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RESEARCH ON VIRTUAL COUPLING TRAINS COOPERATIVE CONTROL METHOD BASED ON IMPROVED ARTIFICIAL POTENTIAL FIELD

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Abstract. *In the field of rail transit, improving transportation capacity is an eternal hot spot. In recent years, with the development of train-to-train communication and intelligent control technologies, virtual coupling has become the focus of research on improving the transportation capacity of existing lines. A cooperative control method for virtual coupling trains based on an improved artificial potential field is proposed in this paper. Firstly, a nonlinear dynamics model of virtual coupling trains based on local dual leader communication topology is established. Then, an improved artificial potential field control method with a speed factor is designed for the cooperative control of virtual coupling trains. Finally, the control effects of the local dual leader model and the improved artificial potential field control method are verified and analyzed under the scenarios of virtual coupling trains in the coupling state and interstation tracking operation.*

Keywords: Virtual coupling, Artificial potential field, Cooperative control

1. **Introduction.** The rail transit industry has proliferated in recent years [1]. However, the capacity of the train control systems under the current control method is approaching the limit. For example, the Beijing-Shanghai high-speed railway has reached 650 trains a day, which has reached the limit of the current control mode, but it still cannot meet the daily travel needs of more than one million passengers along the Beijing-Shanghai line. Therefore, it is urgent to improve the transportation capacity to meet the travel needs of passengers. The new line can improve the transportation capacity, but it cannot be built without limitation due to the limited resources, and the cost is very high, which is not a perfect solution. Improving the transportation efficiency of existing lines becomes the key to solving the contradiction between the current travel pressure and the lack of capacity [2]. Virtual coupling is a kind of train coupling system using wireless communication to substitute the physical linkage between trains, which can effectively improve the transportation efficiency of existing lines by shortening the train interval and optimizing the transportation organization in a more intelligent and flexible coupling way [3].

Bock et al. first introduced the concept of virtual coupling in 2000 [4]. Subsequently, they proposed a virtual train system for freight trains. In 2011, the EU proposed the Shift2Rail initiative, which describes the "virtual coupling" of trains, in which instead of using mechanical hooks between trains, virtual hooks between trains are established using vehicle-vehicle communication, allowing neighboring trains to run at a distance of more than 10 meters [5-7]. Meanwhile, Aydin et al. described the concept of wireless virtual coupling trains, technical difficulties, and other related issues [8].

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Felez et al. conducted a study from the perspective of virtual coupling trains operation control and proposed that using model predictive control for virtual coupling trains can significantly reduce the operating interval between trains [9]. Cao et al. proposed a virtual coupling trains suitable control method based on model predictive control and artificial potential field from the perspective of virtual coupling train cooperative control and collision prevention control [10]. Su et al. from the perspective of heterogeneous virtual coupling, studied the stability of tracking operation of virtual coupling trains with different braking performance in different zones and derived the constraints for stable operation of virtual coupling trains from the operation control of trains [11]. Zhang and Zhang used colored Petri nets to formally model and validate the virtual coupling functional modules and typical scenarios from the virtual coupling train operation process risk analysis [12].

In general, Bock et al. [4-8] only put forward the concept of virtual coupling in the early studies of virtual coupling. The specific implementation method is not studied. It can only provide conceptual support for the application of virtual coupling technology to improve the transportation efficiency of existing railways, but cannot provide theoretical reference for engineering realization. Felez et al. [9] studied the interstation tracking operation of virtual coupled trains by taking power units rather than EMU trains as the research object. Although they have achieved good control effect in tracking operation, they have not solved the problems of how to form and uncoupling virtual coupled trains when they enter and stop at stations. Cao et al. [10] and Su et al. [11] put forward the improved model predictive control method to control multiple scenarios of virtual coupled train operation in their research, but its control effect is too affected by the prediction step size, and it cannot solve the problem of real-time control of multiple trains. Zhang and Zhang [12] only studied the safety of virtual coupled train control, and did not propose corresponding control strategies for specific operation scenarios.

To sum up, in order to solve the engineering application problem of virtual coupled trains, it is necessary to design a control strategy that considers the timeliness of multi-scenario control and the accuracy of parking control, so as to improve the transportation efficiency of the existing lines. Therefore, a virtual coupled train cooperative control method based on dual leader model is proposed in this paper. Secondly, we design an improved artificial potential field with a speed factor for the cooperative control of the virtual coupling trains to improve the accuracy of the virtual train interstation tracking operation. Then the simulation is performed. The main contributions of this paper are as follows.

1) This paper introduces a two-leader model that offers improved speed tracking control compared to the traditional leader-follower model. The two-leader model exhibits superior control stability and reduced cumulative error velocity, making it more suitable for multi-vehicle tracking applications in practical engineering.

