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Robust Torque Distribution Control with Energy Optimization for Four-Wheel Electric Vehicles

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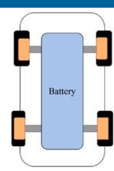
1. Introduction

automotive industry trends
CASE

Control system of 4-IWM EV
- Body motion control
- Energy consumption

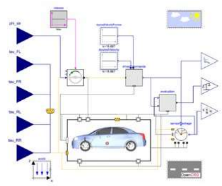


Benchmark Problems

Design the controller which has 5 control inputs (steering angle δ, each torque τ_{ij})

Task1: Speed tracking

Task2: Double lane change



Some of the previous researches
- MPC for energy management [1]
- Robustness against disturbances by SMC [2]

We proposed the torque distribution control Strategy which consider both of them

1. **Robust vehicle motion control**
2. **Energy Optimization**

2. Control System Design

The steering angle δ is governed by default controller.
This research focuses on **designing a controller that optimizes the torque distribution.**

The control architecture consists of two layers:
1. Robust vehicle motion control
2. Torque allocation

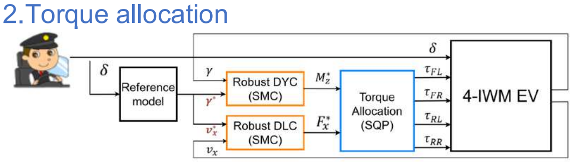


Fig.1 control architecture

2.1 Robust vehicle motion control

It aims **robustness against disturbances and model uncertainties** through DYC and DLC by using SMC.

①**DYC** (Direct Yaw Moment Control)

It contributes a yaw moment M_z^* to track the desired yaw rate γ^*

②**DLC** (Direct Longitudinal Force Control)

It contributes a longitudinal force F_x^* to track the desired speed v_x^*.

Designing SMC

Hyperplanes: $s_1 = \gamma - \gamma^*, \quad s_2 = v_x - v_x^*$

The control inputs:

$$\begin{cases} M_z = -(f_1 + \widehat{D_1} + k_{11} \cdot sign(s_1) + k_{12} \cdot s_1) \\ F_x = -(f_2 + \widehat{D_2} + k_{21} \cdot sign(s_2) + k_{22} \cdot s_2) \end{cases}$$

2.2 Torque allocation

It aims to **minimize power consumption**, while satisfying the desired yaw moment M_z^* and longitudinal force F_x^*.
SQP is employed to optimize this torque distribution.

$$\min_{\tau_{ij}} \sum_{ij=1}^{4} V_b I_{ij}(\tau_{ij})$$

$$\text{s.t.}: \begin{cases} I_{ij} = -Q_b \cdot S\dot{o}C_{ij} \\ S\dot{o}C_{ij} = \dfrac{-V_b + \sqrt{V_b^2 - 4RP_{ij}}}{2RQ_b} \\ P_{ij} = \tau_{ij}\omega_{ij} \\ F_x^* - F_x(\tau_{ij}) = 0 \\ M_z^* - M_Z(\tau_{ij}) = 0 \\ -75 \le \tau_{ij} \le 75 \end{cases}$$

3. Results

3.1 Task1: Speed tracking

Fig.2,3 shows the control inputs obtained from the controller.
Simulation are presented in Table 1.

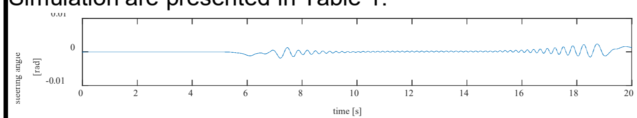


Fig.2 steering angle of Task1

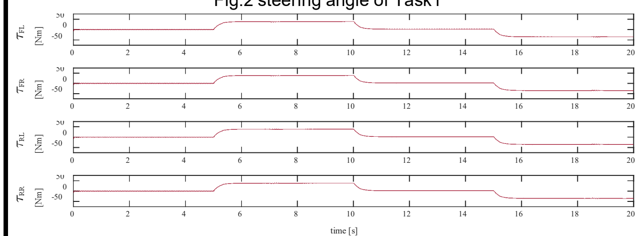


Fig.3 each torque of Task1

- Energy consumption $J_e = \int_0^{t_e} E(t)dt$
- Speed tracking $J_{v1} = \int_0^{t_e} \{v_x(t) - v_x^*(t)\}dt$
- Route following $J_{xy} = \int_0^{t_e} [\{x(t) - x^*(t)\}^2 + \{y(t) - y^*(t)\}^2]dt$

$a_z \cdots$ Vertical acceleration
$\phi \cdots$ Roll angle
$\psi \cdots$ Pitch angle

J_e	J_{v1}	$\max\lvert a_z\rvert, (a_{zt})$	$\max\lvert\phi\rvert, (\phi_t)$	$\max\lvert\psi\rvert, (\psi_t)$
191.3	13.37	0.7584, (1.4)	0.0078, (0.004)	0.0023, (0.0015)

Table1 simulation results of Task1

3.2 Task2: Double lane change

Fig.4,5 shows the control inputs obtained from the controller.
Simulation are presented in Table 2.

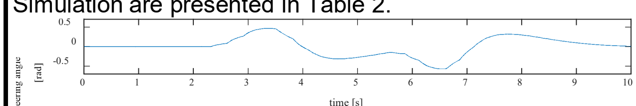


Fig.4 steering angle of Task2

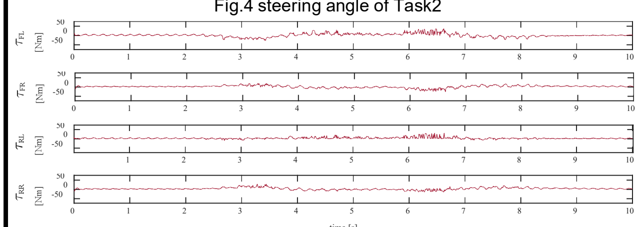


Fig.5 each torque of Task2

J_e	J_{v2}	$\max\lvert a_z\rvert, (a_{zt})$	$\max\lvert\phi\rvert, (\phi_t)$	$\max\lvert\psi\rvert, (\psi_t)$
5.24×10^4	0.752	2.601, (1.4)	0.025, (0.7)	0.0039, (0.14)

Table2 simulation results of Task2

4. Conclusion

- Our study presents **the torque distribution strategy to optimize both robust motion control and energy consumption.**
- **The two-layer control strategy demonstrates remarkable performance** in terms of robustness and energy efficiency.
- However, this proposed method **was unable to satisfy the vehicle constraint of vertical acceleration a_z.**

[1] S. H. Kim and K.-K. K. Kim, 'Model Predictive Control for Energy-Efficient Yaw-Stabilizing Torque Vectoring in Electric Vehicles With Four In-Wheel Motors', IEEE, 2023
[2] S. Ding, L. Liu, and W. X. Zheng, 'Sliding Mode Direct Yaw-Moment Control Design for In-Wheel Electric Vehicles', IEEE, 2017,