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DEVELOPMENT AND VALIDATION OF TRACKED VEHICLE DYNAMIC MODEL FOR MODEL-BASED PATH TRACKING CONTROL

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ABSTRACT

One of the most common intelligent paths tracking controllers is model-based predictive controller. This controller can only be functional with a good dynamic model that can effectively predict the vehicle behaviour within a set prediction horizon. Therefore, this study addresses the challenges of developing a reliable dynamic model for a small-scale tracked vehicle that are crucial for effective implementation of intelligent path tracking controllers. The model will be validated using an instrumented tracked vehicle equipped with controllable DC motor on each track and MPU6050 accelerometer. Validation involves several situations, namely forward motion and left and right cornering by comparing the predicted vehicle trajectories from the model to an actual one from the instrumented vehicle. The validation is quantified using Root-Mean-Square Error (RMSE) to evaluate the amount of deviation between the simulated vehicle and the actual instrumented vehicle trajectory. The utilization of RMSE serves as a quantitative measure, ensuring the accuracy and fidelity of the model to the real-world experimental outcomes. The validation results demonstrate a 0.01177 m deviation for forward motion trajectory and 0.0797 m and 0.00734 m for right and left cornering, respectively. This quantification of validation highlights the precision of the model against actual experimental data, where main source of deviation is due to the ideal assumptions in the vehicle model as well as constraint in data sampling within the vehicle instrumentation system. This establishes a reliable foundation for the development of a model-based controller designed for tracked vehicle path tracking control. The successful implementation of this model-based controller holds the potential to significantly enhance tracked vehicle performance, safety, and autonomy, making substantial contributions to the advancement of these critical aspects in the field.

1.0 INTRODUCTION

A tracked vehicle is a type of large machinery or transportation that operates on tracks rather than wheels. Tracked vehicles, in contrast to those with wheels, employ an uninterrupted track system comprised of interconnected metal or rubber belts that encircle a set of wheels. Furthermore, owing to their enhanced traction and stability, these tracks enable tracked vehicles to traverse demanding terrains with ease [1-2]. Evolving over time, tracked vehicles have grown more sophisticated and adaptable, serving in agriculture, military operations, homeland security, demining, response to terrorist attacks, surveillance, and other applications [3-5]. Based on previous research, the model incorporates considerations for tractive and

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resistance forces exerted on the vehicle's track [6-8]. The analysis explores the vehicle's maneuverability on various surfaces such as dry clay, dry sand, and clayey soil within X-Y coordinates. The dry clay surface condition was chosen for further detailed analysis due to its distinctive properties [6]. Additionally, Zou et al., (2018) has analysed the vehicle's trajectory on a circular path, comparing simulated trajectories with desired ones to evaluate the performance [8].

Ruslan et al., (2023) has briefly discussed several strategies for path tracking control in tracked vehicles, emphasizing the efficacy of a model-based controller [7]. This controller stands out for its exceptional ability to predict regulated inputs, manage constraints, and handle multiple inputs and outputs, surpassing other controllers discussed in their study. However, the accuracy of the mathematical model is pivotal for the development of a Model Predictive Controller (MPC), necessitating thorough validation. The main aim of this study is to validate the mathematical model to facilitate the development of a model-based controller for path tracking in tracked vehicles. The validation process aligns the verified vehicle model with experimental results. By configuring accelerometer signals, the responses of the vehicle will be scrutinized. The simulated responses from the vehicle model, constructed with reference to Ahmadi et al., (2000), will be compared with the actual responses of tracked vehicles in longitudinal, lateral, and yaw directions [9]. This comprehensive validation aims to ensure the fidelity and reliability of the mathematical model, laying the groundwork for the subsequent development of an effective model-based controller for enhanced path tracking control.

