

Article

Multi-Motor Cooperative Control of Tracked Locomotion Mechanisms

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Abstract: In response to the issues of multi-motor drive desynchronization and trajectory deviation in tracked agricultural machinery operating in complex farmland environments due to sudden unilateral load changes, this paper takes the tracked locomotion mechanism as the research object and conducts an in-depth study on multi-motor coordinated control strategies. A double-closed-loop speed regulation system for permanent magnet DC motors and the dynamic model of an H-bridge reversible pulse-width modulation (PWM) converter were first established. On this basis, a deviation coupling control structure based on dynamic correlation was introduced, and a speed difference compensation algorithm between drive axes was developed to design a speed compensator capable of adaptively adjusting the system's moment of inertia. For two typical operating conditions—dual-motor drive and four-motor drive—two coordinated control strategies were respectively proposed: full deviation coupling on both sides, and a hybrid approach combining inter-side deviation coupling with single-side master-slave following. A multi-motor coordinated control simulation model was then built in MATLAB/Simulink, through which the dynamic response characteristics of non-coupled control and deviation coupling control were comparatively analyzed under absolute synchronization and proportional synchronization conditions. The results show that under sudden unilateral load disturbances, the proposed deviation coupling control strategy can significantly suppress speed fluctuations among multiple axes. Compared with non-coupled control, the speed-difference oscillations are slightly reduced, with the speed difference decreasing from 0.00089 to 0.00087 m/s, corresponding to a reduction of approximately 2.25%. This method effectively improves the synchronization accuracy and disturbance rejection capability of multi-motor systems in tracked locomotion mechanisms, providing a solid theoretical basis for stable driving control of agricultural tracked transport machinery.

Keywords: tracked locomotion mechanism; multi-motor system; deviation coupling control; synchronization accuracy; simulation analysis

1. Introduction

With the rapid development of agricultural mechanization and electrification, multi-motor drive systems have been increasingly adopted in agricultural machinery because of their advantages in distributed power delivery, flexible power allocation, and improved traction capability. For agricultural vehicles operating on uneven terrain, however, the mechanical and electrical characteristics of multiple drive units are not completely identical. Differences in motor parameters, load torque, transmission characteristics, and external disturbances may result in inconsistent motor speeds and torque distribution, thereby affecting the driving stability and traction performance



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of the vehicle. Therefore, achieving accurate speed tracking while maintaining synchronization among multiple drive motors is an important issue in the control of electrically driven agricultural machinery.

Multi-axis synchronization control has been extensively investigated in industrial motion systems. Conventional independent-axis control mainly regulates each actuator according to a common reference signal, while the synchronization errors between different axes are not directly incorporated into the control loop. Koren [1] introduced a deviation-coupled control strategy for biaxial computer-controlled manufacturing systems, in which the control errors of different axes were mutually coupled to improve contour accuracy. Sun [2] subsequently incorporated deviation-coupling into an adaptive control framework and established a position synchronization controller capable of simultaneously reducing tracking and synchronization errors. Sun et al. [3] further proposed a model-free deviation-coupled control method for multi-axis motion and experimentally verified its effectiveness. These studies established the theoretical basis for using virtual coupling relationships to improve the coordination performance of multiple actuators.

To improve synchronization performance under system uncertainties and external disturbances, robust and nonlinear control methods have subsequently been introduced into multi-axis coordinated control. Li et al. [4] combined adjacent deviation-coupling control with sliding mode control and a disturbance observer to reduce synchronization errors and compensate for parameter perturbations and unknown torque disturbances. Cheng and Bakhom [5] developed an adaptive robust synchronization controller with deviation-coupling dynamics and experimentally demonstrated its ability to improve both tracking and synchronization accuracy. Sun and Tong [6] further employed synchronization errors between adjacent axes to reduce contouring errors in multi-axis CNC systems. For networked multi-axis motion systems, Wang et al. [7] considered network-induced delays and external load disturbances and developed a generalized extended-state-observer-based synchronization control method. These studies indicate that synchronization compensation and disturbance rejection are essential for multi-actuator systems subjected to parameter uncertainties and external disturbances.

For multi-motor drive systems, the control architecture has gradually evolved from conventional parallel and master-slave strategies toward deviation-coupling and deviation-coupling structures. In a master-slave strategy, one motor is selected as the master and the remaining motors track its output, which results in a relatively simple control structure but may cause error propagation when the master motor is disturbed. Deviation-coupled control introduces the relative deviation between motors into the control loops and therefore provides a direct mechanism for synchronization compensation. Li et al. [8] proposed a mean deviation coupling strategy combined with second-order adaptive sliding mode control and compared it with master-slave, relative coupling, ring coupling, PI, and conventional sliding mode control strategies on a four-motor system. Chen et al. [9] investigated speed synchronization of multiple permanent magnet synchronous motors using an improved deviation-coupling structure, particularly addressing the large synchronization error and long adjustment time during motor start-up. Mean deviation coupling further extends this concept to multiple motors by constructing synchronization compensation according to the deviation from a common or average speed. Wang et al. [10] developed a distributed synchronization controller based on mean deviation coupling and H-infinity control, while Zhu et al. [11] combined mean deviation coupling with global fast terminal sliding mode control and experimentally verified the proposed strategy on a four-motor platform.

Recent studies have further focused on improving the synchronization accuracy, dynamic response, and disturbance rejection capability of deviation-coupling control. Zhang and Wang [12] combined finite-control-set model predictive control with relative-coupling position command shaping for multi-motor position synchronization. Lan et al. [13] developed a multi-motor position synchronization method based on non-singular fast terminal sliding mode control and deviation coupling. Hao and Zhao [14] integrated adaptive integral sliding mode control and a sliding mode disturbance observer into the coupling control framework of multiple permanent magnet synchronous motors. Mu et al. [15] proposed an improved deviation-coupling method for multi-motor speed synchronization and experimentally verified its effectiveness on a six-axis robotic system. Zhao et al. [16] further developed an average deviation-coupling strategy using high-order sliding mode control and an extended-state sliding mode observer. More recently, Zhang et al. [17] introduced synchronization and tracking coefficients into an improved deviation-coupling structure and investigated their effects on the synchronization and tracking performance of multi-motor systems. These studies demonstrate the continuing development of deviation-coupling control from basic relative-error compensation toward adaptive, robust, and observer-assisted synchronization strategies.

The application of multi-motor drive technology to agricultural machinery has also received increasing attention, particularly in electric tractors and other electrically driven agricultural vehicles. Chen et al. [18] investigated parameter matching and optimization of a dual-motor electric tractor powertrain and established a MATLAB/Simulink-based dynamic model to evaluate the traction performance. Li et al. [19] proposed and optimized a dual-input coupling powertrain for pure electric tractors and analyzed the effects of powertrain

parameters on vehicle efficiency and operating performance. Wen et al. [20] developed a dual-motor power-coupling drive system for electric tractors and established a verification framework involving co-simulation, bench testing, and prototype vehicle testing. Zhang et al. [21] further investigated the design and optimization of a dual-motor electric tractor drive system under representative driving cycles. These studies mainly focus on powertrain configuration, parameter matching, energy efficiency, and power distribution, demonstrating the potential of multi-motor electric drives for agricultural machinery.

