Speed and Direction Control Enhancement for Four-Wheel Drive System using Finite-Time Control

Sarkar J. Shareef[1], Fadhil T. Aula[2]
1- Department of Electrical Engineering, College of Engineering, Salahaddin University-Erbil, 44002, Erbil, Iraq.
Email: sarkar.mohammed@su.edu.krd (Corresponding author)
2- Department of Electrical Engineering, College of Engineering, Salahaddin University-Erbil, 44002, Erbil, Iraq.
Email: fadhil.aula@su.edu.krd

Received: 10 June 2023 Revised: 29 July 2023 Accepted: 22 September 2023

ABSTRACT:
Over the past few years, many electrical vehicle manufacturers have focused on developing enhanced controller efficiency for Four-Wheel Drive (FWD) systems. The control of the speed and direction of the FWD is crucial for safe and efficient operation, particularly in challenging maneuvers. The FWD system movements in straight routes and during maneuvers, turning all four wheels right and left, have not been well covered. Therefore, a robust control design that is capable of controlling the FWD system at an optimal time of operation is highly required. In this research, a Finite Time Control (FTC) is designed, implemented, and simulated to improve the robustness and performance of the FWD system during challenging maneuvers. The proposed FTC controls both the speed and direction of all wheels of FWD according to the route situations. The proposed FTC is compared with an FWD system that is controlled by a traditional Proportional, Integral, and Derivative (PID) controller during straight moving and maneuvers. The comparison is based on controlling parameters such as settling time, maximum overshoot, and speed error values. The results showed that the proposed FTC has a much faster settling time, significantly less maximum overshoot, and much lower error values than the PID controller. These factors are considered the main features of the contribution of any controller system that aims for optimal and robustness and FTC proved to have them adequately.

KEYWORDS: Four-wheel drive (FWD), Finite-Time Control (FTC), PID, Speed and Direction Control.

1. INTRODUCTION

The use of Four-wheel drive (FWD) systems can provide significant improvements in vehicle performance, allowing the vehicle to navigate rough terrain with greater ease and safety. The speed and direction control of FWD systems is critical for safe and efficient operation, particularly in challenging environments where the terrain and conditions change rapidly [1].

Control algorithms are widely used in engineering to manage processes. These include various methods like Proportional-Integral-Derivative (PID), Sliding Mode Control (SMC), Model Predictive Control (MPC), Neural Network, H-infinity, Fuzzy Logic, Backstepping, Feedback Linearization Control (FLC), Adaptive Control and Linear Quadratic Regulator (LQR). However, they have limitations such as high computation, the need for lots of training data, and dealing with uncertainty, which limits their use in industries [2] [3] [4].

The PID controller offers a straightforward approach to system control, modifying the control input according to the difference between the desired and measured output [5]. The researchers of [6] presented conventional two-wheel PID steering and sliding mode driving control for self-driving vehicles and subsequently advances to suggest four-wheel adaptations of these controllers. The authors of [7] have introduced a control system to address driver commands and maintain vehicle lateral stability. It employs nonlinear model predictive control in the upper layer and the lower layer features of a PID controller to manage wheel slips and control independent motor torques for driving and regenerative braking. While, [8] introduced a nonlinear triple-step steering controller for four-wheel steer-by-wire vehicles, enhancing stability by accurately tracking yaw rate and sideslip angle. It handled nonlinear tires, including a PID driver model, and its performance was evaluated through simulation. The study in [9] has attempted to improve electric vehicle stability through a PID controller in a four-wheel drive setup. It designs a fuzzy PID controller tied to yaw rate and sideslip angle. The simulation results have shown an improvement.

A Finite-Time Control (FTC) system refers to a class

Paper type: Research paper
DOI: 10.30486/mjee.2023.1987202.1151
How to cite this paper: S. J. Shareef, and F. T. Aula, **"Speed and Direction Control Enhancement for Four-Wheel Drive System using Finite-Time Control"**, *Majlesi Journal of Electrical Engineering*, Vol. 17, No. 4, pp. 23-30, 2023.

of control systems designed to achieve a specific control objective within a finite time. Unlike traditional control systems that are designed to operate indefinitely, FTC systems are designed to achieve a specific goal in a predetermined amount of time.

The development of FTC systems has been driven by applications in fields such as robotics, aerospace engineering, and power systems. In these applications, it is often necessary to achieve a specific control objective, such as stabilization or trajectory tracking, within a finite time. The design of FTC systems necessitates the application of mathematical tools such as Lyapunov stability theory and optimal control theory. These tools are used to develop control laws that can drive the system to its desired state in a finite time while ensuring stability and performance requirements. FTC systems offer a significant benefit in terms of their capability to provide fast and precise control in applications where time is a crucial factor. They also offer the potential for improved energy efficiency and reduced wear and tear on mechanical components. Overall, the development of finite-time control systems has led to significant advances in the design and operation of complex control systems in a range of applications [10].

