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Sliding Mode Controller for Autonomous Tractor-Trailer Vehicle Reverse Path Tracking

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Abstract: In the past few years, there has been a growing interest among researchers in developing control systems for autonomous vehicles, specifically for tractor-trailer systems. This newfound interest is driven by the potential benefits of enhancing safety, reducing costs, and addressing labor shortages in the industry. Two industries that could reap the rewards of these systems' advancements are cargo and agriculture transportation. One of the challenging tasks for the truck trailer vehicle is driving in reverse. Backward path tracking of tractor-trailers is a complex control problem with practical applications. The difficulty in controlling the vehicle arises due to its unstable internal dynamics, coupled nonlinear terms, and the under-actuated nature of the system. There is also a limit to the angle at which the steering can be turned before the risk of a jackknife accident increases significantly. In response to these challenges, this paper introduces a robust sliding mode controller designed for path tracking in reverse-driving tractor-trailer systems. The novelty of our work lies in addressing these challenges, which have not been extensively studied in the past. The proposed controller is analyzed, and its performance is tested and verified using different scenarios. The simulation examples show superior control performance, and we anticipate that this novel controller holds the potential to be widely adopted as a fundamental component in the path-tracking algorithms of autonomous truck trailer systems.

Keywords: sliding mode control; autonomous vehicle; intelligent transportation; nonlinear control; self-driving car

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1. Introduction

1.1. Motivation

The future of transportation is on the edge of a significant transformation. As technology continues to advance at a rapid pace, the vision of fully autonomous vehicles on our roads is becoming a closer reality. In particular, the trucking industry stands to gain substantially from this revolution. Trucks play a pivotal role in our economy, moving goods across vast distances; hence, their automation could usher in a new era of transportation. Developing an autonomous truck trailer (semi-truck) could lead to safer, more efficient, and sustainable transportation. Self-driving trucks can operate continuously and take the most efficient routes, leading to reduced fuel consumption and transportation costs. Additionally, they can enhance supply chain efficiency by speeding up transportation and reducing costs, which can boost the economy. Currently, several companies are working on developing technologies that enable fully autonomous trucks. One of the challenging tasks to be automated is backing up a truck and trailer or driving in reverse. For human drivers, the challenge of this task arises for several reasons, including limited visibility, different turning points, oversteering, length and weight of the trailer, and lack of experience. Thus, backing up a truck and trailer requires careful attention, patience, and practice. It is important to take your time and be aware of your surroundings to avoid accidents or damage to your vehicle or the trailer.

1.2. Related Works

From a system and control point of view, the tractor-trailer is considered a complex and nonlinear system that has limitations on its articulation state as well as the steering input. Although the system is internally stable when moving forward, it becomes unstable and difficult to control when driving in reverse due to its under-actuation [1] and propensity for jackknifing. Additionally, there is a restricted range of articulation angle values beyond which it cannot be maneuvered in the backward direction. Hence, an in-depth treatment of the tractor-trailer maneuverability conditions and a jackknife prevention system are presented by Hejase et al. in ref. [2].

The literature on the topic of truck trailer systems presents a multitude of control methods for both forward motion and backward (reverse) driving. For the forward path-following problem, several controllers were adopted. To name a few, a Linear Quadratic Regulator (LQR) in ref. [1], robust controller via feedback linearization [3], back-stepping [4], Model Predictive Control (MPC) [5], and a Sliding mode approach for formation control [6] have been proposed.

For backward movement, researchers tend to redesign the forward motion controllers to overcome the instability issues in backward motion. Some approaches use geometrical coordinate transformations to make the control algorithms simpler and allow for the application of methods used for forward driving [7,8]. Other methods solve the nonlinear backing control problem directly, by utilizing concepts of artificial neural network controllers [9–12], nonlinear feedback stabilization [13–15], fuzzy control and systems [16–18], or explicit Model Predictive Control [19,20]. The control methods may vary based on the location of the hitch, with on-axle hitch vehicles being differentially flat, while off-axle hitch vehicles are not. These approaches have been successful in addressing the control challenges posed by tractor-trailer vehicles moving in reverse. Moreover, control methods for tractor-trailer vehicles could also be further classified based on the location of the hitch. Systems of articulated vehicles with hitches on the axle exhibit differential flatness, whereas those with hitches off the axle do not, as per previous research [21,22]. Table 1 summarizes the literature review.