For tracked agricultural vehicles, however, the synchronization problem is further complicated by the interaction between the tracks and the soil. Uneven terrain, variations in soil conditions, external load disturbances, and track slip may lead to differences between the actual motor speed and the effective vehicle motion. Zhao et al. [22] established a kinematic model of an agricultural tracked robot considering track-soil slip and slip-rotation and proposed a sliding-mode-observer-based method for estimating slip parameters. Corradini [23] investigated slip estimation and data-driven control for agricultural tracked vehicles operating on rough terrain and narrow spaces, demonstrating the importance of considering actuator effectiveness loss caused by slipping. Therefore, for tracked agricultural machinery, a multi-motor synchronization controller should not only provide accurate motor-speed coordination but also maintain satisfactory tracking and disturbance-rejection performance under asymmetric loading and complex operating conditions.

Despite these advances, most existing studies on multi-motor synchronization have focused on industrial servo systems, permanent magnet synchronous motor platforms, tracked vehicle systems, or electric-vehicle powertrains. Relatively limited attention has been paid to the cooperative speed control of multiple motors directly used for tracked agricultural locomotion, particularly for systems in which different motors are subjected to asymmetric load disturbances. In addition, the control architecture required by a four-motor tracked drive system differs from that of a conventional dual-motor system. A dual-motor system can directly employ bilateral deviation coupling, whereas a four-motor system needs to simultaneously coordinate synchronization between the two sides of the vehicle and the motors within each side. Therefore, an appropriate hierarchical or hybrid synchronization structure is required to balance individual speed tracking and overall multi-motor coordination.

Motivated by these considerations, this study investigates deviation-coupling cooperative control for multi-motor tracked agricultural machinery. A dynamic model of the permanent magnet DC motor and H-bridge PWM drive system is first established. For the dual-motor configuration, a bilateral full-deviation-coupling control strategy is developed to improve the synchronization performance between the two drive motors. For the four-motor configuration, a hybrid synchronization structure combining inter-side deviation coupling and intra-side master-slave control is proposed to coordinate the motors on both sides of the tracked vehicle. The proposed control strategies are investigated under absolute and proportional synchronization conditions with asymmetric load disturbances, and their tracking and synchronization performance is evaluated through MATLAB/Simulink simulations.

2. Permanent Magnet DC Motor and Dynamic Modeling

2.1. Basic Structure of Permanent Magnet DC Motor

Permanent magnet DC motors are devices that convert electrical energy into mechanical energy according to the principle of electromagnetic induction. As the earliest type of motor for converting electrical energy into mechanical energy, DC motors possess the advantages of large starting torque, rapid dynamic response, and superior speed regulation performance, making them a critical component in electromechanical energy conversion. With advancements in power electronics and brushless DC motor technologies, the safety of DC motors has been greatly enhanced while maintenance costs have been reduced. Consequently, DC motors still play a significant role in modern industrial and agricultural machinery applications. The typical structure of the DC motor is illustrated in Figure 1.

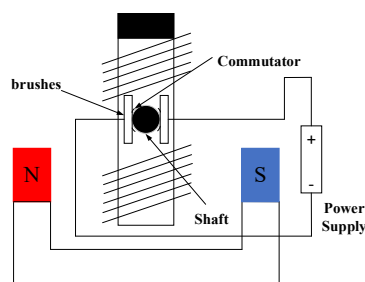


Figure 1. Structure of the DC motor.

For a motor to achieve electromechanical energy conversion, relative motion must occur between the electrical circuit and the magnetic circuit. Consequently, rotary motors consist of a stationary component and a rotating component. A specific clearance, known as the air gap, exists between the stationary and rotating parts. The stationary part is referred to as the stator, which produces the magnetic field and provides mechanical support for the motor; it is primarily composed of main poles, commutating poles, and other elements. The rotating part is called the rotor (or armature), which accomplishes energy transformation through induced electromotive force and consists of the armature core, armature windings, commutator, etc.

2.2. Speed Regulation Characteristics of Permanent Magnet DC Motor

DC motors, as the earliest power devices for converting electrical energy into mechanical energy, offer the advantages of high starting torque, wide speed regulation range, rapid dynamic response, and excellent linearity in speed control characteristics. Considering that the tracked locomotion mechanism in this system operates in complex farmland environments characterized by highly fluctuating loads, high-performance permanent magnet DC motors are employed as the propulsion source in this paper. The stator magnetic field is produced by high-performance permanent magnet materials, which eliminates stator circuit power losses inherent in traditional electrically excited motors. This leads to a markedly wider high-efficiency operating range and significantly lower temperature rise compared to conventional motors. Moreover, the permanent magnet structure removes the need for stator coil winding, thereby reducing the risk of electrical failures such as internal short circuits and cold solder joints. By utilizing permanent magnets with high magnetic energy product, the motor's volume and weight can be substantially reduced while delivering the same output power and torque. Additionally, the inherent remanence of the permanent magnets provides natural auxiliary braking torque during power-off conditions.

The electromechanical energy conversion of rotating electrical machines is based on the law of electromagnetic induction. Structurally, it primarily consists of a stationary stator part and a rotating rotor (armature) part, with a reasonable air gap maintained between them. The stator part is mainly used to generate the main magnetic field and simultaneously serve as the overall mechanical support for the machine; meanwhile, the rotor generates electromagnetic torque through the interaction between the permanent magnetic field and the armature current.

3. Design of Multi-Motor Cooperative Control Strategy Based on Deviation Coupling

3.1. System Composition of Multi-Motor Cooperative Control

The structure of the dual-closed-loop DC speed control system based on pulse-width modulation (PWM) is shown in Figure 2.

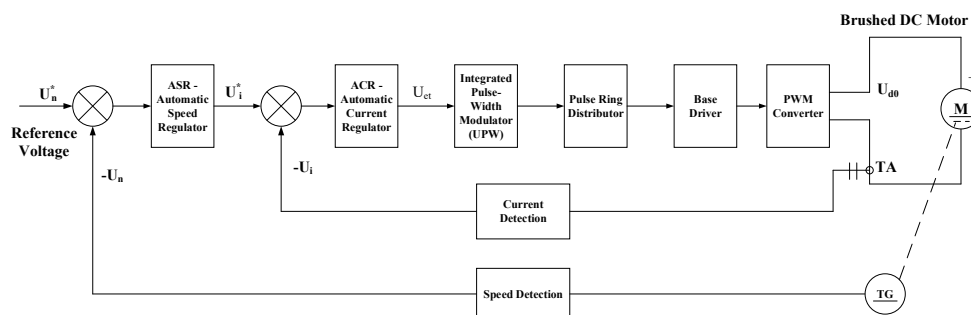


Figure 2. Schematic diagram of a PWM-controlled dual-closed-loop DC speed control system.