In recent years, there has been a growing interest in the development and application of finite-time control across a range of fields. The researchers in [11] have addressed the challenge of overseeing the trajectory of autonomous underwater vehicles by employing finite-time output feedback. In a similar manner, the authors in [12] have proposed an adaptive and robust finite-time tracking control strategy for a fully actuated marine surface vehicle, accommodating unknown disturbances. Additionally, the study in [13] presented a control approach for multirotor unmanned aerial vehicles by merging finite-time sliding mode control technique with other methods. This was tailored to scenarios where output limitations are relevant. The authors of [14] explored the domain of adaptive finite-time attitude tracking control, focusing on rigid spacecraft systems. The investigation considered full-state constraints and external disturbances. Moreover, the researchers in [15] put forward a solution for the finite-time command filtered course tracking issue concerning ships. This method tackled challenges such as unknown bounded disturbances, unmodeled dynamics, and input saturation. Finally, the article in [16] investigated the complex task of guiding AUVs along finite-time trajectories.

In the domain of FWD, the researchers in [17] introduced a lane-keeping controller for independently driven electric vehicles using the non-smooth finite-time control method. The article involved the direction control of the FWD only. While the authors in [18] addressed lane-keeping control for autonomous vehicles with independent four-wheel actuators using FTC. They introduced a steering control system for estimating lane-keeping errors to control autonomous vehicles steering. Furthermore, the authors in [19] focused on stabilizing the yaw moment of a four-wheel independent-drive electric vehicle. It proposed a second-order sliding mode along with a finite-time control method to ensure desired values for both yaw rate and sideslip angle.

Previous studies in the area of FTC for FWD, have concentrated on directional control only, leaving speed control as a potential focus for future investigations. In this research, an FTC is designed and implemented for controlling the speed and direction of the four Permanent Magnet Direct Current motors (PMDCM) of an FWD system. Then, the simulation results have been compared with the traditional PID controller.

This work makes a sound contribution to the FWD domain using the FTC. The system design is not only managing speed on straight routes but also handling speed control while making maneuvers. This is a significant improvement compared to the literature which didn't account for this aspect.

This research is organized as follows: Section 2 introduces the mathematical model of the FWD system. While Section 3 presents the design of the FTC. The simulation results are discussed in Section 4. Finally, conclusions are presented in Section 5.

2. FWD MATHEMATICAL MODEL

The model used in this work is a four-wheel drive system which is a multi-body system consisting of three bodies, namely the Forward wheels, Rear wheels, and Chassis. The forward wheels as well as the rear wheels are turned separately to keep track of the route. Each wheel is driven by a DC motor and controlled separately with four FTCs. The distance between the front and rear wheels (i.e., FWD length) of the FWD model is 154mm and the distance between the left and right wheels (the FWD width) is 135mm. The maximum turning angle for the FWD model is 14.7 degrees. The position and orientation of each body can be described by utilizing the coordinates and turning angles of each body. Fig. 1 presents the FWD dynamic model with both front and rear wheels and different angles and dimensions.

The DC motors that are used to drive each of the four-wheel are PMDCM with the parameters shown in Table 1. These parameters were taken from data of the motor used in [20].

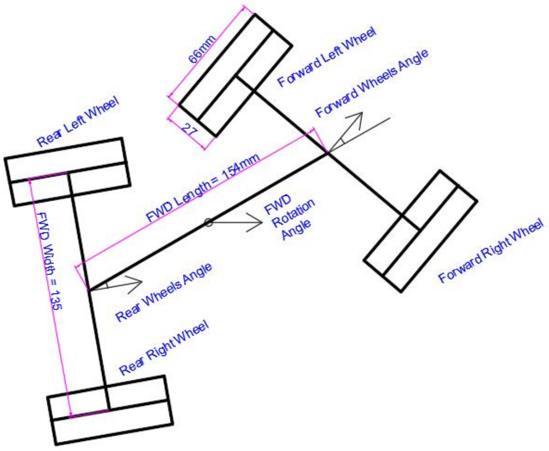

Fig. 1. Dynamic Model of Four-Wheel Drive System.

Table 1. PMDCM parameters.

Parameter	Value
Moment of inertia of the rotor J	$5.902 \times 10^{-4}\ kg.m^2$
Motor viscous friction constant B	$5.663 \times 10^{-5}\ N.m.s$
Electromotive force constant K_b	$0.062\ V.s.rad^{-1}$
Motor torque constant K_t	$0.062\ N.m.Amp^{-1}$
Electric resistance R	$8.5\ \Omega$
Electric inductance L	$5.621\ mH$

The block diagram of PMDCM model is shown in Fig. 2.

