A Review of Tracking Control Method for Tractor-Trailer Vehicles

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ABSTRACT

Unmanned tractor–trailer vehicles play a particularly important role in various fields today. Vehicle tracking control technology is a key part of automatic driving, and its performance directly determines the vehicle's movement performance and even the success of the task. In this review, the current research status of tractor–trailer vehicles is summarized, several main tracking control methods of the vehicles are classified, and the advantages and disadvantages of each method are summarized. At the same time, the existing problems and future development direction in this field are summarized and prospected.

CCS CONCEPTS

• **General and reference** → Document types; Surveys and overviews.

KEYWORDS

tractor-trailer vehicles, tracking control method

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1 INTRODUCTION

Due to its large load capacity, high freight efficiency and low transportation cost, tractor–trailer vehicles are in large demand and widely used in today's commercial material transportation and military equipment loading and transportation [1]. They play an important role in the modern transportation development system [2]. With the rapid development of information technology and vehicle industry, the development of autonomous driving technology is advancing by leaps and bounds, and it is widely used in military and civilian fields [3-7]. Compared with traditional vehicles, Unmanned vehicles have the better control performance, reduce the drivers' labor intensity and greatly weaken the potential factors of traffic accidents [8]. Therefore, the research and application of unmanned tractor–trailer vehicles have gradually become an inevitable important trend.

Unmanned vehicle technology is mainly composed of three parts: environment perception, planning and decision-making, and motion control [9]. Tracking control is one of the core links of the driverless system, and its performance directly determines the success of the scheduled task. Therefore, the tracking control of tractor–trailer vehicles have great research value, which is of great significance for improving transportation efficiency, enhancing traffic safety, and promoting the development of transportation.

In this interview, the research status of tractor-trailer vehicles is summarized, the main tracking control algorithms of the vehicles are classified and summarized, and the future development direction is prospected.

2 RESEARCH STATUS OF TRACTOR–TRAILER VEHICLES

In the commercial field, tractor–trailer vehicles are gradually developing from manual driving and auxiliary driving to automatic driving. Most unmanned tractor–trailer vehicles are developed for fixed scenarios, such as short-distance cargo transportation in parks and airports, point-to-point long-distance high-speed logistics transportation, cargo loading at docks, material transfer in mines and farmland, etc.

TuSimple is a repress entative enterprise in the field of driverless freight trucks. The company focuses on the research, development and application of unmanned freight truck technology, and creates L4 level unmanned truck products in logistics scenarios such as highways, ports and yards. An autonomous truck in TuSimple is shown in Figure 1. It is a kind of tractor-trailer system. it has level L4 self-driving system, which allows it to see 360 degrees around the entire vehicle and up to 1000 meters away. it processes massive amounts of information and is capable 600 trillion operations per second, so it can see a problem identify the situation and react 15X faster than a human driver can.

In the military field, because the tractor–trailer vehicles can change its attitude structure, passively adapt to different terrain,

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Figure 1: TuSimple's autonomous truck

Figure 2: Warrior

and the wheels can fully contact the ground, they have good ground trafficability and obstacle crossing performance. In addition, tractor–trailer vehicles have enough capacity to carry equipment, so they are also widely used in transportation, reconnaissance, attack and so on.

The all-terrain articulated transport vehicle "Warrior" successfully developed by Russia is shown in Figure 2. "Warrior" is a typical trailer system vehicle. Two car bodies are connected by a hinged joint. The biggest feature of the vehicle is its strong ground and wading performance: the four tracks of the vehicle are actively driven, which can easily cross obstacles and climb slopes. The front body can tow the rear vehicle, and the rear body can also actively push the front vehicle, so as to ensure the smooth progress of the vehicle. When the vehicle is in the water, it can push the vehicle with the help of crawler paddle. In addition, the vehicle also has strong traction capacity and high-quality loading capacity.