The functional modules of the control system mainly comprise the Automatic Speed Regulator (ASR), Automatic Current Regulator (ACR), PWM waveform generator (i.e., pulse-width modulator, UPW), PWM converter composed of controllable devices, DC motor, current detection, and speed detection. Consistent with conventional dual-closed-loop DC speed control systems, the ASR and ACR here still employ proportional-integral (PI) controllers, thereby achieving speed and current regulation with zero steady-state error.

3.2. Operating Principle of Dual-Closed-Loop DC Speed Control System

The primary difference between this system and a conventional dual-closed-loop DC drive lies in the use of a PWM converter to deliver the motor's armature voltage U_d . Nevertheless, the working principles of their ASR and ACR are exactly the same. Because the ACR adopts a PI controller, during steady-state operation of the drive

system, the ACR input deviation voltage becomes $\Delta U_i = U_i^* - U_i = U_i^* - \beta I_d = 0$. This implies that $I_d = U_i^*/\beta$, where β denotes the current feedback gain, as shown in Figure 2. When $I_d > U_i^*/\beta$, the automatic adjustment process unfolds as follows:

$$I_d \uparrow \rightarrow \Delta U_i \downarrow \rightarrow U_{et} \downarrow \rightarrow U_d \downarrow \rightarrow I_d \downarrow$$

Here, U_{et} denotes the output control voltage of the armature current regulator ACR, which serves as the input signal to the subsequent PWM converter control stage. When the armature current I_d increases, the input deviation voltage ΔU_i decreases, leading to a decrease in U_{et} . This reduces the converter output voltage U_d , thereby decreasing the armature current I_d and providing negative feedback to the control system.

Thereby sustaining a stable current. Conversely, a similar regulation process occurs when the current decreases.

Furthermore, owing to the implementation of a PI controller in the ASR, the following condition must be satisfied once the system enters the steady state:

$$\Delta U_n = U_n^* - U_n = U_n^* - \alpha n = 0 \quad (1)$$

where α denotes the speed feedback coefficient. Given that U_n^* remains constant, the rotational speed n will stabilize at the value of U_n^*/α . When $n < U_n^*/\alpha$, the automatic regulation process upon a sudden application of load torque T_L is outlined below:

$$\begin{aligned} T_L \uparrow &\rightarrow n \downarrow \rightarrow U_n \downarrow \rightarrow \Delta U_n \uparrow \rightarrow \\ U_i^* \uparrow &\rightarrow \Delta U_i \uparrow \rightarrow U_{et} \uparrow \rightarrow U_d \uparrow \rightarrow n \uparrow \end{aligned}$$

Thereby consistently maintaining a stable rotational speed. Conversely, a similar regulation process occurs when the load decreases and the speed rises.

3.3. Mathematical Model of the H-Bridge Reversible PWM Converter

The H-bridge reversible PWM converter is a bridge circuit consisting of four controllable switching devices and four freewheeling diodes. Its control schemes are generally categorized into three types: bipolar, unipolar, and limited unipolar. In this paper, the bipolar control method is adopted for the H-bridge reversible PWM converter, and its schematic diagram is illustrated in Figure 3. The base drive voltages for the four switching devices are divided into two complementary groups. Specifically, VT1 and VT4 turn on and off simultaneously, with their drive voltages satisfying $U_{g1} = U_{g4}$. Concurrently, VT2 and VT3 turn on and off simultaneously, and their drive voltages are given by $U_{g2} = U_{g3} = -U_{g1}$.

Assume t_{on} is the turn-on time, then:

(1) When $0 \leq t \leq t_{on}$, U_{g1} and U_{g4} are positive, VT1 and VT4 are saturated and conducting, and the motor rotates forward. Meanwhile, U_{g2} and U_{g3} are negative, and VT2 and VT3 are turned off. At this time, the power supply voltage U_s is applied to both ends of the armature AB, $U_{AB} = U_s$, and the armature current I_d flows along Loop 1, as shown in Figure 3.

(2) When $t_{on} < t < T$, U_{g1} and U_{g4} become negative, switching off VT1 and VT4. Concurrently, although U_{g2} and U_{g3} turn positive, VT2 and VT3 cannot conduct immediately. Instead, the armature current I_d freewheels along Loop 2 via diodes VD2 and VD3, as illustrated in Figure 3. The voltage drop across VD2 and VD3 subjects the collector-emitter (C-E) junctions of VT2 and VT3 to a reverse voltage. During this interval, $U_{AB} = -U_s$; consequently, U_{AB} exhibits an alternating positive and negative pulse waveform within one switching cycle.

(3) When the armature current reverses and VT2 and VT3 conduct, the armature current I_d flows along Loop 3, placing the motor in a braking state.

(4) In the subsequent cycle, when VT2 and VT3 are turned off, VT1 and VT4 cannot conduct immediately either. The armature current I_d circulates through freewheeling Loop 4, which is composed of VD4 and VD1. Consequently, the average armature terminal voltage of the motor is calculated as:

$$U_d = \frac{t_{on} U_s}{T} - \frac{T - t_{on}}{T} U_s = \left(\frac{2t_{on}}{T} - 1 \right) U_s = (2\rho - 1) U_s \quad (2)$$

where $\rho = t_{on}/T$ is the duty cycle.

According to Equation (2), when $\rho > 0.5$, the motor rotates in the forward direction; when $\rho < 0.5$, the motor rotates in the reverse direction; and when $\rho = 0.5$, the motor comes to a standstill.

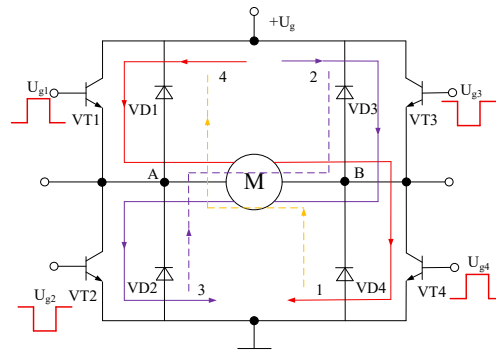


Figure 3. Circuit schematic of the H-bridge PWM converter.

4. Simulation and Analysis of Dual-Motor Collaborative Control

4.1. Control Structure and Mathematical Derivation of Dual-Motor Systems

Regarding the synchronization issue of the left and right tracks during front dual-motor drive, a deviation coupling control scheme is implemented between the left and right motors. This control is achieved by establishing dynamic deviation-coupling between the motors; specifically, the speed of each motor within the system is compared with that of the other, from which speed deviations are calculated. These deviation values are then processed through a specific compensation algorithm to generate compensation signals, which are superimposed onto the speed loops of the respective motors. This minimizes the proportional difference in rotational speed, and the overall architecture of the control system is illustrated in Figure 4.

