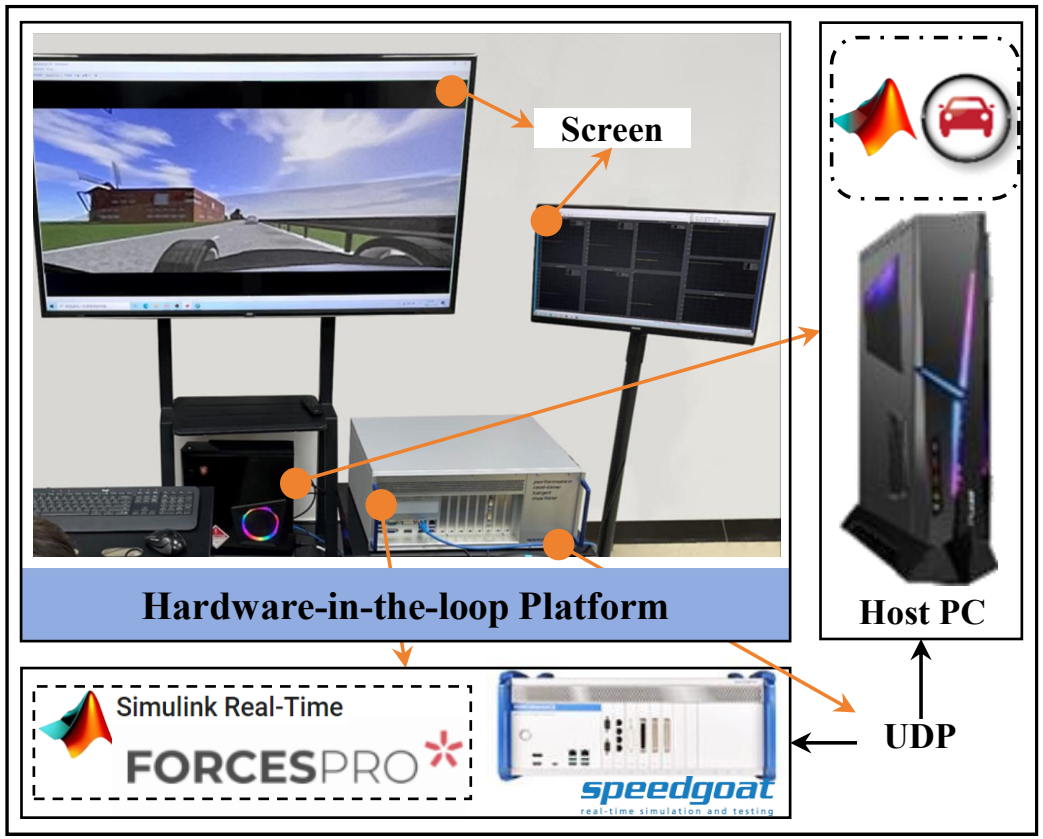
$$\delta_{\text{f}}, M_z = w_{\text{trk}} M_{z,\text{trk}} + w_{\text{stab}} M_{z,\text{stab}}$$

$$\delta_{\text{f}} \downarrow \quad T_{\text{ij}} \, (\text{QP})$$



3.3 Simulation Platform

Hardware-in-the-Loop Platform (HiL)



F-class Sedan



PARAMETERS OF THE TEST VEHICLE

Parameter	Value	Parameter	Value
m	2045 kg	r_w	0.345 m
I_z	4095 kg · m^2	l_f, l_r	1.265, 1.895 m
I_w	2 kg · m^2	B_f, B_r	1.605 m