Generally, throughout this study, a critical challenge is the development of a validated dynamic vehicle model which is essential for creating an accurate model-based controller for path tracking in tracked vehicles. The existing kinematic model for tracked vehicles only considered limited parameters which only concentrates on a vehicle's motion characteristics in relation to its geometric properties. Meanwhile, dynamic models are often more suitable for tracked vehicle maneuvers due to their ability to consider the forces involved, allowing for a comprehensive model that can accurately predict vehicle responses. Therefore, in this study, a dynamic tracked vehicle model is specifically formulated and focused to serve as the foundation for developing a model-based controller designed for path tracking control.

2.0 METHODS

This section describes the main methodology used in this project. It begins with the development of a tracked vehicle model, drawing from the previous research. This model is then developed using MATLAB-Simulink for a comprehensive analysis. The next phase involves conducting simulations of the tracked vehicle model followed by real-time experimental tests to validate the developed vehicle model. The final stage encompasses the validation of both simulated and experimental results by computing the Root-Mean-Square-Error (RMSE) values for various manoeuvring of the tracked vehicle. This entire process is depicted in Figure 1.

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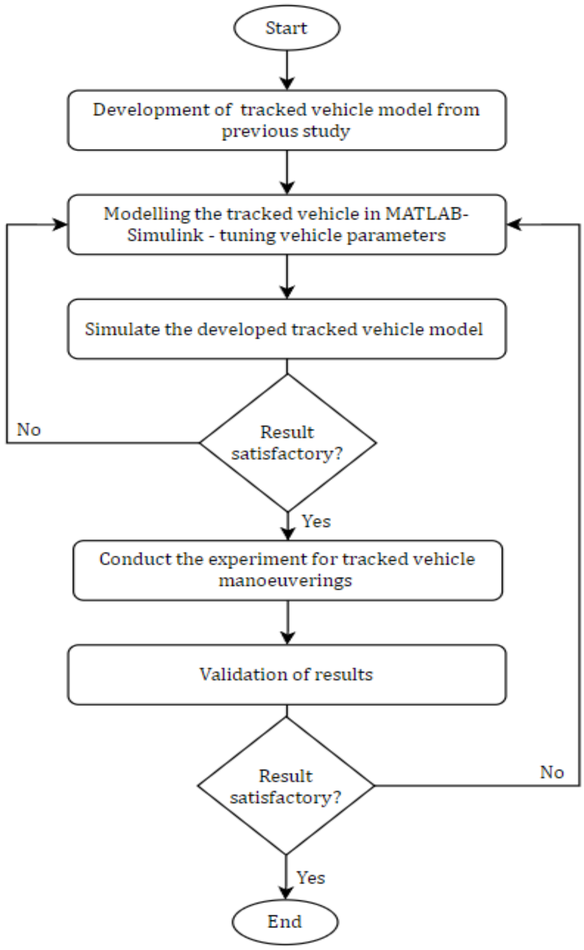
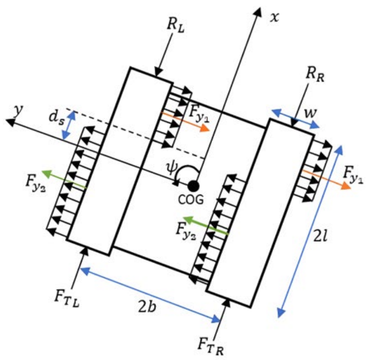


Figure 1. Flowchart of the study

2.1 Tracked Vehicle Dynamic Model

The tracked vehicle system is represented through a mathematical model, employing a dynamic approach to model the vehicle's response. Dynamic solutions are derived by considering internal energy components, encompassing momentum, moment, force, and energy. In this study, a dynamic model considering forces and moment in longitudinal plane is developed as shown in Figure 2(a). The actual tracked vehicle, shown in Figure 2(b) is interpreted using a dynamic model, where the Newtonian method is employed to derive equations. This method is well-suited for accurately describing the movements and mechanical aspects within the system.