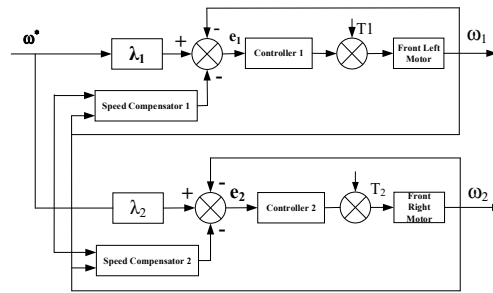


Figure 4. Block diagram of the dual-motor control system.

ω^* is the given reference motor speed, which yields the target speed of the front-left motor through the proportional coefficient λ_1 , and the target speed of the front-right motor through the proportional coefficient λ_2 . In order to mutually couple the rotational speeds of both motors to achieve absolute proportional control, the real-time speeds ω_1 and ω_2 are fed back into Speed Compensator 1 to obtain the speed compensation signal for the front-left motor after processing, and the real-time speeds ω_1 and ω_2 are fed back into Speed Compensator 2 to obtain the speed compensation signal for the front-right motor after processing. The left and right motors are mutually coupled through Speed Compensator 1 and Speed Compensator 2, thereby achieving synchronous control of the rotational speed.

The structure of the speed compensator is illustrated in Figure 5. Specifically for Speed Compensator 1, the actual speed ω_1 of the front-left motor corresponds to the input speed ω_1 in the diagram, and the actual speed ω_2 of the front-right motor corresponds to the input speed ω_2 in the diagram, which satisfies:

$$\omega_1 = \lambda_1 \cdot \omega_a \quad (3)$$

where ω^* denotes the common reference speed, ω_1 and ω_2 represent the actual angular speeds of motor 1 and motor 2, respectively, and λ_1 and λ_2 are the speed allocation coefficients.

$$\omega_2 = \lambda_2 \cdot \omega_a \quad (4)$$

where ω_2 represents the actual angular speed of motor 2, and λ_2 is the proportional coefficient of motor 2.

It follows that:

$$\omega_1/\omega_2 = \lambda_1/\lambda_2 \quad (5)$$

where ω_1/ω_2 is the speed ratio of the two motors, which is determined by λ_1/λ_2 .

Therefore, the left and right motors can operate at a proportional speed ratio. According to the speed calculation required during actual operation, $\omega_1/\omega_2 = \lambda_1/\lambda_2$. Taking the front-left motor as an example, the tracking error is defined as:

$$\varepsilon_{12}(t) = \omega_1(t)/\lambda_1 - \omega_2(t)/\lambda_2 \quad (6)$$

where e_1 is the tracking error of motor 1, and ω_1 is the actual speed of motor 1.

To maintain synchronous operation of the left and right tracks, the tracking errors of the front-left and front-right motors must converge, which satisfies the following condition:

$$\lim_{t \rightarrow \infty} \varepsilon_{12}(t) = \lim_{t \rightarrow \infty} [\omega_1(t)/\lambda_1 - \omega_2(t)/\lambda_2] = 0 \quad (7)$$

where e_1 and e_2 are the tracking errors of motor 1 and motor 2, respectively.

Where K_{12} represents the coupling gain of the speed feedback. Its function is to drive the relative speed of each motor to zero when the motors are subjected to external environmental disturbances, such as sudden load increases or decreases, shock loads, etc. The calculation method is as follows:

$$K_{12} = \frac{J_1}{J_2} \quad (8)$$

where K_{12} is the coupling gain from motor 2 to motor 1, and J_1 and J_2 are the equivalent moments of inertia of motor 1 and motor 2, respectively.

In the equation: J_1 is the moment of inertia of the motor with the actual speed ω_1 , and J_2 is the moment of inertia of the motor with the actual speed ω_2 . According to the actual motor data of the tracked vehicle, the four motors used by the tracked vehicle are identical, then there is $J_1 = J_2$, which means $K_{12} = 1$, and the speed compensation value of the front-left motor is given by:

$$\beta_1 = K_{12}(\omega_1/\lambda_1 - \omega_2/\lambda_2) = \omega_1/\lambda_1 - \omega_2/\lambda_2 \quad (9)$$

where β_1 is the speed compensation signal of motor 1, and K_{12} is selected according to the inertia ratio of the two motors.

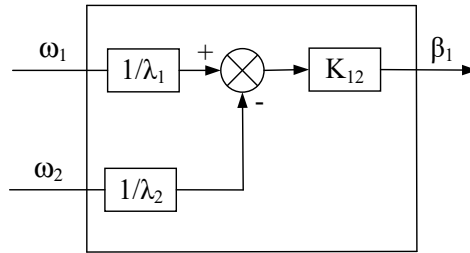


Figure 5. Structure of speed compensator.

Speed Compensator 2 can be derived in the same manner as described above:

$$\beta_2 = K_{21}(\omega_2/\lambda_2 - \omega_1/\lambda_1) = \omega_2/\lambda_2 - \omega_1/\lambda_1 \quad (10)$$

where β_2 is the speed compensation signal of motor 2, and K_{21} is the coupling gain from motor 1 to motor 2.

Since the two motors used in this study are identical, $J_1 = J_2$, and thus $K_{12} = K_{21} = 1$.

In this study, the coupling gains were determined according to the inertia ratio between the coupled motors. Since all motors have identical mechanical parameters, the inertia ratio is equal to one, and therefore K_{12} and K_{21} were both set to 1. For systems with parameter mismatch, these gains can be adjusted according to the measured inertia ratio to achieve better synchronization performance.

4.2. Simulation Settings and Parameters

The simulations were conducted using MATLAB/Simulink R2016b based on the double-closed-loop motor model established in Sections 2 and 3. The simulation was performed on a personal computer equipped with an Intel Core i7 processor (Intel Corporation, Santa Clara, United States) and 16 GB RAM (SK Hynix Inc., Icheon, Republic of Korea). The solver type and sampling period were configured according to the requirements of the motor control model, as listed in Table 1. Two benchmark controllers were considered: (i) uncoupled control, in which each motor regulates its own reference independently, and (ii) the proposed deviation-coupling control.

The simulations were implemented in MATLAB/Simulink using the double-closed-loop motor model described in Sections 2 and 3. Two benchmark controllers were considered: (i) uncoupled control, in which each motor regulates its own reference independently, and (ii) the proposed deviation-coupling control. Both absolute synchronization and proportional synchronization were evaluated. A unilateral step-like load disturbance was applied to one drive axis while the remaining axes retained their commanded references. The motor shaft speed was converted into track linear speed through the reducer transmission ratio and driving-sprocket radius. The principal performance indices were the peak speed-deviation amplitude, the duration of each fluctuation stage, and the reduction in these quantities relative to uncoupled control.