Sliding mode is a robust control method that has been widely investigated for complex and nonlinear systems subject to uncertainties and disturbance [23,24]. It has been a popular choice for truck trailer systems. Shahmirzadi et al. [25] explored how to prevent tractor semitrailers from rollover (jackknifing). A new algorithm is used to control a model of a tractor semitrailer. In addition, Matveev et al. [26] explored the path-tracking challenges of autonomous farming vehicles, especially concerning wheel slips common in agricultural environments. In scenarios demanding heightened stability for vehicles transporting liquids, Saeedi et al. [27] employed an active roll control system, leveraging two distinct approaches. Esmaeili et al. [28] primarily focused on crafting an adaptive sliding mode controller (SMC) that can handle variations in trailer loads and cope with sensor noise. In another study, an active disturbance rejection control technique to enhance the stability of elongated articulated vehicles has been explored [29]. This was underpinned by a nineteen-degree-of-freedom dynamic model simulated in a virtual environment. In [30], the authors examine the adaptive back-stepping sliding mode control for tractor-trailer systems, specifically addressing input delays using an RBF neural network. This research emphasizes an adaptive sliding mode neural network control approach tailored for tractor-trailers that have two degrees of freedom and confront input delays. Sun et al. [31] aim to devise a dynamic tractor model suitable for sloped terrains, introducing a robust control strategy anchored in sliding mode observers. Additionally, [32] investigates the trajectory tracking of agricultural tractors utilizing an enhanced fuzzy sliding mode control. This approach targets tractors equipped with electric power steering mechanisms. Other significant contributions in this domain are showcased in refs. [33,34].

Table 1. Literature summary.

References	Methods	Remarks
[1,3,4]	Path following for forward motion	The problem of stability in forward motion arises at high speed.
[9–12]	Neural network techniques	For reverse (backward) motion.
[16–18]	Fuzzy Control and Systems	It does not depend on precise mathematical models
[19,20]	Model Predictive Control	Compensates for the uncertainty of the system
[25–30,33,34]	Sliding Mode Control	Robust Control for systems subject to uncertainties and disturbance.

1.3. Contributions

This work builds upon our previous efforts to develop control systems for safe path tracking of an off-axle hitched tractor-trailer vehicle in reverse motion [2,35,36]. Namely, we design and analyze a sliding mode controller for reverse path tracking. Compared with existing works in sliding mode path tracking, this paper focuses on its application for autonomous trucks in backward motion scenarios. The key contributions of this paper are summarized as follows. (1) We address the path tracking problem for a truck trailer vehicle that is moving backward using the theory of sliding mode control. This problem has been addressed for a simple moving vehicle or a truck trailer in a forward direction; however, the truck trailer moving backward has its own complexity that needs to be addressed while designing the controller. (2) We suitably integrate the controller with a jackknife prevention mechanism that enforces safety on any backing controller with a bounded steering rate [2] to ensure safe reverse driving. (3) The proposed controller is easy to implement and the overall mechanism ensures robust tracking. (4) The comparisons with some state-of-the-art works with similar problem setups are summarized in the simulation section.

1.4. Organization

The rest of this paper is organized as follows. The succeeding section provides an overview of the mathematical model pertinent to the tractor-trailer system and explores an analysis of its maneuverability conditions. In the third section, we introduce the proposed sliding mode controller, detailing its structure and performing a stability analysis of the system when in closed-loop operation. The fourth section is dedicated to a discussion of the results derived from simulations. The paper concludes with a final section where the concluding thoughts and reflections on the study are presented.

2. System Model

A tractor-trailer system is a mode of transportation where a heavy truck pulls a trailer, mainly to carry freight. The tractor in this particular study has a hitch located off-center and the trailer has only one axis. We considered a kinematic model that captures the positional capabilities and constraints of the system to design a smooth sliding mode controller. In this paper, we utilize a control-oriented model for the tractor-trailer, conceptualized as a double bicycle model, drawing inspiration from the models presented in [8,37]. The tractor's design emulates a light-duty truck, with its hitch positioned at the rear, just past the back bumper, connecting to a trailer with a single axle. The dynamics of this model are outlined in the subsequent equations:

$$\dot{x}_1 = v \cos\theta_1 \tag{1a}$$

$$\dot{y}_1 = v \sin\theta_1 \tag{1b}$$

$$\dot{\theta}_1 = v \tan\varphi / L_1 \tag{1c}$$

$$\dot{\psi} = -\frac{v\tan\varphi}{L_1} - \frac{v(L_1\sin\psi + \mathrm{sgn}(v)l\tan\varphi\cos\psi)}{L_1L_2} \tag{1d}$$

$$\dot{\theta}_2 = -\frac{v(L_1\sin\psi + \mathrm{sgn}(v)l\tan\varphi\cos\psi)}{L_1L_2} \tag{1e}$$

The parameters pertinent to path tracking control in the tractor-trailer vehicle model are illustrated in Figure 1. Here, θ_1 and θ_2 signify the heading angles of the tractor and the trailer, respectively, as defined by the Earth coordinate frame. The articulation angle is expressed as $\psi = \theta_2 - \theta_1$, representing the difference between the two. The front wheel steering angle of the tractor, denoted as φ, serves as the control variable in this scenario and is restricted to $\varphi \in \left[\underline{\varphi}, \overline{\varphi}\right]$. In this study, all angular state variables are regarded as positive in the counterclockwise direction.

