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Research Article

Research on Cooperative Control of the Hydraulic System of Multiple Intelligent Vehicles Combined Transportation

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The multi-vehicle combined transportation of large-scale equipment or goods is studied, and various combined transportation modes are obtained. The research on four-vehicle combined transportation is studied, the four transport vehicles must ensure synchronization in the process of running, and the steering must be coordinated, otherwise major accidents may occur. Aiming at the stability control of multi-vehicle running synchronization, the system transfer function of pump-controlled motor in driving system is established, and the PID control is added. The simulation results show that adding the PID control algorithm can improve the speed stability of the transport vehicle. And the geometric model of the steering mechanism is established, the functional relationship between the steering angle and the stroke of the steering cylinder is obtained, and the relationship between the electric signal of proportional valve and the steering angle is deduced. On this basis, the coordinated control system of four-vehicle running synchronization and steering coordination based on CAN (controller area network) bus is designed. The master-slave synchronization control strategy and the PID control are applied to the four-vehicle combined transportation. According to the data collected from the test, it is proved that the control strategy fully meets the transportation requirements, and can provide theoretical basis and design method reference for the safe and reliable combined transportation of various types of transport vehicles.

1. Introduction

The size and weight of super-large equipment or goods are very large. In order to reduce transportation cost and improve efficiency, it is necessary to use combined transportation of multiple large hydraulic trucks [1]. The coordinated control among multiple transport vehicles will greatly improve the safety of combined transportation, this transport method can complete the work easier than using a super large transport vehicle, and have the advantages of high efficiency and low cost. Multi-vehicle communication can achieve coordinated control of speed consistency and cooperate with each other to accomplish tasks, and it has broad application prospects [2–8]. Now, the transport vehicle is intelligent equipment, and the combined transport vehicle system belongs to a multi-agent system, multi-agent coordinated control has many applications, such as multi-robot system [9, 10], unmanned aerial vehicle system [11], satellite formation [12], and so on.

The coordinated control of multiple vehicles belongs to the high-precision hydraulic control. In the aspect of high-precision hydraulic control, a novel sliding mode control based high-precision hydraulic pressure feedback modulation is proposed [13], that is based on linear pressure-drop modulation in valve critical equilibrium state. And the practices proved that the closed-loop modulation method is effective and has superior performance. The cooperative control of multiple vehicles is similar to the technique of autonomous vehicles. And an automated vehicle with an optimized plant and controller can perform its tasks well. Recently, a cyber-physical system-based framework is proposed for

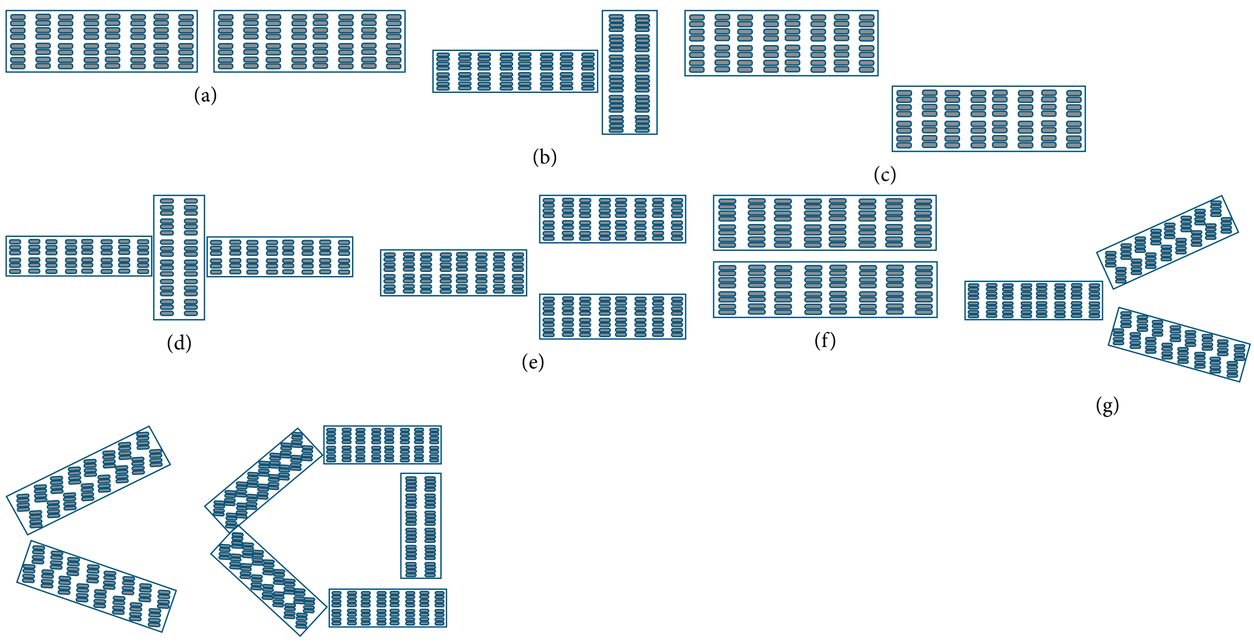

Figure 1: The common combined modes of multi-transport vehicles.

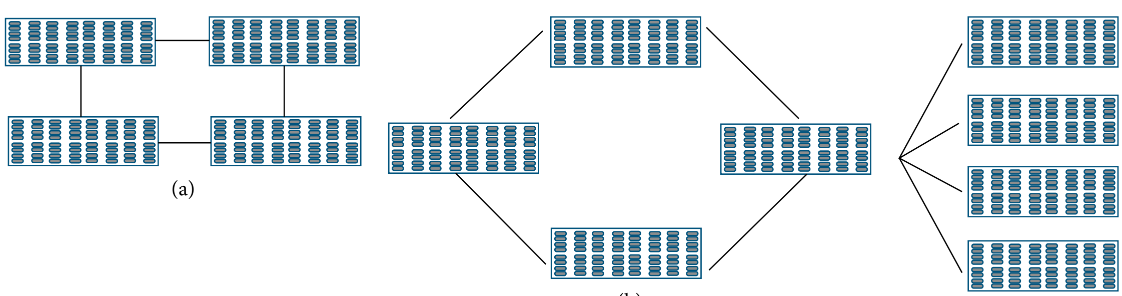

Figure 2: The common combined modes of four transport vehicles.

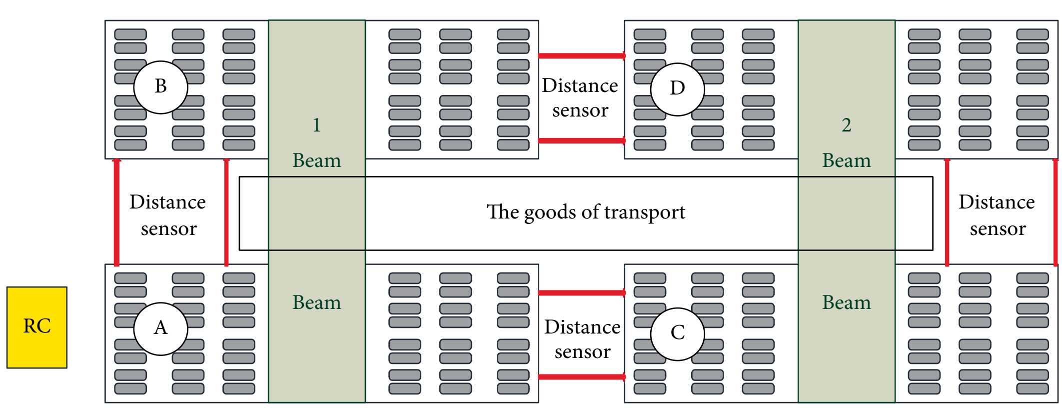

Figure 3: The combined transportation of the four vehicles.

