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ORIGINAL RESEARCH PAPER

Review and performance evaluation of path tracking controllers of autonomous vehicles

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Abstract

Autonomous Vehicles (AVs) have shown indelible and revolutionary effects on accident reduction and more efficient use of travel time, with outstanding socio-economic impact. Despite these benefits, to make AVs accepted by a wide demographic and produce them on an industrial scale with a reasonable price, there are still a number of technological and social challenges that need to be tackled. Path Tracking Controller (PTC) of AVs is one of the high potential subsystems that can be further improved in order to achieve more accurate, robust and comfortable tracking performance. This study provides a critical review and simulation study of several selected techniques used for the design of PTC of AVs. The AVs are assumed to have limited controllability due to non-holonomic constraints, such as car-like vehicles and differential drive mobile robots. A detailed discussion will be provided on the simulation outcomes as well as the pros and cons of each technique for the sake of implementation and improvement of state-of-the-art PTC.

1 | INTRODUCTION

The interest in Autonomous Vehicles (AVs) has been increasing over the last few decades with rapid advancements in sensor technology and portable computing devices. The socio-economic impact of AVs is not only confined to the end vehicle users; they have also shown an indelible and revolutionary impact on public transportation systems [1, 2]. According to the World Health Organization (WHO), each year around 1.35 million people die globally due to traffic accidents or accident-related injuries [3]. More than 80% of these accidents are related to human errors [3] which can be significantly reduced with the adoption of Advanced Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS) technologies. Moreover, AVs can considerably help with reduction and more efficient use of travel time, with economic benefits as well as a positive impact on the physical and mental health of the passengers. In Australia, 79% of 9.2 million daily commuters drive their cars and spend 25 min on average traveling to work [4]. In the context of AVs' social impact, they can provide an excellent alternative for the mobility of disabled or elderly people who are incapable of driving conventional vehicles.

In spite of all the aforementioned benefits, to make AVs accepted by a wide demographic and produce them on an industrial scale with a reasonable price, there are still several technological and social challenges that need to be tackled. The complexity of ADS is highly dependent on the required autonomy level. According to the standard (SAE-J3016) introduced by the Society of Automotive Engineers (SAE), ADS can be categorised into six levels (levels 0–5) from 'no autonomy' to 'fully autonomous' [5]. The autonomy level increases with the complexity of driving assistance systems, the responsibility of the human subject in the driving task, and the operating conditions of the vehicles.

Level-1 and 2 vehicles are already matured and being produced on an industrial scale. For any vehicle of level-3 and above, the driving task is generally divided into three subsystems (i) sensing and perception, (ii) path planning, and (iii) path tracking. In the sensing and perception stage, the information about the environment such as road conditions, traffic and pedestrians are collected using different sensors and fused to be applicable for mapping and localisation. Based on the mapped data, a reference trajectory is planned by the path planner for the vehicle to follow. Finally, the path tracking unit controls the vehicle

adaptive approach was proposed for tuning gain parameters for different road conditions and velocities [50]. In this approach, a 'knowledge base' was created from optimised gains calculated using the Particle Swarm optimisation technique. An FLS is then used to choose the appropriate gains from the knowledge base based on the current velocity and path tracking error.

3.3 | Feedback linearisation

For vehicles with non-holonomic constraints, the point stabilisation problem is much more complex than the path following or trajectory tracking problem [9]. Although the kinematic model in (6) is fully controllable [9], stabilisation at a given terminal point is not possible using a linear static state feedback [51, 52]. To address this problem, researchers used discontinuous [53] or dynamic state feedback [52, 54]. Hybrid controllers, a combination of discontinuous and dynamic feedback, has been also used to solve point stabilisation problem for AGVs with non-holonomic constraints [55].

FL)is a popular approach for designing nonlinear control systems enabling the use of well-defined linear control techniques. Feedback linearisation of an AGV can be performed using two approaches: i) full-state linearisation [9, 56, 57], and ii) input-output linearisation [9, 56, 58–62]. In the full-state linearisation approach, a linear relationship between the states and the inputs is established by transforming both states and inputs. On the other hand, for input-output linearisation, a linear relationship between the output and input is found by taking the derivatives of the output until the inputs or derivatives of the inputs appear independently [63].

The vehicle model in (6) is not input-output linearisable using static feedback if the controlled point is taken on the centre of the wheel axis [9]. However, the static FL can be used if the output is chosen properly [9]. For instance, Figure 5 shows the geometry of a car-like vehicle where the controlled point is chosen as p at d distance ahead of the front wheel (x , y), where the error is calculated correspondingly.