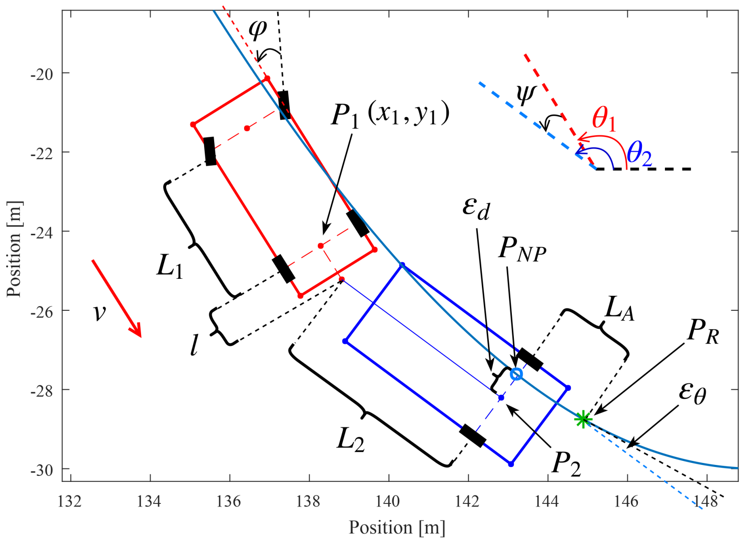

Figure 1. Notation of the tractor-trailer vehicle model and control. The points P_R (green asterisk) and P_{NP} (blue circle) represent the reference point, and the nearest points from the trailer to the path, respectively.

In a control-oriented model focused on low-speed scenarios, the steering kinematics of a tractor-trailer vehicle are determined by four distinct parameters: the wheelbase of the tractor vehicle, L_1, spanning from the front to the rear axle; the wheelbase of the trailer vehicle, L_2, extending from the hitch to the trailer's axle; the hitch length, l, measured from the tractor's rear axle to the hitch; and the longitudinal speed of the tractor, v, with negative values representing reverse motion. The used parameters and symbols are summarized in Table 2. The rear axle center location of the tractor, represented as (x_1, y_1), in the Earth coordinate frame, summarizes the control system model, as denoted in (1). It should be noted that the *sgn* operator is utilized to alternate the model between forward and backward driving modes.

Definition 1. *The system is said to be maneuverable within a maneuverability range* $(\underline{\psi}_M, \overline{\psi}_M)$ *if* $\forall\psi \in (\underline{\psi}_M, \overline{\psi}_M), \exists\varphi_1, \varphi_2 \in [\underline{\varphi}, \overline{\varphi}] | \dot{\psi}(\varphi_1) > 0, \dot{\psi}(\varphi_2) < 0$.

Proposition 1. *For a tractor-trailer system with an off-axle hitch, the system remains maneuverable as long as the articulation angle remains within the range* $(\underline{\psi}_M, \overline{\psi}_M)$*, where*

$$\underline{\psi}_M = \tan^{-1}(-L_1)/(l\tan(\underline{\varphi})) - \cos^{-1}\{\tan(\underline{\varphi})/[l/L_2\tan(\underline{\varphi}))^2 + (-L_1/L_2)^2]^{-1/2}\} \tag{2}$$

$$\overline{\psi}_M = \tan^{-1}(-L_1)/(l\tan(\overline{\varphi})) +$$

$$\cos^{-1}\{\tan(\overline{\varphi})/[l/L_2\tan(\overline{\varphi}))^2+(-L_1/L_2)^2]^{-1/2}\} \tag{3}$$

Proof. Proof can be found in ref. [2]. □

Table 2. Summary of model parameters and symbols.

Parameter	Description	Unit
θ_1	Tractor's heading angle	rad
$\dot{x}_1$	Tractor's velocity in the x-axis	m/s
$\dot{y}_1$	Tractor's velocity in the y-axis	m/s
$\dot{\theta}_1$	Tractor's heading angular rate	rad/s
φ	Tractor's steering angle	rad
v	Speed of the tractor system	m/s
L_1	Tractor's wheelbase length	m
L_2	Length between the tractor's hitch and the trailer's rear axle	m
l	Length between the tractor's hitch and the tractor's rear axle	m
$\dot{\psi}$	Articulated angle rate	rad/s