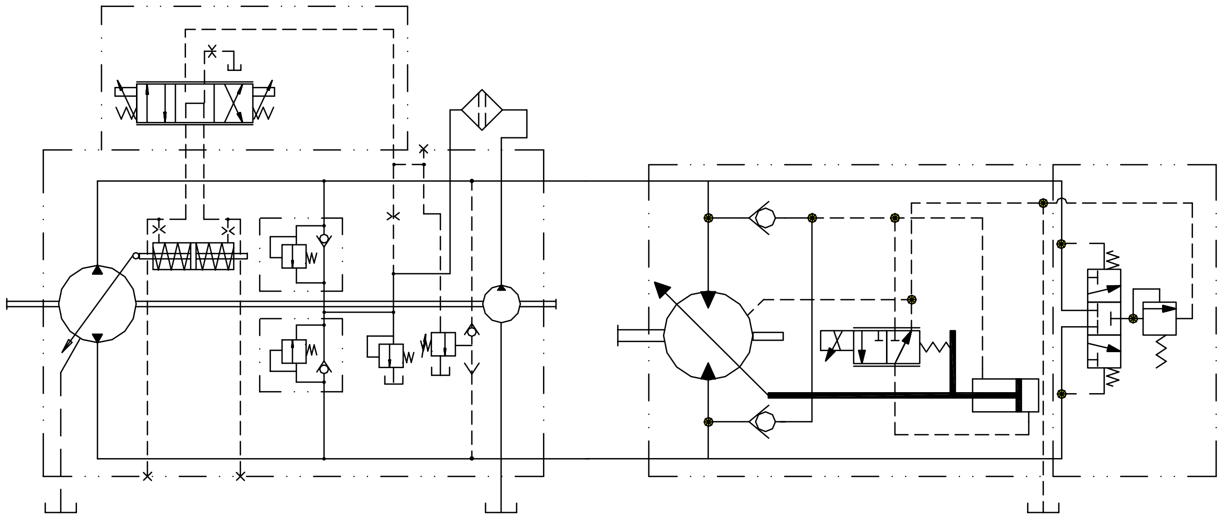

Figure 4: Principle diagram of driving system of transport vehicle.

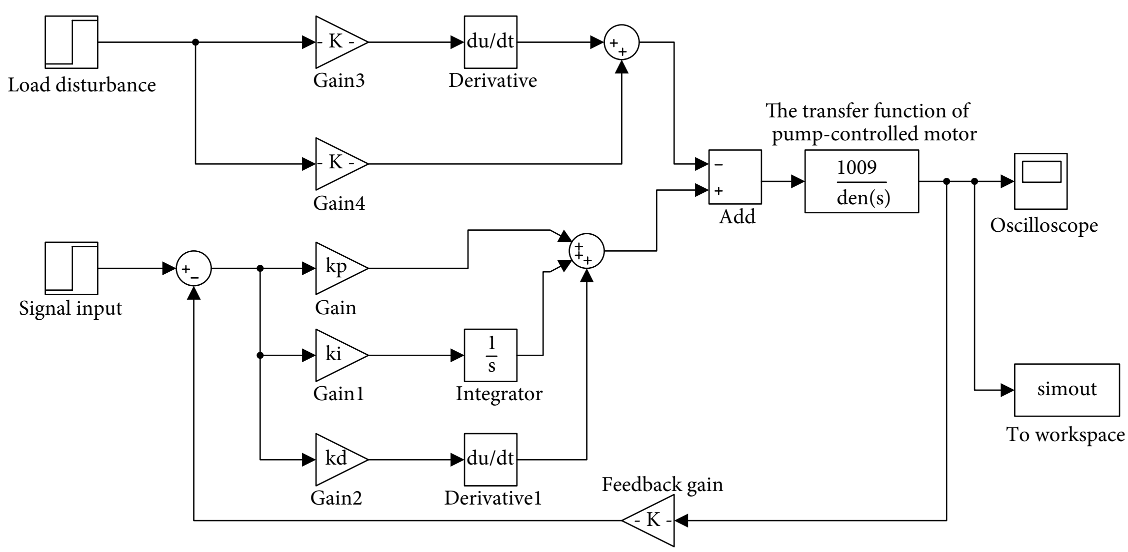

Figure 5: The model of pump-controlled motor system.

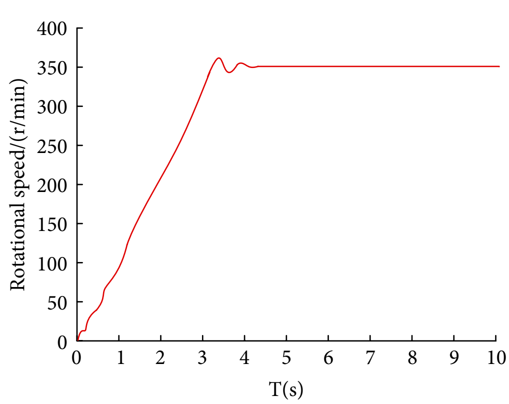

Figure 6: The step response curve of hydraulic motor.

codesign optimization of the plant and controller parameters for an automated vehicle [14]. The results validate the feasibility and effectiveness of the approach. The Intelligent vehicles can make right decisions without taking the driver-intended maneuver into consideration [15].

In this paper, the synchronous running and steering of combined transportation are studied. According to the synchronous technical requirements, the electro-hydraulic closed loop control system and the "master-slave" control scheme are designed. The research results can improve the synchronization accuracy for combined transportation. The popularization and application of the research results can effectively achieve the rapid and safe transportation of large-scale equipment or goods. At the same time, the research results also have the guidance significance to the synchronization control of other multiple equipment.

