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MODEL REFERENCE ADAPTIVE CONTROL BASED MOPID CONTROLLER FOR INDEPENDENT STEER-BY-WIRE SYSTEM

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A thesis submitted
in fulfillment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "Model Reference Adaptive Control Based MOPID Controller for Independent Steer-By-Wire System" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :...

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Date : 18/6/2025

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Enigineering.

Signature :..

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Date : 18/6/2025

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DEDICATION

To my beloved mother and father.

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ABSTRACT

Recent developments in Steer-by-Wire (SBW) systems have opened new possibilities for vehicle steering without mechanical linkages. However, most existing research either applies advanced control strategies to simplified vehicle models or uses basic controllers on high-fidelity models, limiting the accuracy of performance evaluation. This study addresses that gap by integrating a Model Reference Adaptive Control (MRAC) strategy with a comprehensive 14 Degrees of Freedom (DOF) full-vehicle model, enabling a realistic and robust assessment of an Independent Steer-by-Wire (ISBW) system. The proposed controller is implemented and tested using MATLAB Simulink and validated against CarSim as a benchmark. Simulation results from a Double Lane Change test at 110 km/h show that MRAC reduces yaw rate error from 11.67% (PID) and 16.67% (MOPID) to 3.33%, reflecting improvements of 71.45% and 80%, respectively. MRAC also maintains lateral acceleration and sideslip angle errors below 5%, outperforming conventional controllers in both accuracy and stability. These results demonstrate that combining a high-order vehicle model with an adaptive control approach yields significant improvements in steering performance, offering valuable insights for the development of safer and more responsive steering systems.

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SISTEM KAEDAH MOPID BERASASKAN MODEL RUJUKAN ADAPTIF UNTUK KEMUDI BEBAS WAYAR

ABSTRAK

Kemajuan dalam sistem kemudi kenderaan telah membawa kepada kemunculan teknologi Steer-by-Wire (SBW) yang menggantikan sambungan mekanikal bersama kawalan elektronik. Namun begitu, kebanyakan kajian terdahulu hanya menggunakan model kenderaan ringkas bersama sistem kawalan yang canggih, atau sebaliknya, menjadikan penilaian prestasi sistem kurang tepat. Kajian ini menangani jurang tersebut dengan menggabungkan strategi kawalan Model Reference Adaptive Control (MRAC) bersama model kenderaan penuh 14 Darjah Kebebasan (DOF), sekali gus membolehkan penilaian sistem Independent Steer-by-Wire (ISBW) yang lebih realistik dan menyeluruh. Model ini dibangunkan dalam perisian MATLAB Simulink dan divalidasi menggunakan perisian CarSim sebagai penanda aras. Hasil simulasi ujian Double Lane Change pada kelajuan 110 km/j menunjukkan bahawa MRAC mengurangkan ralat yaw rate daripada 11.67% (PID) dan 16.67% (MOPID) kepada 3.33%, iaitu penambahbaikan sebanyak 71.45% dan 80% masing-masing. Selain itu, MRAC mengekalkan ralat pecutan lateral dan sudut gelincir sisi di bawah 5%, dengan prestasi yang lebih unggul berbanding sistem kawalan konvensional dari segi ketepatan, kestabilan, dan tindak balas dinamik. Hasil dapatan ini membuktikan bahawa gabungan model kenderaan kompleks dengan kawalan adaptif dapat meningkatkan keupayaan sistem kemudi, ke arah kenderaan yang lebih selamat dan responsif.

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LIST OF ABBREVIATIONS

AFS	-	Active Front Steering
CG	-	Center of Gravity
DC	-	Direct Current
DLC	-	Double Lane Change
DOF	-	Degree of Freedom
EV	-	Electric Vehicle
FBD	-	Free Body Diagram
HIL	-	Hardware-in-the-Loop
IAE	-	Integral of Absolute Error
ISBW	-	Independent Steer-By-Wire
ISE	-	Integral of Squared Error
MOPID	-	Multi-Order Proportional-Integral-Derivative
MRAC	-	Model Reference Adaptive Control
PID	-	Proportional-Integral-Derivative
RA	-	Arm resistance
SBW	-	Steer-By-Wire
UTeM	-	Universiti Teknikal Malaysia Melaka
4WID-4WISEVs	-	Four-Wheel Independent Drive/Steering Electric Vehicles
4WIS	-	Four-Wheel Independent Steering