2) The control performance of the artificial potential field method with an enhanced velocity factor surpasses that of the traditional artificial potential field method. This approach maintains stability with minimal changes as the number of trains increases, aligning with the intricate multi-car formation conditions encountered in practical engineering applications.

In summary, the virtual coupling scheme based on the double lead model proposed in this paper is feasible, and the artificial potential field control method with improved speed factor can realize the tracking control of the nonlinear virtual coupling train, which is more suitable for the complex working conditions in practical engineering applications than the traditional method.

2. Virtual Coupling Trains Based on Dual Leader-Follower Model.

The virtual coupling technology allows trains to be tracked information on the track. The concept of virtual coupling is based on advanced autonomous driving technology, which can improve the efficiency of existing lines by replacing physical hook connections with vehicle-vehicle communication and determining the distance between trains with high accuracy speed measurement and positioning.

[13-15] introduced the concept of train coupling operation similar to virtual coupling trains and proposed a corresponding implementation scheme. The scheme takes the first train as the leader of the whole virtual coupling trains coupling (Leader), and the rest of the trains are the followers of the coupling (Follower). This control method is simple but challenging to implement, especially since the data transmission between the leader and the follower has a great uncertainty, and this uncertainty will significantly impact the control of the whole virtual coupling trains. Therefore, this paper proposes a virtual coupling scheme based on a local dual leader-follower model to improve the stability of the coupling. The virtual coupling scheme is shown in Figure 1.

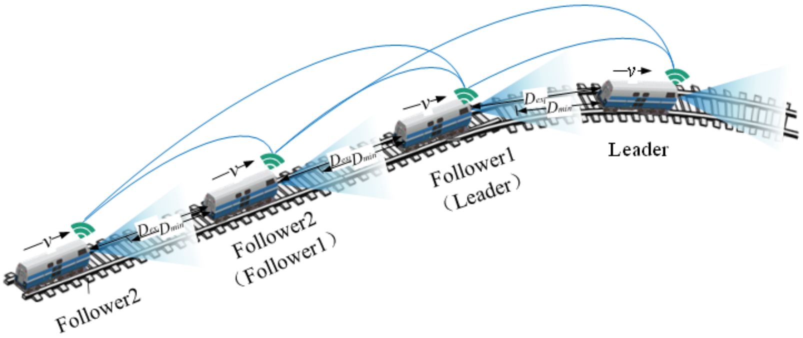


FIGURE 1. Schematic diagram of virtual coupling train scheme

Each train in the virtual coupling is a follower concerning the first two trains and a leader concerning the following two trains, and a communication link is established between the trains that are leaders and followers for data transmission. A coupling relationship is established until the coupling is released or withdrawn. The leader train of the virtual coupling trains is controlled by the virtual leader method, using the Automatic Train Operation (ATO) curve of the virtual coupling trains as the virtual leader, i.e., tracking the ATO curve. At the same time, the curve is also used as the virtual leader of the second train of the virtual coupling trains, forming a local dual leader at the second train. The current train uses the relative speed and position of the two trains before it or the virtual leader as inputs for the cooperative train operation control and applies the actively measured relative distance and relative speed as inputs for the collision avoidance control.

From a macroscopic point of view, the virtual train coupling realizes the same speed operation as the whole virtual train coupling through cooperative control. Microscopically, the tracking distance of each train in the virtual train coupling is dynamically adjusted according to the line information and the speed of the virtual train coupling. The safety distance is always maintained to avoid the virtual coupling train collision in the operation process.

3. Materials and Methods.

The actual operating conditions of virtual coupling trains are complex, and the operation safety, stopping accuracy, and transportation efficiency should be considered. Therefore, analyzing the virtual train operation process is the basis for studying virtual train operation control.

In modeling the longitudinal dynamics, the train can be considered a mass point subject to drive/braking forces, rolling and bearing resistance, air pressure, air resistance, grade, and curve resistance [16,17]. The detailed analytical procedure is shown in Equation (1), and the longitudinal dynamics model of train i is

$$s_i' = v_i \quad M_i v_i' = u_i - A_i - B_i v_i - T_{fi} C_i v_i^2 - F_{ei} \tag{1}$$

where s_i and v_i are the position and speed, u_i is the driving or braking force; F_{ei} is the force exerted by the track on the wheel; M_i is the mass; A_i includes rolling friction and bearing sliding friction; B_i is the drag coefficient; C_i is the aerodynamic coefficient, and T_{fi} is the wind tunnel coefficient. In the model, M_i, A_i, B_i, and C_i are characteristic parameters of trains.