Quantitative comparison with the uncoupled baseline shows that, for dual-motor proportional synchronization, the peak fluctuation amplitude decreases from 0.49630 m/s to 0.00954 m/s (98.08% reduction), while the primary fluctuation duration decreases from 0.49400 s to 0.22200 s (55.06% reduction). For four-motor proportional synchronization, the peak fluctuation amplitude decreases from 0.16521 m/s to 0.00953 m/s (94.23% reduction), while the primary fluctuation duration decreases from 0.49421 s to 0.44512 s (9.93% reduction). These values are reported as peak fluctuation and recovery-duration metrics rather than classical overshoot because the available simulation data do not separately define a steady-state overshoot metric.

A simulation model of the front dual-motor drive is constructed in MATLAB/Simulink. The rotational speed of the motor output shaft is converted into the linear velocity of the tracks through the reducer transmission ratio and the track driving-wheel radius. Therefore, the track linear velocity is obtained from the commanded motor speed. The deviation-coupling control models are illustrated in Figures 6 and 7.

Table 1. Main simulation parameters and reproducibility information.

Parameter	Symbol	Value/Source
Motor armature resistance	R_a	0.50 Ω
Motor armature inductance	L_a	0.02 H
Torque constant	K_t	0.10 N·m/A
Back-EMF constant	K_e	0.10 V·s/rad
Equivalent motor inertia	J	0.010 kg·m ²
Speed-loop	K_{po}, K_{io}	2.20
Current-loop PI gains	K_{pi}, K_{ii}	1.10
DC supply voltage	U_s	48 V
Load disturbance magnitude	T_L, t_d	10 N·m
Application time	t_d	2 S
Reducer ratio	i_g	20
Sprocket radius	r_s	0.15 m
Solver type	—	ode45
Sampling period	T_s	0.001 s

4.3. Simulation Model and Result Analysis of Dual-Motor Systems

A simulation model of the front dual-motor drive is constructed in MATLAB/Simulink. The rotational speed of the motor output shaft is converted into the linear velocity of the tracks through the proportional relationships of the reducer transmission mechanism and the track driving wheels; thus, the track linear velocity can be obtained once the target motor speed is given. The deviation coupling control models are illustrated in Figures 6 and 7. The obtained rotational speed and speed difference are shown in Figures 8 and 9.

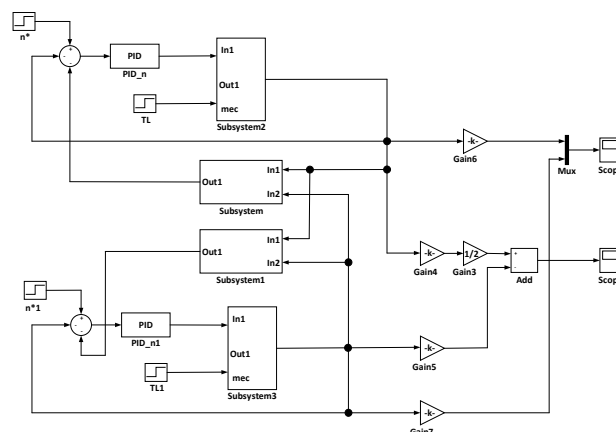


Figure 6. Deviation coupling proportional synchronization model of front dual-motor drive.

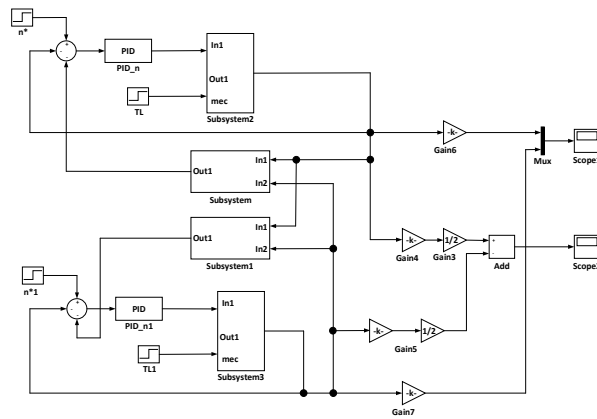


Figure 7. Deviation coupling absolute synchronization model of front dual-motor drive.

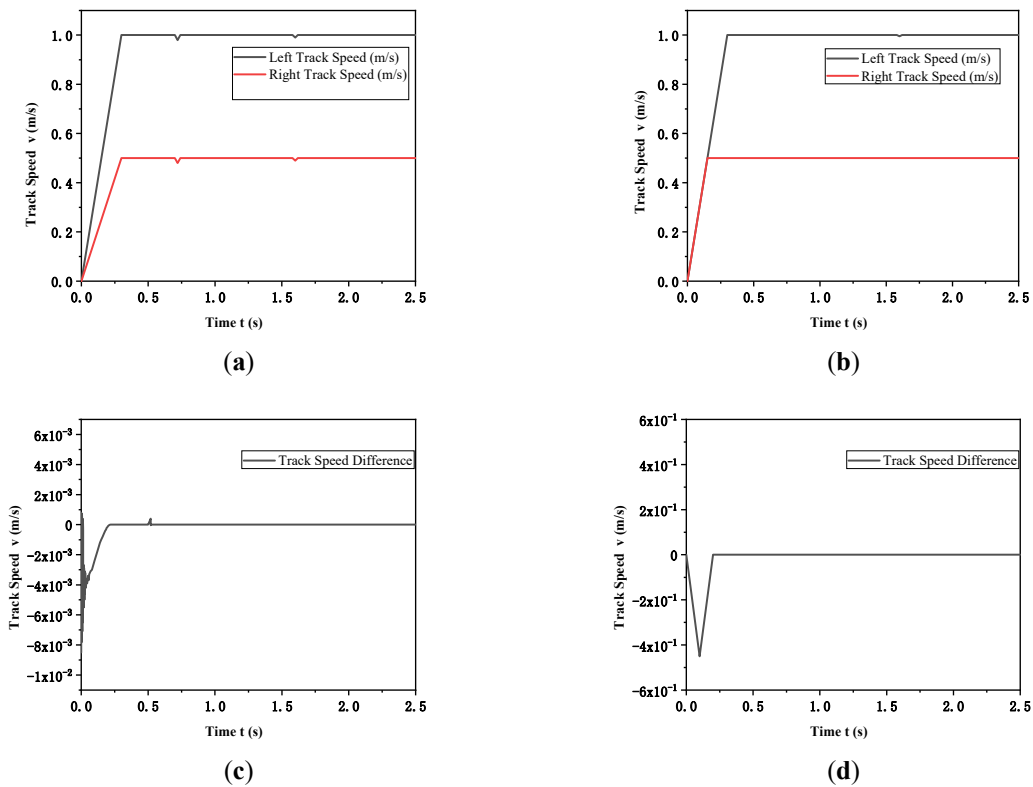


Figure 8. Rotational speeds and speed differences of the two models under dual-motor proportional synchronization: (a) uncoupled track speeds; (b) deviation-coupling track speeds; (c) uncoupled track-speed difference; (d) deviation-coupling track-speed difference.