3.4 Simulation Results

Single Lane Change under μ=0.2, v_x=90km/h

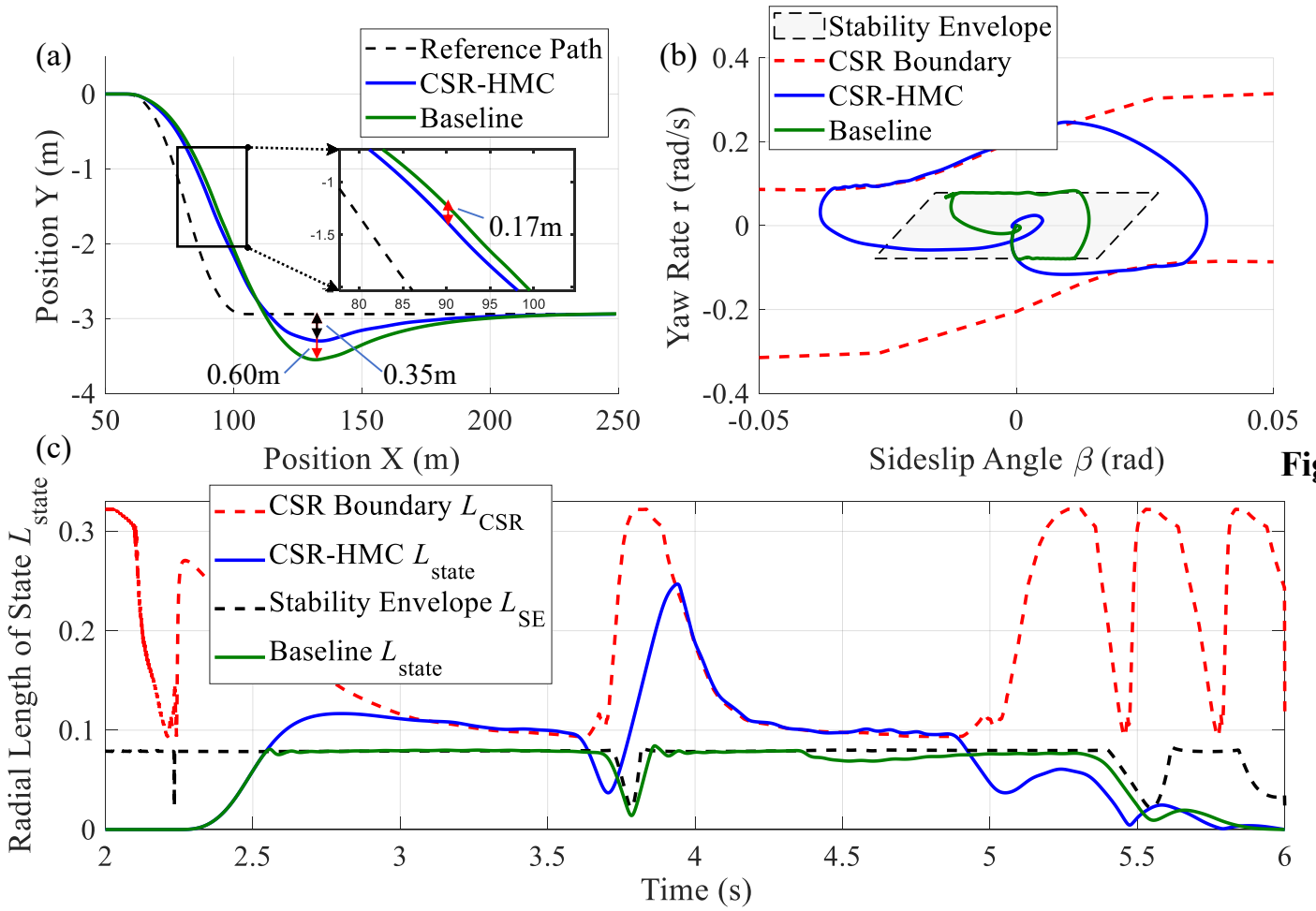


Fig. 1. Tracking performance. (a) X-Y tracking results; (b) Phase plane trajectory; (c) Radial length of the state.