The external force F_{ei} of the track of train i contains two parts: the tangential component of gravity F_{gi} and the curve friction F_{Ri}:

$$F_{ei} = F_{gi} + F_{Ri} = -M_i g \times \mathit{slope} - \frac{6M_i}{R_i} \tag{2}$$

where *slope* is the gradient of the line, obtained by retrieving the line information in the database, g is the acceleration of gravity, and R_i is the curvature of the line, which can be obtained from the database along with the slope. u_i is the control force output of train i.

$$u_i = u_{di} - u_{bi} \tag{3}$$

where u_{di} is the driving force of the control output of train i, which can be expressed by

$$u_{di} = \frac{P_i}{v_i} \tag{4}$$

where P_i is the traction or braking power of train i. u_{bi} is the braking force of the control output of train i. The desired braking acceleration is constant since the train braking process belongs to uniform deceleration motion. u_{bi} can be expressed by

$$u_{bi} = a_{bi} \cdot M_i \tag{5}$$

The following equation describes the running process s_l of the main train during the virtual coupling trains tracking operation:

$$s_l = \sum_{i=1}^{n} v_{li} \cdot \Delta t + \frac{1}{2} \cdot v_{li}' \cdot \Delta t^2 \tag{6}$$

where v_{li} is the speed of the main vehicle at moment i, v_{li}' is the acceleration of the main vehicle at the moment i, and Δt is the interval time from moment i to the next moment.

The following equation describes the running process s_f of the slave train during the virtual coupling trains tracking operation:

$$s_f = \begin{cases} \displaystyle\sum_{j=0}^{j=n} v_{fj} \Delta t, & n \leq m \\ \displaystyle\sum_{j=0}^{j=n} v_{fj} \Delta t + \sum_{j=0}^{j=n} v_{fj} \Delta t + \frac{1}{2} v_{fj}' \Delta t^2, & n > m \end{cases} \tag{7}$$

where v_{fj} is the speed of leader at the moment j, v_{fj}' is the acceleration of leader at the moment j, and Δt is the interval time from moment j to moment $j+1$. n is the control period and m is the communication delay.

The following equation can express the tracking distance between leader and follower:

$$d = p_l + s_l - p_f - s_f - L \tag{8}$$

where p_l, p_f are the initial positions of the master and slave trains, which are obtained by the combined positioning method.

In order to ensure the safety of the operation of virtual coupling trains, the safe distance between trains should always be maintained, and the tracking interval d between adjacent trains needs to be always greater than the minimum tracking interval $d_{\min}$. Because the end speed in case of emergency braking is zero, the braking power is determined that then according to the line parameters, $d_{\min}$ can be determined as the control system expectation.

4. Velocity Factor Improvement of Artificial Potential Field and Stability Proof.

Among the existing control methods for virtual coupling trains, model predictive control is most commonly used. This is essentially a speed tracking control method with a poor distance tracking effect. In contrast, the artificial potential field method is commonly used for path planning and obstacle avoidance and has a better distance-tracking effect. The artificial potential field reflects information such as the distribution and position relationship between obstacles and target points in the potential field value of each point in the environment. For the nonlinear virtual coupling trains system, the artificial potential field-based method, which is insensitive to the system model, has a greater advantage in distance keeping control. The main idea of artificial potential field method tracking control is to construct a potential field function that can represent the risk of trains at different positions. Under the action of this potential field force, the train will be modified to a low-risk state. The potential field force acting on the train is determined by the gradient of the potential field function. The inter-train potential field is shown in Figure 2.

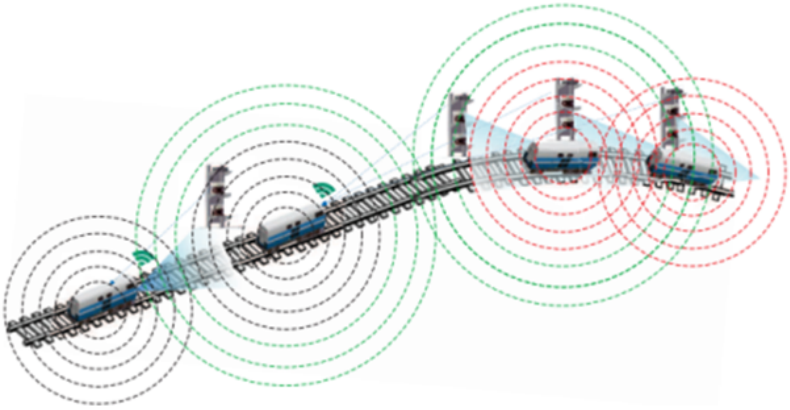


Figure 2. Inter-train potential field of virtual coupling train

Artificial potential fields exist only between virtual coupling trains that establish communication, which coincides with the actual communication topology. The virtual coupling trains cannot obtain information about the position and speed of trains that do not communicate with them and are not adjacent. No artificial potential field can be formed for them. The existence of gravitational and repulsive fields between any two objects in the conventional artificial potential field is inconsistent with the actual situation.

