MODELLING AND VALIDATION OF A TRACKED VEHICLE FOR AUTONOMOUS PATH TRACKING CONTROLLER

NOOR AMIRA ILYANIE BINTI RUSLAN

MASTER OF SCIENCE
(MECHANICAL ENGINEERING)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

2024

MODELLING AND VALIDATION OF A TRACKED VEHICLE FOR AUTONOMOUS PATH TRACKING CONTROLLER

NOOR AMIRA ILYANIE BINTI RUSLAN

Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, in fulfilment of the requirements for the Degree of Master of Science (Mechanical Engineering)

2024

ABSTRACT

The demand for autonomous technology in tracked vehicles is increasing, where path tracking controllers are vital. Developing stable and reliable in-track Direct Current (DC) motor controllers is essential for effective implementation. Therefore, this study presents a dynamic modelling and validation of a tracked vehicle, focusing on an in-depth analysis of the in-track DC motor system. To achieve this, three specific objectives were set: i) creating a dynamic vehicle model for path tracking control of an autonomous vehicle; ii) developing a motor model by analysing the speed characteristics of an in-track DC motor on a tracked vehicle; and iii) experimentally validating the proposed model against actual vehicle responses. The methodology begins with modelling and simulating the tracked vehicle in MATLAB/Simulink, followed by developing the DC motor model based on vehicle speed and turning radius during straight and cornering manoeuvres. Upon validating the motor model, an independent controller is developed for the DC motor on each side of tracked vehicle, incorporating all data from the characterization phase. The controller's effectiveness is validated by comparing the desired and actual response for DC motor model, motor controller, and vehicle model. With this, the Root-Mean-Square (RMS) of percentage difference is evaluated to quantify the validation between actual values and model predictions. The developed motor model agrees with the actual system with RMS of the percentage difference of 1.8% in vehicle speed during straight manoeuvring and 3.7% and 7.1% in turning radius for right and left cornering, respectively. The developed tracked vehicle model agrees with the actual setup, with 10.90% and 12.66% differences in terms of vehicle trajectory in X-Y coordinates for right and left cornering. With these findings, each objective has been achieved demonstrating the model’s suitability for path tracking controller development.

ABSTRAK

Permintaan untuk teknologi autonomi dalam kenderaan penjejak meningkat, menjadikan pengawal pengesan laluan penting. Pembangunan pengawal motor DC yang stabil dan boleh dipercayai adalah penting untuk pelaksanaan berkesan. Kajian ini membentangkan pemodelan dinamik dan pengesahan kenderaan penjejak, memfokuskan pada sistem motor DC dalam trek. Untuk mencapai matlamat ini, tiga objektif khusus telah ditetapkan: i) mencipta model kenderaan dinamik untuk kawalan penjejakan laluan kenderaan autonomi; ii) membangunkan model motor dengan menganalisis ciri-ciri kelajuan motor DC dalam trek pada kenderaan penjejak; iii) mengesahkan model yang dicadangkan terhadap tindak balas kenderaan sebenar secara eksperimen. Metodologi bermula dengan pemodelan dan simulasi kenderaan penjejak dalam MATLAB-Simulink, diikuti dengan pembangunan model motor DC berdasarkan kelajuan kenderaan dan jejari pusingan semasa pergerakan lurus dan membelok. Setelah mengesahkan model motor, pengawal bebas dibangunkan untuk setiap motor DC, menggunakan data dari fasa pencirian. Keberkesanan pengawal disahkan dengan membandingkan sambutan yang dikehendaki dan sebenar untuk model motor DC, pengawal motor, dan terakhir, model kenderaan. Dengan ini, RMS peratus perbezaan dinilai untuk mengukur pengesahan antara nilai sebenar dan ramalan model. Model motor yang dibangunkan sepadan dengan sistem sebenar, dengan perbezaan RMS peratusan 1.8% dalam kelajuan kenderaan semasa manuver lurus, dan 3.7% serta 7.1% untuk jejari pusingan kanan dan kiri. Model kenderaan penjejak yang dibangunkan selaras dengan susunan sebenar, dengan perbezaan 10.90% dan 12.66% dalam trajektori kenderaan pada koordinat X-Y, untuk belokan kanan dan kiri. Dengan penemuan ini, semua objektif telah tercapai, menunjukkan kesesuaian model ini untuk pembangunan pengawal penjejak laluan.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful. Peace Be Upon Him Our Prophet Muhammad S.A.W. Firstly, I would like to express my deepest gratitude towards my supervisor, Dr. Noor Hafizah Binti Amer for her patience in providing guidance throughout the completion of this research. Also, not to be forgotten are my corresponding supervisors, Associate Professor Dr. Khisbullah Hudha, Dr. Zulkiffli Bin Abd. Kadir and Associate Professor Ir. Dr. Saiddi Ali Firdaus Bin Mohamed Ishak that always dedicated in giving advices throughout this research study.