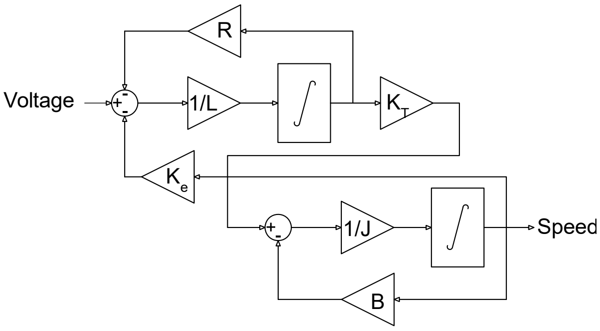

Fig. 2. PMDCM Model Block Diagram.

The state-space model of PMDCM is given by the following expressions [21].

$$\dot{\omega} = -\frac{B}{J}\omega + \frac{K_t}{J}i \qquad (1)$$

$$i = -\frac{K_b}{J}\omega + \frac{R}{L}i + \frac{V}{L} \qquad (2)$$

3. DESIGN OF A FINITE-TIME CONTROL

In order to regulate the speed of FWD, the FTC method can be employed to develop a control approach for managing the speed of a PMDCM. This approach aims to accurately follow a set of reference speeds within a specified time constraint, as outlined in the reference [22].

Definition: The system's finite-time stability:

$$\dot{z} = g(z), g(0) = 0, z \in R^n \qquad (3)$$

Where $g(\cdot): R^n \rightarrow R^n$ is a continuous function, if the equilibrium $z = 0$ of the system is Lyapunov stable and converges in the finite time, that is, there is a limit time $T(z(0))$ as $lim_{t \to T(z(0))} z(t) = 0$ and $z(t) = 0$ for all $t \geq T(z(0))$, so it is called the equilibrium of finite-time stability (FTS).

The following functions are introduced for designing finite-time feedback controllers:

$$sat^{\alpha}(x) = \begin{cases} sign(x) for |x| > 1 \\ sign(x)|x|^{\alpha} for |x| \leq 1 \end{cases} \qquad (4)$$

Lemma 1: Further down the form of the regular system (3) is globally asymptotically stable, the system is also globally FTS.

Lemma 2: In the case of the system (6) when there is a function of Lyapunov $V(z)$ sustaining $\dot{V}(z) \leq -kV^{\alpha}(z)$, where $k > 0$, $0 < \alpha < 1$, so z = 0 is finite-time stability equilibrium of system.

The PMDCM model is used for rotating the wheels of an FWD and consists of two separate loops. The first loop deals with the current, denoted as $\boldsymbol{i}$, while the second deals with speed, denoted as $\boldsymbol{\omega}$. The specific configuration of the FTC system depends on the dynamic model governing the armature current:

$$\dot{x}_1 = -\beta_1 sat^{\alpha_1}(x_1) - \beta_2 sat^{\alpha_2}(x_2) \qquad (5)$$

where $\beta_1 > 0, \beta_2 > 0, 0 < \alpha_1 < 1$ and $0 < \alpha_2 < 1$

$$V = -\beta_1 sat^{\alpha_1}(x_1) - \beta_2 sat^{\alpha_2}(x_2) \qquad (6)$$

$$x_1 = \omega_r - \omega \qquad (7)$$

$$x_2 = \omega \qquad (8)$$

$$V = -\beta_1 sat^{\alpha_1}(\omega_r - \omega) - \beta_2 sat^{\alpha_2}(\omega) \qquad (9)$$

Then,

$$i = -\frac{R}{L}i - \frac{\beta_1 sat^{\alpha_1}(\omega_r - \omega)}{L} - \frac{\beta_2 sat^{\alpha_2}(\omega)}{L} - \frac{K_b}{L}\omega \qquad (10)$$

the Lyapunov function is chosen as [22],

$$H = \frac{1}{2}i^2 \qquad (11)$$

And the derivative of the Lyapunov function,

$$\dot{H} = i \cdot i \tag{12}$$

$$\dot{H} = \frac{i}{L}(-Ri - \beta_1 sat^{\alpha_1}(\omega_r - \omega) - \beta_2 sat^{\alpha_2}(\omega) - K_b\omega)\dot{H} = \frac{i}{L}(-Ri - \beta_1 sat^{\alpha_1}(\omega_r - \omega) - \beta_2 sat^{\alpha_2}(\omega) - K_b\omega) \tag{13}$$

In order to verify that the Lyapunov function, H, represents the equilibrium state of the FTS. It is necessary to ensure that the derivative of this function is consistently less than zero. This means that Equation (13) must be negative throughout the system's operation [23]. Once this condition is satisfied, the finite-time control parameters can be computed using PMDCM parameters shown in Table 1 and FTC parameters as follows: $\alpha_1 = 0.31$, $\beta_1 = 3500$, $\alpha_2 = 0.35$ and $\beta_2 = 8$, then,

$$\dot{H} = \frac{i}{0.005621}(-8.5i - 3500sat^{0.31}(1500 - \omega) - 8sat^{0.35}(\omega) - 0.062\omega) \tag{14}$$

The values of speed (w) and current (i) are positive all the time, if the derivative of the Lyapunov function $\dot{H}$ is negative. According to Lemma 2, H represents a state of finite-time stability for the system [22].