The connection weight A_{ij} of the communication topology is introduced, which also means that the potential field forces between different virtual coupling trains may differ even when the distances are the same. When a virtual coupling train is controlled for collision avoidance, it prioritizes avoiding the virtual coupling trains with a high connection weight, i.e., the closer the connection weight is, the higher the connection weight is. In this way, the priority of collision avoidance between virtual coupling trains is linked to the communication topology, ensuring that no collision occurs with the preceding train first while maintaining synchronous operation and relative position relationship with the leader train or more preceding trains to ensure its safety.

It can be seen that this potential field force design approach has specific stability and robustness. In contrast, in a traditional artificial potential field, where every virtual coupling of trains is treated equally, there may be a train that is close to the first train ahead, but far away from the second train ahead. This imbalance results in potential field forces with both gravitational and repulsive components, with the gravitational force potentially exceeding the repulsive force. Such conditions can lead to a train collision, posing a significant risk to transportation safety. The weight matrix can be expressed as

$$A_{ij} = \begin{cases} a_{ij}, & \text{connect} \\ 0, & \text{other} \end{cases} \tag{9}$$

where a_{ij} is the weight value.

In summary, the inter-train potential field is the core of collision prevention for virtual coupling trains. Trains are both dynamic tracking targets and dynamic obstacles. When the distance between two trains is large, they attract each other. As the distance between virtual trains increases, the attraction effect becomes weaker. Conversely, as the distance between virtual trains decreases, the repulsion effect becomes stronger. The aim is to stabilize the distance between trains until they reach a stable state. The potential field function of the distance between trains can be expressed as

$$U_a(s_{ij}) = k_i \sum_{j=1}^{n} a_{ij} \ln\left(\cosh\left(\frac{s_{ij} - d_{ij}}{s_{ij} - d_{i\min}}\right)\right), \quad s_{ij}(0) > d_{i\min} \tag{10}$$

where $k_i > 0$ represents the weighting factor, s_{ij} represents the actual operating interval between train i and train j, d_{ij} and $d_{i\min}$ represent the desired tracking distance and minimum safety distance between train i and train j, respectively. From Equation (10), it can be concluded that when $s_{ij} = d_{ij}$, the value of $U_a(s_{ij})$ equals 0. When $s_{ij} \to d_{i\min}$, $U_a(s_{ij}) \to \infty$.

Then the output formula of the artificial potential field control force is

$$\begin{aligned} F_a(s_{ij}) &= k_i \sum_{j=1}^{n} a_{ij} \ln\left(\cosh\left(\frac{s_{ij} - d_{ij}}{s_{ij} - d_{i\min}}\right)\right) \\ &= k_i \sum_{j=1}^{n} a_{ij} \tanh\left(\left(\frac{s_{ij} - d_{ij}}{s_{ij} - d_{i\min}}\right) - \left(\frac{v_{ij}\left(d_{ij} - d_{i\min}\right)}{\left(s_{ij} - d_{i\min}\right)^2}\right)\right) \end{aligned} \tag{11}$$

where F_a is the potential field force, and v_{ij} is the speed error between train i and train j. The system model is nonlinear and time-varying for the virtual coupling trains system. The above simulation results show that the speed tracking effect of the traditional artificial potential field method is poor. In order to improve the control accuracy and stability of the virtual coupling trains and ensure the safety of the train operation, the traditional artificial potential field function needs to be modified [18,19]. Based on the original potential field function, a speed factor based on the real-time speed of the train is introduced. This paper further improves the potential field function with fixed parameters to a potential field function with time-varying parameters [20,21]. The improved potential field function is

$$F_a\left(X_{ij}\right) = -k_i k_v \sum_{j=1}^{n} a_{ij} \tanh\left(\frac{s_{ij} - d_{ij}}{s_{ij} - d_{i\min}}\right)\left(\frac{v_{ij}\left(d_{ij} - d_{i\min}\right)}{\left(s_{ij} - d_{i\min}\right)^2}\right) \tag{12}$$

The coupling k_v of the dual leader is

$$k_v = \frac{2v_f + (v_{l1} - v_f) + (v_{l2} - v_f)}{v_{\max}} \tag{13}$$

where v_{l1} is the velocity of the first leader. v_{l2} is the velocity of the second leader.

By deriving the potential field function, the value of the control force can be obtained. The control force is applied to the virtual coupling train controller to complete the accurate control of the nonlinear virtual coupling trains.