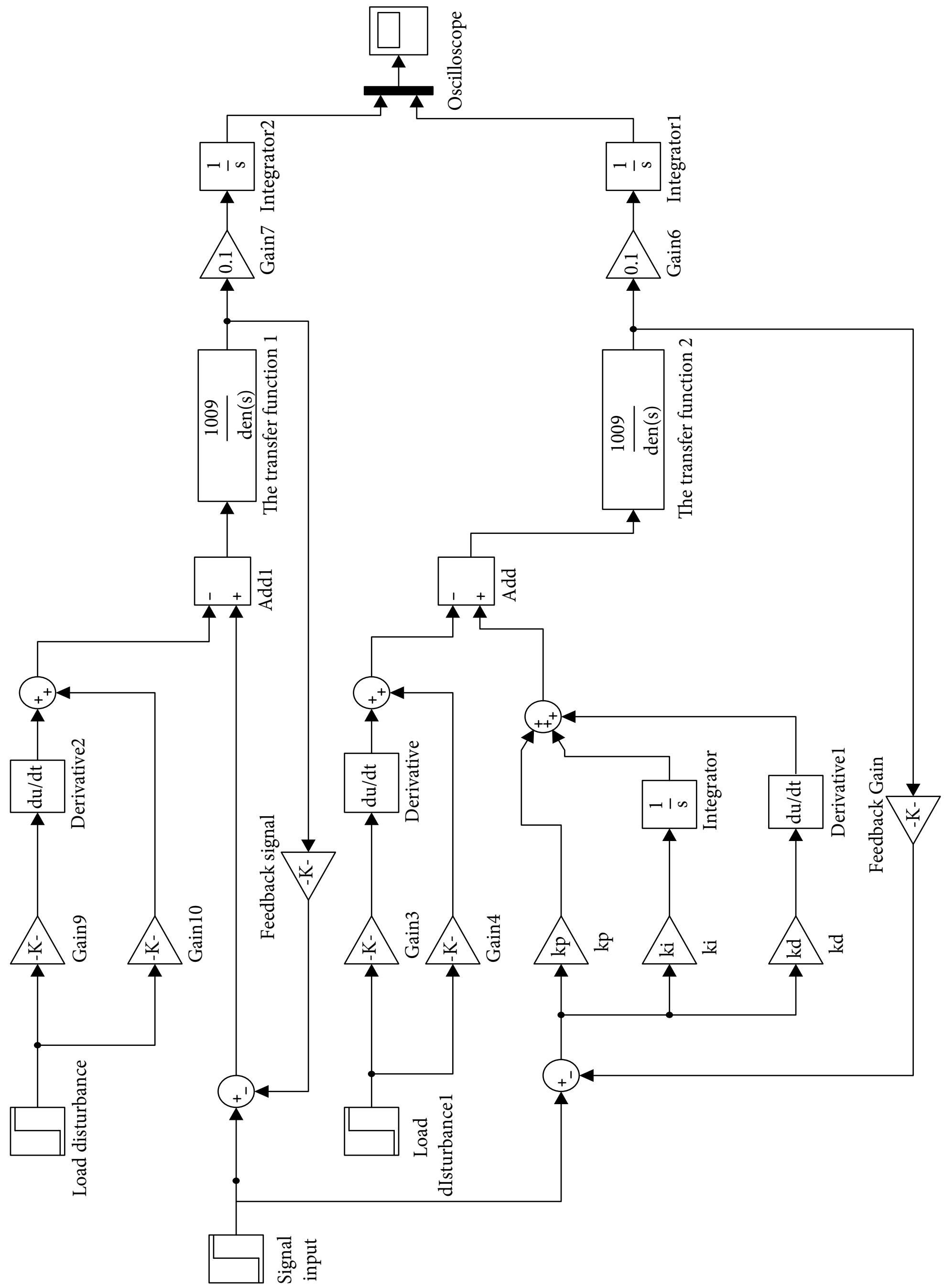

FIGURE 7: The simulation model with displacement output.

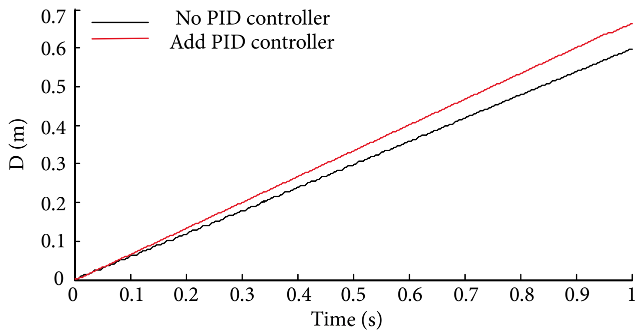

Figure 8: The displacement curves.

This paper is organized as follows. The multi-vehicle combined transportation is analyzed in Section 2. The scheme of four-vehicle combined transportation is designed in Section 3. The synchronous running of the transport vehicles is studied, and the principle of synchronization is described, on the basis of the above research, the synchronization simulation and analysis are carried out in Section 4. The synchronous steering of combined transportation is studied in Section 5. The control system based on CAN bus is designed in Section 6. In order to verify the synchronization performance of the control system, the field debugging of the combined transportation is carried out in Section 7.

2. Multi-Vehicle Combined Transportation

The coordinated control of driving and steering of multiple hydraulic vehicles in the process of transportation must be needed to reduce the synchronous error and realize safe transportation. Therefore, the study of coordinated control of multi-vehicle combined transportation has important scientific research value and practical application value. Multi-vehicle combined transportation can be used as an important method in the transportation of the large equipment or goods. In order to ensure the safety in the transportation process, the distance between the transport vehicles must be fixed. The asynchronization will lead to the increase of the route deviation and even serious construction accidents, and this finally will cause personal and property losses.

The multi-vehicle combined transportation has more advantages than the single-vehicle transportation in large-scale transportation. It is easier and cheaper to use multi-vehicle combined transportation than to design and manufacture single large hydraulic truck. The combined transportation of multi-vehicle can save construction time and improve efficiency greatly because of its convenient combination and various modes. According to the shape and characteristics of the goods transported, multi-vehicle combined transportation is usually realized by mechanical or contactless connection, and controlled by cab operation or wireless remote control operation [16].

When the multi-vehicle mechanical connection is a fixed connection, the operation is tedious and the utilization rate is low, it can only be used in special occasions. The contactless connection uses data communication lines to communicate and control between transport vehicles. The multiple combined modes of transport vehicles are shown in Figure 1, which can be used in many occasions.

Taking the four-vehicle combined transportation as the research objective, according to the shape characteristics of common cargo, the common combined modes of four transport vehicles is shown in Figure 2.

3. The Scheme of Four-Vehicle Combined Transportation

Four-vehicle combined transportation can adopt mechanical rigid connection on the structure, but sometimes according to transportation needs, the contactless connection and the centralized control must be adopted [17]. The transport vehicle is fully hydraulic drive, so the stability of the combined transportation depends on the synchronization of multiple transport vehicles.

The contactless connection mode requires higher control accuracy of each transport vehicle. All transport vehicles must keep a fixed distance, the distance between any two vehicles can be detected by draw-wire displacement sensor or laser displacement sensor. The transporting mode of heavy goods is shown in Figure 3. A vehicle and B vehicle, C vehicle and D vehicle are equipped with crossbeams, and the goods transported are mounted on the two beams.

4. Research on Synchronous Running of Combined Transportation

Because of manufacturing errors, different wear and leakage of hydraulic components, and different road conditions, it is difficult for the four hydraulic transport vehicles to achieve synchronous and coordinated control, so it is necessary to study the driving system.

4.1. Speed Measurement and Skid Prevention. The transport vehicle has many wheels, and the friction coefficients between the tire and the ground cannot be the same. If the driving force of the wheel is greater than the friction force, it will lead to skidding [18]. If the problem is not solved in time, the oil from the hydraulic pump will completely enter into the hydraulic motor of the skid wheel, the other wheels will lose the drive power, resulting in the vehicle not running normally [19]. So it is of great significance to adopt an effective antiskid scheme for safe transportation.

A rotating speed sensor is installed on the driving hydraulic motor of the transport vehicle, which can realize the closed-loop control of the speed and effectively prevent the wheel from skidding. The method of calculating the vehicle speed is to convert the hydraulic motor rotating speed measured by the rotating speed sensor into the wheel rotating speed, and to get the average wheel rotating speed, which can be converted into the speed of the vehicle.