The FTC design relies on functions derived from [22], and a novel FWD design was shown in Fig. 1, using FTC techniques. The FTC implementation for the FWD block diagram is illustrated in Fig. 3. The first element of this diagram is a line tracker, which independently monitors the positions of the front and rear wheels. While, in the second element (Determine Front and Rear Wheel Angles), the angles of front and rear wheels are determined. These angles play a significant role in establishing the speeds of all four FWD wheels. The FTC modules dedicated to each wheel, ensure that measured speeds, as detected by the speed sensors, align with their respective reference speeds, thus converging the speed errors toward zero.

4. SIMULATION AND RESULTS

In this research, MATLAB Simulink was used to test and validate the proposed controller. The system was modeled mathematically considering the physical limitations detailed in Section 3 and the parameter settings provided by Table 1. The PID model described in [9] was utilized for the comparison. The PID parameters underwent refinement through the PID tuner within MATLAB Simulink. The final tuned values for the parameters were determined to be as follows: Proportional (P) = 13.8490, Integral (I) = 23.9996, and Derivative (D) = -0.5289.

The simulation model diagram is shown in Fig. 4. The model begins with a line tracker that independently monitors the positions of the front and rear wheels. The "turning angles calculation" step follows which determines the angles of the wheels. These angles play a crucial role in determining the speeds of all four FWD wheels through voltage regulation in the "input voltage regulator" block. The FTC modules for each wheel and individual PID controllers are then employed to manage and control each wheel separately.

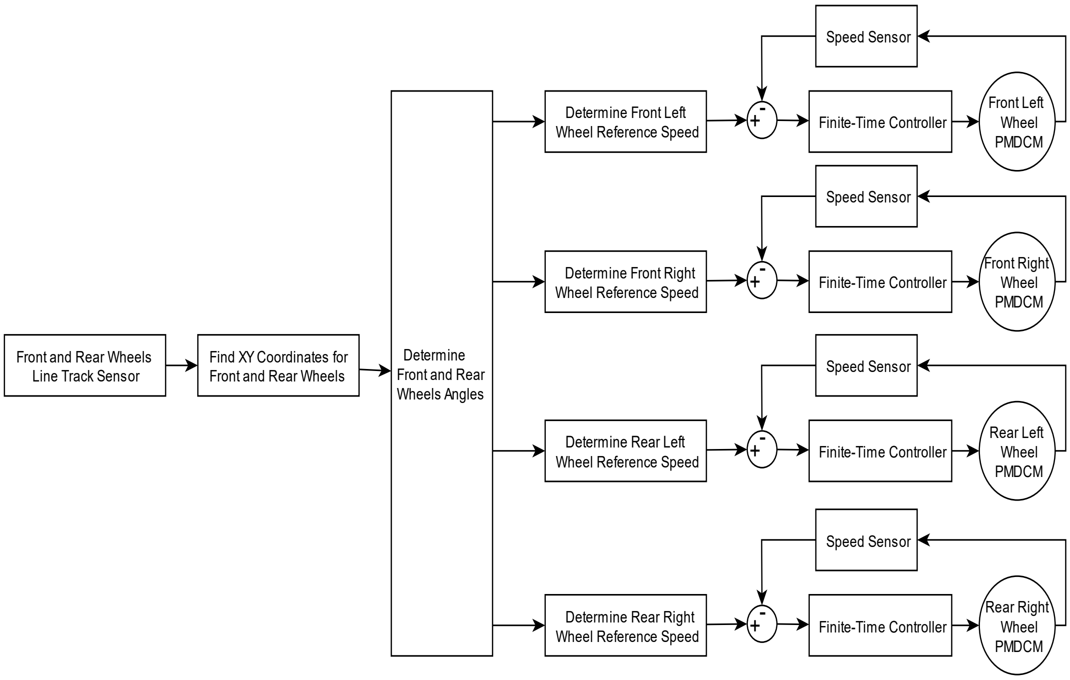

Fig. 3. The simulation model of FTC of FWD block diagram.