5. **Simulation.** The simulation scenario constructed in this paper covers five stations and four zones. Considering the length of the stations, the number of trains with virtual linkage is set to 3. Among them, the target of train stopping point spacing at the stations is 2 meters, and the target of zone tracking spacing is two times the minimum safety distance. Other relevant parameters are taken in the following table.

TABLE 1. Parameters of EMU

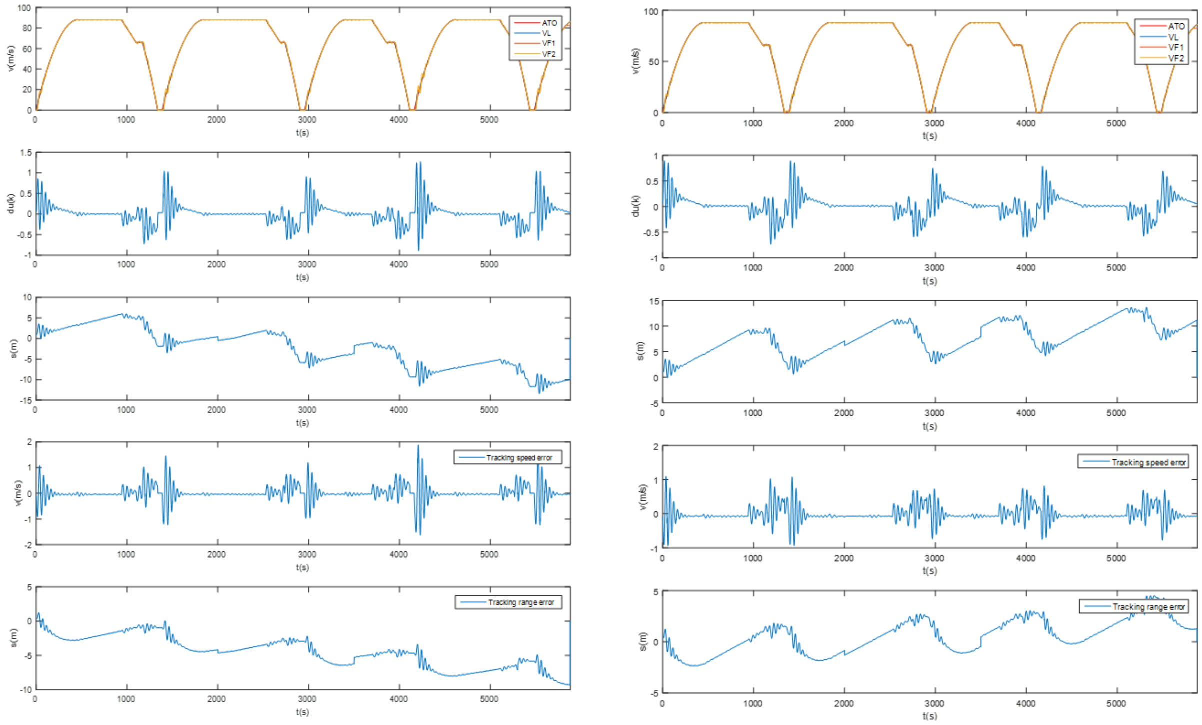
Name	Value
Gross weight	890 (t)
Maximum speed	380 (km/h)
Continuous running speed	350 (km/h)
Traction power	9600 (kw)
Emergency braking deceleration	1.2 (m/s^2)
Common basic resistance models	$w = 0.53 + 0.0039v + 0.00011v^2$

The simulation results of follower speed tracking for the leader-follower model and the local dual leader model are shown in Figure 3, where the vertical coordinates control force change, distance, velocity error, and distance error, respectively.

The simulation results in Figure 3 and Figure 4 show that the virtual coupling trains control model based on the dual leader-follower model has a better control effect than the leader-follower model under the traditional artificial potential field control method. The maximum speed tracking error of the third train under the virtual coupling train control model based on the dual leader-follower model is 1.114 m/s, and the maximum speed tracking error of the leader-follower model is 1.976 m/s. Moreover, the tracking distance between trains in the leader-follower model gradually becomes smaller as time passes, and there is a risk of collision if there is no error correction. In the dual leader-follower model, the tracking distance between trains increases gradually, and the speed is lower than that of the leader-follower model, so there is no risk of collision. However, it may cause the trains to break away from the formation, so it is necessary to improve the artificial potential field control method to keep the formation stable without the risk of collision.

