

**ROLLOVER PREVENTION SYSTEM OF  
TRUCK-TRAILER VEHICLE USING  
STEERABLE-WHEEL FOR MIDDLE AXLE**

**MUHAMMAD NADWI HAKIMI BIN ADNAN**

**MASTER OF SCIENCE  
(MECHANICAL ENGINEERING)**

**UNIVERSITI PERTAHANAN NASIONAL  
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STEERABLE-WHEEL FOR MIDDLE AXLE**

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Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional  
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(Mechanical Engineering)

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## ABSTRACT

It is well-known that single-trailer trucks are one of the common vehicles in transporting goods. Normally, single-trailer truck will lose its manoeuvrability when driving at a high speed during cornering or sudden lane changing manoeuvres due to excessive yaw and roll moments at the body center of gravity. In order to enhance the manoeuvrability as well as to avoid rollover accident in high speed manoeuvres, this study proposes an active roll control using steerable-wheel system middle axle of single-trailer truck. The steerable-wheel system is developed mainly focused to maintain the directional manoeuvrability and stability of the single-trailer truck by providing an electronically controlled wheel angle of middle axle mechanism. The system is designed to reject the unwanted lateral, yaw and roll motions based on trailer responses. Firstly, the control structure of the active roll control system is developed on a verified 18 degree-of-freedom of single-trailer truck model. The control structure consists of trailer's roll angle feedback control using PID controller and additional roll moment cancellation control using Skyhook controller. The controller is then enhanced by optimising the controller's parameters using Particle Swarm Optimisation. From the simulation results, it can be seen that the proposed control structure is able to reject the unwanted motions in single-lane and double-lane change manoeuvres as compared to passive system. The benefits of PID-Skyhook controller are also discussed in this study by comparing the performances against the PID controller. Finally, active roll control with PID-Skyhook controller is then tested experimentally through hardware-in-the-loop simulation approach using a small-sized of single-trailer truck with steerable-wheel test rig. From the experimental results, a significantly good agreement between experiment and simulation is observed for lateral acceleration, yaw rate and roll angle responses. It also shows that the proposed steerable-wheel system was proven managed to reduce the unwanted lateral, yaw and roll motions by producing the appropriate wheel steer angle for middle axle to maintain the manoeuvrability and stability of the single-trailer truck from rollover accident.

## ABSTRAK

Diketahui bahawa trak treler tunggal adalah salah satu kenderaan yang digunakan dalam pengangkutan barang. Pada kebiasaannya, trak treler tunggal akan kehilangan kemampuan bergerak ketika memandu dengan kelajuan tinggi menular lorong secara tiba-tiba kerana momen rewang dan gulung pada pusat graviti badan. Untuk meningkatkan kemampuan pengendalian dan juga untuk mengelakkan kemalangan pada kelajuan yang tinggi, kajian ini mencadangkan kawalan gulungan aktif menggunakan sistem roda boleh dikendalikan pada gandar tengah untuk trak treler tunggal. Sistem roda stereng ini memfokuskan bagi mengekalkan kemampuan bergerak dan kestabilan trak tunggal treler dengan menyediakan sudut roda pada mekanisme gandar tengah yang boleh dikawal secara elektronik. Sistem ini direka untuk menolak pergerakan sisi, rewang dan gulung yang tidak diingini berdasarkan tindak balas treler. Pertama sekali, struktur kawalan sistem kawalan gulung aktif dibangunkan berdasarkan pada model 18-darjah kebebasan trak treler tunggal yang telah disahkan. Struktur kawalan terdiri daripada kawalan maklum balas sudut gulungan treler menggunakan pengawal *PID* dan kawalan pembatalan momen gulungan tambahan menggunakan pengawal *Skyhook* serta dioptimumkan menggunakan *Particle Swarm Optimisation*. Hasil simulasi mendapati bahawa struktur kawalan yang dicadangkan mampu menolak gerakan yang tidak diingini dalam pengendalian perubahan lorong tunggal dan jalur dua berbanding sistem pasif. Kelebihan pengawal *PID-Skyhook* juga dibincangkan dalam kajian ini dengan membandingkan prestasinya dengan pengawal *PID*. Akhir sekali, kawalan gulungan aktif dengan pengawal *PID-Skyhook* diuji secara ujikaji melalui pendekatan simulasi dengan menggunakan trak treler tunggal bersaiz kecil dengan rig ujian roda. Dari hasil ujikaji, persamaan yang sangat baik antara ujikaji dan simulasi dapat diperhatikan untuk pecutan sisi, kadar rewang dan gerakan gulungan. Ini juga menunjukkan bahawa sistem roda kemudi yang dicadangkan terbukti berjaya mengurangkan gerakan pecutan sisi, rewang dan gulungan yang tidak diingini dengan menghasilkan sudut roda kemudi yang sesuai untuk gandar tengah bagi mengekalkan kemampuan pengendalian dan kestabilan trak tunggal daripada berlaku kemalangan.