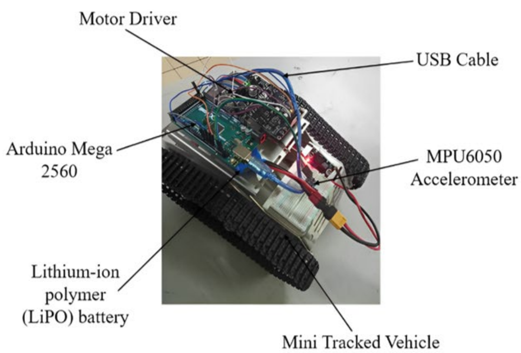


Figure 2. (a) A tracked vehicle force model (Ahmadi et al., 2000); (b) Miniature tracked vehicle used in the study

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Equations of motion (1)–(3) derived by Le et al., (2006) have been developed for validation using actual movement data obtained from the accelerometer mounted on the vehicle body [6]. The derived equations seamlessly integrate crucial parameters such as the vehicle's mass, (m), moment of inertia about the z-axis, (I) and accelerations associated with longitudinal, ($\ddot{x}$), lateral, ($\ddot{y}$), and yaw motions about the z-axis, ($\ddot{\psi}$), specifically tailored for tracked vehicles. These equations account for various forces, including tractive forces exerted by the left and right tracks, ($F_{T,L}$ and $F_{T,R}$) impacted by the interaction between the track and soil caused by to soil shear stress. Additionally, resistance forces (R_L and R_R) for the left and right tracks are considered. In the lateral direction, the model factors in a uniformly distributed lateral force per unit length (f_y), the distance between the instantaneous center of rotation and the center of gravity (d_s), and the vehicle's half width (b) and half length (l) as depicted in Figure 2 (a).

$$\ddot{x} = \frac{1}{m} * \left(F_{T,R} + F_{T,L} - R_L - R_R\right) \tag{1}$$

$$\ddot{y} = \frac{1}{m} * (4 f_y d_s) \tag{2}$$

$$\ddot{\psi} = \frac{1}{I} * [\left(F_{T,R} - R_R\right) * b - \left(F_{T,L} - R_L\right) * b - 2 f_y (l^2 - d_s^2)] \tag{3}$$

Subsequently, tractive force describes the traction applied to the tracks and the force that is transferred to the ground while the vehicle is travelling in the same direction as shown in Equation 4 where k is the modulus of soil deformation [9]. Additionally, the maximal tractive force, represented by F_{max} is defined by the terrain's shear strength, (τ_{max}) and track contact area, (A) as obtained from Equation 5. In this equation, C is the apparent cohesion of the soil and p is the normal pressure beneath the tracks. Equations (6)−(8) are used to compute the slips, ($i_{L/R}$) that occur on the vehicle's left and right tracks, where $V_{L/R}$ indicates the speed at which the left and right tracks slip; the sprocket radius is indicated by r; ψ indicates the vehicle's yaw; $\dot{x}$ indicates the velocity in longitudinal direction; and ω_L and ω_R indicate the left and right tracks of the tracked vehicle angular speed, respectively.

$$F_{T,L/T,R} = F_{max}\left[1 - \frac{\left(\frac{k}{l}\right)}{\left|i_{L/R}\right|}\left(1 - e^{-\left|i_{L/R}\right|}\right)\right] sign\left(i_{L/R}\right) \tag{4}$$

$$F_{max} = A\tau_{max} = A[C + p \tan(\psi)] \tag{5}$$

$$i_{L/R} = \frac{V_{L/R}}{r\omega} \tag{6}$$

$$V_L = \left[\dot{x} - b\dot{\psi}\right] - r\omega_L \tag{7}$$

$$V_R = \left[\dot{x} + b\dot{\psi}\right] - r\omega_R \tag{8}$$

Next, Equation (9) represents the longitudinal resistive forces for left and right tracks, ($R_{L/R}$) that arise from the interaction between the soil and vehicle's tracks. The longitudinal coefficient of friction is represented by μ_x and the gravitational acceleration is represented by g. Equation (10) provides the lateral friction force per unit length, (f_y) due to the lateral soil shear distribution force acting on the tracked vehicle. Here, l is the tracked vehicle's half-length and μ_y is the lateral friction coefficient.