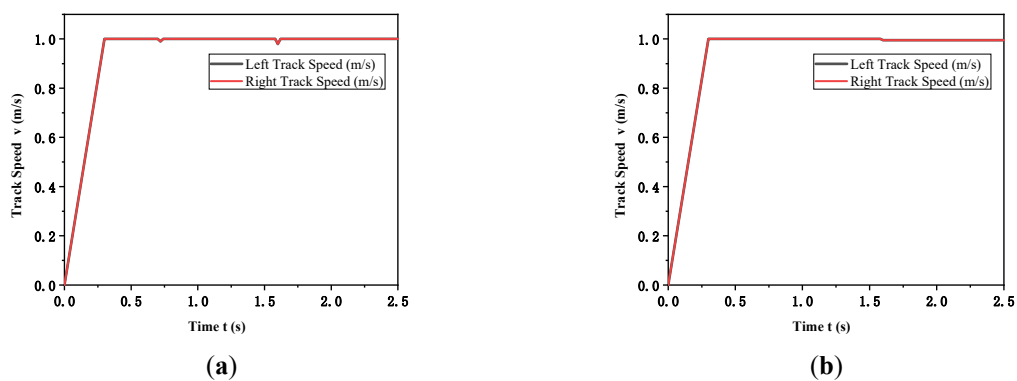


Figure 9. Cont.

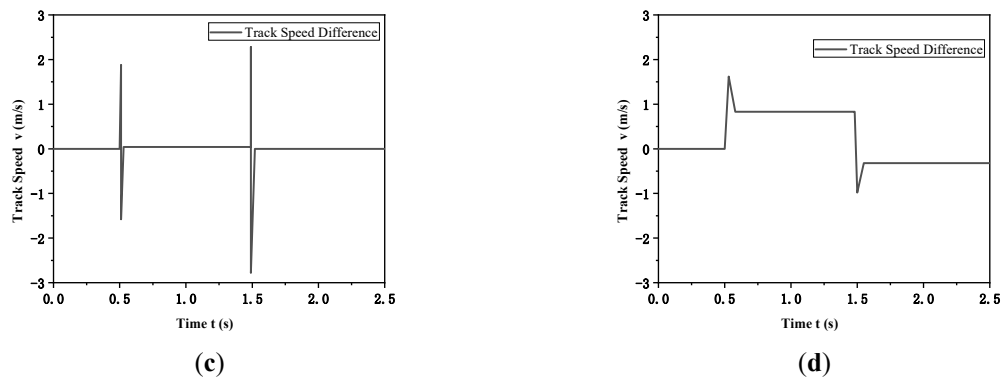


Figure 9. Rotational speeds and speed differences under two modes with dual-motor absolute synchronization: (a) uncoupled track speeds; (b) deviation-coupling track speeds; (c) uncoupled track-speed difference; (d) deviation-coupling track-speed difference.

According to the simulation data in Table 2, under absolute synchronization conditions, the uncoupled control exhibits a secondary fluctuation amplitude of 0.00142 m/s and a secondary fluctuation duration of 0.11811 s after the load disturbance. In contrast, after introducing the proposed deviation-coupling control, the secondary fluctuation amplitude is reduced to 0.00018 m/s, and the corresponding fluctuation duration is shortened to 0.01400 s. Under proportional synchronization conditions, the primary maximum dynamic speed deviation of the uncoupled system reaches 0.49630 m/s, whereas the proposed deviation-coupling control suppresses this value to 0.00954 m/s, corresponding to a reduction of approximately 98.08%. Meanwhile, the primary fluctuation duration decreases from 0.49400 s to 0.22200 s. These results demonstrate that the proposed deviation-coupling strategy effectively uses dual-axis feedback compensation to improve synchronization accuracy, disturbance rejection capability, and transient convergence performance.

Table 2. Coupling control performance of dual-motor systems.

		Single Fluctuation Amplitude (m/s)	Secondary Fluctuation Amplitude (m/s)	Tertiary Fluctuation Amplitude (m/s)	Primary Fluctuation Duration (s)	Secondary Fluctuation Duration (s)	Tertiary Fluctuation Duration (s)
Uncoupled control	Absolute synchronization	0	0.00142	0.00170	0	0.11811	0.06712
	Proportional synchronization	0.49630	0.00285	0.00170	0.49400	0.11800	0.06721
Deviation-coupling control	Absolute synchronization	0	0.00018	0.00026	0	0.01400	0.01611
	Proportional synchronization	0.00954	0.00049	0.00028	0.22200	0.02312	0.01111

5. Simulation and Analysis of Multi-Motor Collaborative Control

5.1. Composite Control Topology for Multi-Motor Systems

Under the four-motor drive configuration of a tracked vehicle, mechanical structural constraints can easily lead to internal power circulation between the front and rear motors on a single side if they are improperly controlled. In practical operating conditions, the real-time speed of a single track is largely determined by the rear driving motor. To address this four-motor driving condition, a composite coordinated control topology based on “inter-side deviation coupling + single-side master-slave following” is formulated in this paper. Specifically, the left and right rear motors serve as the main driving axes, and a full deviation-coupling control is implemented between them to guarantee the synchronization accuracy of the vehicle during steering and straight-line driving. Meanwhile, the front-left and front-right motors act as auxiliary axes, utilizing a master-slave proportional following control structure to track the actual speed of the corresponding rear motor on the same side in real time. The architecture of the control system is illustrated in Figure 10.

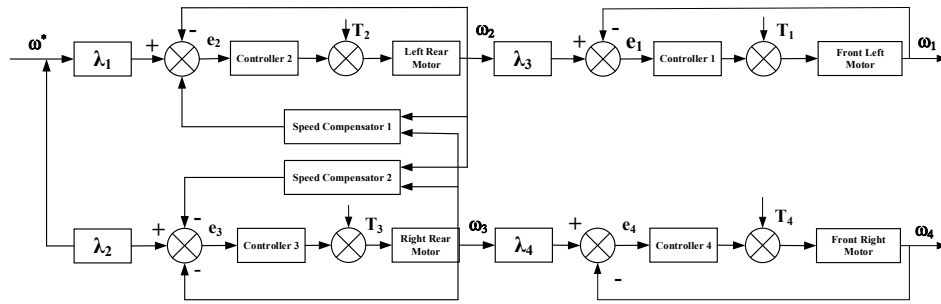


Figure 10. Block diagram of multi-motor control system.

5.2. Simulation Model and Result Analysis for Multi-Motor Systems

Based on the aforementioned composite topology, the simulation models for multi-motor cooperative control under both proportional and absolute synchronization are constructed in Simulink. The deviation coupling control models are illustrated in Figures 11 and 12, and the obtained rotational speed responses and speed deviations are shown in Figures 13 and 14, with simulation data summarized in Table 3.