3 TRAJECTORY TRACKING CONTROL METHOD

At present, the tracking control methods of unmanned trailer vehicles mainly include PID control, Linear quadratic regulator control (LQR), model predictive control (MPC), sliding mode control (SMC), fuzzy control, robust control and neural network control. According to different needs and theories, researchers also combined and

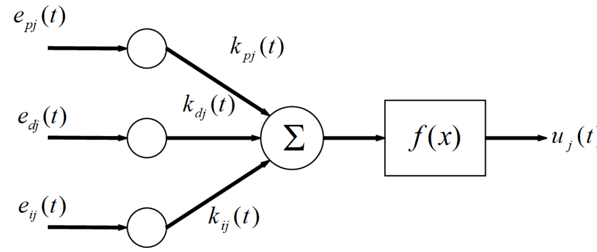

Figure 3: Block diagram of a nonlinear PID-based neural network

improved different control methods. Characteristics of different methods are compared in Table 1.

3.1 PID Control Methods

Proportion Integral Differential (PID) control mainly deals with the deviation of the vehicle position and attitude information fed back by the vehicle, and forms the control quantity through the linear combination of proportion, integral and differential, so as to control the controlled object. The principle of the algorithm is relatively simple, there is no need to establish an accurate mathematical model [10]. It is easy to implement and is widely used in the industrial field.

Zhu et al. [11] designed a PD controller based on feedback control theory to solve the linear reversing problem of tractor–trailer vehicles. The nonlinear tractor–trailer vehicles control system was linearized. Aiming at the problem of nonlinear control of vehicles, Ye perfectly combined the traditional PID controller with a neural network with powerful online learning and processing nonlinear capabilities, and proposed an analog neural network controller based on nonlinear PID. The controller block diagram is shown in Figure 3 [12]. It is suitable for a class of devices with nonlinearity, uncertainty and disturbance. According to the kinematic and dynamic model of tractor-trailer vehicles, Khanpoor et al. [13] developed a Lyapunov-PID control algorithm to control vehicles by combining Lyapunov method with PID control. Simulation and experimental results verify the stability and effectiveness of the proposed algorithm.

PID control is simple and effective. Theoretically, good results can be achieved by adjusting PID parameters appropriately However, when the model is unknown or time-varying, it is often difficult to adjust the parameters, which needs to be combined with experience, and the workload is huge. Moreover, when the system uncertainty and external disturbance exist, the control stability is poor and the effect is not ideal.

3.2 LQR Control Methods

Linear quadratic regulator (LQR) is generally used in non-linear systems such as wheeled vehicle systems. After the vehicle system model is established, the feedback linearization method is used to linearize the nonlinear system, and then a linear quadratic optimization objective is solved based on this to obtain the optimal state feedback control, so as to achieve the optimal trajectory following control input.

Table 1: Characteristic of Different Methods For Tracking Control

Methods	Refs	Advantages	Disadvantages
PID Control	[2-4]	Independent of vehicle model Simple principle Easy to accomplish	Rely on experience Heavy workload Poor stability
LQR Control	[5-8]	Standardized process Easy to accomplish	Multivariate constraints cannot be handled Complex solution process
Model Predictive Control	[9-12]	Solve multi-constraint optimization Easy to build models High stability	Large amount of calculation Poor real-time performance
Sliding Mode Control	[13-16]	Fast response High robustness	Accompanied by chattering problems
Fuzzy Control	[17-20]	Strong adaptability Strong fault tolerance Independent of accurate models	Lack of system Large error
Robust Control	[21-22]	Effectively resolve external disturbances No manual intervention required	Poor steady-state accuracy Large amount of calculations
Neural Network Control	[23-25]	Strong learning ability Strong nonlinear fitting ability and mapping ability	Poor adaptability to different scenarios

Divelbiss et al. [14] used LQR in the trajectory tracking of tractor–trailer vehicles at an earlier time, and verified the performance of the controller through experiments on three different forms of tractor-trailer vehicles. Chen et al. [15] applied the optimal control theory to design a linear quadratic controller for the straight-line reversing of tractor–trailer vehicles. The experiments on asphalt and unstructured roads showed that the control method could realize the automatic straight-line reversing of tractor–trailer vehicles, and the relationship between vehicle speed and vehicle lateral deviation was obtained. Some scholars applied LQR to the active braking conditions of tractor–trailer vehicles, and through experiments showed that the designed controller could effectively improve the stability of the vehicle during braking, which proved the superiority of the LQR controller [16, 17].