When the transport vehicle is running, the average value of wheel speed n is set as the reference value. If the rotating speed of a wheel is greater than $1.3n$, that means the wheel is

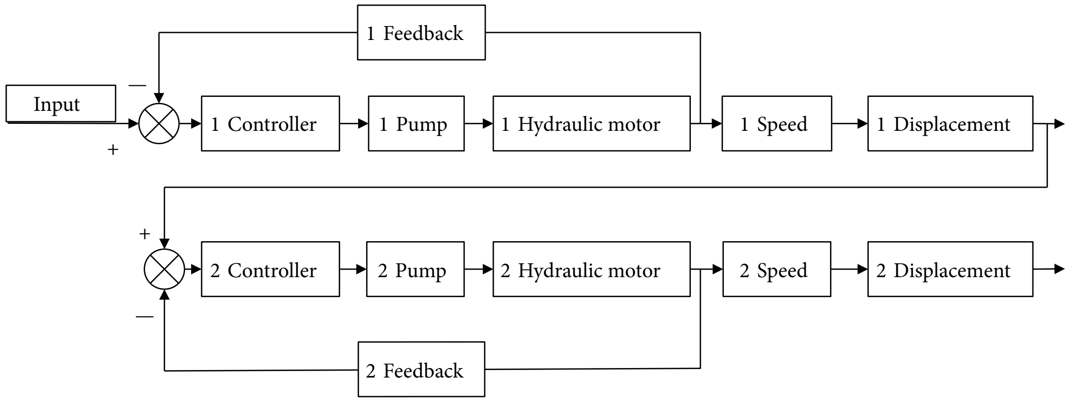

FIGURE 9: The principle diagram of master-slave synchronization control.

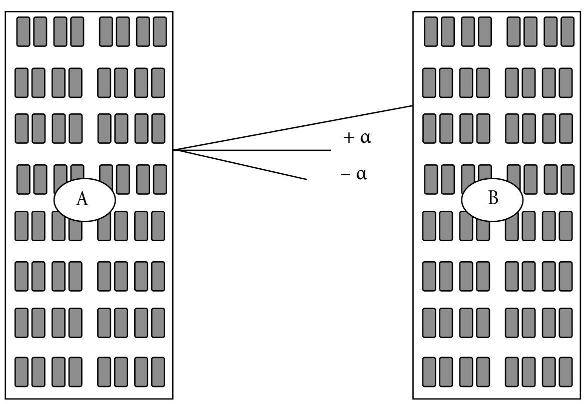

FIGURE 10: The synchronization adjustment principle diagram of A vehicle and B vehicle.

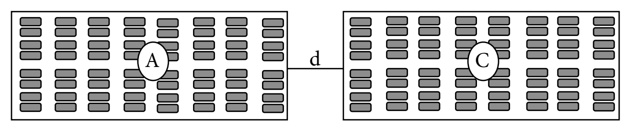

FIGURE 11: The synchronization adjustment principle diagram of the A vehicle and C vehicle.

skidding. When the wheel is skidding, the detection signal will be fed back to the control system, which will quickly cut off the motor-pump oil path, and turn the skidding wheel into a driven wheel, thus wheel skidding is eliminated.

4.2. Modeling of Pump-Controlled Motor System. Hydraulic transmission is used in the driving system of transport vehicles. The variable hydraulic pump is driven directly by the engine, the variable motor is driven by the variable pump, and the tire is driven directly by the wheel reducer. Therefore, the volumetric speed control is adopted in the speed regulation of the transport vehicle. The principle of the pump-controlled motor drive system is shown in Figure 4.

The leakage of the hydraulic pump and motor is relatively small and can be regarded as ignored. According to the relevant parameters of transport vehicle, the transfer function of pump-controlled motor is obtained as follows.

$$G(s) = \frac{n_m(s)}{U(s)} = \frac{k_p}{1/\omega_n^2 \cdot s^2 + 2\xi/\omega_n \cdot s + 1} = \frac{1009}{9.53 \times 10^{-4} s^2 + 0.00239 s + 1}, \quad (1)$$

where K_p is the coefficient of proportionality, ω_n is the natural frequency, ξ is the damping coefficient.

According to the transfer function, the simulation model of the system is established as shown in Figure 5. By adjusting the parameters of the PID controller [20], the step response curve of the hydraulic motor is obtained as shown in Figure 6. It can be seen from Figure 6, the maximum overshoot value of the system is about 3%, and the time for the system to reach stability is about 4 seconds.

4.3. PID Simulation of Pump-Controlled Motor System. According to the need of research, converting the speed of the motor into the displacement of the vehicle can more directly reflect the research content. According to the designed PID controller, the model is established as shown in Figure 7.

The displacement comparison curves with PID control algorithm and without PID control algorithm are obtained in the simulation, as shown in Figure 8.

From the simulation results, it can be seen that the displacement of the vehicle is relatively stable when the PID control algorithm is added. The displacement curve without the PID control algorithm has obvious oscillation, and the deviation between the two curves is getting larger as time goes on, it can be concluded that adding the PID control algorithm can improve the stability of vehicle speed.

4.4. Selection of Synchronization Control Strategy. At present, there are two main methods of hydraulic synchronization control. One is the open-loop control method, which consists of a dividing-combining valve or synchronous motor. Its characteristics are simple principle, low cost, but low precision. The second method is to use electro-hydraulic servo valve or electro-hydraulic proportional valve to form a closed-loop control system. And the master-slave control