$$R_{L/R} = \frac{\mu_x m g}{2} \tag{9}$$

$$f_y = \frac{\mu_y m g}{2l} \tag{10}$$

Moreover, the lateral resistive forces, denoted as F_y, manifested in two directions forces aligned with and opposing the lateral direction, represented as F_{y1} and F_{y2}, respectively, as defined in Equations (11) and (12) and shown in Figure 2. The motion of the tracked vehicle is determined employing right-hand

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rules, where a positive lateral force is applied in the left direction. Consequently, the lateral friction for the tracked vehicle, as expressed in Equation (13), is derived from the summation of all lateral resistive forces on both tracks using Equations (11) and (12).

$$F_{y1} = f_y(l - d_s) \tag{11}$$

$$F_{y2} = f_y(l + d_s) \tag{12}$$

$$F_y = -2F_{y1} + 2F_{y2} = 4f_y d_s \tag{13}$$

Besides, it is necessary to convert the local coordinates of the tracked vehicle's motion into global coordinates to analyse the translational mobility in a real system. Global coordinates of the vehicle in longitudinal ($\dot{X}$) and lateral ($\dot{Y}$) directions are provided in Equations (14) and (15) where ψ indicates the yaw, $\dot{x}$ and $\dot{y}$ denotes the local coordinates in longitudinal and lateral directions, respectively.

$$\dot{X} = \dot{x}\cos\psi - \dot{y}\sin\psi \tag{14}$$

$$\dot{Y} = \dot{x}\sin\psi + \dot{y}\cos\psi \tag{15}$$

Furthermore, a more comprehensive model is necessary when velocities vary, as existing friction models were specifically designed for a particular direction of motion. Hence, Equation (16) is incorporated into the vehicle model, where the vector G represents the combined effect of both friction and the applied force on the vehicle. In simpler terms, this equation shows that if the friction force surpasses the tractive force, the vehicle will remain stationary. This is to avoid the model to treat the larger friction force as negative force that will move the vehicle in the opposite direction. Mathematical model from Equations (1) to (16) are developed in MATLAB Simulink. For this model, the actual vehicle parameters from Figure 2(b) are used, as tabulated in Table 1.

$$G(F, f, \dot{x}) = \begin{cases} F - f sign(\dot{x}) & \dot{x} \neq 0 \\ 0 & \dot{x} = 0, |F| \leq f \\ F - f sign(F) & \dot{x} = 0, |F| \geq f \end{cases} \tag{16}$$

Table 1. Parameters of the tracked vehicle

Vehicle parameter	Value (unit)
Initial velocity, V_o	0.228 m/s
Gravitational acceleration, g	9.81 m/s^2
Radius of sprocket, r	0.025 m
Contact area between soil and tracked vehicle, A	0.0068 m^2
Apparent cohesion of the soil, c	$68.95e^{-2}$ Pa
Modulus of soil deformation, k	$0.6e^{-2}$ m
Longitudinal friction coefficient, μ_x	0.2
Lateral friction coefficient, μ_y	0.55
Half-width of the tracked vehicle, b	0.0925 m
Half-length of the tracked vehicle, l	0.1425 m
Mass moment of inertia, I	0.0345 kgm^2
Mass of the tracked vehicle, m	1.7 kg
Angle of internal friction, Ø	0.5934 rad

2.2 Validation Of Mathematical Model Against Actual Vehicle Response

Developed model in MATLAB Simulink is then validated against actual vehicle response. To do this, an existing tracked vehicle is instrumented. Several manoeuvres is carried out both on mathematical model and actual vehicle where both vehicle responses are collected. Overall data collection processes can be summarized in Figure 3. Both vehicle setups will be evaluated by its trajectory X and Y in global coordinates. As shown in the figure, data collection for the validation process involved both software and hardware setups. In the software setup, the mathematical model was constructed based on Equations (1) to (16). The angular speed inputs for both tracks are set to the developed tracked vehicle model and the

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outputs on X and Y coordinates are measured. In addition, the simulation duration is set to 10 seconds and for the solver selection, a fixed-step Bogacki-Shampine method with a step size of 0.001 second was utilized.