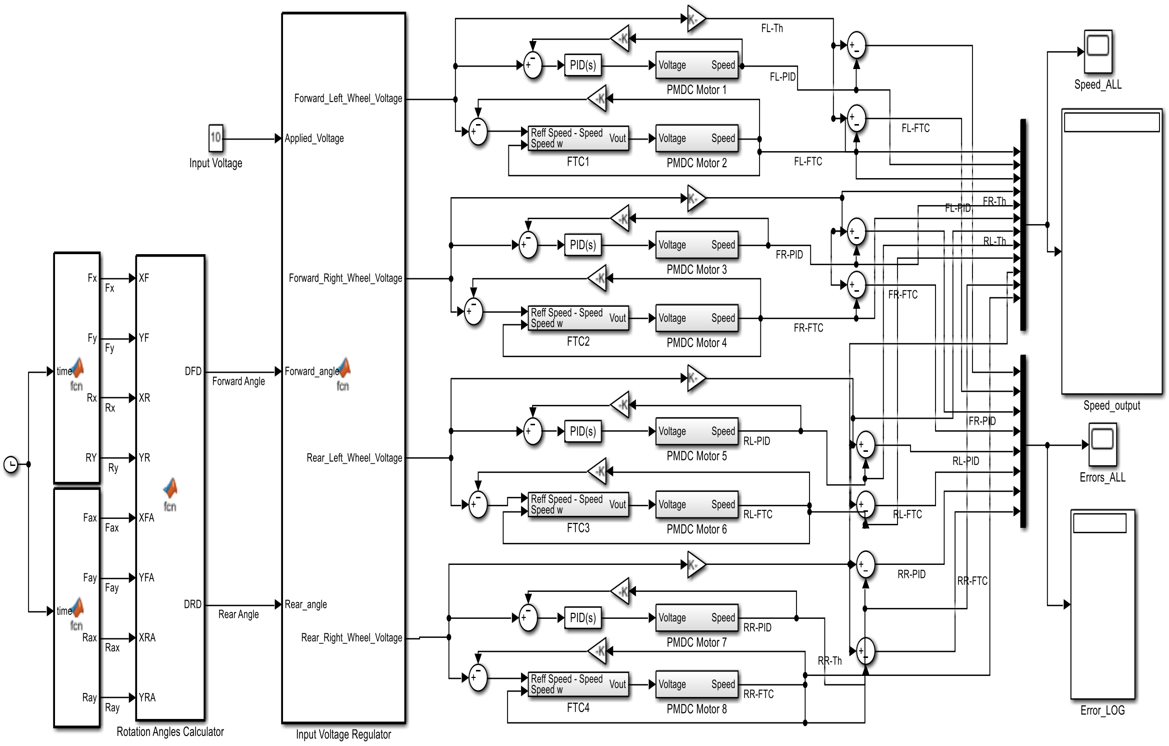

Fig. 4. The simulation model diagram.

The proposed trajectory route to test the FWD system is shown in Fig. 5. The FWD system is moving at the rated speed of 1500 rpm when the route is a straight line and decreases its speed to 1020 rpm during FWD system turning to left and right with a maximum turning angle of 14.7 degrees. To avoid slipping, the speed decreases depending on the wheels' turning angles.

The FWD system is tracking a route starting from a straight line toward the east with a rated speed of 1500 rpm for 34.5 seconds. Then, it starts to turn to the left side toward the north decreasing its speed gradually from 1500 rpm to 1020 rpm at 50 seconds (Front left wheel speed is 794 rpm, front right wheel speed is 1248 rpm, rear left wheel speed is 793 rpm and rear right wheel speed is 1247 rpm). It continues at this speed for 80 seconds and then increases to reach its rated speed of 1500 rpm at the end of the turning period at 97.2 seconds.

The FWD system is continuous on the straight-line route toward the north until time 121.6 seconds with a rated speed of 1500 rpm. Then, it turns to the right toward the east, gradually decreasing its speed from 1500 rpm to 1020 rpm at 137.1 seconds (Front left wheel speed is 1248 rpm, front right wheel speed is 794 rpm, rear left wheel speed is 1247 rpm and rear right wheel speed is 793 rpm). It continues at this speed until 168.6 then increases its speed gradually to reach its rated speed of 1500 rpm at the end of the turning period at 184.3 seconds.

The FWD system is continuous on the straight-line route toward the east until the end of the route at time 220 seconds with a rated speed of 1500 rpm.

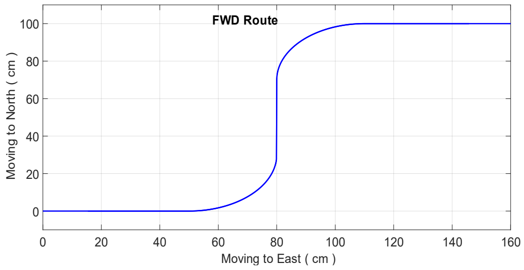

Fig. 5. A proposed trajectory route of the FWD system.

The results of this research show that the FTC is better than the PID controller in settling time, overshoot value, and speed errors for all motor wheels. For all four wheels, the FTC settling time is 650 milliseconds, and for the PID controller is 23 seconds. While the overshoot for FTC is 5.1 rpm and for PID controller is 119.3 rpm. Figs. 6 to 9 show the comparison between FTC and PID controllers.