The linear quadratic optimal control problem has formed a standardized solution process, and the analytical expression of the optimal solution can be obtained, and multiple performance indicators can be considered. The controller designed according to the feedback linearization theory is simple and easy to implement, but it cannot handle the multi-variable constraint problem in the vehicle driving control process, and the solution process is more complicated.

3.3 Model Predictive Control Methods

Model predictive control (MPC) is also called rolling time domain control. It can predict the future output behavior of the system according to the dynamic model and current state of the control system, and obtain the optimal system control input by solving the optimal control problem with constraints. In addition, it has the ability to deal with multi-constraint optimization problems, and can consider safety constraints and actuator constraints while optimizing control objectives. It is suitable for complex and diverse automatic driving application scenarios.

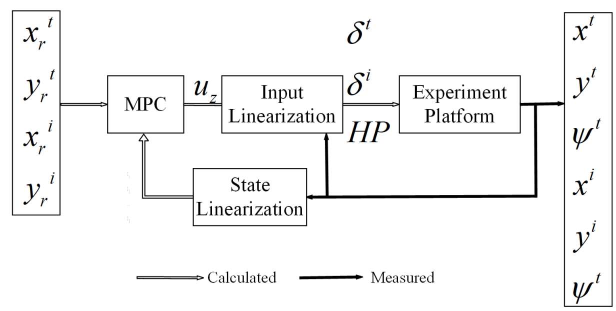

Figure 4: Control scheme for the LMPC by using the input-state linearization

Kayacan et al. [18, 19] proposed two MPC methods for tractor–trailer vehicles control. One was to combine nonlinear model predictive controller (NMPC) with nonlinear motion level estimator (NMHE) to generate control strategy. The other is to linearize the input state of the original model and then perform linear model predictive control (LMPC). The experimental results showed that NMHE-NMPC method had higher tracking accuracy, and ISL-LMPC required shorter real-time calculation time. The block diagram of the control scheme for the IST-LMPC framework is shown in Figure 4. The MPC controller designed by Wu [20] could control the tractor–trailer vehicle to move forward and backward, and significantly reduced the tracking error of the vehicle when turning. Kassaeiyan [21] used MPC method to solve the self-collision problem of the tractor-trailer vehicles during the movement, and verified the effectiveness of the controller through experiments.

MPC has good robustness, high stability, convenient modeling, good dynamic performance and anti-interference performance. However, the computational complexity of the MPC is large, and the real-time performance is poor. Most of the researches only limit in the simulation stage, and the practical application is more difficult. Therefore, improving the real-time performance of MPC has always been a research hotspot.

3.4 Sliding Mode Control Methods

Sliding mode control (SMC) is also called sliding mode variable structure control. Its principle is to force the initial state of the system in any position to control the pre-designed sliding mode surface in a limited time, and through the control action, the system state slides along the sliding mode surface to the origin, so as to enter the steady state of the system.

Taghia et al. [22] proposed a SMC controller with nonlinear disturbance observer for tracking control of tractor-trailer vehicles, and compared it with backstepping control and model predictive control through experiments. Experimental results showed that the controller had better robustness and accuracy. Yue et al. [23] combined MPC and SMC on the kinematic and dynamic models, and achieved the acoordinated trajectory tracking performance of tractor-trailer vehicles. In literature [24, 25], the effectiveness of SMC in tractor–trailer vehicles control was verified through simulation.

SMC can overcome the uncertainty of the control system, and has good robustness and a fast response speed. But it needs to overcome the chattering phenomenon that occurs when the state trajectory reaches the sliding mode surface.

3.5 Fuzzy Control Methods

Fuzzy control is an intelligent control method that uses multi-valued fuzzy logic and simplified reasoning principles to imitate human thinking and reactions. It does not rely on precise mathematical models during the control process, so it has strong adaptability and is widely used in the tracking control of tractor-trailer vehicles.

