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AUTONOMOUS COLLISION AVOIDANCE SYSTEM USING COMBINED FOUR-WHEEL STEERING AND DIRECT YAW-MOMENT CONTROL

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AUTONOMOUS COLLISION AVOIDANCE SYSTEM USING COMBINED FOUR-WHEEL STEERING AND DIRECT YAW-MOMENT CONTROL

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Mechanical Engineering (Automotive)

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2021

DECLARATION

I declare that this thesis entitled "Autonomous Collision Avoidance System using combined Four-wheel Steering and Direct Yaw-moment Control" 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 : Amerin ....

Name : NUR AMALINA BINTI SHAHARUDIN

Date : 09-04-2021

APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfillment of Master of Mechanical Engineering (Automotive).

Signature	:	……………………………………………………
Supervisor Name	:	DR. AMRIK SINGH A/L PHUMAN SINGH
Date	:	09.04.2021

DEDICATION

To my beloved mother, father, husband, and my baby boy.

ABSTRACT

Nowadays autonomous vehicle becomes an important topic in the automotive research world. The evolution of an autonomous vehicle caused by the increase in an accident happened due to human error. In reducing the number of accidents that commonly happen on the road, many researchers conducted several studies on the collision avoidance system. This project will focus on modelling the eight-degree-of-freedom vehicle model using Dugoff's Tire Model and the development of the quintic polynomial trajectory generation as the reference trajectory for overtaking maneuver by reducing the jerk. Then, the integrated controller for the lateral and longitudinal dynamics is based on combined four-wheel steering control and direct yaw-moment control is designed to track the reference trajectory. The performance of the collision avoidance controller is evaluated by using MATLAB Simulink. The results show that the proposed controller is able to follow the desired trajectory of the overtaking maneuver. However, two-stage square sum minimization provides better trajectory tracking and vehicle stabilization performances compared to square sum minimization.

ABSTRAK

Pada masa kini, kenderaan autonomi menjadi topik penting dalam dunia penyelidikan automotif. Perkembangan dalam penyelidikan kenderaan autonomi adalah disebabkan oleh peningkatan kemalangan yang berlaku hasil daripada kecuaian manusia. Dalam mengurangkan jumlah kemalangan yang biasa berlaku di jalan raya, ramai penyelidik melakukan kajian mengenai sistem penghindaran perlanggaran. Projek ini akan memfokuskan pada pemodelan kenderaan lapan darjah kebebasan menggunakan Model Tayar Dugoff dan penjanaan trajektori hasil daripada lima darjah fungsi polinomial sebagai trajektori rujukan untuk mengatasi manuver dengan mengurangkan kejutan yang dihasilkan. Kemudian, pengawal bersepadu untuk dinamik sisi dan membujur berdasarkan pada gabungan kawalan stereng empat roda dan kawalan momen rewang direka untuk mengesan trajektori rujukan. Prestasi pengawal penghindaran perlanggaran dinilai dengan menggunakan MATLAB Simulink. Hasil kajian menunjukkan bahawa pengawal yang dicadangkan dapat mengikuti trajektori pergerakan manuver yang diinginkan. Walau bagaimanapun, pengurangan jmlah persegi dua peringkat memberikan prestasi trajektori pergerakan manuver dan penstabilan kenderaan yang lebih baik berbanding pengurangan jumlah persegi.