From the geometric relationship of Figure 5, the output of the system can be expressed as [56]

$$j = \begin{matrix} x \\ y \end{matrix} = \begin{matrix} x + l\cos(\ ) + d\cos(\ +\ ) \\ y + l\sin(\ ) + d\sin(\ +\ ) \end{matrix} . \tag{25}$$

The derivatives of the output, j can be expressed in the following form [9]

$$j = \mathrm{M}(\ ,\ )\,\mathrm{v}, \tag{26}$$

where,

$$\mathrm{M}(\ ,\ ) = \begin{matrix} \cos(\ ) & (\sin(\ ) + d\sin(\ +\ )\ \ l)\tan(\ ) & d\sin(\ +\ ) \\ \sin(\ ) + & (\cos(\ ) + d\cos(\ +\ )\ \ l)\tan(\ ) & d\cos(\ +\ ) \end{matrix} . \tag{27}$$

Choosing an auxiliary input u = j, we have [9]

$$\mathrm{v} = M\ \ (\ ,\ )\,\mathrm{u}. \tag{28}$$

Now, the trajectory tracking problem can be solved using a linear state feedback law such that [53]

$$\begin{aligned} u &= x + k\,(x \quad x\ ), \\ u &= y + k\,(y \quad y\ ), \end{aligned} \tag{29}$$

where (x , y) is the reference trajectory.

For a car-like vehicle, the input-output linearised system has nonlinear internal dynamics, so the stability of the internal dynamics also needs to be considered. For example, for the controller in (25)-(29), the yaw angle is not controlled. It is noted that for a non-holonomic wheeled vehicle, internal dynamics are asymptotically stable when the reference point is moving forward; however, for a backward moving reference point, internal dynamics are unstable [64].

The dynamic feedback approach has also been used to achieve full-state linearisation of AGVs. One of the primary advantages of full-state linearisation is that it does not have any internal dynamics. Full-state linearization can be achieved using the dynamic extension technique [9, 65, 66]. In this technique, new auxiliary inputs are added as the derivative of the original system input until all the system inputs explicitly appear. If

177]	Dynamic Planning	NN	-	Path following
Ramirez et al. (1999) [180]	Genetic Algorithm	NMPC		Path following and obstacle avoidance
Gu and Hu (2000) [178]	Gradient Descent	WNN	NMPC	Path following
Gu and Hu (2002) [179]	Gradient Descent	WNN	NMPC	
Kuhne et al. (2004) [181]	QP	Linearised kinematic	Linear MPC	
Borelli et al. (2005) [155]	SQP (NPSOL)	Nonlinear dynamic	NMPC	Path following
Kuhne et al. (2005) [154]	QP (fmincon)	Nonlinear kinematic	NMPC	Point stabilization
Keviczky et al.(2006) [156]	SQP (NPSOL)	Nonlinear dynamic	NMPC	Path following
Falcone et al. (2007) [161]	QP and SQP	Linearised and nonlinear dynamics	Linear MPC	Comparison of MPC and NMPC for Path following
Vougiouka (2007) [173]	Gradient Descend	Nonlinear kinematic	NMPC	Path following
Besselmann and Morari (2008)[21]	QP	Linearised dynamic	Hybrid	Path following
Falcone et al. (2008) [182]	QP	Linearised dynamic	LTV MPC	Local planning and path following
Falcone et al. (2008) [22]	SQP	Non-linear dynamic both 4 wheel and bicycle	NMPC	Active steering and braking for path following
Peters and Lagnemma (2008) [183]	QP	Linear kinematic and dynamic	Linear MPC	Path following in sloped terrain.
Raffo et al. (2009) [18]		Linear kinematic and dynamic	Linear MPC	Path following
Katriniok and Abel (2011) [24]	QP	Linearised dynamic	LTV MPC	Path following at handling limit
Katriniok et al. (2013) [162]	QP	Linearised dynamic	LTV MPC	Path following at handling limit
Katriniok et al. (2013) [162]	QP (qpOASES)	Linearised dynamic	LTV MPC	Path following at handling limit
Kim et al. (2014) [171]	QP	Linearised dynamic Steering dynamics	Linear MPC	Path following
Kim et al. (2014) [171]	QP	Vehicle dynamic and steering dynamics	Linear MPC	Path following
Li et al. (2014) [174]	QP	Linearised dynamic		Local planning and path following
Lima et al. (2015) [165]	QP	Linearised dynamic	Linear MPC	Clothoid fitting between way points for path following
Yakub and Mori (2015) [163]	QP	Linearised dynamic	Linear MPC	Path following
Zhang et al. (2015) [167]	QP	Linearised kinematic and Dynamic	Switched MPC	path following
Du et al. (2016) [184]	Genetic Algorithm	Nonlinear kinematic	NMPC	Path following
Amir and Givargis (2017) [168]	QP(ACADO)	Hybrid state machine	Switched MPC	Path following
Brown et al. (2017) [28]	QP (CVXGEN)	Linearised dynamic	Linear MPC	Path following and obstacle avoidance
Funke et al. (2017) [27]	QP (CVXGEN)	Linearised dynamic	Linear MPC	Path following and obstacle avoidance
Liu et al. (2017) [185]	IPM (IPOPT)	Nonlinear dynamic	NMPC	Path following and obstacle avoidance.
Batkovic et al. (2019) [158]	SQP(ACADO)	Nonlinear kinematic	NMPC	Path following and obstacle avoidance