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## APPROVAL

The Examination Committee has met on **28 October 2021** to conduct the final examination of **Muhammad Nadwi Hakimi bin Adnan** on his degree thesis entitled **‘Rollover Prevention System of Truck-Trailer Vehicle using Steerable-Wheel for Middle Axle’**.

The committee recommends that the student be awarded the of Master of Science (Mechanical Engineering).

Members of the Examination Committee were as follows.

**Prof. Dr. Abdul Ghapor bin Hussin**

Fakulti Sains dan Teknologi Pertahanan  
Universiti Pertahanan Nasional Malaysia  
(Chairman)

**Prof. Madya Ir. Dr. Saiddi Ali Firdaus bin Mohamed Ishak**

Fakulti Kejuruteraan  
Universiti Pertahanan Nasional Malaysia  
(Internal Examiner)

**Prof. Madya Ir. Dr. Mohd Azman bin Abdullah**

Fakulti Kejuruteraan Mekanikal  
Universiti Teknikal Malaysia Melaka  
(External Examiner)



## **APPROVAL**

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Mechanical Engineering)**. The members of the Supervisory Committee were as follows.

**Dr. Zulkiffli bin Abd Kadir**

Fakulti Kejuruteraan  
Universiti Pertahanan Nasional Malaysia  
(Main Supervisor)

**Prof. Madya Dr. Khisbullah Hudha**

Fakulti Kejuruteraan  
Universiti Pertahanan Nasional Malaysia  
(Co-Supervisor)

**Dr. Noor Hafizah binti Amer**

Fakulti Kejuruteraan  
Universiti Pertahanan Nasional Malaysia  
(Co-Supervisor)

# UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

## DECLARATION OF THESIS

Student's full name : Muhammad Nadwi Hakimi bin Adnan  
Date of birth : 12<sup>th</sup> September 1996  
Title : Rollover Prevention System of Truck-Trailer Vehicle using Steerable-Wheel for Middle Axle  
Academic session : September 2019 – August 2021

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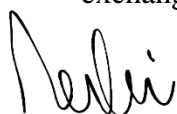
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## LIST OF ABBREVIATIONS

ABS	-	Antilock Braking System
ESC	-	Electronic Stability Control
RSC	-	Roll Stability Control
HiLS	-	Hardware-in-the-Loop Simulation
PSO	-	Particle Swarm Optimisation
GA	-	Genetic Algorithm
RGA	-	Real-Coded Genetic Algorithm
GSA	-	Gravitational Search Algorithm
EP	-	Evoloutinary Programming
DOF	-	Degree-of-Freedom
ECU	-	Electric Control Unit
ARB	-	Anti-roll Bar
AARB	-	Active Anti-roll Bar
LQR	-	Linear Quadratic Regulator
STF	-	Self-Tuning Fuzzy
LTR	-	Load Transfer Ratio
SLC	-	Single Lane Change
DLC	-	Double Lane Change
RMS	-	Root Mean Square
ARC	-	Active Roll Control
SW	-	Steerable-wheel
CG	-	Center of Gravity

## LIST OF SYMBOLS

$r$	-	yaw
$\theta$	-	pitch
$\phi$	-	roll
$\delta$	-	steering angle
$\beta$	-	hitch angle
$m_{truck}$	-	mass of the truck
$m_{trailer}$	-	mass of the trailer
$m_{ufl}$	-	unsprung mass at front-left wheel
$m_{ufr}$	-	unsprung mass at front-right wheel
$m_{uml}$	-	unsprung mass at middle-left wheel
$m_{umr}$	-	unsprung mass at middle-right wheel
$I_{roll1}$	-	roll inertia of the truck
$I_{roll2}$	-	roll inertia of the trailer
$I_{pitch1}$	-	pitch inertia of the truck
$I_{pitch2}$	-	pitch inertia of the trailer
$I_{ztruck}$	-	yaw inertia of the truck
$I_{ztrailer}$	-	yaw inertia of the trailer
$K_p$	-	proportional constant
$K_i$	-	integral constant
$K_d$	-	derivative constant
$\Delta e$	-	roll angle error rate
$u(t)$	-	control signal
$a$	-	distance from truck CG to the front wheels