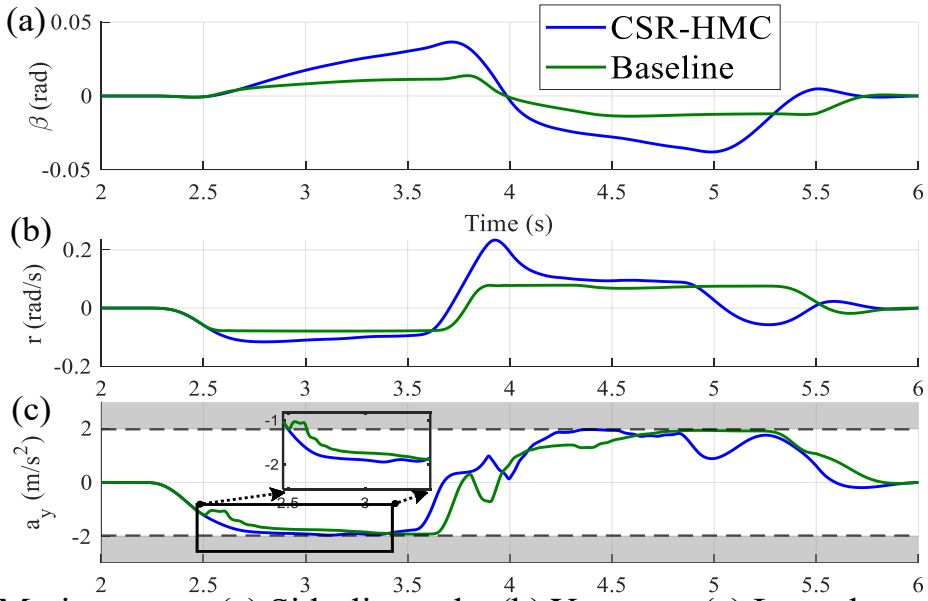


Fig. 2. Motion states. (a) Sideslip angle; (b) Yaw rate; (c) Lateral acceleration.