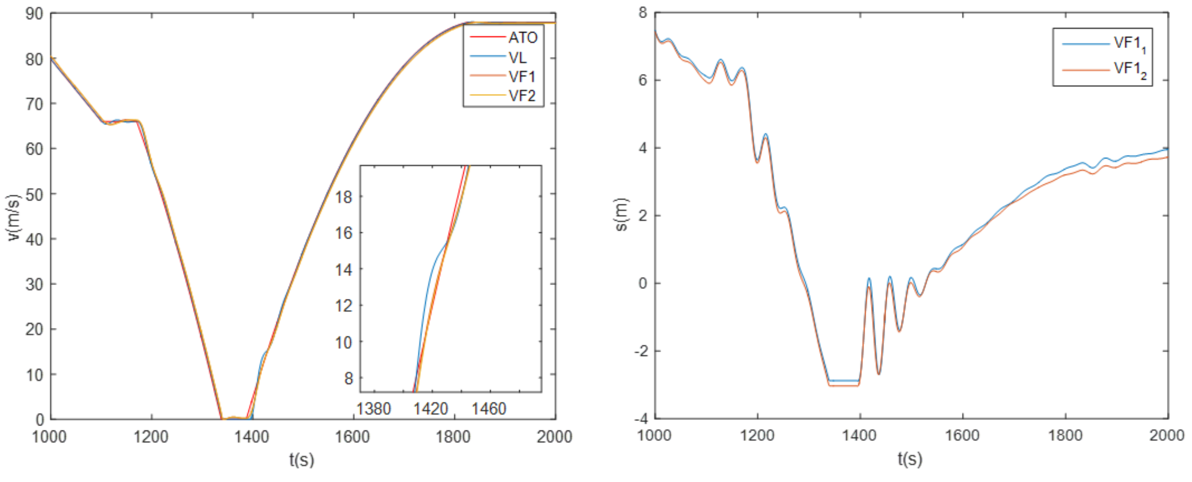
The simulation results of the improved artificial potential field based on the dual leader-follower model and the traditional artificial potential field inbound parking scenario are shown in Figure 4 and Figure 5.

From the simulation results in Figure 6 and Figure 7, it can be seen that the artificial potential field control method with improved speed factor has a better control effect than the traditional artificial market method in the incoming parking lot scene, and its speed fluctuation and tracking distance error are always smaller than the traditional artificial potential field method. However, with the increase of the number of trains in the coupling, the fluctuation gradually increases, so the number of trains in the coupling process is due to controling the number of trains.



(a) (b)

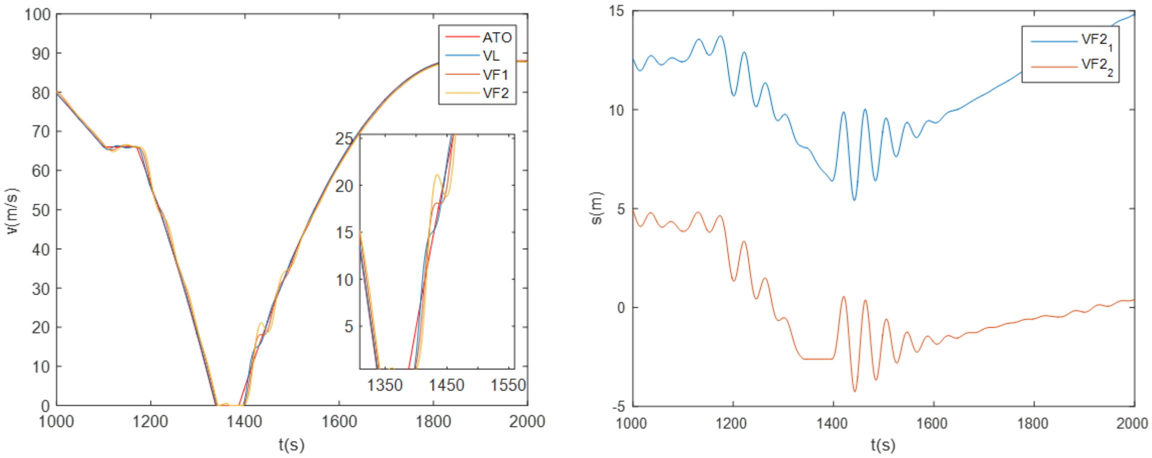
Figure 3. (color online) (a) Track simulation results of leader-follower model; (b) track simulation results of dual leader-follower model



(a) (b)