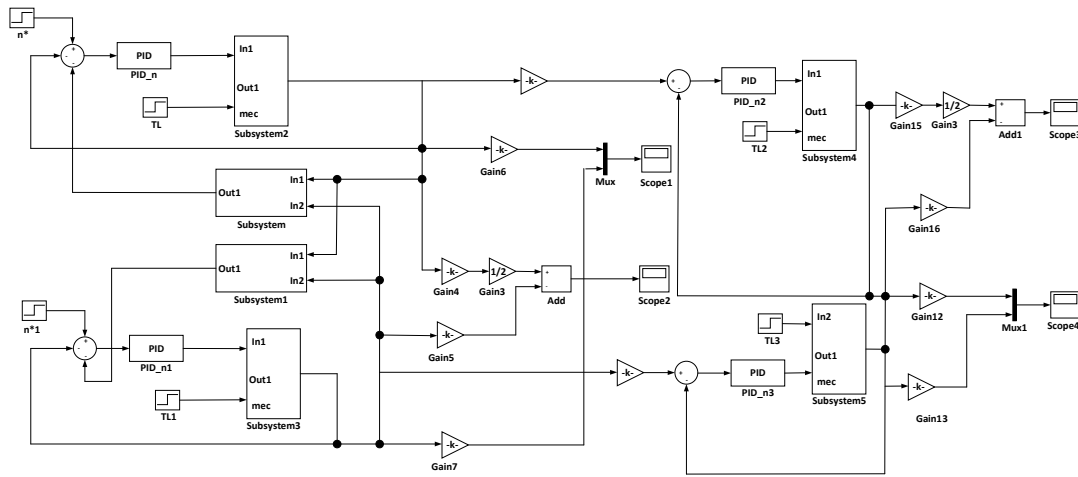


Figure 11. Proportional synchronization simulation model for multi-motor cooperative control.

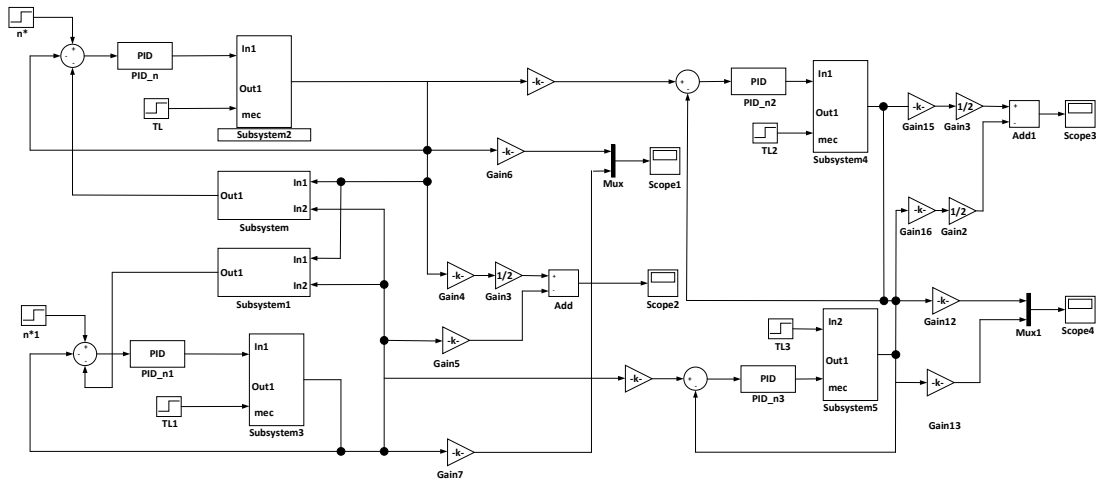


Figure 12. Simulation model of multi-motor cooperative control under absolute synchronization.

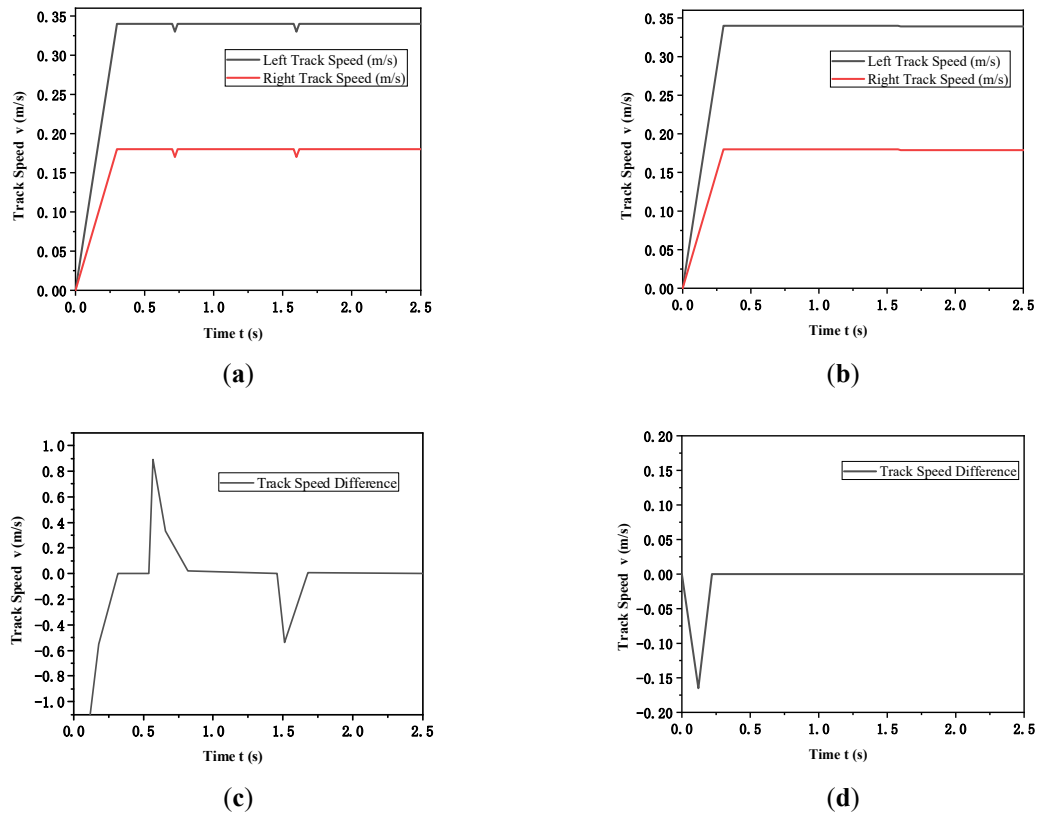


Figure 13. Track speeds and speed deviations of two control models under four-motor proportional synchronization: (a) uncoupled track speeds; (b) deviation-coupling track speeds; (c) uncoupled track-speed difference; (d) deviation-coupling track-speed difference.