Meanwhile, the actual vehicle data was collected from a real tracked vehicle shown in Figures 2(b) and Figure 3. The vehicle is fitted with Arduino MEGA microcontroller, and an MPU6050 accelerometer sensor. Real time data logger was carried out through a standard Windows PC (AMD Ryzen 5, 4500U, 2.38 GHz) that is connected to the microcontroller. The similar inputs from the simulation that are converted in terms of byte are initially set to the Arduino Mega 2560. The commands are then sending the signal to the motor driver to actuate both right and left DC motors. The resulting movement of the tracked vehicle based on the input setting produced acceleration data through MPU6050 accelerometer which will be integrated twice to generate the trajectories in *X*-*Y* coordinate. All hardware involved will be setup within MATLAB Simulink and carried out in real time containing the control algorithm in moving the car as well as the data logger to record the data from the real vehicle.

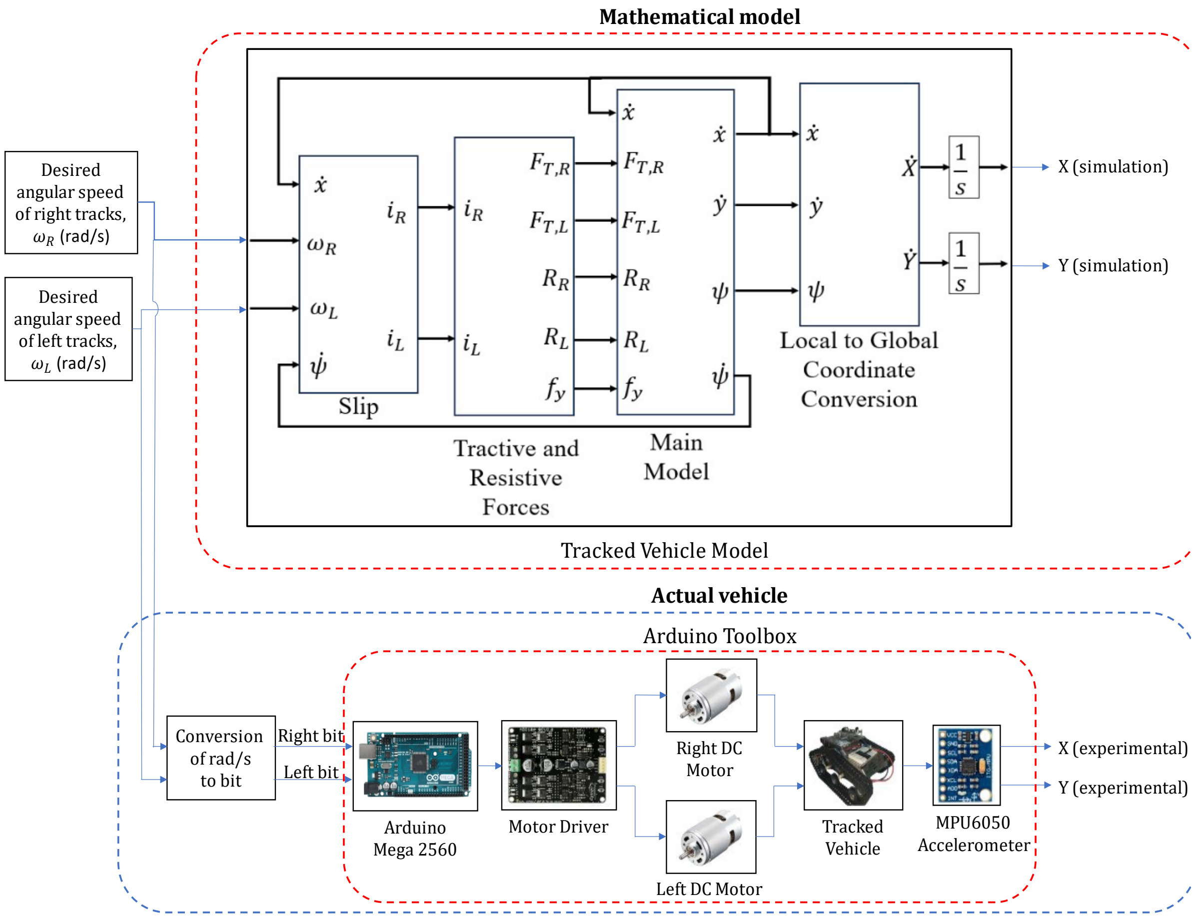

Figure 3. Setup for tracked vehicle validation including both software and hardware components

Both configurations were carried out in parallel within MATLAB Simulink environment as shown in Figure 3. The analysis of the results obtained from both simulation and the experiment tests were conducted using the calculations of RMSE for the three resulting paths traversed by the tracked vehicle which facilitates a comprehensive comparison and validation of the model's accuracy.

Table 2. MATLAB software and hardware specifications

Hardware	Software
Mini tracked vehicle	MATLAB and Simulink academic release 2020b
Cytron dual channel DC motor drive	Simulink Support Package for Arduino Hardware
12V Lithium-ion polymer (LiPO) battery	
Arduino Mega 2560	
MPU6050 Accelerometer sensor	
USB type A to type B cable	

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3.0 RESULTS AND DISCUSSION