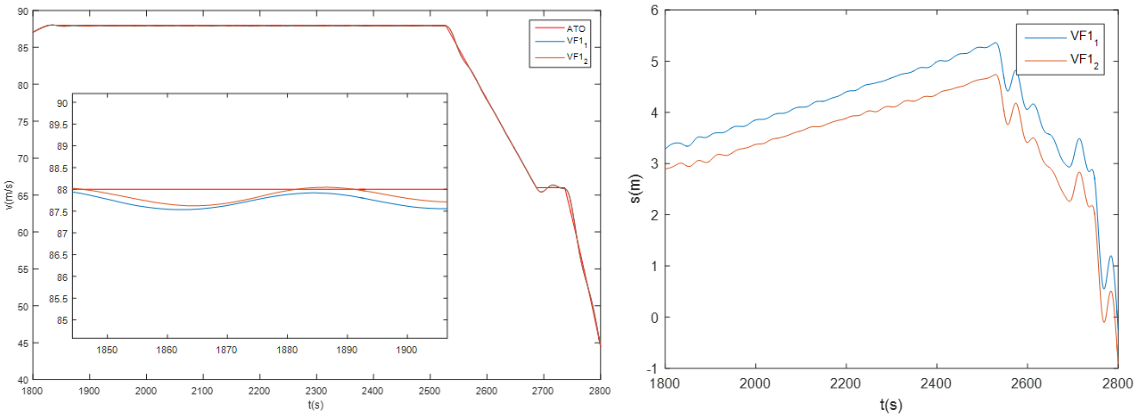
Figure 4. (color online) Follower 1 inbound parking simulation results: (a) Speed following simulation results; (b) distance error simulation results

With the increase in the number of trains in the formation, the distance tracking error of the traditional artificial potential field method gradually increases, and there is a risk of coupling disintegration. The tracking distance of the artificial potential field method with an improved speed factor will increase but not significantly, and the error is always less than 5 m.



(a) (b)

FIGURE 5. (color online) Follower 2 inbound parking simulation results: (a) Speed following simulation results; (b) distance error simulation results



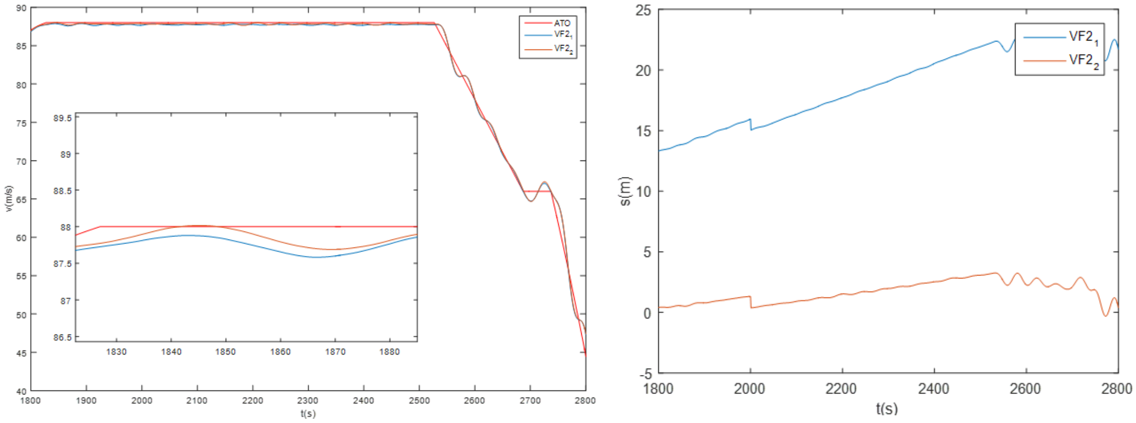
(a) (b)

FIGURE 6. (color online) Simulation results of Follower 1 inter-station tracking operation: (a) Speed following simulation result; (b) distance error simulation results

The tracking curve of the artificial potential field method with an improved velocity factor is shown in Figure 8. And the average velocity error and average distance error of the three methods are shown in Table 2.

The output results fluctuate around the target velocity with the velocity control of the artificial potential field method with an improved velocity factor. The velocity fluctuation is more minor than the traditional artificial potential field method, and there is no evident hysteresis. The average speed tracking error of the trailing train can reach 0.013 m/s, and the distance tracking error can reach 0.0272 m. In summary, the artificial potential field method with improved speed factor is more suitable for tracking control of virtual coupling trains.