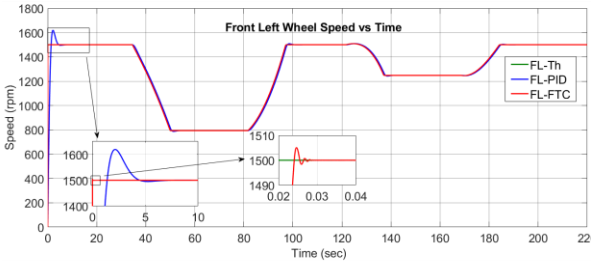

Fig. 6. Front Left Wheel Speed vs Time.

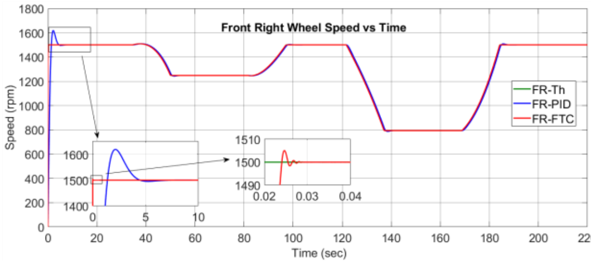

Fig. 7. Front Right Wheel Speed vs Time.

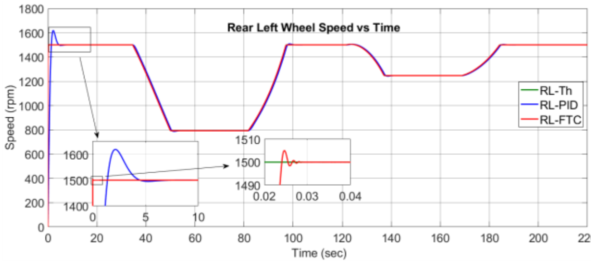

Fig. 8. Rear Left Wheel Speed vs Time.

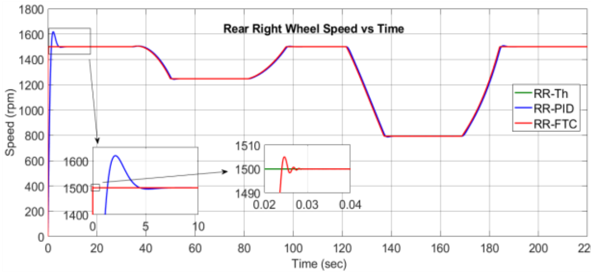

Fig. 9. Rear Right Wheel Speed vs Time.

Figs. 10 to 13 show the comparison between the FTC and PID controllers' errors for all wheels of FWD. The figures show that the FTC model is better than the PID in terms of the speed error value. The speed error values for all wheels with the same settling time for both controllers (23 seconds) are found to be 9.92×10^{-10}rpm and 6.93×10^{-8}rpm for FTC and PID controllers, respectively.

During turning the FWD to the right and left sides, the FTC performed better than PID controller for each wheel. For the front left wheel, during turning, the FWD to the left direction, the FTC speed error is 0.1 rpm, and for PID controller is 24.3 rpm. Moreover, during turning the FWD in the right direction, the FTC speed error is 0.1 rpm, and for PID controller is 31.6 rpm as shown in Fig. 10.

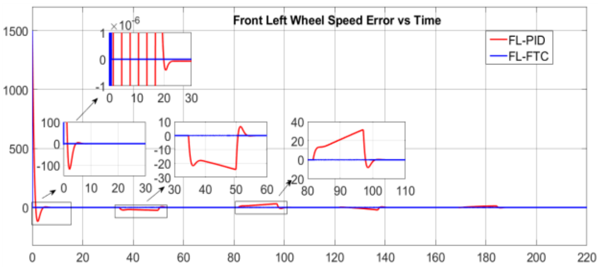

Fig. 10. Front Left Wheel Speed Error vs Time

The speed errors of the front right wheel are 0.1 rpm and 21.1 rpm for FTC and PID controllers, respectively when the FWD is turned to the left direction. During the turning of FWD in the right direction, the FTC speed error is 0.1 rpm, while for PID controller is 12.4 rpm as evidenced by Fig. 11.

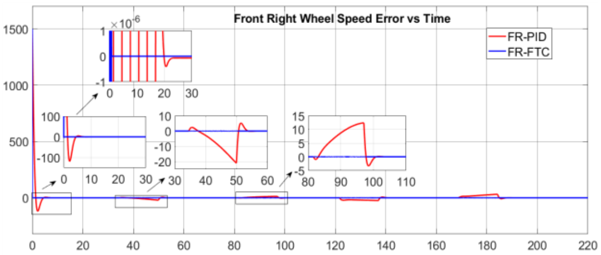

Fig. 11. Front Right Wheel Speed Error vs Time.