3.4 Simulation Results

Double Lane Change under μ=0.8, v_x=120km/h

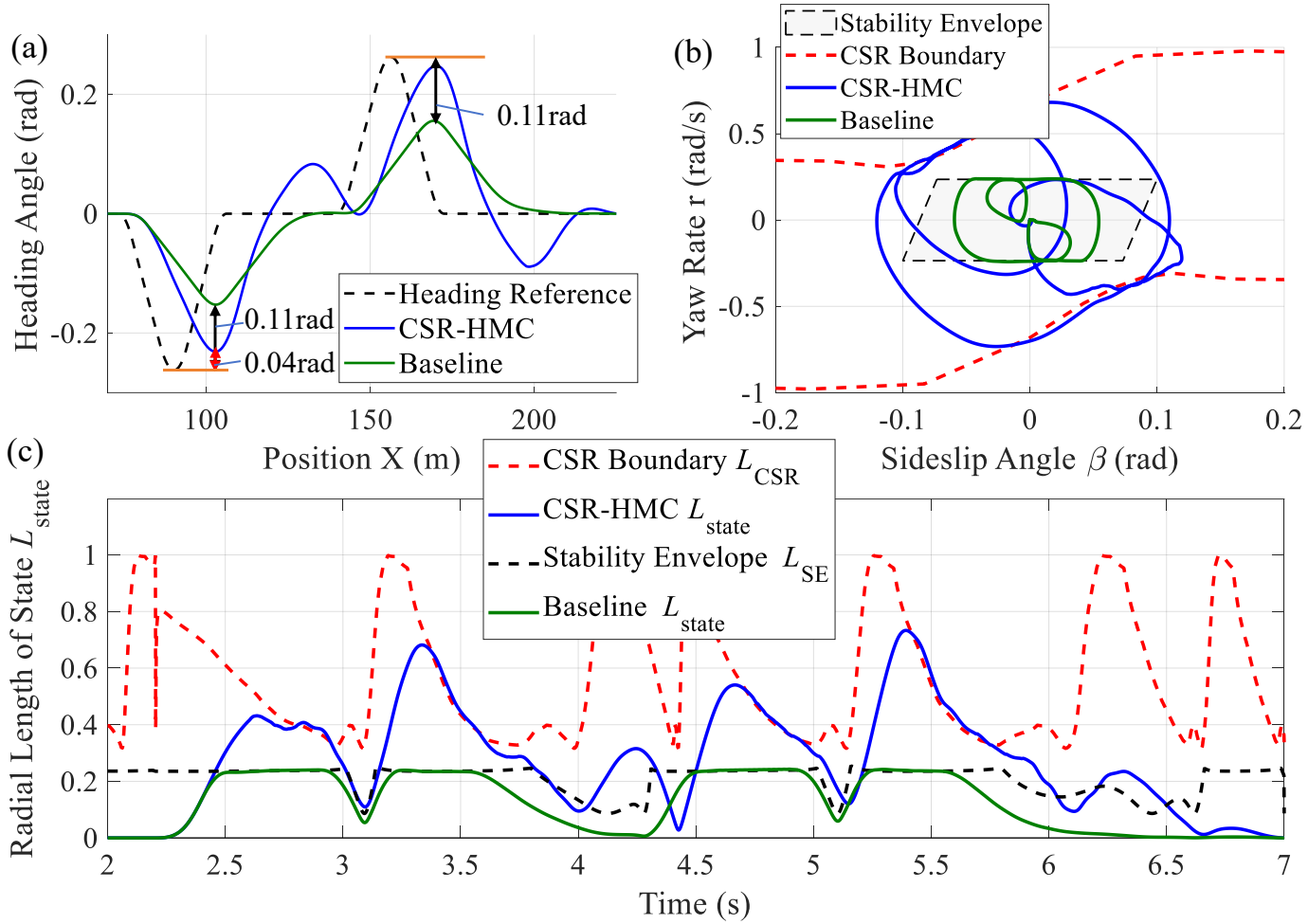


Fig. 3. Tracking performance. (a) Heading tracking results; (b) Phase plane trajectory; (c) Radial length of the state.

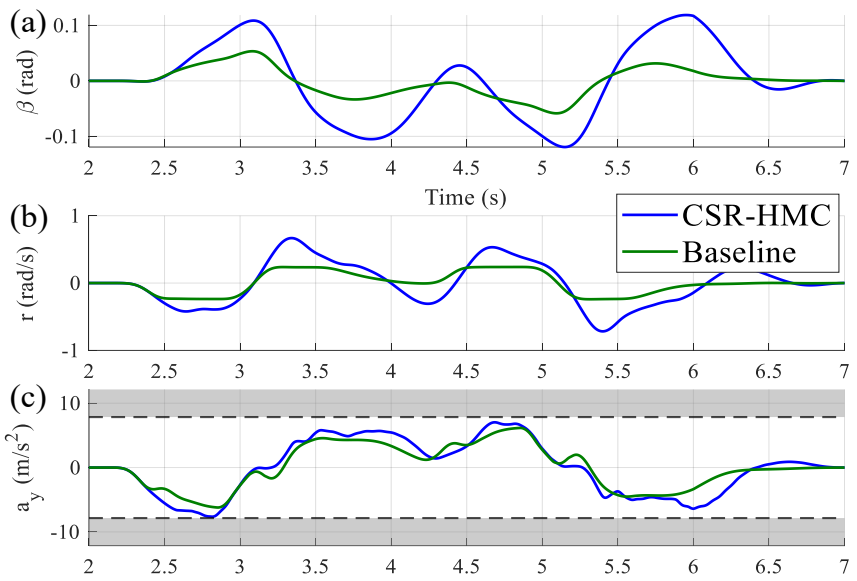


Fig. 4. Motion states. (a) Sideslip angle; (b) Yaw rate; (c) Lateral acceleration.