I would like to acknowledge all those who played a direct and indirect role in the progress and completion of this research. To begin with the Ministry of Higher Education in providing the financial support for this research study and to the Universiti Pertahanan Nasional Malaysia which have gave me an opportunity to earn experiences and also in providing me the good facilities during this research study. Lastly, I am very thankful of the prayers and encouragement received from my parents: Mr. Ruslan Bin Saad and Mrs. Hayati Binti Jahaya, siblings and my beloved friends: ‘Alawiyah Hasanah Binti Mohd. Alawi, Amrina Rasyada Binti Zubir and Nurulhani Adlina Binti Madzan that always give moral support in completing this thesis writing. This accomplishment would not been possible without them. Thank you.

APPROVAL

The Examination Committee has met on **2 August 2024** to conduct the final examination of **Noor Amira Ilyanie Binti Ruslan** on his degree thesis entitled **'Modelling and Validation of a Tracked Vehicle for Autonomous Path Tracking Controller'.**

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

Members of the Examination Committee were as follows.

Ir. Dr. Abd Rahim Bin Mat Sarip
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Chairman)

Associate Professor Ir. Dr. Mohd Rosdzimin Bin Abdul Rahman
Centre for Research and Innovation Management
Universiti Pertahanan Nasional Malaysia
(Internal Examiner)

Ts. Dr. Mohamad Heerwan Bin Peeie
Faculty of Mechanical & Automotive Engineering Technology
Universiti Malaysia Pahang Al-Sultan Abdullah
(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. Noor Hafizah Binti Amer
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Main Supervisor)

Associate Professor Dr. Khisbullah Hudha
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

Dr. Zulkiffli Bin Abd. Kadir
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

Associate Professor Ir. Dr. Saiddi Ali Firdaus Bin Mohamed Ishak
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

Student's full name	:	Noor Amira Ilyanie Binti Ruslan
Date of birth	:	5 February 1998
Title	:	Modelling and Validation of a Tracked Vehicle for Autonomous Path Tracking Controller
Academic session	:	2024/2025

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

I further declare that this thesis is classified as:

☐	**CONFIDENTIAL**	(Contains confidential information under the official Secret Act 1972)*
☐	**RESTRICTED**	(Contains restricted information as specified by the organisation where research was done)*
☐	**OPEN ACCESS**	I agree that my thesis to be published as online open access (full text)

I acknowledge that Universiti Pertahanan Nasional Malaysia reserves the right as follows.

1. The thesis is the property of Universiti Pertahanan Nasional Malaysia.
2. The library of Universiti Pertahanan Nasional Malaysia has the right to make copies for the purpose of research only.
3. The library has the right to make copies of the thesis for academic exchange.

Signature	**Signature of Supervisor/Dean of CGS
980205-14-6254 IC/Passport No.	**Name of Supervisor/Dean of CGS
Date:	Date:

*If the thesis is CONFIDENTAL OR RESTRICTED, please attach the letter from the organisation with period and reasons for confidentiality and restriction.
** Witness

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
DC	-	Direct Current
GND	-	Ground
ICE	-	Internal Combustion Engine
I2C	-	Inter-Integrated Circuit
LiPo	-	Lithium-ion Polymer
PC	-	Personal Computer
PID	-	Proportional-Integral-Derivative
PWM	-	Pulse-Width Modulation
RMS	-	Root- Mean-Square
RPM	-	Revolutions Per Minute
SCL	-	Serial Clock
SDA	-	Serial Data
UPNM	-	Universiti Pertahanan Nasional Malaysia
VCC	-	Voltage Controlled Capacitor