3. Sliding Mode Controller

3.1. Controller Design

In our design, the objective of the controller is to adhere to a predefined trajectory. Figure 2 shows the proposed controller. Given the non-holonomic constraints inherent to this motion problem, the appropriate selection of the sliding surface is imperative to ensure that deviations in both position and orientation asymptotically approach zero within a finite time frame. We utilize the control-oriented model delineated in Equation (1) and adhere to the notations depicted in Figure 1. Hence, the following sliding surface is then selected as

$$\gamma(t) = \dot{\varepsilon_d} + k_1\varepsilon_d. \tag{4}$$

where k_1 is a positive constant that is suitably large, and the lateral error (ε_d) is given by

$$\varepsilon_d = -\sin(\theta_d)(x_2 - x_d) + \cos(\theta_d)(y_2 - y_d). \tag{5}$$

where x_2 and y_2 are the coordinates of P_2, shown in Figure 1. The parameters x_d, y_d, and θ_d denote the desired position and orientation, as delineated by a trajectory planner. The time derivative of $\gamma(t)$ is given by

$$\dot{\gamma}(t) = \ddot{\varepsilon}_d + k_1\dot{\varepsilon}_d. \tag{6}$$

Utilizing Gao's reaching law methodology as elucidated in [38], the encompassing generic form of the reaching law can be expressed as

$$\dot{\gamma}(t) = -Q\,\mathrm{sgn}(\gamma). \tag{7}$$

Here, Q belongs to the set $\in \mathbf{R}_{>0}$. The desired steering input is given by merging the kinematics Equation (1) into (6) and (7):

$$\begin{aligned}\varphi_d^{SMC} = \tan^{-1}(&-\frac{\tan(\psi)}{l} + \frac{k_1L_2\sin(\varepsilon_\theta)}{vl\cos(\psi)\cos(\varepsilon_\theta)} \\ &+ \frac{L_2\,Q\,\mathrm{sgn}(s)}{v^2l\cos(\psi)cos(\varepsilon_\theta)}).\end{aligned} \tag{8}$$

It should be noted that the computed steering input command incorporates a heading angle error term, thereby coupling the lateral distance and heading angle errors. Moreover, the potential singularity occurring at $|\psi| = \frac{\pi}{2}$ is mitigated by the use of the Control Steering Geometry (CSG). The objective is to adhere to a feasible trajectory such that $|\varepsilon_\theta| < \frac{\pi}{2}$.

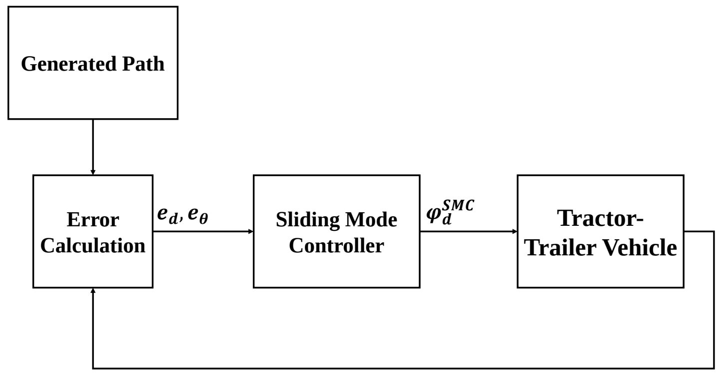

Figure 2. Block diagram of proposed control law.

3.2. Stability Analysis

To assess the stability of the introduced controller, consider the function $V(t) = \frac{1}{2}\gamma^2(t)$ as a potential Lyapunov candidate. Differentiating $V(t)$ with respect to time and incorporating the relationship given in Equation (6), we obtain

$$\begin{aligned} \dot{V}(t) &= \gamma(t)\dot{\gamma}(t) \\ &= \gamma(t)(\ddot{\varepsilon}_d + k_1\dot{\varepsilon}_d) \\ &= -\gamma(t)(Q\,\mathrm{sgn}(\gamma(t))) \\ &= -Q\frac{\gamma^2(t)}{|\gamma(t)|} \end{aligned} \tag{9}$$

When $Q > 0$, $V(t)$ is determined to be negative semi-definite. Consequently, a value of $\gamma(t) = 0$ will be attained in finite time.