$b$	-	distance from truck CG to the rear wheels
$c$	-	distance from truck CG to the hitch
$d$	-	distance from trailer CG to the hitch
$e$	-	distance from trailer CG to the trailer wheels
$w$	-	width of the truck
$w_t$	-	width of the trailer
$S$	-	longitudinal slip
$R$	-	wheel radius
$\omega$	-	angular velocity
$u$	-	axle speed
$\alpha_f$	-	slip angle for the front tyres
$\alpha_r$	-	slip angle for the rear tyres
$v_{f}$	-	speed of the front tyre
$v_{r}$	-	speed of the rear tyre
$f(\sigma)$	-	saturation function
$a_p$	-	tyre contact patch lengths
$K_s$	-	longitudinal stiffness coefficient
$K_c$	-	lateral stiffness coefficient
$\sigma$	-	composite slip
$\mu_o$	-	nominal coefficient of friction dependent on the road conditon
$\gamma$	-	camber angle
$F_{sfl}$	-	spring force in the front left
$F_{sfr}$	-	spring force in the front right
$F_{sml}$	-	spring force in the middle left

$F_{smr}$	-	spring force in the middle right
$F_{srl}$	-	spring force in the rear left
$F_{srr}$	-	spring force in the rear right
$F_{dfl}$	-	damping force in the front left
$F_{dfr}$	-	damping force in the front right
$F_{dml}$	-	damping force in the middle left
$F_{dmr}$	-	damping force in the middle right
$F_{drl}$	-	damping force in the rear left
$F_{drr}$	-	damping force in the rear right
$K_{sfl}$	-	spring constant in the front left
$K_{sfr}$	-	spring constant in the front right
$K_{sml}$	-	spring constant in the middle left
$K_{smr}$	-	spring constant in the middle right
$K_{srl}$	-	spring constant in the rear left
$K_{srr}$	-	spring constant in the rear right
$C_{sfl}$	-	damping constant in the front left
$C_{sfr}$	-	damping constant in the front right
$C_{sml}$	-	damping constant in the middle left
$C_{smr}$	-	damping constant in the middle right
$C_{srl}$	-	damping constant in the rear left
$C_{srr}$	-	damping constant in the rear right
$F_{tfl}$	-	tyre force in the front left
$F_{tfr}$	-	tyre force in the front right
$F_{tml}$	-	tyre force in the middle left
$F_{tmr}$	-	tyre force in the middle right



$F_{trl}$	-	tyre force in the rear left
$F_{trr}$	-	tyre force in the rear right
$K_{tfl}$	-	tyre constant in the front left
$K_{tfr}$	-	tyre constant in the front right
$K_{tml}$	-	tyre constant in the middle left
$K_{tmr}$	-	tyre constant in the middle right
$K_{trl}$	-	tyre constant in the rear left
$t_{rr}$	-	tyre constant in the rear right
$\ddot{Z}_{s1}$	-	acceleration of the truck sprung mass at CG
$\dot{Z}_{s1}$	-	acceleration of the truck sprung mass at CG
$\ddot{\theta}_{pitch1}$	-	pitch acceleration for the truck at the CG
$\ddot{\theta}_{pitch2}$	-	pitch acceleration for the trailer at the CG
$\ddot{\phi}_{roll1}$	-	roll acceleration for the truck at the CG
$\ddot{\phi}_{roll2}$	-	roll acceleration for the trailer at the CG
$\ddot{x}$	-	longitudinal acceleration
$v_x$	-	longitudinal velocity
$x$	-	displacement in longitudinal direction
$\ddot{y}$	-	lateral acceleration
$v_y$	-	lateral velocity
$y$	-	displacement in lateral direction
$\ddot{\delta}$	-	steering angular acceleration
$\dot{\delta}$	-	steering angular velocity
$F_{xh}$	-	longitudinal force acting on hitch
$F_{yh}$	-	lateral force acting on hitch
$\mathcal{E}_o$	-	magnitude of the output response