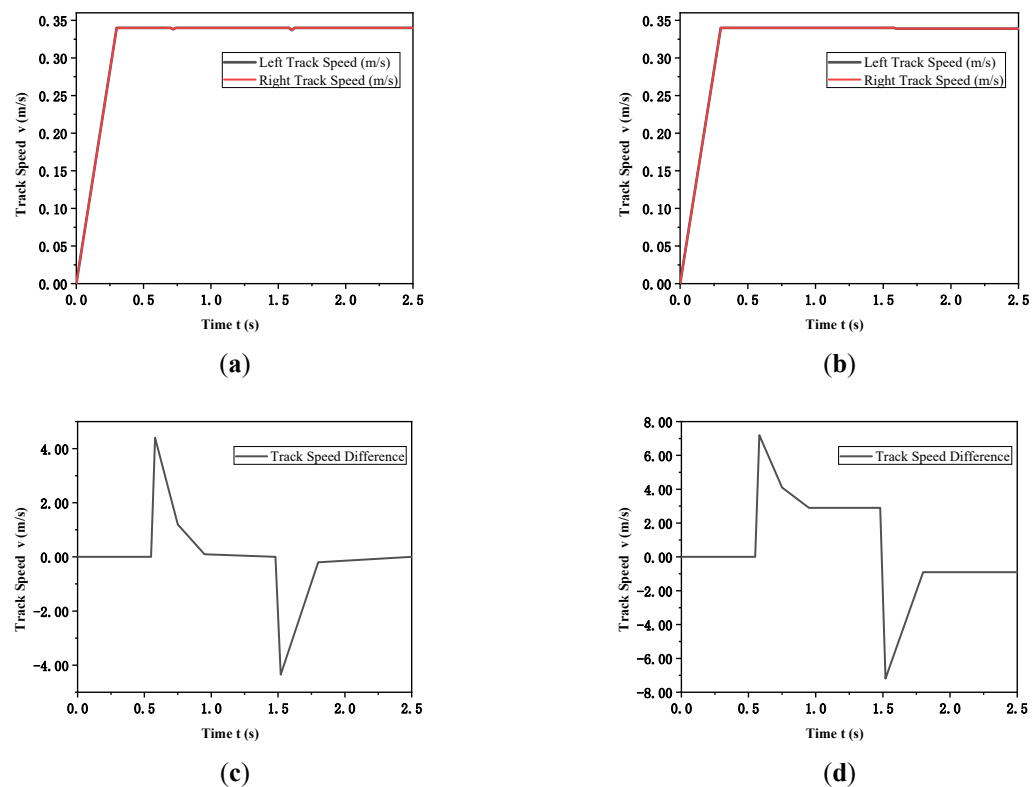


Figure 14. Track speeds and speed deviations of two control models under four-motor absolute synchronization: (a) uncoupled track speeds; (b) deviation-coupling track speeds; (c) uncoupled track-speed difference; (d) deviation-coupling track-speed difference.

Table 3. Performance of multi-motor coupling control.

		Single Fluctuation Amplitude (m/s)	Secondary Fluctuation Amplitude (m/s)	Tertiary Fluctuation Amplitude (m/s)	Primary Fluctuation Duration (s)	Secondary Fluctuation Duration (s)	Tertiary Fluctuation Duration (s)
Uncoupled control	Absolute synchronization	0	0.00089	0.00071	0	0.68811	0.37911
	Proportional synchronization	0.16521	0.00179	0.00043	0.49421	0.68821	0.37921
Deviation- coupling control	Absolute synchronization	0	0.00087	0.00035	0	0.40912	0.26011
	Proportional synchronization	0.00953	0.00087	0.00035	0.44512	0.40921	0.26231

Simulation results indicate that under multi-axis over-constrained driving conditions, the composite control strategy of “inter-side deviation-coupling + single-side master-slave following” exhibits excellent anti-disturbance advantages. During proportional synchronization operations, when a sudden load is applied to a single side, the uncoupled control generates a maximum transient speed slip deviation of 0.165 m/s among multiple axes; furthermore, its disturbance regulation process is complex, with secondary and tertiary settling times lasting as long as 0.688 s and 0.379 s, respectively. In contrast, with the proposed composite deviation-coupling control, the primary peak fluctuation amplitude is suppressed within 0.00953 m/s, and the settling time is shortened by approximately 40% compared to the uncoupled control. This validates that the composite topology can guarantee inter-side steering synchronization accuracy while effectively avoiding high-frequency dynamic overload among the four axes.

6. Conclusions

Aiming at the multi-motor drive control issue of agricultural tracked transport machinery, this paper proposes a cooperative control strategy based on deviation-coupling theory. Through dynamic simulation and comparative analysis of the dual-motor front-drive mode and the four-motor tracked drive configuration under complex working conditions, the following main conclusions are drawn:

(1) Feasibility of the multi-motor cooperative control topology design: For the dual-motor drive mode, implementing full deviation-coupling control on both sides enables high-precision speed linkage. For the four-motor drive mode, the formulated composite control topology-incorporating deviation-coupling between the left and right rear motors as the primary layer and single-side front-rear master-slave proportional following as the auxiliary layer-effectively resolves the power balancing and synchronization challenges inherent in multi-axis over-constrained driving.

(2) Significant disturbance rejection advantages of the deviation-coupling strategy: Simulation results demonstrate that when a sudden load or impact load causes speed fluctuations on a single track, the deviation-coupling controller swiftly feeds back and decouples the real-time errors, compensating them into the speed loops of each motor. Compared with conventional uncoupled control, the primary, secondary, and tertiary fluctuation amplitudes of the speed deviation in the deviation-coupling control system are reduced by orders of magnitude.

(3) Substantial enhancement in dynamic response and convergence rate: Under sudden load disturbances, the deviation-coupling control effectively suppresses speed deviation fluctuations and shortens the corresponding recovery time. This indicates that the proposed control strategy not only efficiently suppresses the maximum inter-axis deviations during transient processes but also accelerates the asymptotic convergence of errors, thereby significantly improving the trajectory-keeping capability and anti-slip performance of the tracked vehicle during field traveling.

(4) Although the proposed deviation-coupling cooperative control strategy has demonstrated improved synchronization performance through MATLAB/Simulink simulations, several practical factors have not been fully considered in the current model. In actual farmland environments, communication delays, sensor noise, actuator saturation, track-soil interaction uncertainty, and complex track-slip behaviors may affect the synchronization performance. These unmodeled dynamics require further investigation. Future work will focus on prototype-based laboratory experiments and field tests under different soil and load conditions to further verify the robustness and practical applicability of the proposed strategy.

Author Contributions

B.T. conceptualized the study, performed the investigation, prepared the original draft of the manuscript, and contributed to visualization; H.W. acquired funding, provided resources, supervised the project, performed review

and editing of the manuscript, and managed project administration; Y.P. conducted formal analysis; T.L. contributed to investigation and validation; Y.L. contributed to the study; Y.W. contributed to visualization; H.L. contributed to the study; J.Y. contributed to visualization; L.L. acquired funding, provided resources, and managed project administration. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

Data will be made available on request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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