For the practical implementation of the controller, specifically tailored to this context, namely a low-velocity parking task, the presence of speed terms in the denominator can lead to undesirable steering commands. Hence, the design of the gain coefficients Q and k_1 is as follows:

$$Q = \hat{Q}v^2 l \cos(\psi)/L_2, \tag{10}$$

$$k_1 = \hat{k_1} l v \cos(\psi)/L_2. \tag{11}$$

Therefore, the expression for steering input can be reformulated as

$$\varphi_d^{SMC} = \tan^{-1}\left(-\frac{\tan(\psi)}{l} + \hat{k}_1 \tan\varepsilon_\theta + \hat{Q}\tan^{-1}\gamma(t)\right). \tag{12}$$

4. Simulation Results

The developed sliding mode controller (SMC) for path tracking is assessed through simulation using a challenging path signal containing sharp turns representing difficult scenarios. This path was constructed from a series of multiple sinusoidal waves, each with varying frequencies, sequentially linked in order of increasing frequency. Supplementary path details, including curvature and heading angle, are inferred by fitting a quadratic function to the waypoints within a limited distance horizon. Initially, we tested the controller during forward motion, and the outcomes are illustrated in Figure 3. Notably, despite the fact that the controller parameters are not finely tuned, we observed effortless path tracking. This is attributed to the system's inherent stability during forward motion.

In reverse motion, the challenge escalates due to the potential for jackknifing if errors accumulate. This phenomenon, where the trailer pushes the towing vehicle from behind, causes it to spin around, leading to hazardous situations. Figure 4 displays the outcome when driving backward from an off-path starting position. This visualization offers a clear picture of how the vehicle behaves under various conditions. The demonstrated path-tracking outcomes primarily focus on evaluating the trailer vehicle's tracking accuracy. Accurate tracking ensures that the trailer stays on course, reducing the risk of accidents and enhancing overall safety. We measure this performance using multiple metrics, as shown in Figure 5.

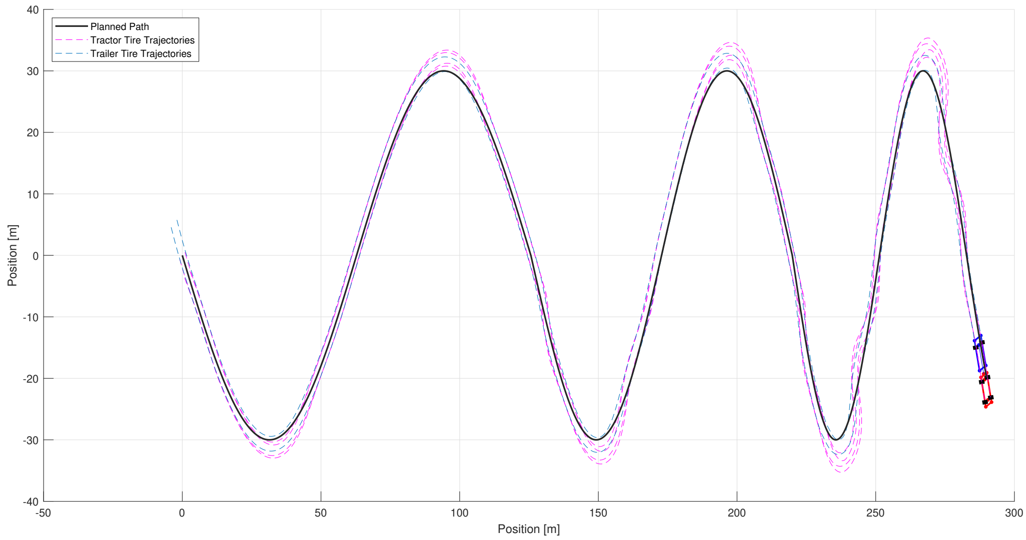

Figure 3. Simulation results illustrating the forward motion scenario. The red square represents the tractor, while the blue square represents the trailer.

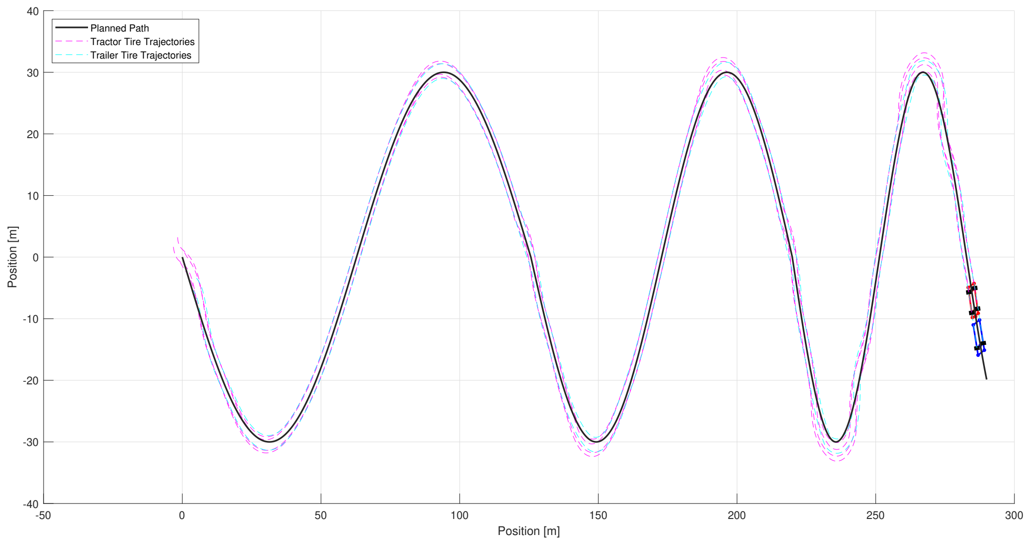

Figure 4. Simulation results illustrating the backward motion scenario. The red square represents the tractor, while the blue square represents the trailer.