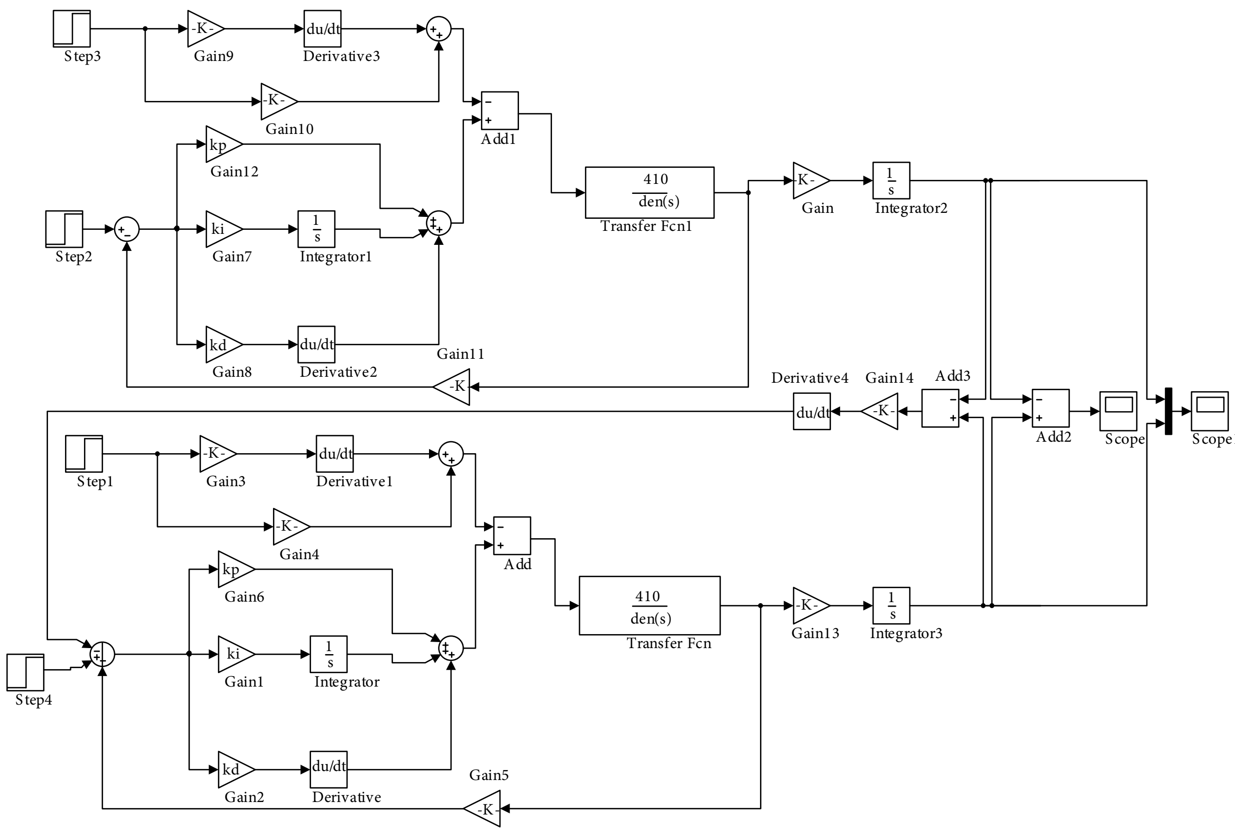

Figure 12: Simulating model of synchronous control for A vehicle and B vehicle.

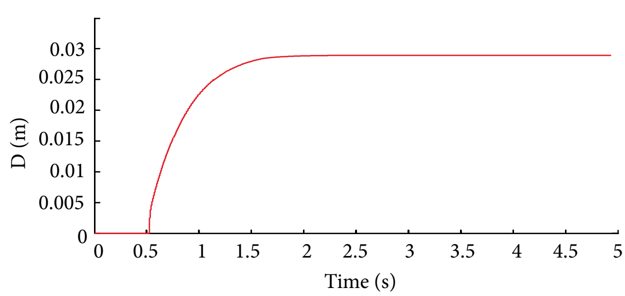

Figure 13: Displacement deviation curve of A vehicle and B vehicle.

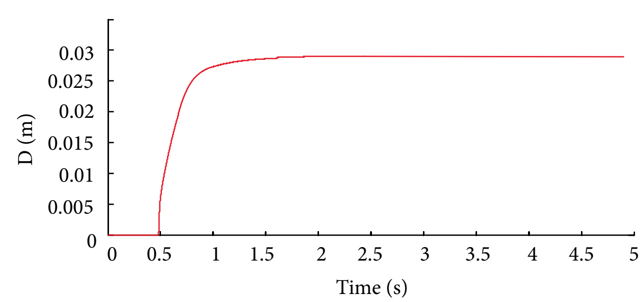

Figure 15: Displacement deviation curve of A vehicle and C vehicle.

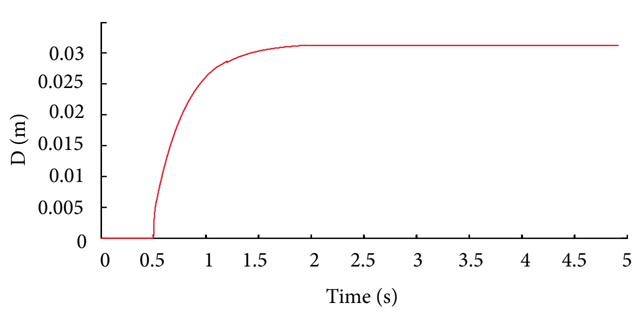

Figure 14: Displacement deviation curve of C vehicle and D vehicle.

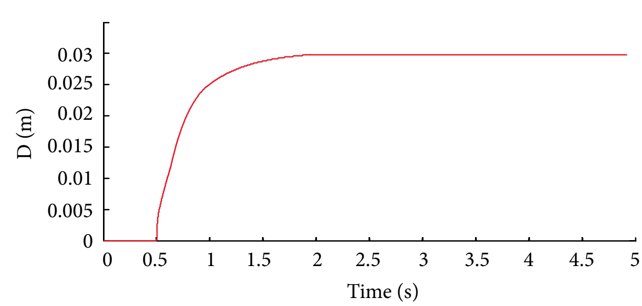

Figure 16: Displacement deviation curve of B vehicle and D vehicle.

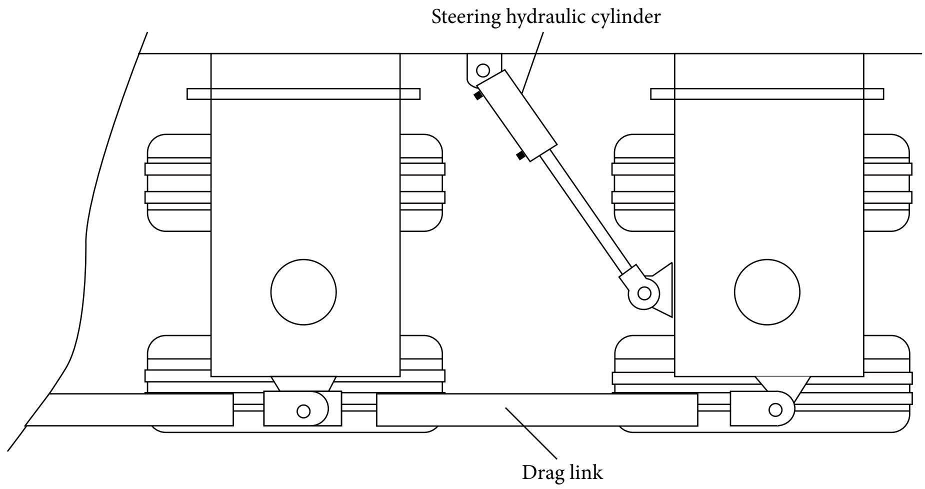

FIGURE 17: The schematic diagram of steering system.

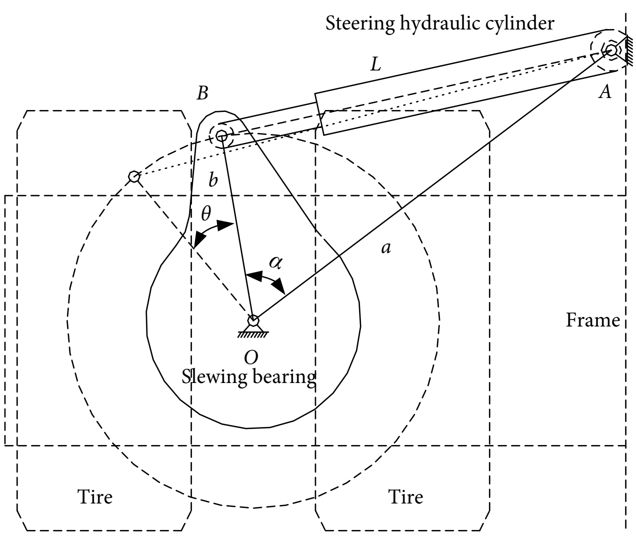

FIGURE 18: The geometric model of steering mechanism.

strategy is commonly used. The control strategy can meet the requirement of high precision synchronization control [21].