4. Future Work

Hybrid Model- and Data-Driven Motion Control

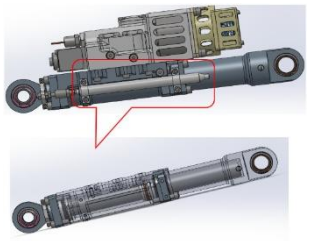
- Residual Reinforcement Learning for Emergency Obstacle Avoidance
- Real-Vehicle Experimental Validation of the Control Algorithm

5.1 Real Vehicle Platform-4WD Electric Vehicle





Steer-by-Wire



Electro-Hydrostatic Actuator (EHA)





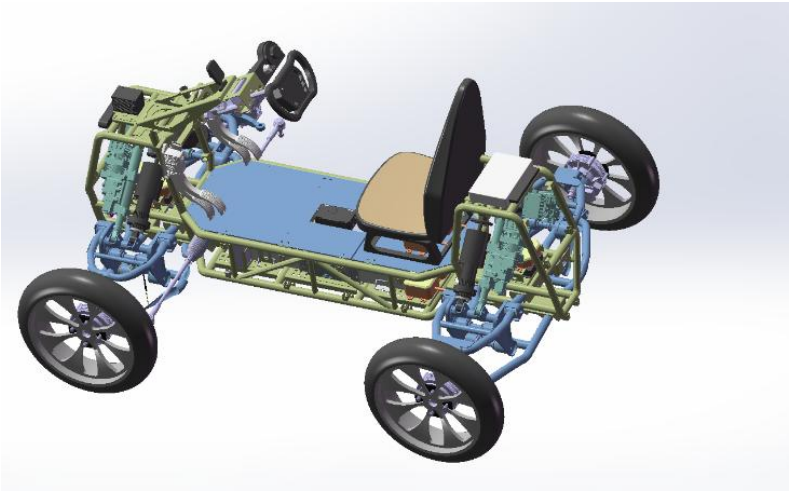