This section discusses the validation results for the tracked vehicle. Validation is a pivotal stage in system testing, confirming that it meets specified criteria during a particular development phase, thereby ensuring the modeled system provides an optimal response aligned with real-life data from the actual system. This comparison between the model and actual data is essential in simulation projects, guaranteeing the accuracy, reliability, and credibility of the simulation results by evaluating the model's capacity to faithfully reproduce physical movements. The simulation results are obtained from the developed vehicle model in MATLAB Simulink, while the experimental results are gathered using the MPU6050 accelerometer sensor. The data collected from the accelerometer is subsequently processed and compared with the model's trajectory response.

In this study, the vehicle model is validated using three distinct cases, namely forward motion, right and left cornering as shown in Fig. 4. Based on the dynamics of the tracked vehicle, similar inputs on angular speeds of the tracks are applied to both the right and left tracks during forward movement. During right cornering, the angular speed setting applied for the left track is set to be higher than the right track. Meanwhile during left cornering, the angular speed setting for the left track is set to be lower than the right track of the tracked vehicle. The validation process for the tracked vehicle mathematical model is carried out with the fundamental forward movement, as illustrated in Figure 4(a). During this forward movement, both the model and actual tracked vehicle are configured with an identical track speed of 4 rad/s for the left and right tracks. Analyzing the tracked vehicle trajectory response in X and Y global coordinates reveals that initially, within the first 1.5 m the model closely mirrors follows the path traveled by the actual tracked vehicle. However, starting approximately from 1.5 m to 3 m, it is observed that the model begins to diverge from the actual tracked vehicle path.