In the synchronization control scheme, the master-slave control strategy is adopted, and one of the vehicles is used as the leader vehicle. The displacement deviation between the vehicles is taken as the control objective, so that the displacement errors of the four vehicles can be reduced so that they can run synchronously. The control of the leader vehicle is by manual driving or remote control [22]. The speed of the hydraulic motor is taken as the feedback signal, and the control principle is shown in Figure 9.

4.5. Principle of Synchronization Adjustment. The synchronous adjustment principle of A vehicle and B vehicle is shown in Figure 10. Take A vehicle as the leader vehicle, B vehicle can adjust its speed according to the PID output of encoder angle α. Only when $\alpha = 0$, the A vehicle and B vehicle is synchronized.

When the four vehicles are driving forward, if $\alpha > 0$, it means that the B vehicle is faster than the A vehicle, and the PID output is a negative value, the B vehicle will adjust to decelerate. And if $\alpha < 0$, it means that the B vehicle is slower than the A vehicle, and the PID output is a positive value, the B vehicle will adjust to speed up.

When the four vehicles are driving backward, if $\alpha > 0$, it means that B vehicle is slower than the A vehicle, and the output of PID is a negative value, the B vehicle will adjust to speed up. And if $\alpha < 0$, it means that the B vehicle is faster than the A vehicle, the output of PID is a positive value, the B vehicle will adjust to speed up. The adjustment of the C vehicle and D vehicle is the same as the A vehicle and the B vehicle.

The adjusting principle of A vehicle and C vehicle is shown in Figure 11. Based on A vehicle, C vehicle can adjust its speed according to the length of the draw-wire displacement sensor and the PID output.

When the four vehicles are driving forward, if the actual distance is longer than the set distance, it shows that C vehicle is slower, and the PID output is a negative value, the C vehicle will adjust to speed up. And if the actual distance is less than the set distance, it shows that C vehicle is faster, and the PID output is a positive value, the C vehicle will adjust to decelerate. When driving backward, if the actual distance is longer than the set distance, it shows that C vehicle is faster, the PID output is negative, and the C vehicle will adjust to decelerate, when the actual distance is less than the set distance, it shows that the C vehicle is slower, when the PID output is positive, the C vehicle will adjust to speed up. The adjustment of B vehicle and D vehicle is the same as the A vehicle and C vehicle, and the set distance is related to the length of the goods.

4.6. Synchronization Simulation and Analysis. On the basis of the above research, the synchronization of two transport vehicles is further analyzed. After adding PID control, the simulation model of the master-slave control of A vehicle and B vehicle is established as shown in Figure 12. The displacement deviation curve of A vehicle and B vehicle is obtained in the simulation as shown in Figure 13. From the result, it can be seen that the two vehicles can achieve a good synchronization effect, and the displacement deviation is about 28 mm.

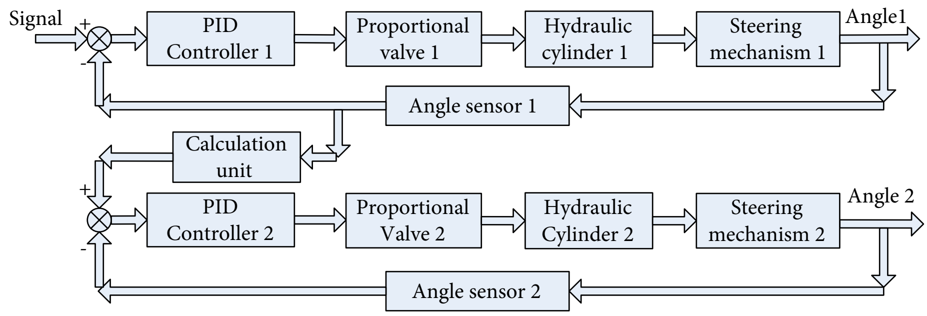

FIGURE 19: The steering synchronization adjustment principle diagram.

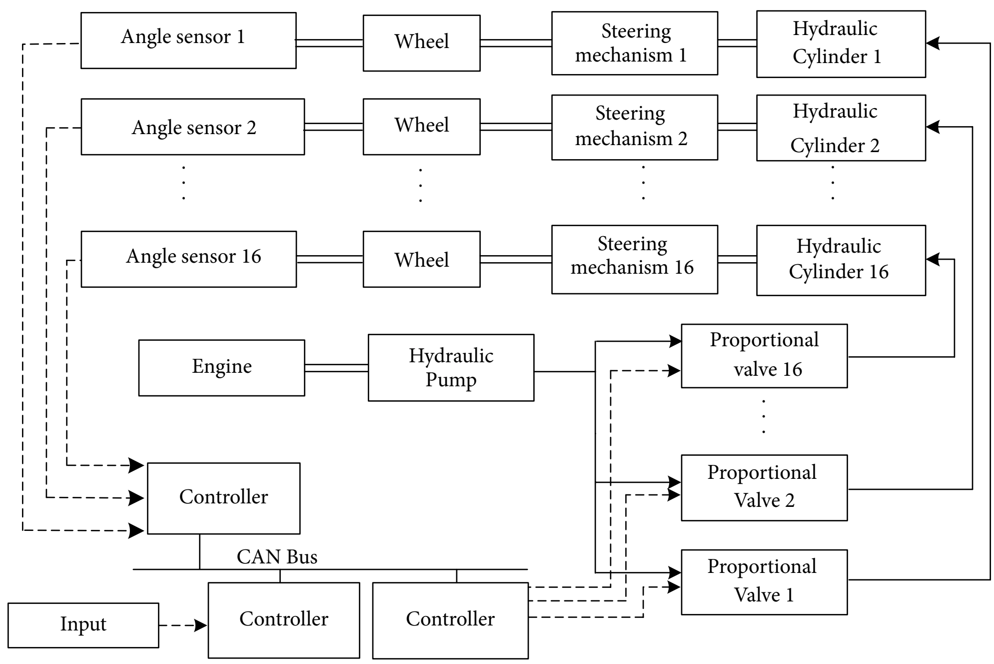

FIGURE 20: The steering synchronization control strategy.

Similarly, the displacement deviation curves of C vehicle and D vehicle, A vehicle and C vehicle, B vehicle and D vehicle are shown in Figures 14–16. The maximum displacement deviation is about 30 mm, and the deviation curves are all within the required displacement deviation range.

5. Research on Synchronous Steering of Combined Transportation

5.1. Transport Vehicle Steering System. The steering system of the transport vehicle is a connecting rod system as shown in Figure 17, which is driven by a hydraulic cylinder. There are four steering hydraulic cylinders in one transport vehicle. Each hydraulic cylinder can control 10 groups of wheels. The synchronous steering of these 10 groups of wheels can be realized simultaneously by controlling the steering cylinder, and the range of steering angle is ±30 degrees [23, 24].

There are 16 steering hydraulic cylinders in the four vehicles. In theory, the synchronous control of these hydraulic cylinders can make the wheel groups achieve the same steering angle. However, due to manufacturing errors and leakage, the steering angles of the groups of wheels may be different. In serious cases, it may cause damage to the mechanism, or even a major overturning accident.