LIST OF SYMBOLS

A	-	Contact Area
a_x	-	Acceleration of Longitudinal Motion
a_y	-	Acceleration of Lateral Motion
b	-	Distance Between Each Track's Centerline of The Vehicle
c	-	Soil Cohesion Coefficient
C_d	-	Drag Coefficient
C_m	-	Mass Coefficient
d_s	-	Distance Between The Instantaneous Center of Rotation and The Center of Gravity
F	-	Input Force
f	-	Friction Force
F_c	-	Centrifugal Force
F_j	-	Tractive Force of an j-th Tracks
F_L	-	Tractive Force for Left Tracks
F_{max}	-	Maximum Tractive Effort
F_R	-	Tractive Force for Right Tracks
F_w	-	Hydrodynamic Force
F_y	-	Lateral Friction Force
F_{y1}	-	Forces Aligning with Lateral Direction
F_{y2}	-	Forces Opposing The Lateral Direction
f_y	-	Force Per Unit Length for The Uniformly Distributed
g	-	Gravitational Acceleration Constant
I	-	Tracked Vehicle's Moment of Inertia
i_L	-	Slip of Left Tracks

i_R	-	Slip of Right Tracks
k	-	Modulus of Soil Deformation
K_c, K_γ	-	Coefficients of Passive Earth Pressure
K_c, K_θ, n	-	Pressure Sinkage Characteristics
K_s	-	Angular Speed Ratio
l	-	Length of The Vehicle
m	-	Mass of The Vehicle
p	-	Normal Pressure from The Track Acting on The Soil
R	-	Turning Radius
r	-	Track Rolling Radius
R_b	-	Bulldozing Force
R_c	-	Compaction Force
R_L	-	Resistance Force for Left Tracks
R_R	-	Resistance Force for Right Tracks
$r_{sprocket}$	-	Radius of Sprocket
V / V	-	Forward Speed of Track / Vehicle Speed
V_t	-	Theoretical Speed
W	-	Vehicle Weight
$\dot{X}$	-	Vehicle Velocity in Global *X*-Coordinate
$\dot{x}$	-	Vehicle Velocity in Local *x*-Coordinate
$\ddot{x}$	-	Acceleration of Longitudinal Motion in *x*-direction
$\dot{Y}$	-	Vehicle Velocity in Global *Y*-Coordinate
$\dot{y}$	-	Vehicle Velocity in Local *y*-Coordinate
$\ddot{y}$	-	Acceleration of Lateral Motion in *y*-direction
z	-	Sinkage
α	-	Slip Angle

γ	-	Density of The Sediment
μ_t, μ_y	-	Lateral Friction Coefficient
μ_x	-	Longitudinal Friction Coefficient
ω_L	-	Left Track Rotational Velocities
ω_R	-	Right Track Rotational Velocities
ω_{track}	-	Angular Speed of Tracks
ϕ	-	Angle of Internal Shearing Resistance
ψ	-	Yaw Angle
$\dot{\psi}$	-	Yaw Rate
$\ddot{\psi}$	-	Yaw Acceleration
ρ_w	-	Density of Water
τ_{max}	-	Terrain's Shear Strength
θ	-	Heading Angle

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Tracked vehicles have been developed to excel in a variety of challenging terrains, including snow, loose sand, mud, steep sloped, and rugged combinations, where traditional wheeled vehicles would struggle (Ben-tzvi, 2018). Tracked vehicles are preferred for its ability to operate effectively in hazardous terrains, offering advantaged such as exceptional traction even on slippery surfaces, robust load-bearing capabilities, and efficient power delivery. This tracked vehicle designs allows for tight turns with a smaller radius and consistent speed on uneven terrain, making tracked vehicles superior in traction and grip for tasks in civilian and military sectors (Salah & Al-Jarrah, 2019; Ugenti et al., 2023).

Furthermore, tracked vehicles are extensively used in agriculture for activities such as planting, harvesting, and transporting crops. One of the notable advantages is the reduction of soil compaction, achieved by evenly distributing the weight over a larger area (Saito et al., 2013; Wenju et al., 2022; Yang et al., 2023). This minimizes harm to both crops and soil structure. In military sectors, the exceptional off-road mobility, ability to transport heavy loads, deploy weaponry, and maintain operational readiness in diverse environments underline its crucial role in military logistics and combat operations (Yang et al., 2023).