Firstly, we consider the Trailer Lateral Distance Tracking Error. Here, the controller managed to sustain an error below 0.5 m for the initial three turns. This is a significant achievement considering the complexity of the motion. Even in the more challenging turns, the controller exhibited commendable performance, keeping the error within a range of ± 2 m. Secondly, the Trailer Heading Angle Tracking Error is examined. Maintaining a consistent heading angle is crucial for the stability of both the towing vehicle and the trailer. For the first three turns, the controller effectively maintained a heading error within $\pm 10°$. For tougher turns, the error stayed within $\pm 20°$.

Focusing exclusively on the trailer vehicle's tracking, the distance tracking error remains consistently low. This precision speaks volumes about the system's robustness. This is notable even when the SMC control gain and look-ahead distance are not finely calibrated. Furthermore, the steering control maxes out at ψ_{max} for roughly 2 s, leading to sporadic peaks in error accumulation. Adjusting these parameters could potentially further refine the system's performance in the future.

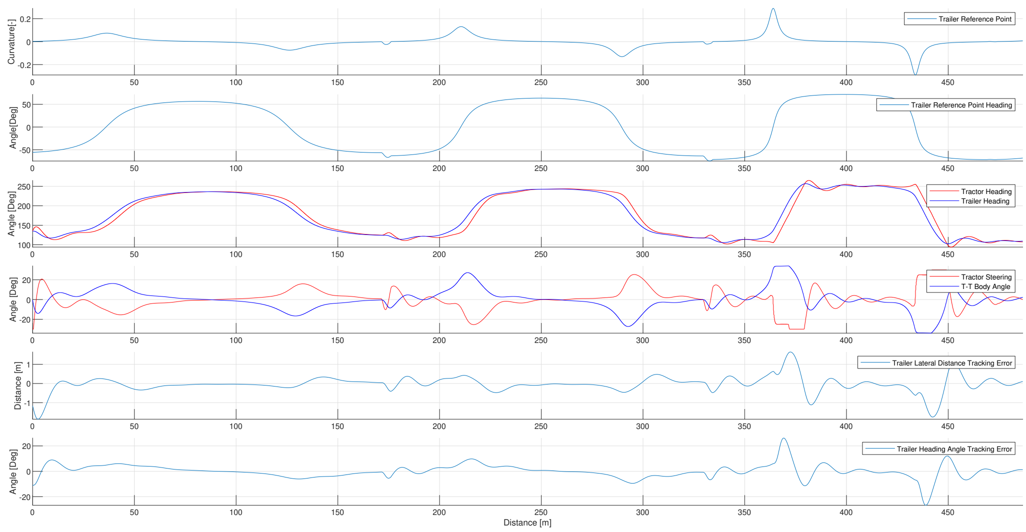

Figure 5. Several plots illustrate the performance of the controller in tracking the test path.

Additionally, we compare the developed controller with an Evolving Neural Network (NN)-based controller, similar to the one described in ref. [12]. The NN controller design was refined using a genetic algorithm, adjusting the weights of a pre-defined neural network structure. Evolving Neural network controllers, often praised for their adaptability and capability to learn complex representations, can sometimes falter when faced with unseen data or if they are not adequately trained. They are particularly proficient at managing systems with complex, nonlinear dynamics due to their architecture's ability to approximate any function. However, they may be vulnerable to over-fitting and might not generalize well in scenarios that diverge from their training data, making them less reliable in certain unpredictable real-world applications. Despite these challenges, neural network controllers serve as a valuable baseline for comparison with other controllers, due to their versatility and widespread use in various control applications. Figure 6 illustrates the path tracking results from both controllers in backward motion. It can be seen that there is identical behavior and good tracking for both controllers. However, when comparing the Evolving Neural Network and the sliding mode controller, several distinguishing features become evident, most notably the NN controllers, recognized for their complexity with high accuracy of tracking with good training. Conversely, the sliding mode controller is renowned for its resilience and robustness against system uncertainties and external disturbances. It can adapt to a range of operating conditions and is proficient at handling nonlinearities, making it highly suitable for systems with intricate dynamics and undefined environments. Sliding mode controllers' capability to maintain system stability and performance in the presence of uncertainties and disturbances renders it a more versatile and reliable control strategy in comparison to the NN controller, particularly in complex, dynamic environments where robustness is pivotal.