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LIST OF SYMBOLS

α	-	Tire slip angle
β	-	Vehicle sideslip angle at CG
γ	-	Yaw rate
$\dot{\gamma}$	-	Yaw acceleration
δ_f	-	Front steer angle
δ_r	-	Rear steer angle
λ	-	Arc length fraction
μ	-	Tire road friction coefficient
σ	-	Sharpness
σ_x	-	Longitudinal slip ratio of the tire
ψ_p	-	Direction of the path
ψ_{pv}	-	Direction of the vehicle relative to the direction of the path
ω	-	Wheel rotational velocity
ϕ	-	Roll angle
$a_{\max}$	-	Maximum acceleration
a_x	-	Longitudinal acceleration
a_y	-	Lateral acceleration
B	-	Stiffness factor
b	-	Coefficient of the polynomial
C	-	Shape factor
C_σ	-	Longitudinal tire stiffness
C_α	-	Cornering stiffness of the tire
$c_{\phi f}$	-	Roll damping coefficient for the front suspension
$c_{\phi r}$	-	Roll damping coefficient for the rear suspension
D	-	Peak value
E	-	Curvature factor
e_ψ	-	Heading error
$\dot{e}_x$	-	Velocity error
$\dot{e}_y$	-	Lateral error

FL	-	Front-left tire
FR	-	Front-right tire
F_r	-	Rear Tire cornering force
F_{x1}	-	Longitudinal tire force on the front-left
F_{x2}	-	Longitudinal tire force on the front-right
F_{x3}	-	Longitudinal tire force on the rear-left
F_{x4}	-	Longitudinal tire force on the rear-right
$F_{x,total}$	-	Total longitudinal force acting on the vehicle
F_{y1}	-	Lateral tire force on the front-left
F_{y2}	-	Lateral tire force on the front-right
F_{y3}	-	Lateral tire force on the rear-left
F_{y4}	-	Lateral tire force on the rear-right
$F_{y,total}$	-	Total lateral force acting on the vehicle
F_z	-	Vertical tire force
g	-	Gravitational acceleration=9.81 m/s
h_f	-	Height of the front roll centre
h_r	-	Height of the rear roll centre
h_s	-	Height of the sprung mass CG
h_{sr}	-	Height of the sprung mass CG from the roll centre of the sprung mass
h_{uf}	-	Height of the CG of front unsprung mass
h_{ur}	-	Height of the CG of rear unsprung mass
I_x	-	Roll moment of inertia
I_z	-	Yaw moment of inertia
I_ω	-	Moment of inertia for the wheel
k	-	Gradient
$k_{øf}$	-	Front roll stiffness
$k_{ør}$	-	Rear roll stiffness
L	-	Length of the path
l	-	Distance from the front to the rear axle to the CG of the vehicle
l_f	-	Distance from the front axle to the CG of vehicle
l_r	-	Distance from the rear axle to the CG of vehicle
l_w	-	Track width
M	-	Direct yaw moment
M_{opt}	-	Optimal direct yaw moment
$M_{z,total}$	-	Total yaw moment
m	-	Total mass of the vehicle
m_s	-	Sprung mass

m_{uf}	-	Front unsprung mass
m_{ur}	-	Rear unsprung mass
RL	-	Rear-left tire
RR	-	Rear-right tire
r	-	Radius of the tire
S_h	-	Horizontal shift
S_v	-	Vertical shift
s	-	Path length
T	-	Driving wheel torque
t	-	Time
V_x	-	Longitudinal velocity
V_y	-	Lateral velocity
v	-	Desired speed
W	-	Tire workload
X	-	Input variable for slip angle or slip ratio
X_1	-	Longitudinal tire force on the front-left
X_2	-	Longitudinal tire force on the front-right
X_3	-	Longitudinal tire force on the rear-left
X_4	-	Longitudinal tire force on the rear-right
X_L	-	Longitudinal tire force on the left
X_R	-	Longitudinal tire force on the right
x	-	Initial longitudinal position at starting point
x_e	-	Longitudinal distance
Y	-	Output variable for longitudinal or lateral force or aligning moment
Y_1	-	Lateral tire force on the front-left
Y_2	-	Lateral tire force on the front-right
Y_3	-	Lateral tire force on the rear-left
Y_4	-	Lateral tire force on the rear-right
y_e	-	Lane width