For the rear left wheel and during turning the FWD to the left direction, the speed errors are 0.1 rpm and 22.5 rpm for FTC and PID, respectively. While, during the turning of FWD in the right direction, the FTC speed error is 0.1 rpm, and for the PID controller is 31.5 rpm as indicated in Fig. 12.

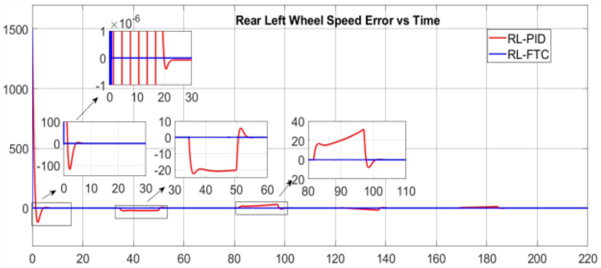

Fig. 12. Rear Left Wheel Speed Error vs Time.

Finally, for the rear right wheel, the speed errors are 0.1 rpm and 17.2 rpm for the FTC and PID controllers, respectively when the FWD is turned in the left direction. Whereas, they are 0.1 rpm and 12.4 rpm for FTC and PID controllers respectively during the FWD right direction turnover as evidenced by Fig. 13.

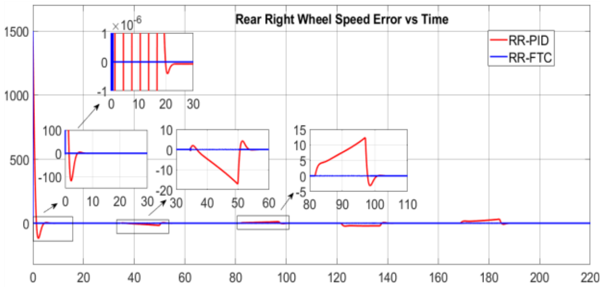

Fig. 13. Rear Right Wheel Speed Error vs Time.

5. CONCLUSION

This research has studied the potential of Finite-Time Control (FTC) as a robust control approach for enhancing the speed and direction of FWD systems. The FTC system was designed and simulated to validate the performance of the FWD control system. Additionally, a PID controller was designed and simulated to serve as a benchmark for comparing against the FTC system. The comparison between the two control approaches was conducted in two scenarios: the straight-line route and the turning periods of the FWD system. It can be concluded from the simulation results that the FTC has significantly performed better than the PID in terms of control properties. The PID controller compared to the FTC, in which the PID took more than 35 times longer to reach the steady state as the FTC settled in only 0.65 seconds, while the PID took 23 seconds This fast-settling time allowed the FTC to reach and stabilize around the desired setpoint in less than a second, which can be used in applications that require rapid and precise control. In addition to the settling time, overshoot is another important factor to consider when comparing the performance of control systems. The simulation results showed that the FTC exhibits an overshoot of 5.1 rpm, while the PID controller showed a significantly higher overshoot of 119.3 rpm. This proves that the FTC system provides a precise control response with minimal overshooting whereas the higher overshoot value of the PID controller causes the system's output to significantly exceed the desired setpoint before stabilization. Such a large overshoot can be undesirable in applications where precise control and minimal deviation from the setpoint are important. Furthermore, the FTC had better speed error values compared to the PID controller. The error value of the FTC in the straight-line route after settling time was smaller than the PID controller by 69.8. During the FWD turning to the left and right, the maximum error value for FTC was 0.1 rpm in all cases and for all four wheels, while for the PID controller, the maximum error value when the FWD turns to the left side was 24.3 rpm and when it turns to the right was 31.6 rpm. In conclusion, considering the shorter settling time, lower overshoot, and potentially lower error values, the FTC proved to be the superior choice for controlling the FWD system. The faster response, higher precision, and ability to minimize deviations of FWD make the FTC a more effective control solution compared to the PID controller.

REFERENCES

[1] S. C. Peters and K. Iagnemma, **"Stability measurement of high-speed vehicles,"** *Vehicle System Dynamics*, vol. 47, no. 6, pp. 701-720, 2009.

[2] R. Roy, M. Islam, N. Sadman, M. A. Parvez Mahmud, D. K. Gupta and M. M. Ahsan, **"A Review on Comparative Remarks, Performance Evaluation and Improvement Strategies of Quadrotor Controllers,"** *Technologies*, vol. 9, no. 37, pp. 1-22, 2021.

[3] M. Rinaldi, S. Primatesta and G. Guglieri, **"A Comparative Study for Control of Quadrotor UAVs,"** *Applied Sciences*, vol. 13, no. 6, p. 3464, 2023.

[4] Haruna, Z. Mohamed, A. M. Abdullahi and M. A. M. Basri, **"A Review of Control Algorithms for Twin Rotor Systems,"** *Applications of Modelling And Simulation*, vol. 7, pp. 93-99, 2023.