In the side-by-side comparison shown in Figures 7 and 8, we can observe the error distribution of the Lateral Distance Tracking Error and the Heading Angle Error, respectively, presented in the form of histograms. These histograms provide a visual representation of the frequency distribution of errors, allowing us to easily compare the performance of the Neural Network (NN) controller and the Sliding Mode Control (SMC) controller. Specifically, focusing on the Lateral Distance Tracking Error, the histogram in Figure 7 clearly demonstrates that the NN controller has a tighter and more centralized distribution of errors compared to the SMC controller. This is quantitatively supported by the Root Mean Square Error (RMSE) values, with the NN controller achieving a lower RMSE of

0.32651, compared to the SMC controller's RMSE of 0.44742. The lower RMSE value and the concentrated distribution of errors in the histogram indicate that the NN controller is more accurate and consistent in tracking lateral distance, successfully minimizing deviations from the desired path.

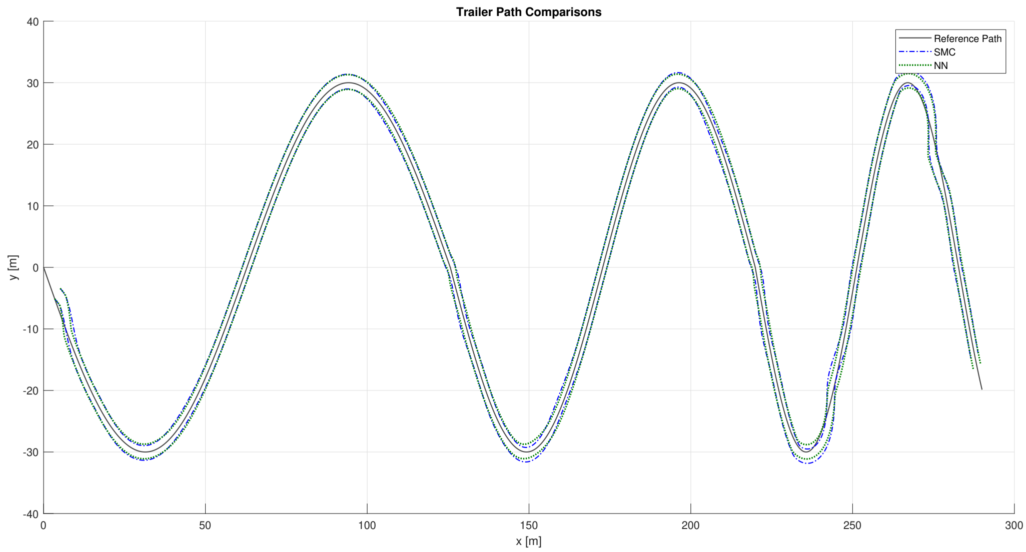

Figure 6. Simulation results illustrating the path tracking results from both controllers in backward motion.

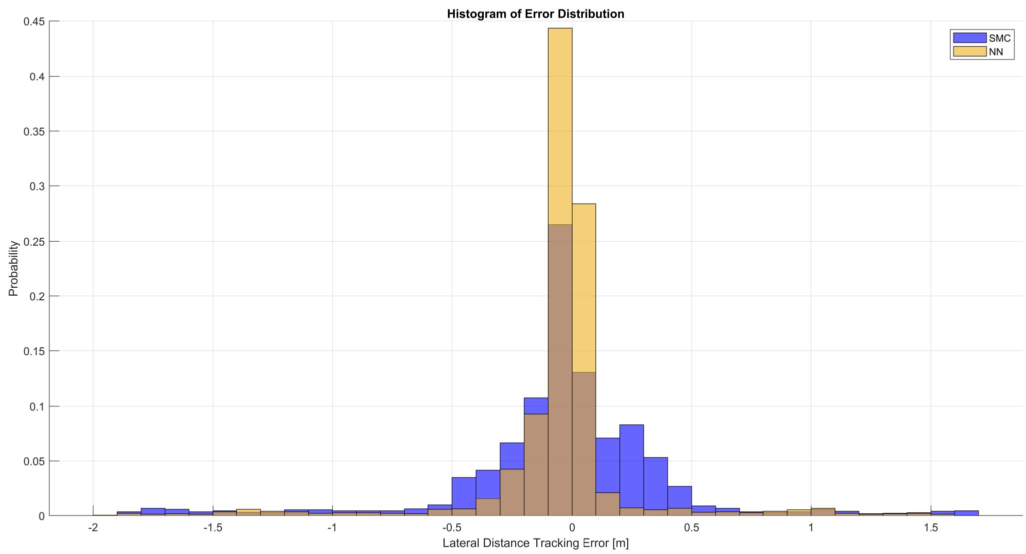

Figure 7. Histogram of the lateral error distribution for both SMC and NN. Brown color represents the overlap between SMC and NN.