LIST OF ABBREVIATIONS

ADAS	-	Advanced Driver Assistance System
CG	-	Centre of gravity
DYC	-	Direct Yaw-moment Control
MPC	-	Model Predictive Control
2WS	-	Two-wheel Steering
4WS	-	Four-wheel Steering
SCP	-	Single Cartesian-polynomial

CHAPTER 1

INTRODUCTION

1.1 Background

In order to alleviate the frequency and effects of road accidents, automotive safety contributes to being one of the highest priority concerns in the construction, design of vehicles, and equipment. In developed countries, advancements in the construction of vehicles and roadways have gradually decreased accident and death rates. Passive and active safety systems that have been studied and measures have led to better progress. Several kinds of active safety systems such as the Advanced Driver Assistance System (ADAS) have been developed to help drivers cope with complicated traffic situations. The vehicles fitted with these systems are referred to as "Intelligent Vehicles".

During the past decades, the invention of autonomous and intelligent vehicles has received significant attention. Even in critical driving conditions, the motivation is to ensure efficient and safe vehicle navigation. An autonomous vehicle can respond faster than a human driver, reducing road accidents that are often caused by errors made by the driver. One of the important system in an autonomous vehicle to relieve traffic accident is called a collision avoidance system. This system has been implemented to evade collision scenarios such as lane changing, overtaking, avoiding departure, unintended road departure *etc.* The scenario of autonomous overtaking maneuver will be considered in this project. In general, overtaking maneuver is a movement of a vehicle to pass another vehicle hindered in the same lane. Overtaking maneuver is one of the intricate maneuver to carry out in autonomous vehicle control because it consists of three consecutive movements which are lane changing to the adjacent lane, then passing through the hindered vehicle and again execute lane change returning to the original lane. Shamir (2004) provide a study on estimating the time and distance to make an overtaking maneuver for a lower speed lead vehicle. The optimal lane change trajectory was used with the compliance of two limitations which are velocity to ensure the vehicle always in forwarding direction throughout the maneuver and acceleration to align with the chosen maximum acceleration during overtaking. The proposed model shows high accuracy in estimating the suitable time and position to execute the overtaking as well as total time and distance. Petrov and Nashashibi (2014) in their work come up with the development of an adaptive controller and mathematical model of three-phase overtaking maneuver for an autonomous vehicle without considering the vehicle-to-vehicle communication and pavement marking.

Towards achieve an efficient and precise collision avoidance system, various controller which are mainly based on two-wheel steering (2WS) or four-wheel steering (4WS) were proposed by researchers to track the desired path for overtaking or avoid an obstacle. The 4WS concept, in which both the front and rear wheels rotate at the same time, was proposed in the late 1980s and a few cars were equipped with this mechanism. The driver rotates the front wheels on a conventional 4WS and sends a control signal from the ECU to a rear-wheel actuator by turning the steering wheel. In the previous study, many researchers proposed a combination of 4WS with several controllers to achieve good vehicle handling and capability of path tracking in the application of the autonomous vehicle. Hiraoka *et al.* (2009) proposed a 4WS controller with sliding mode control theory to maintain the unpredictable deviation of vehicle system such as path radius, interference of crosswind and disruption of cornering power and ability to follow the path-tracking closely compare to 2WS. In a study by Mostavi and Kazemi (2014), a 4WS with an optimal controller was proved to have good and effective performance in executing vehicle lane change maneuver in the highway.

This project focus on the autonomous vehicle for overtaking maneuver based on the vehicle dynamics handling model, development of polynomial trajectory generation, and design of the trajectory tracking controller. The integrated controller for the lateral and longitudinal dynamics is based on combined four-wheel steering control and direct yaw-moment control is used to track reference trajectory. The desired path and velocity profiles define the reference trajectory. The performance evaluation of the vehicle model and controller then will be analyze using MATLAB Simulink.