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LIST OF SYMBOLS

a_x	-	Longitudinal acceleration
a_y	-	Lateral acceleration
A	-	Frontal area of the vehicle
a	-	Distance front axle to CG
α	-	Side Slip Angle
a	-	Distance between front axle and CG
B_{b1}	-	Damping coefficient of the bearing 1
B_{b2}	-	Damping coefficient of the bearing 2
$B_{bearing1}$	-	Arm upper bearing stiffness
B_m	-	Damping due to the motor
B_{mArm}	-	Motor arm damping coefficient
B_{ms}	-	The damping coefficient of motor steering
B_{sc}	-	The damping coefficient of the steering column
B_{sc}	-	The damping coefficient of the steering column
b	-	Distance rear axle to CG
b	-	Distance between rear axle and CG
C_{df}	-	Suspension damping coefficient front
C_{dr}	-	Suspension damping coefficient rear
C_{sfl}	-	Front-left damping stiffness
C_{srl}	-	Rear-left damping stiffness
C_{srr}	-	Rear-right damping stiffness

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$\frac{de_m}{d\theta}$	-	The sensitivity
d	-	Displacement from the centre tyre to centre of the shaft
e_a	-	Motor back electromotive force (back emf)
e_m	-	The model error
F_{dfl}	-	Front-left damper force
F_{dfr}	-	Front-right damper force
F_{drl}	-	Rear-left damper force
F_{drr}	-	Rear-right damper force
F_{sfl}	-	Front-left spring force
F_{sfr}	-	Front-right spring force
F_{srl}	-	Rear-left spring force
F_{srr}	-	Rear-right spring force
F_{tfl}	-	Front-left tyre force
F_{tfr}	-	Front-right tyre force
F_{trl}	-	Rear-left tyre force
F_{trr}	-	Rear-right tyre force
F_{xfl}	-	Longitudinal force at the front-left
F_{xfr}	-	Longitudinal force at the front-right
F_{xrl}	-	Longitudinal force at the rear-left
F_{xrr}	-	Longitudinal force at the rear-right
F_{yfl}	-	Lateral force at the front-left
F_{yfr}	-	Lateral force at the front-right
F_{yrl}	-	Lateral force at the rear-left

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F_{yrr}	-	Lateral force at the rear-right
F_{zfi}	-	Normal force at the front tyre, where i indicates left or right tyre
G_m	-	Reference Model
h	-	Distance from ground to CG
I_θ	-	Pitch moment of inertia
I_φ	-	Roll moment of inertia
I_ψ	-	Yaw moment of inertia
i_a	-	Motor arm armature current
K_{b1}	-	Stiffness of the bearing 1
K_{b2}	-	Stiffness of the bearing 2
$K_{bearing1}$	-	Arm upper bearing stiffness
$K_{bearing2}$	-	Arm lower bearing stiffness
K_m	-	Torque constant of the motor
K_{sc}	-	The spring stiffness of the steering column
K_{sf}	-	Suspension spring stiffness front
K_{sfl}	-	Front-left spring stiffness
K_{sfr}	-	Front-right spring stiffness
K_{sr}	-	Suspension spring stiffness front
K_{srl}	-	Rear-left spring stiffness
K_{srr}	-	Rear-right spring stiffness
K_{tfl}	-	Front-left tyre stiffness
K_{tfr}	-	Front-right tyre stiffness
K_{tmArm}	-	Motor arm stiffness