According to the steering mechanism of the transport vehicle, it is simplified to the geometric model as shown in Figure 18.

According to the geometric model, the following equation can be obtained.

$$L + x_c = \sqrt{a^2 + b^2 - 2ab\cos(\theta + \alpha)}, \quad (2)$$

where L is the length of AB, x_c is the extension length of the hydraulic cylinder piston rod, a is the length of OB, b is the length of OA, θ is the steering angle, and α is the initial angle.

The torque equation of the steering actuator is as follows.

$$M = Fd, \quad (3)$$

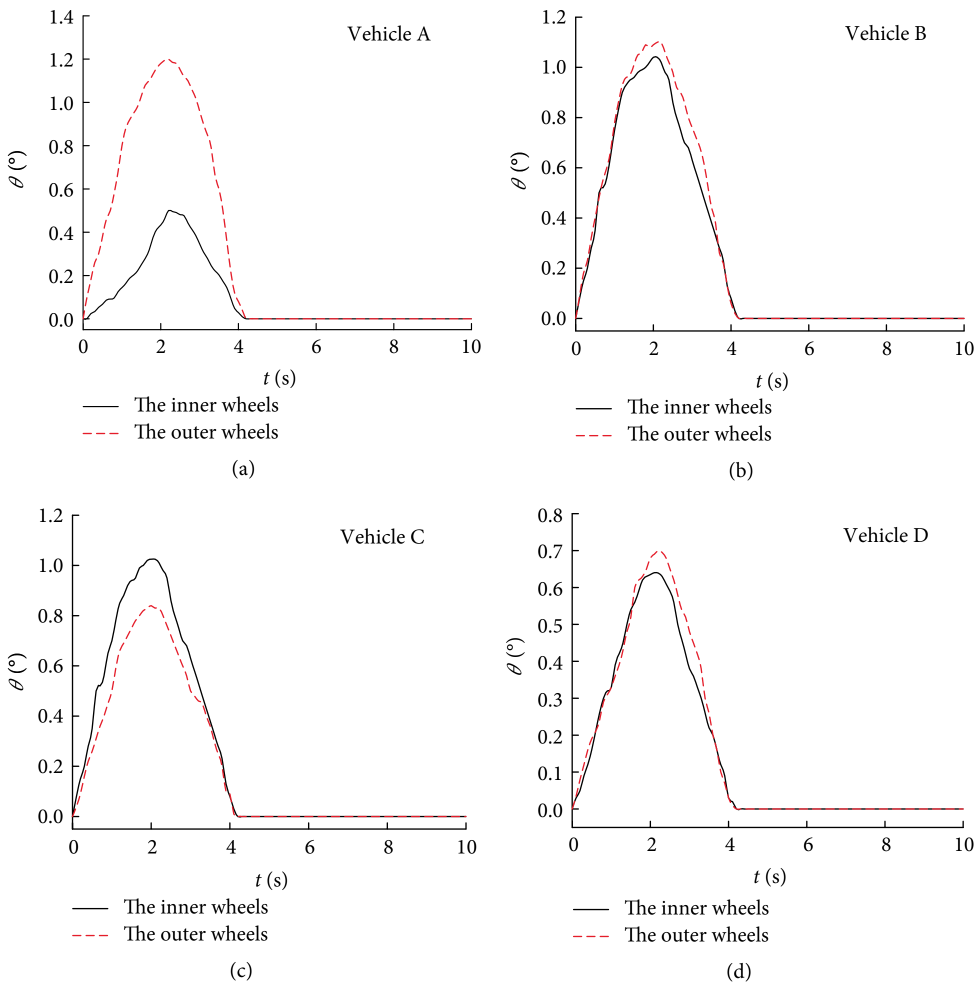

FIGURE 21: The steering angle errors of the four vehicles.

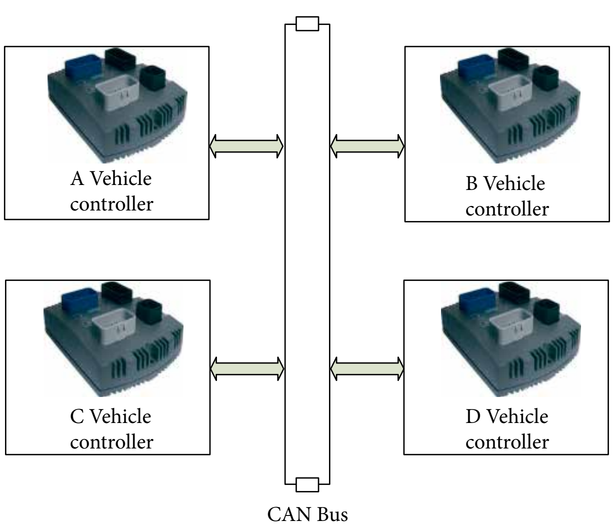

FIGURE 22: The control system of the four vehicles.

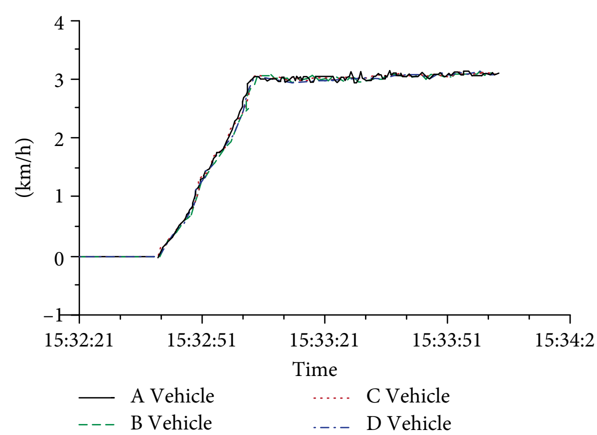

FIGURE 23: The speeds of the four vehicles.

where M is the driving torque of hydraulic cylinder, F is the output force of hydraulic cylinder, and d is the arm of force.

According to the area equation of the triangle, the following equation can be obtained.

$$\frac{1}{2}ab\sin(\alpha+\theta)=\frac{1}{2}(L+x_c)d. \quad (4)$$

According to Equation (4), the following equation can be obtained.

$$d=\frac{ab\sin(\alpha+\theta)}{\sqrt{a^2+b^2-2ab\cos(\alpha+\theta)}}. \quad (5)$$