1.2 Problem Statement

Schittenhelm (2011) stated that many of the accidents that happened are from overtaking maneuvers and loss of control conditions and they typically result in severe injury or fatalities. Therefore, this project focuses on collision avoidance scenario for overtaking maneuver. Yoshida *et al.* (2008) studied the conventional front-wheel steering with Model Predictive Control to obtain the steering angle input for lane-change maneuver. The controller proposed by Yoshida *et al.* (2008) was effective for collision avoidance performing the lane-change maneuver. Raksincharoensak *et al.* (2001) investigated path tracking for straight and curve paths by using 4WS. The results demonstrated that the 4WS vehicle's path tracking performance was significantly improved compared to 2WS. Hiraoka *et al.* (2009) proposed a controller of 4WS sliding mode control for automatic path tracking and the simulation results indicate that the controller was capable of following the desired path precisely compared to the 2WS controller. A study on the trajectory generation method for single lane change with the proposed trajectory tracking controller of combined 4WS sliding mode control and DYC was conducted by Singh and Nishihara (2017). The result showed that the integrated controller has improved trajectory tracking performance. However, the study by Singh and Nishihara (2017) was limited to the single lane-change maneuver. In this project, a collision-avoidance system by using integrated control of 4WS and direct yaw moment for an autonomous overtaking maneuver is developed.

1.3 Research Objective

The research objectives of this project are:

i. To develop a trajectory generation method for overtaking maneuver by using fifth order polynomials.

ii. To design a trajectory tracking controller using integrated four-wheel steering and direct yaw-moment control.

1.4 Scope of Research

This project includes the following scope:

i. Design of the trajectory tracking control system in MATLAB/Simulink environment.

ii. Evaluation of the effects of the controller on the trajectory tracking and stabilization of the vehicle.

1.5 Contribution of Research

The contributions of this research are:

i. Trajectory tracking controller by using combined 4WS and DYC for autonomous overtaking maneuver.

ii. Comparison between two optimization methods for tire workload minimization: minimization of the sum of squared tire workloads and minimization of the two-stage sum of squared tire workloads.

1.6 Thesis Outline

This thesis comprises of five chapters. The introduction chapter consists of general information of the research, the overview, problem statement, research objectives, scopes of work, and the contribution of the project have been stated in Chapter 1.

The literature review is given in Chapter 2 where the review from previous studies related to the research is being carried out. The topics enclosed for the literature review include collision avoidance scenarios, trajectory generation, trajectory tracking and vehicle dynamic model.

Chapter 3 provides the methodology used in conducting this project. A flowchart to indicate the strategy to achieve the main goal in conducting the task is included. The equations used in this project are described and MATLAB/Simulink diagrams are developed for the simulation.

Chapter 4 presents the results and discussions. The performance of the integrated controller in collision avoidance is discussed. Finally, the conclusions about the proposed control system and the recommendations for improvement are provided in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section purposes to review previous studies related to the research being carried out. It concentrates on reviewing literature in the areas surrounding the collision avoidance scenarios, trajectory generation, trajectory tracking, and vehicle dynamic model. Some related works of literature will be reviewed and discussed in this chapter.

2.2 Collision Avoidance Scenarios

In most transportation networks and many other applications, preventing collisions is a crucial issue. In several different fields of operation such as air traffic control (ATC), vehicle collision avoidance, robot manipulator control *etc.*, the identification and avoidance of a potential collision have been studied. Inevitably, the task of any collision avoidance system is to prevent the collision of two or more objects. The highest percentage of crash frequency which is 45% happened by lead vehicle stop followed by losing control of the vehicle without earlier action (Najm *et al.* 2007).