In-Wheel Motor



Controller-ECU

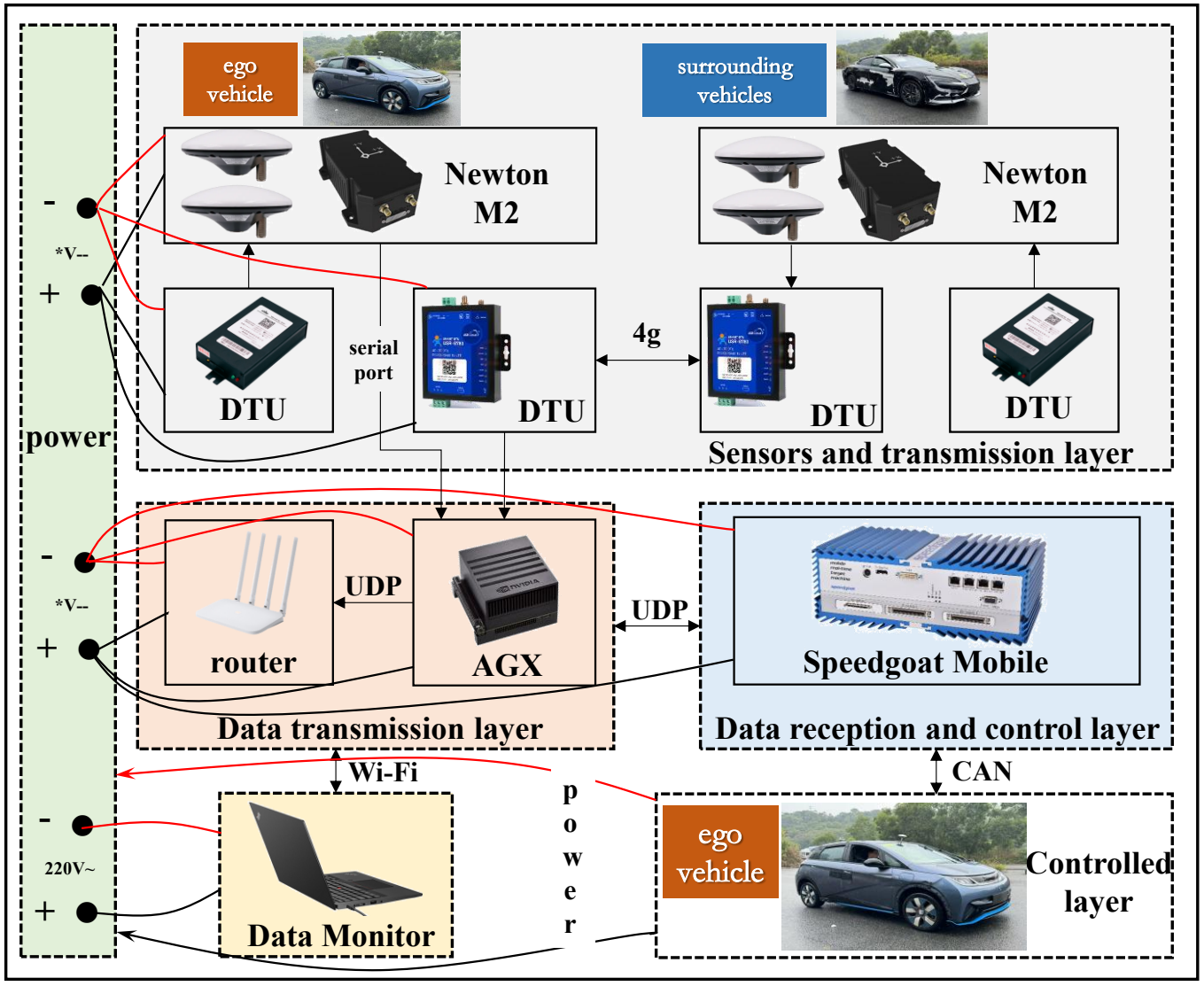


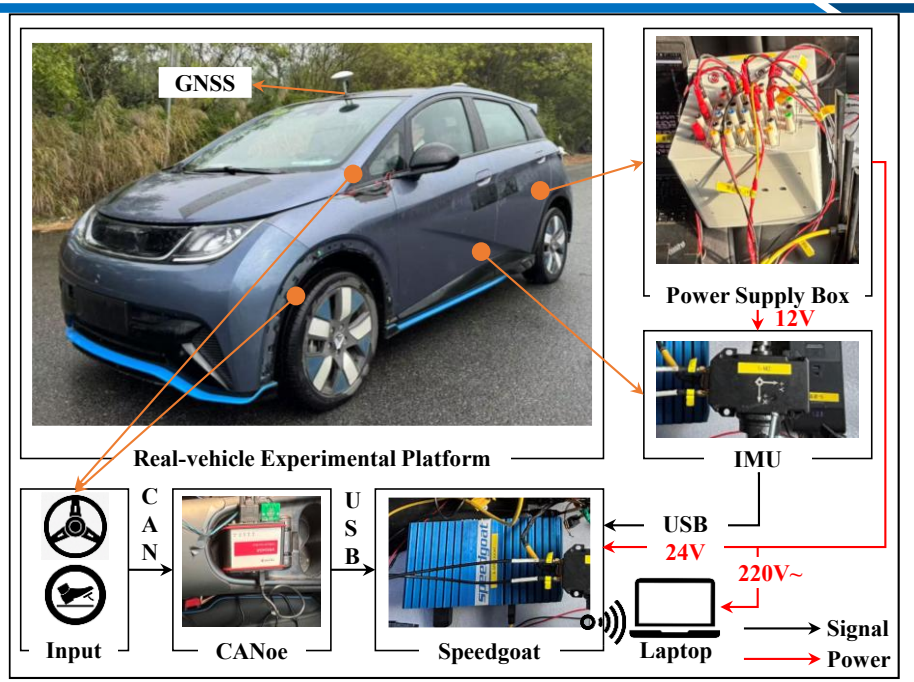
IMU&GPS



4WD Electric Vehicle

5.2 Real Vehicle Platform-BYD





MCTP: A Multi-Coupled Dynamics Trajectory Planning Scheme for Autonomous Driving in Extreme Conditions

Thanks

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