In terms of tractor-trailer vehicles reversing control, Tanaka et al. [26] designed a fuzzy controller for tractor-trailer vehicles reversing control based on the concept of robust stability earlier. Then a fuzzy control method was designed using linear matrix inequalities (LMIs) to solve the reversing control problem of a vehicle with triple trailers [27]. Two independent fuzzy controllers were designed in [28], which were used for target search and obstacle avoidance respectively to solve the parking problem of tractor-trailer vehicles. Cheng et al. [29] proposed a fuzzy control method based on Line-of-sight method for backward trajectory tracking.

Fuzzy control algorithm does not require precise mathematical models, has strong fault tolerance and good stability, and is suitable for complex systems such as nonlinear and hysteresis. However, the fuzzy control algorithm has strong subjectivity, lack of system, large uncertainty and arbitrariness, and will produce large errors.

3.6 Robust Control Methods

The H∞ robust control method is to control the system parameter perturbation caused by the working condition change of the research target, external interference and modeling error, so as to maintain the system stability. If conventional theories are not suitable for the design of multiple input and multiple output systems, the H∞ robust control theory can be applied to design controllers or propose control strategies.

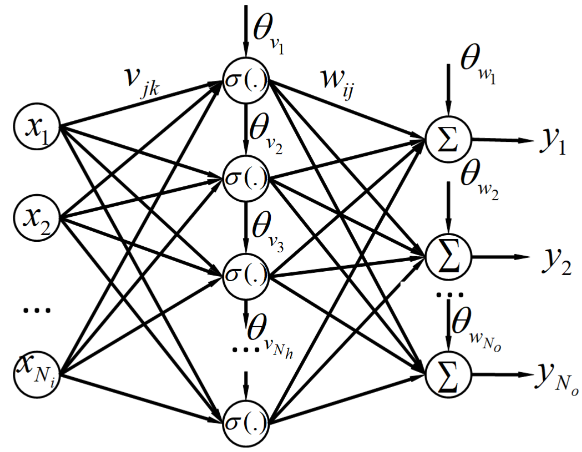

Figure 5: The structure of a multi-layer neural network.

In view of the uncertainties and external disturbances of tractor-trailer vehicles control, Khalaji et al. [30] first established a vehicle dynamic model. Based on this, they proposed a robust adaptive feedback linearizing dynamic controller (RAFLDC). The robustness and stability of the controller are verified through simulation and experiments. Rigatos et al. [31] linearized the kinematics model of the vehicle, and a H∞ feedback controller was designed based on this equivalent linearized model. In addition, the stability of the control scheme was proved by the Lyapunov method.

When applying H∞ robust control theory to design controller, it is not necessary to establish accurate process model. and no manual intervention is required after the controller is successfully designed. However, because the robust control system generally does not work in the optimal state, the steady-state accuracy of the system is poor. In addition, the general problem of H∞ robust control is that the controller has a high order and a large amount of calculation.

3.7 Neural Network Control Methods

Neural network control is a control method for optimized calculation or reasoning diagnosis for systems with high complexity but difficult to carry out accurate models.

Nguyen et al. [32] built a neural network to control the nonlinear dynamic system by learning and controlling the simulator, and used the network for the reverse control of tractor-trailer vehicles, thus verifying the feasibility of the method. Aiming at the formation tracking control problem of tractor-trailer vehicles, Shojaei [33] built a multi-layer neural network controller illustrated in Figure 5, and adopted a dynamic surface control method, which effectively reduced the complexity of the controller. Bejar et al. [34] proposed a neuro-fuzzy controller based on preview control and deep reinforcement learning. The controller was composed of a neural network trained by reinforcement learning and was used for backward parking control of tractor-trailer vehicles.

Neural network has strong learning ability, good nonlinear fitting ability and mapping ability, which is convenient for computer processing. However, when dealing with new environments and application scenarios, specific problems need to be analyzed in detail, and the adaptability is poor.

4 CONCLUSION

The tracking control of tractor-trailer vehicles has been researched for more than 20 years. Many scholars have done a lot of work in this field. This paper classifies several main tractor-trailer vehicles tracking control methods, summarizes the advantages and disadvantages of different methods, and finally obtains the following three conclusions and prospects:

4.1 Accurate Models

The performance of the controller largely depends on the accurate vehicle model. The current construction process of dynamic models for tractor-trailer vehicles is not perfect, and most of the models are too ideal. The dynamic models of vehicles and tires under different working conditions should be considered to establish a more accurate mathematical model.