Next, during right cornering maneuvers, specifically, the left track speed is set at 4 rad/s, while the right track speed is set at 2 rad/s, resulting in the tracked vehicle executing a right cornering action, as depicted in Figure 4(b). Throughout this right cornering, it is observed that the model closely aligns with the path travelled by the actual tracked vehicle. Beginning at approximately 2 m, a noticeable difference between the model and actual path travelled by the tracked vehicle can be seen, as the model starts to diverge from the actual tracked vehicle path. Similarly, the validation for left cornering is conducted with the left track speed at 2 rad/s, while the right track speed is set at 4 rad/s, yielding a left cornering, as indicated in Figure 4(c). During this left cornering, the developed model closely tracks the path travelled by the actual tracked vehicle for the first 2 m, like the behavior observed during the right cornering. The deviation between the model and the actual path travelled by the tracked vehicle during the left cornering is lower compared to the right cornering.

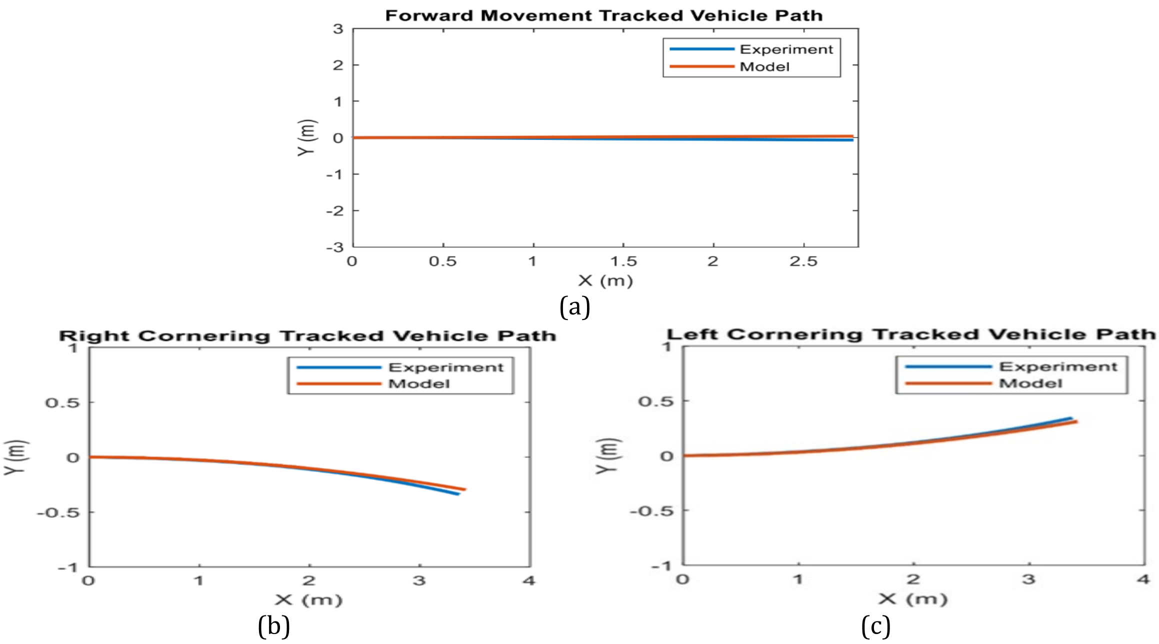

Figure 4. Validation of forward (a), left (b), and right (c) maneuver for tracked vehicle

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Overall, as depicted in Figure 4, it shows that the developed dynamic model is capable of closely tracking the actual path of the tracked vehicle. However, upon analysis of the data from forward, right, and left cornering maneuvers, slight discrepancies are observed when comparing the model to the actual trajectory response of the tracked vehicle. Deviation is visible in cornering maneuver. This can be attributed to the lack of friction consideration within the mathematical model. This includes rolling resistance on the tracked sprocket. It can be seen from the results that the right track has more friction than the left making it to turn more to the right than it should. However, from visual observation from the graph, it is evident that both model and vehicle behave similarly during maneuver.