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K_{trl}	-	Rear-left tyre stiffness
K_{trr}	-	Rear-right tyre stiffness
l	-	Wheelbase
L	-	Motor electric inductance
M_s	-	Sprung mass weight
M_{ufl}	-	Unsprung mass at the front-left
M_{ufr}	-	Unsprung mass at the front-right
M_{url}	-	Unsprung mass at the rear-left
M_{urr}	-	Unsprung mass at the rear-right
M_w	-	Mass wheel
M_z	-	Moment at the center of gravity
M_{zfi}	-	Front wheel self-aligning moment, where i indicate the left or the right tyre
M_{zfl}	-	Moment at the front-left
M_{zfr}	-	Moment at the front-right
M_{zrl}	-	Moment at the rear-left
M_{zrr}	-	Moment at the rear-right
m_t	-	Total vehicle mass
R_a	-	Motor electric resistance
R_w	-	Wheel radius
$\dot{r}$	-	Angular velocity of the vehicle around the z-axis
S_{wa}	-	Steering Wheel Angle
T_b	-	Braking torque
T_d	-	Drive Torque

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T_{ms}	-	The torque on the motor steering
T_{rr}	-	Rolling resistance torque
T_{sw}	-	Steering torque applied
T_{tr}	-	Traction torque
t	-	Track width
v_x	-	Longitudinal velocity
v_{xw}	-	Velocity at the wheel in longitudinal direction
v_y	-	Lateral velocity
$\dot{x}$	-	Longitudinal velocity of the vehicle
$\ddot{x}$	-	Longitudinal acceleration of the vehicle
$\ddot{y}$	-	Lateral acceleration of the vehicle
$\dot{y}$	-	Lateral velocity of the vehicle
$\ddot{Z}_s$	-	Acceleration of the sprung mass at the body center of gravity (CG)
$\dot{Z}_{sfl}$	-	Sprung mass vertical velocity at the front-left
$\dot{Z}_{sfr}$	-	Sprung mass vertical velocity at the front-right
$\dot{Z}_{srl}$	-	Sprung mass vertical velocity at the rear-left
$\dot{Z}_{srr}$	-	Sprung mass vertical velocity at the rear-right
$\dot{z}_{ufl}$	-	Unsprung mass vertical velocity at the front-left
$\dot{z}_{ufr}$	-	Unsprung mass vertical velocity at the front-right
$\dot{z}_{url}$	-	Unsprung mass vertical velocity at the rear-left
$\dot{z}_{urr}$	-	Unsprung mass vertical velocity at the rear-right
Z_{rfl}	-	Road profile applied to the front-left
Z_{rfr}	-	Road profile applied to the front-right

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Z_{rrl}	-	Road profile applied to the rear-left
Z_{rrr}	-	Road profile applied to the rear-right
Z_{sfl}	-	Sprung mass vertical displacement at the front-left
Z_{sfr}	-	Sprung mass vertical displacement at the front-right
Z_{srl}	-	Sprung mass vertical displacement at the rear-left
Z_{srr}	-	Sprung mass vertical displacement at the rear-right
Z_{ufl}	-	Unsprung mass vertical displacement at the front-left
Z_{ufr}	-	Unsprung mass vertical displacement at the front-right
Z_{url}	-	Unsprung mass vertical displacement at the rear-right
Z_{urr}	-	Unsprung mass vertical displacement at the rear-right
δ	-	Steering angle
$\ddot{\varphi}$	-	Body roll acceleration at CG
$\ddot{\theta}$	-	Body pitch acceleration at CG
δ	-	Steering angle
$\ddot{\psi}$	-	Yaw acceleration
ψ	-	Yaw angle
σ	-	Steering torque
ω	-	Angular velocity of the wheel
ω_{ij}	-	Angular velocity of wheel
δ	-	Steering angle
J_{sw}	-	Steering wheel inertia
$\ddot{\theta}_{sw}$	-	Steering wheel acceleration
θ_{sw}	-	Angle of the steering wheel

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θ_{ms}	-	Angle of the motor steering wheel
$\dot{\theta}_{ms}$	-	The angular velocity of the motor steering
τ_{mArm}	-	Motor arm torque
J_{mArm}	-	Moment inertia of the motor arm
J_{Arm}	-	Total integrated suspension-steering arm inertia
$\dot{\vartheta}_{mArm}$	-	Motor arm angular velocity
ϑ_{mArm}	-	Motor arm angular displacement
$\ddot{\delta}$	-	Wheel steer angular acceleration
$\dot{\delta}$	-	Wheel steer angular velocity
δ	-	Wheel steer angular displacement
θ	-	The controller parameter
γ	-	The learning rate

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