There are multiple types of collision avoidance scenarios that happen either on the single lane or double lane changing, overtaking maneuver, avoiding departure, avoidance rear, and so on. As indicated by the National Highway Traffic Safety Administration (NHTSA), lane changing is the process of maneuver the vehicle sideways from one lane into another. Transportation analysts report that 4 to 10 percent of all collisions account for lane-change collisions (Fitch *et al.* 2009). In a study by Yoshida *et al.* (2008), a single lane-change scenario was used as shown in Figure 2.1 where a running vehicle comes across a stopping car at a two-lane-road. To evade the collision, the running vehicle needs to switch to the adjacent lane. Figure 2.2 shows an overview of the overtaking maneuver scenario in which a vehicle encounters a lead vehicle with a constant slow-moving speed. To prevent a collision with the slowing vehicle in front, a vehicle switches the lane twice. The overtaking maneuver consists of three phases which are first lane change to the adjacent lane, passing the lead vehicle, and cutting in the lead vehicle by moving to the original lane (Naranjo *et al.* 2008).

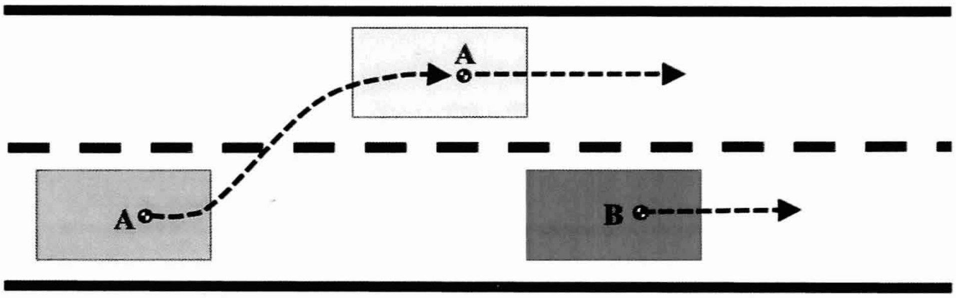

Figure 2.1: Single lane change scenario

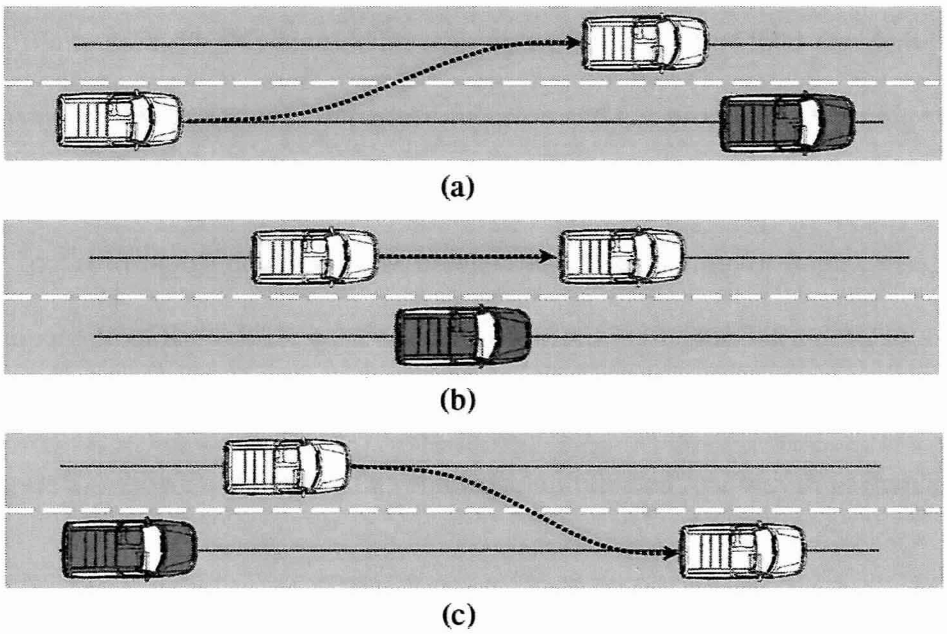

Figure 2.2: Overtaking maneuver scenario. (a) First lane change to the adjacent lane. (b) Passing the lead vehicle. (c) Cutting-in to the original lane. (Naranjo *et al.,* 2008)