In analysing this, Zuñiga-Peña et al., (2022) recommend employing the RMSE for lateral coordinates as a mean of comparison. RMSE is a mathematical measure that quantifies the overall accuracy of a model or prediction [10]. In essence, this transformation of longitudinal values mitigates any directional influence, ensuring a uniform and consistent representation. This method not only provides a detailed understanding of deviations but also contributes to the reliability and accuracy of the assessment, offering a robust foundation for analyzing the trajectory's performance. It emphasizes a meticulous approach to data analysis, crucial for applications where precision and consistency are paramount. In this study, lateral error involving the vehicle position in Y-direction is considered. Therefore, lateral error, E is $Y_{actual} - Y_{model}$ and RMSE can be calculated using Equation (17).

$$RMSE = \sqrt{\left[\frac{1}{n}\sum(Y_{actual} - Y_{model})^2\right]} \tag{17}$$

Applying Equation (17) for all maneuverings yield RMSE values shown in Table 3. When comparing lateral errors with experimental data, the forward motion results in an error of 0.0797 m. Whereas right and left cornering maneuvers produce lateral errors of 0.0797 m and 0.00734 m, respectively. Based on the obtained RMSE values for three types of paths traversed by the tracked vehicle, it can be shown that there exists minor deviation between the simulated and actual vehicle trajectory in all maneuvers. This is due to the ideal assumptions in the vehicle model which neglects various friction and interaction reaction forces within the system. This also happens due to the sampling frequency within the vehicle instrumentation system which gives rise to a slight deviation in the analysed data. In addition, interpolation method used in the ω-bit conversion as shown in Figure 3 gives rise to a possible source of deviation. However, positively, the recorded RMSE values are low – lower than 0.08 m. This indicated that the method used managed to predict response close to the actual value, effectively reducing the RMSE values and thereby improving the accuracy of the predictions.

Table 3. Global coordinate error

Path	RMSE (m)
Forward	0.01177
Right Corner	0.0797
Left Corner	0.00734

In an overall evaluation, the mathematical model exhibits positive outcomes for all three fundamental maneuvers, with all motions recording lateral error below 0.08 m. Based on Jia et al., (2023), the recorded lateral error is 0.142 m when utilizing a tracked vehicle width of 0.79 m [11]. In contrast, in this study, the maximum lateral error obtained is 0.0797 m with the width of the tracked vehicle used is 0.185 m as shown in Table 4. This suggests that as the width of the tracked vehicle increases, the cornering trajectory widens leading to higher errors. Through this research, this indicates that the lateral errors for all maneuvers fall within an acceptable range, as supported by prior research findings [11]. The model adeptly adheres to the designed path, indicating the success of the validation process. This accomplishment is further underscored by the minimal RMSE observed when compared to the sensor data, affirming the precision and dependability of the validated model.

Table 4. Comparison of tracked vehicle dynamic model parameters with previous research

Comparison Parameters	Previous research [11]	Current research (Tracked vehicle dynamic model)
Maximum lateral error (m)	0.1420	0.0797
Width of the tracked vehicle (m)	0.7900	0.1850

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4.0 CONCLUSIONS

In conclusion, the mathematical model for tracked vehicles has been successfully validated, demonstrating a maximum RMSE of 0.08 m in lateral error. The comparison of the model with real-world data during the validation process is of utmost importance. This study has carried out the critical need for validation to provide a robust Model-based Controller for path tracking control of tracked vehicles. Further enhancement can be achieved through refinement of the data collection method.

5.0 CONFLICT OF INTEREST

The authors declare no conflicts of interest.

6.0 AUTHORS CONTRIBUTION

Ruslan, N. A. I. (Methodology; Data curation; Visualisation; Writing - review & editing)
Ani Sirafudin, A. R. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Investigation; Writing - original draft)
Amer, N. H. (Conceptualisation; Writing - review & editing; Funding acquisition; Project administration; Supervision)
Hudha, K. (Resources; Software; Supervision)
Abd. Kadir, Z. (Resources; Software; Supervision)
Mohamed Ishak, S. A. F. (Funding acquisition; Supervision)
Syed Mohd Dardin, S. M. F. (Resources; Software; Supervision)

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