Autonomous tracked vehicle (ATV) is a type of robotic vehicle equipped with tracks instead of wheels for mobility. It is known as an autonomous type vehicle because of its designs and functionality to operate without direct human control, relying on various sensors, algorithms, and computing systems to navigate and perform tasks autonomously. The general architecture for autonomous tracked vehicle is shown in Figure 1.1. Each of these modules is important and numerous studies have been conducted on some of these topics such as path planning techniques and control mechanisms in ATV (Rigatos, 2021; Amokrane et al., 2024) as well as the sensors technologies used for trajectory tracking in ATV (Barakat et al., 2020; Wang et al., 2023). Based on Figure 1.1, this thesis will consider four aspects: trajectory tracking control, actuator control, vehicle system and sensors interface. These aspects will be further discussed throughout this thesis.

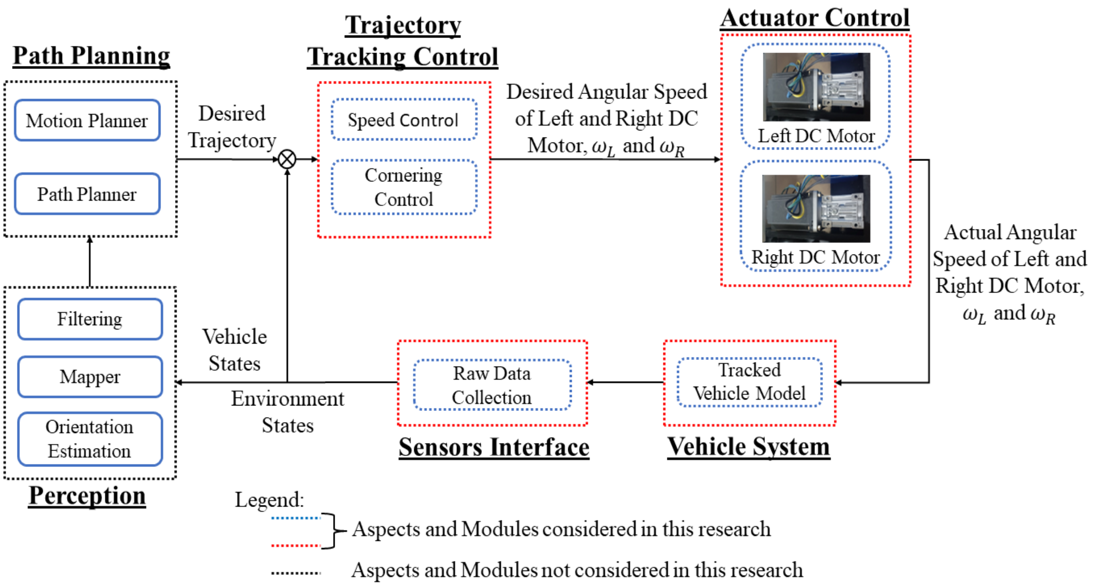

Figure 1.1 General architecture of ATV system

Next, in the field of modelling the tracked vehicles, there are two types of models commonly used in modelling the tracked vehicle namely a kinematic and dynamic model. Kinematic model focuses on describing the vehicle's motion in terms of its position, velocity and acceleration without considering the vehicle's internal dynamics (Strawa et al., 2021). Meanwhile, a dynamic vehicle model, similar to the kinematic model, additionally incorporates considerations of internal forces, energy or momentum (Han et al., 2011). This study will develop the dynamic model for tracked vehicles addressing the gap noted in existing literature where research on this specific model type remains limited.

Traditionally, tracked vehicles have predominantly used Internal Combustion Engines (ICEs) as its main powertrain. However, in the autonomous field, DC motors are favoured for powering tracked vehicles due to the ease of control, as these motors adapt easily to different terrains with variable speed control, efficiently overcome inertia during startup with high starting torque, and maintain consistent torque across a wide speed range, ensuring stability in vehicle performance (Muhammad et al., 2023). With advancements in technology and increasing environmental concerns, electrically powered tracked vehicles are becoming more common. Therefore, this study will used DC motor as the main powertrain of the tracked vehicles.

Lastly, tracked vehicle mostly used Internal Combustion Engines (ICEs) as its main powertrain to power up the tracked vehicle. In autonomous field, it is more feasible to used DC motor to power up the tracked vehicle due to its ease of control. With advancements in technology and increasing environmental considerations, electrically powered tracked vehicles are becoming more common. Therefore, this study will used DC motor as the main powertrain.