6. **Conclusions.** This paper proposes a local dual leader model based virtual coupling train control method based, focusing on the control algorithm of the nonlinear virtual coupling train control system to ensure the operational safety of the virtual coupling



(a) (b)

Figure 7. (color online) Simulation results of Follower 2 inter-station tracking operation: (a) Speed following simulation result; (b) distance error simulation results

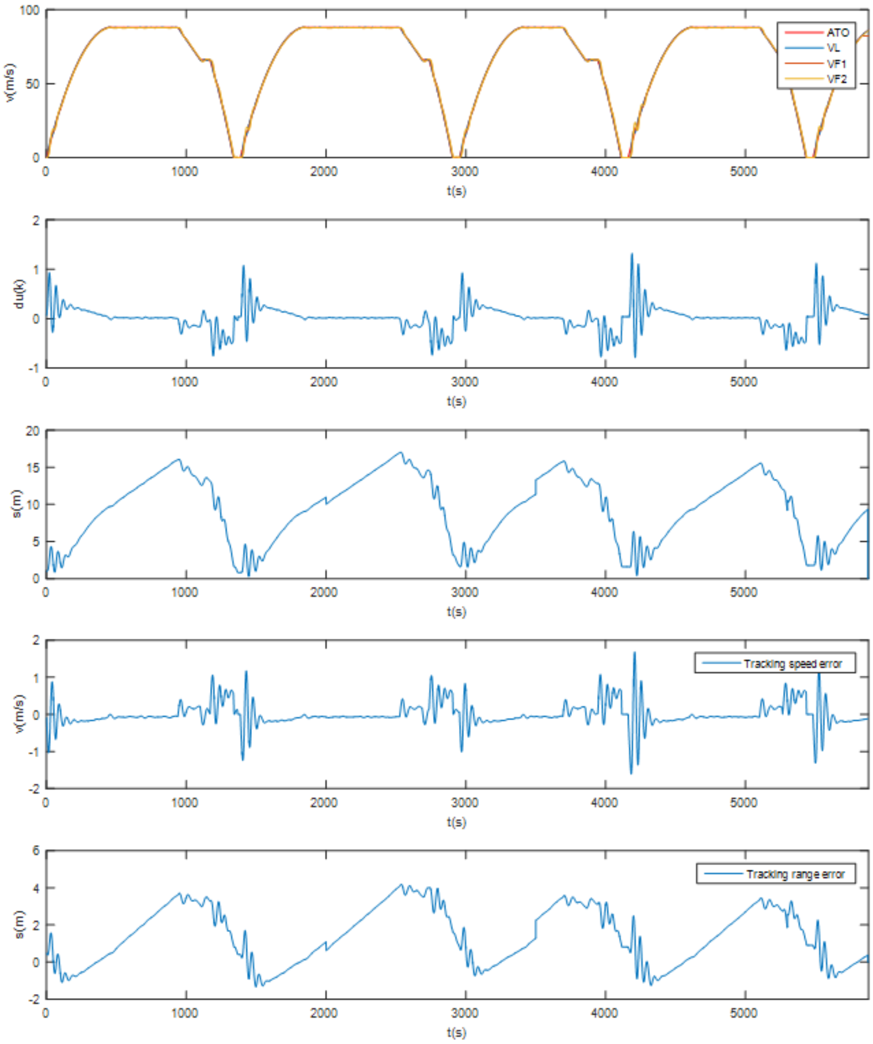


Figure 8. (color online) Improved velocity factor artificial potential field tracking simulation results

Table 2. The average velocity error and average distance error of the three methods

Method	Distance error1	Distance error2	Velocity error1	Velocity error2
Leader-Follower-APF	−0.2937	−0.4219	0.177	0.381
Dual Leader-APF	0.0706	0.1348	0.014	0.016
Dual Leader-IAPF	0.0007	0.0272	0.012	0.013

trains. Based on the longitudinal dynamics model of the virtual coupling single train, a local dual leader control model is established, and the nonlinear virtual coupling trains are controlled by using the improved velocity factor artificial potential field. Moreover, MATLAB is used for simulation to verify the control effect of the control algorithm. A feasible solution is provided for the design of a nonlinear virtual coupling train control system.

The specific details are as follows.

1) The dual leader model performs better than the leader-follower model in speed tracking control. The dual leader model has better control stability and less accumulated error speed. However, as the number of trains increases, the proposed model's stability worsens. So the number of trains in the coupling needs to be controlled.

2) In the train arriving parking scenario, the control effect of the artificial potential field method with improved speed factor is better than the traditional artificial potential field, but the stopping error increases with the number of trains.

3) In the train interval tracking operation scenario, the control performance of the artificial potential field method with improved speed factor is better than the traditional artificial potential field. Meanwhile, the control stability changes less with the increase of the number of trains. In conclusion, the proposed dual leader model based virtual coupling scheme in this paper is feasible, and the artificial potential field control method with improved speed factor proposed in this paper can realize nonlinear virtual coupling trains tracking control. Compared with the traditional method, this method possesses lower speed and distance tracking errors. However, to achieve the best control effect, the coupling length of the virtual coupling train needs to be controlled.

This paper does not consider the effect of communication time delay and line condition changes on the control effect. Next, we will focus on the effect of the change of communication delay and line conditions on the control effect and the optimization of the control method.

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