4.2 Real Experiments

The performance of the controller in simulation and real experiment is often different. Some control methods are currently only used in the simulation stage. With the rapid development of tractor-trailer vehicles, real vehicle experiments will be an indispensable part. Corresponding experimental methods and adaptability of hardware equipment will also be a problem that needs to be solved.

4.3 Other Aspects

In order to achieve a better tracking control effect, improving the accuracy of the model and the performance of the controller is only one aspect. It also requires the overall role of the perception layer, the planning and decision-making layer, and the mechanical structure.

REFERENCES

[1] Hancock, Kathleen L., and Michael Glass. "Considering Alternatives for Extended Tractor-Trailer Parking on Rural Interstates." Transportation Research Board 100th Annual MeetingTransportation Research Board TRBAM-21-02235 (2021).

[2] Delgado, Oscar, and Nic Lutsey. "Advanced tractor-trailer efficiency technology potential in the 2020–2030 timeframe." Washington, DC, The International Council on Clean Transportation. Report in preparation (2015).

[3] Gempton, Nicole, *et al.* "Autonomous control in military logistics vehicles: Trust and safety analysis." International Conference on Engineering Psychology and Cognitive Ergonomics. Springer, Berlin, Heidelberg, 2013.

[4] Farooq, Waqar, Muazzam Ali Khan, and Saad Rehman. "Amvr: A multicast routing protocol for autonomous military vehicles communication in vanet." 2017 14th International Bhurban Conference on Applied Sciences and Technology (IBCAST). IEEE, 2017.

[5] Van, Nam Dinh, *et al.* "A hierarchical control system for autonomous driving towards urban challenges." Applied Sciences 10.10 (2020): 3543.

[6] Amini, Alexander, *et al.* "Learning robust control policies for end-to-end autonomous driving from data-driven simulation." IEEE Robotics and Automation Letters 5.2 (2020): 1143-1150.

[7] Peng, Haonan, *et al.* "Path tracking and direct yaw moment coordinated control based on robust MPC with the finite time horizon for autonomous independent-drive vehicles." IEEE Transactions on Vehicular Technology 69.6 (2020): 6053-6066.

[8] Braver, Elisa R., *et al.* "Long hours and fatigue: a survey of tractor-trailer drivers." Journal of Public Health Policy 13.3 (1992): 341-366.

[9] Liu, Shaoshan, *et al.* "Creating autonomous vehicle systems." Synthesis Lectures on Computer Science 6.1 (2017): i-186.

[10] Khalaji, Ali Keymasi. "PID-based target tracking control of a tractor-trailer mobile robot." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 233.13 (2019): 4776-4787.

[11] Ryo, Zhu Zhongxiang, Chen Jun, Torisu. "Automatic Backward Driving System of Tractor-trailer Combination along Rectilinear Path Using PD Control [J]." Transactions of the Chinese Society for Agricultural Machinery 7 (2006).

[12] Ye, Jun. "Adaptive control of nonlinear PID-based analog neural networks for a nonholonomic mobile robot." Neurocomputing 71.7-9 (2008): 1561-1565.

[13] Khanpoor, Asghar, Ali Keymasi Khalaji, and S. Ali A. Moosavian. "Modeling and control of an underactuated tractor–trailer wheeled mobile robot." Robotica 35.12 (2017): 2297-2318.

[14] Divelbiss, Adam W., and John T. Wen. "Trajectory tracking control of a car-trailer system." IEEE Transactions on Control systems technology 5.3 (1997): 269-278.

[15] Zhongxiang, Chen Jun1 Han Bing1 Zhu, and Takeda Jun-ichi. "Optimal Control for Automatic Backward Driving System of Tractor-trailer Combination along Rectilinear Path [J]." Transactions of the Chinese Society for Agricultural Machinery 1 (2008).