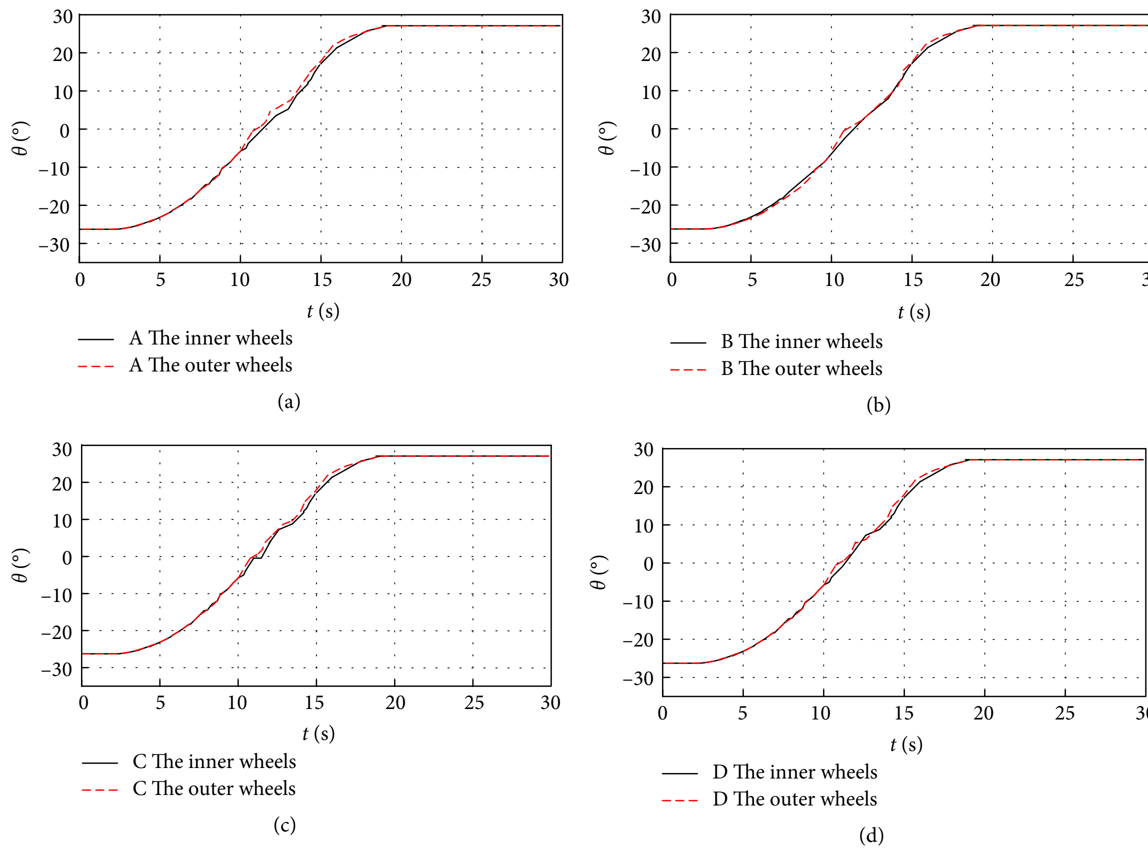

FIGURE 24: The steering angle curves of the four vehicles.

Through Equations (3) and (5), the equation can be obtained as follows.

$$M = F \cdot \frac{ab\sin(\alpha+\theta)}{\sqrt{a^2+b^2-2ab\cos(\alpha+\theta)}}. \tag{6}$$

Through Equations (2) and (5), the equation can be obtained as follows.

$$x_c = \frac{ab\sin(\alpha+\theta)}{d} - L. \tag{7}$$

The required flow Q of the steering hydraulic cylinder can be obtained from the extension length of the hydraulic cylinder piston rod.

$$Q = x_c A. \tag{8}$$

According to the required flow, the corresponding opening of the proportional valve can be obtained, and the corresponding control signal can be obtained by referring to the manual of the proportional valve. Finally, the relationship between the steering angle and the required current signal of the proportional valve can be obtained as follows.

$$kI = A\left(\frac{ab\sin(\alpha+\theta)}{d} - L\right), \tag{9}$$

where I is the current signal, and k is the proportional coefficient of the valve opening and current signal.

5.2. Synchronized Steering Control Mode. In order to realize the steering synchronization of all wheels, it is necessary to realize by the control system [25]. Through the study of hydraulic synchronization control modes, the master-slave control mode is selected, the control principle is shown in Figure 19.

When the running is oblique, it is required that all wheels of the four vehicles achieve the same steering angle. Each wheel group is equipped with an angle sensor to monitor the actual steering angle of the wheel group. The corresponding control instructions are sent to the controller. This controller will drive all the steering hydraulic cylinders until the wheels turn to the synchronous angle [26], and the control strategy is shown in Figure 20.

5.3. Simulation and Analysis of Synchronous Steering. During the combined transportation steering process, overshooting and frequent adjustment under slight deviation will cause system oscillation, which will affect the stability of the transportation [27].

In order to ensure the stability of the transportation, excessive overshooting and frequent adjustment under slight deviation should be avoided. Therefore, according to the functions of the proportional element, differential element, and integral element of the PID controller, the best parameter values can be obtained by using trial and error [28, 29].

In the simulation, the combined mode of the four transport vehicles is adopted as shown in Figure 4. The master-slave synchronization control strategy is used to the synchronous steering, and the steering angle is set to 30 degrees. The internal and external steering angles of the four vehicles are collected in the simulation, the steering angle errors are shown in Figure 21. It can be seen that the reference wheel groups steering angle errors of A vehicle are 0.5 degrees, while the steering angle errors of other wheels are about 1 degrees. And after four seconds, the steering angle errors of all wheels are eliminated, that is, all wheels achieve synchronous steering. The results show that the master-slave synchronous control strategy can achieve high synchronous steering precision.

6. The Control System Design Based on CAN Bus

The synchronous control accuracy of the four vehicles should be guaranteed in the process of transportation. The electro-hydraulic proportional control is adopted in the transport vehicle, so the CAN bus technology can be applied to complete the communication between the controllers of the transport vehicles, thus the synchronous control of the four vehicles can be realized [17].

The control system is designed as shown in Figure 22. The speed signals and steering angle signals of each vehicle are collected by the sensors and sent to the main controller through the CAN bus. The main controller can analyze and compare the preset input signals with the feedback signals, and control the output electric current of each sub-controller to achieve closed-loop control. The speed of each vehicle can be changed by controlling the displacement of the hydraulic pump or motor, which can realize the synchronous control of the four vehicles [30, 31].

7. The Actual Test Results

The purpose is to transport the goods to the destination safely and effective. All the vehicles have their own controllers, vehicle A will be operated or remotely controlled by a driver, and its output displacement signal or the steering signal is tracked as the input signal of the other vehicles to keep the four vehicles synchronized through the CAN bus.

In order to verify the synchronization performance of the four vehicles and the practicability of the control system, the field debugging of the combined transportation is carried out. The speeds of the four vehicles are collected in the debugging as shown in Figure 23. It can be seen that the speeds of the four vehicles are basically the same, that is, the synchronization accuracy can meet the transport requirements.

In the construction, the running direction of the combined transportation is generally straight, lateral, and oblique, that is to say that all the wheels must turn at the same angle. The steering angle is set to 27 degrees in the test, and the steering angle curves of the inner and outer wheels of the first axle of the four vehicles are collected. The steering angle curves are shown in Figure 24. It can be seen that the four transport vehicles can finally achieve the same steering angle.

8. Conclusion

(1) The fixed distance between vehicles is used as the control target. The master-slave control strategy and PID controller are adopted. Through simulation analysis and field test, the synchronous control accuracy of the control strategy is verified. It is proved that the PID controller plays an important role in the multi-vehicle cooperative control.

(2) According to the steering mechanism, the mathematical model of steering system is established and the appropriate control strategy is selected. Through the simulation and test, the steering process angle curves of the inner and outer wheels of the four vehicles are collected, and the correctness of the control strategy is verified.

(3) The driving system and the steering mechanism of multi-vehicle combined transportation are analyzed and studied. The control system based on CAN bus is designed, which can achieve high precision synchronization in the running and steering process of the four vehicles.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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