1.2 Problem Statement

The development of an efficient path tracking controller is critically dependent on the precision of the vehicle model used. Most commonly, vehicle models employ a three-degree-of-freedom (3DoF) framework and consider slip dynamics to accurately capture the internal interactions between a vehicle's tracks and the ground. Previous studies have predominantly utilized kinematic models (Ben-tzvi, 2018; Salah & Al-Jarrah, 2019; Strawa et al., 2021; Subari et al., 2020; Tazzari et al., 2021; Yu & Vantsevich, 2021), which do not adequately account for the internal dynamic interactions between a vehicle's tracks and the ground. In contrast, dynamic models, despite their complexity, are essential for path tracking controllers as it takes into account critical forces such as tractive, lateral friction, and longitudinal resistance (Han et al., 2011; Hong et al., 2009). These models offer a more detailed and accurate representation of vehicle behavior due to the consideration of the non-linear track-soil interaction which contributes to overall vehicle motion. This is crucial for the development of a precise controller capable of actively observing and controlling the vehicle's dynamic responses.

Additionally, vehicle modelling often focusses on tracked vehicles with traditional main powertrain which is internal combustion engines (ICE), thus missing out on the potential of alternative powertrains. This study proposes to explore vehicle models equipped with in-track DC motors on both tracks. This is because it offers significant advantages, including high efficiency, compact size combined with powerful performance, precise control of torque and speed, and produce fewer emissions, which are not only environmentally friendly but also effective in handling heavy tasks (Prasanthi et al., 2023). Therefore, this study aims to develop a robust dynamic vehicle model, equipped with in-track DC motor on each track. The characteristic of the DC motor needs to be investigated in order to develop an accurate motor model and controller to complement the tracked vehicle model. The accuracy of this model will be validated against the actual vehicle responses to ensure its applicability and effectiveness in path tracking applications.

Lastly, it is important to highlight the differences between wheeled and tracked vehicles control systems. Tracked systems usually involve complex interactions between the track and the ground which requires different control strategies compared to wheel-based systems due to its slip and friction characteristics. This study will also address these differences to enhance the model's performance and controller effectiveness.

1.3 Research Objectives

The main aim of this study is to produce a validated dynamic vehicle model that can be used for autonomous tracked vehicle control. Several aspects of the vehicle should be modeled to ensure an accurate representation of the model. The objectives have been outlined to accomplish this main aim, which are as follows:

(a) To formulate a dynamic tracked vehicle model for path tracking control of an autonomous tracked vehicle

(b) To elucidate the motor model by evaluating the speed characteristics and turning radius of an-in track DC motor on tracked vehicle.

(c) To experimentally validate the proposed vehicle model against actual vehicle response.

1.4 Research Scopes

The research scopes and the limitations are as follows:

(a) Development of a dynamic tracked vehicle model for path tracking control purposes. This will involve motions on longitudinal plane.

(b) The proposed vehicle model is validated by real time experiment.

(c) The open-loop type controller is implemented to develop the independent speed controller of in-track DC motor.

(d) The tracked vehicle model parameters are obtained from the real tracked vehicle developed at Automotive Laboratory, UPNM.

(e) The path chosen for validating the developed tracked vehicle model are right and left cornering.

(f) Modelling and control design are developed using MATLAB-Simulink software.

(g) The validated dynamic vehicle model is developed by considering tractive and resistive forces in longitudinal and lateral motion.

(h) The experiment to validate the vehicle model's trajectory is carried out in the Automotive Laboratory, UPNM.

1.5 Research Methodology

The initial stage of this research project begins with a thorough literature review encompassing four key areas: tracked vehicle modelling, DC motors and internal combustion engines (ICE), types of DC motor control, and methods used in past research to validate findings and models. Following the literature review, the focus shifts to the modelling and verification of the dynamic model of a tracked vehicle. Subsequently, the study examines the influence of DC motor characteristics on the vehicle's speed and turning radius. This phase includes developing and validating a model of the DC motor, using the observed characteristics as a reference. The validation process involves comparing the desired vehicle speed with the actual speed achieved.

After completing the validation of the DC motor model, the research progresses to the development and validation of an independent controller for the DC motor. This controller's design is based on an inverse kinematic model and an inverse motor model, with the validation process focusing on the comparison between the desired and actual angular speeds of the left and right sprockets. The final phase of the research validates the tracked vehicle equipped with an in-track DC motor as shown in Figure 1.2. This is achieved by comparing the simulated and experimental responses in the global *X*-*Y* coordinates of the vehicle. The comprehensive findings and analyses of this research will be presented and discussed in this thesis report.