[16] Sever, Mert, *et al.* "Active trailer braking system design with linear matrix inequalities based multi-objective robust LQR controller for vehicle-trailer systems." 2016 IEEE Intelligent Vehicles Symposium (IV). IEEE, 2016.

[17] Sun, Tao, *et al.* "Lateral stability improvement of car-trailer systems using active trailer braking control." Journal of Mechanics Engineering and Automation 2.9 (2012): 555-562.

[18] Kayacan, Erkan, Herman Ramon, and Wouter Saeys. "Robust trajectory tracking error model-based predictive control for unmanned ground vehicles." IEEE/ASME Transactions on Mechatronics 21.2 (2015): 806-814.

[19] Kayacan, Erkan, *et al.* "Experimental validation of linear and nonlinear MPC on an articulated unmanned ground vehicle." IEEE/ASME Transactions on Mechatronics 23.5 (2018): 2023-2030.

[20] Wu, Tong, and John Y. Hung. "Path following for a tractor-trailer system using model predictive control." SoutheastCon 2017. IEEE, 2017.

[21] Kassaeiyan, Pouya, Bahram Tarvirdizadeh, and Khalil Alipour. "Control of tractor-trailer wheeled robots considering self-collision effect and actuator saturation limitations." Mechanical Systems and Signal Processing 127 (2019): 388-411.

[22] Taghia, Javad, *et al.* "A sliding mode controller with a nonlinear disturbance observer for a farm vehicle operating in the presence of wheel slip." Autonomous Robots 41.1 (2017): 71-88.

[23] Yue, Ming, *et al.* "Trajectory tracking control for tractor-trailer vehicles: a coordinated control approach." Nonlinear Dynamics 91.2 (2018): 1061-1074.

[24] Alipour, Khalil, Arsalan Babaei Robat, and Bahram Tarvirdizadeh. "Dynamics modeling and sliding mode control of tractor-trailer wheeled mobile robots subject to wheels slip." Mechanism and Machine Theory 138 (2019): 16-37.

[25] Yin, Chengqiang, *et al.* "Trajectory tracking based on adaptive sliding mode control for agricultural tractor." IEEE Access 8 (2020): 113021-113029.

[26] Tanaka, Kazuo, and Manabu Sano. "A robust stabilization problem of fuzzy control systems and its application to backing up control of a truck-trailer." IEEE Transactions on Fuzzy systems 2.2 (1994): 119-134.

[27] Tanaka, Kazuo, Shigeki Hori, and Hua O. Wang. "Multiobjective control of a vehicle with triple trailers." IEEE/ASME Transactions on mechatronics 7.3 (2002): 357-368.

[28] Sharafi, M., and S. Nikpoor. "Intelligent parking method for truck in presence of fixed and moving obstacles and trailer in presence of fixed obstacles: Advanced Fuzzy logic technologies in industrial applications." 2010 International Conference on Electronics and Information Engineering. Vol. 2. IEEE, 2010.

[29] Cheng, Jin, Yong Zhang, and Zhonghua Wang. "Backward tracking control of mobile robot with one trailer via fuzzy line-of-sight method." 2009 Sixth International Conference on Fuzzy Systems and Knowledge Discovery. Vol. 4. IEEE, 2009.

[30] Khalaji, Ali Keymasi, and S. Ali A. Moosavian. "Robust adaptive controller for a tractor–trailer mobile robot." IEEE/ASME Transactions on Mechatronics 19.3 (2013): 943-953.

[31] Rigatos, Gerasimos, *et al.* "Nonlinear optimal control for autonomous navigation of a truck and trailer system." 2017 18th International Conference on Advanced Robotics (ICAR). IEEE, 2017.

[32] Nguyen, Derrick H., and Bernard Widrow. "Neural networks for self-learning control systems." IEEE Control systems magazine 10.3 (1990): 18-23.

[33] Shojaei, Khoshnam. "Neural network formation control of a team of tractor–trailer systems." Robotica 36.1 (2018): 39-56.

[34] Bejar, Eduardo, and Antonio Moran. "A preview neuro-fuzzy controller based on deep reinforcement learning for backing up a truck-trailer vehicle." 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE). IEEE, 2019.