When assessing the Heading Angle Error, both controllers perform similarly. The SMC has a slightly better RMSE at 0.10284, whereas the ENN's RMSE is marginally higher at 0.10403. The difference is minimal, suggesting that, in terms of heading angle tracking, both controllers are nearly equivalent in performance. However, a distinct advantage of the SMC controller is its ease of implementation. While neural networks may require extensive training, parameter tuning, and validation on diverse datasets, SMC controllers are often simpler to design, implement, and validate, especially for systems with known dynamics. This ease of implementation can lead to faster deployment times and reduced complexities, particularly valuable in scenarios where rapid prototyping or deployment is essential. In summary, the NN controller demonstrates superior performance in lateral distance tracking, but the simplicity and straightforwardness of implementing the SMC controller make it an attractive choice for certain applications. A predictive path-tracking control design can potentially reduce such error peaks, but it involves substantial computational effort, particularly when the model's inherent nonlinearity complicates the optimization problem. The sliding mode controller, with its robustness against uncertainties and its ability to handle nonlinearities, proves to be a viable solution for maintaining the desired trajectory, even with the presence of model uncertainties and external disturbances, providing a balance between performance and computational efficiency.

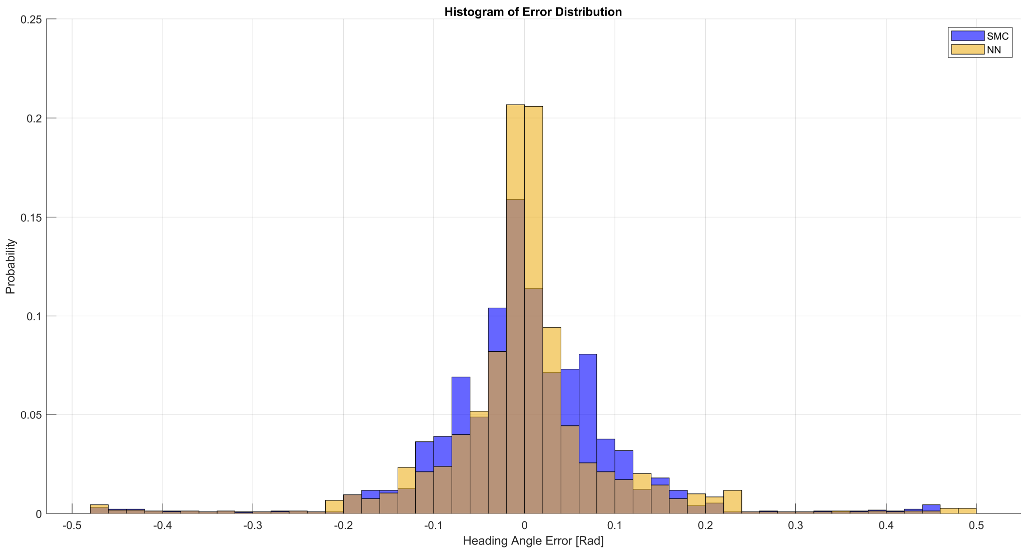

Figure 8. Histogram of the heading angle error distribution for both SMC and NN. Brown color represents the overlap between SMC and NN.

It is important to note that our control law in Equation (12) is formulated as a function of the vehicle parameters, which underlines its robustness in the face of parameter variations. In the context of truck trailer systems, it is a valid assumption to consider the parameters as fixed, given the prevalent local regulations and standards that govern real articulated vehicles. This further enhances the practical applicability and reliability of our proposed control approach.

5. Conclusions

In this paper, we addressed and explored the intricate and challenging domain of control systems for autonomous tractor-trailer systems, with a distinct emphasis on the complex control problem of backward path tracking. Given the inherent instability and under-actuated nature of tractor-trailers, compounded by coupled nonlinear terms, developing robust and reliable control solutions is paramount. In this work, we successfully developed and analyzed a sliding mode controller aimed at providing robust path tracking for tractor-trailers operating in reverse. The devised controller has demonstrated superior performance across various scenarios, highlighting its potential applicability and efficacy in real-world implementations. Given the advancements made in this study, it is anticipated that the proposed controller can significantly contribute to the development of sophisticated path-tracking algorithms for autonomous tractor-trailer systems, potentially revolutionizing sectors such as cargo and agriculture transportation by enhancing safety, reducing operational costs, and addressing labor shortages in the industry. For future work, this study holds the potential to move beyond simple simulation outcomes. By doing so, it paves the way for groundbreaking innovations and advancements in the practical realm of autonomous vehicle technology.

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