[5] K. H. Ang, G. Chong and Y. Li, **"PID control system analysis, design, and technology,"** *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 559-576, 2005.

[6] B. Li, H. Du and W. Li, **"Trajectory control for autonomous electric vehicles with in-wheel motors based on a dynamics model approach,"** *IET Intelligent Transport Systems*, vol. 10, no. 5, pp. 318-330, 2016.

[7] H. Zhou, F. Jia, H. Jing, Z. Liu and L. Güvenç, **"Coordinated Longitudinal and Lateral Motion Control for Four Wheel Independent Motor-Drive Electric Vehicle,"** *IEEE Transactions on Vehicular Technology*, vol. 67, no. 5, pp. 3782-3790, 2018.

[8] S. Yu, W. Li, W. Wang and T. Qu, **"Nonlinear Control of Active Four Wheel Steer-By-Wire Vehicles,"** *IEEE Access*, vol. 7, pp. 127117-127127, 2019.

[9] J. Wang, **"Application of Pid Algorithm In Drive Fault-Tolerant Control of Four-Wheel Drive Electric Vehicle,"** *International Journal of Mechatronics and Applied Mechanics,*, vol. 1, no. 8, pp. 235-242, 2020.

[10] F. Amato, M. Ariola, M. Carbone and C. Cosentino, **"Finite-time control of linear systems: A survey,"** *Systems and Control: Foundations and Applications*, pp. 195-213, 2006.

[11] S. Li, X. Wang and L. Zhang, **"Finite-time output feedback tracking control for autonomous underwater vehicles,"** *IEEE Journal of Oceanic Engineering*, vol. 40, no. 3, pp. 727-751, 2015.

[12] N. Wang, C. Qian, J. C. Sun and Y. C. Liu, **"Adaptive Robust Finite-Time Trajectory Tracking Control of Fully Actuated Marine Surface Vehicles,"** *IEEE*

Transactions on Control Systems Technology, vol. 24, no. 4, pp. 1454-1462, 2016.

[13] Raza, F. M. Malik, N. Mazhar, H. Ullah and R. Khan, **"Finite-Time Trajectory Tracking Control of Output-Constrained Uncertain Quadrotor,"** *IEEE Access*, vol. 8, pp. 215603 - 215612, 2020.

[14] L. Zhao and G. Liu, **"Adaptive Finite-Time Attitude Tracking Control for State Constrained Rigid Spacecraft Systems,"** *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 12, pp. 3552 - 3556, 2021.

[15] D. Yang, X. Hu, W. Liu and C. Guo, **"Finite-time control design for course tracking of disturbed ships subject to input saturation,"** *International Journal of Control*, vol. 95, no. 5, pp. 1409 - 1418, 2022.

[16] X. Liu, M. Zhang, C. Yang and B. Yin, **"Finite-time tracking control for autonomous underwater vehicle based on an improved non-singular terminal sliding mode manifold,"** *International Journal of Control*, vol. 95, no. 3, pp. 840 - 849, 2022.

[17] Q. Meng, X. Zhao, C. Hu and Z.-Y. Sun, **"High Velocity Lane Keeping Control Method Based on the Non-Smooth Finite-Time Control for Electric Vehicle Driven by Four Wheels Independently,"** *Electronics*, vol. 10, no. 6, p. 760, 2021.

[18] C. Hu, Y. Qin, H. Cao, X. Song, K. Jiang, J. J. Rath and C. Wei**, "Lane keeping of autonomous vehicles based on differential steering with adaptive multivariable super-twisting control,"** *Mechanical Systems and Signal Processing*, vol. 125, pp. 330-346, 2018.

[19] S. Ding and J. Sun**, "Direct yaw-moment control for 4WID electric vehicle via finite-time control technique,"** *Nonlinear Dyn*, vol. 88, p. 239–254, 2017.

[20] Z. M. Tun and T. L. Naing, **"Double Loop Control of H-Bridge DC Chopper Fed Permanent Magnet DC Motor Drives Using Low Cost Hardware,"** *International Journal of Electrical and Computer Engineering*, vol. 12, no. 11, pp. 857 - 866, 2018.

[21] B. Theraja and A. Theraja, **"D.C. Motor,"** in A Text Book of Electrical Technology, 2008.

[22] V. T. Haimo, **"Finite Time Controllers,"** *SIAM Journal on Control and Optimization*, vol. 24, no. 4, pp. 760 - 770, 1986.

[23] H. Du, G. Wen, Y. Cheng and J. Lu, **"Design and Implementation of Bounded Finite-Time Control Algorithm for Speed Regulation of Permanent Magnet Synchronous Motor,"** *IEEE Transactions on Industrial Electronic*s, vol. 68, no. 3, pp. 2417 - 2426, 2021.