For training the NN, a number of techniques and data sets have been used. In some cases, an adaptive NN is formulated where no offline training was required [112, 131, 140, 141, 191]. In these works, the NN training and the adaptation of weights were conducted online. Even though these works show satisfactory results in high-fidelity simulations, no practical implementations were provided. In some early works, the data set was generated by controlling the AV in a simulated environment using some available control techniques [177–179, 188]. For example, in [179], a PID controller was used to control the vehicle on a reference path and generating training data set. More recently, in [189], the training data set was generated using pseudo random binary signals by ensuring input signal excited necessary operating regions. In [192], the training dataset was collected by using real-world driving data using a drive-by-wire vehicle.

In the NN-based controllers, where it was used to estimate the full dynamics or some parameters of the vehicle, the constraints violation and safety of the system is generally dependent on the design of the controller. On the other hand, in

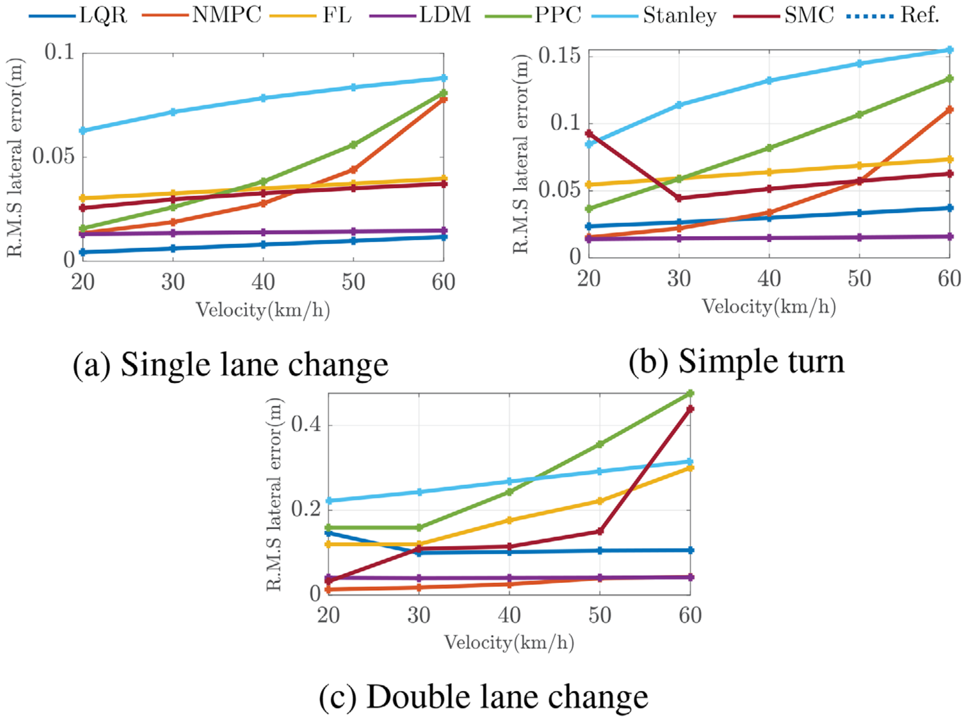

FIGURE 13 RMS lateral error for different velocities (20-60 km/h) for (a) single lane change, (b) simple turn and (c) double lane change

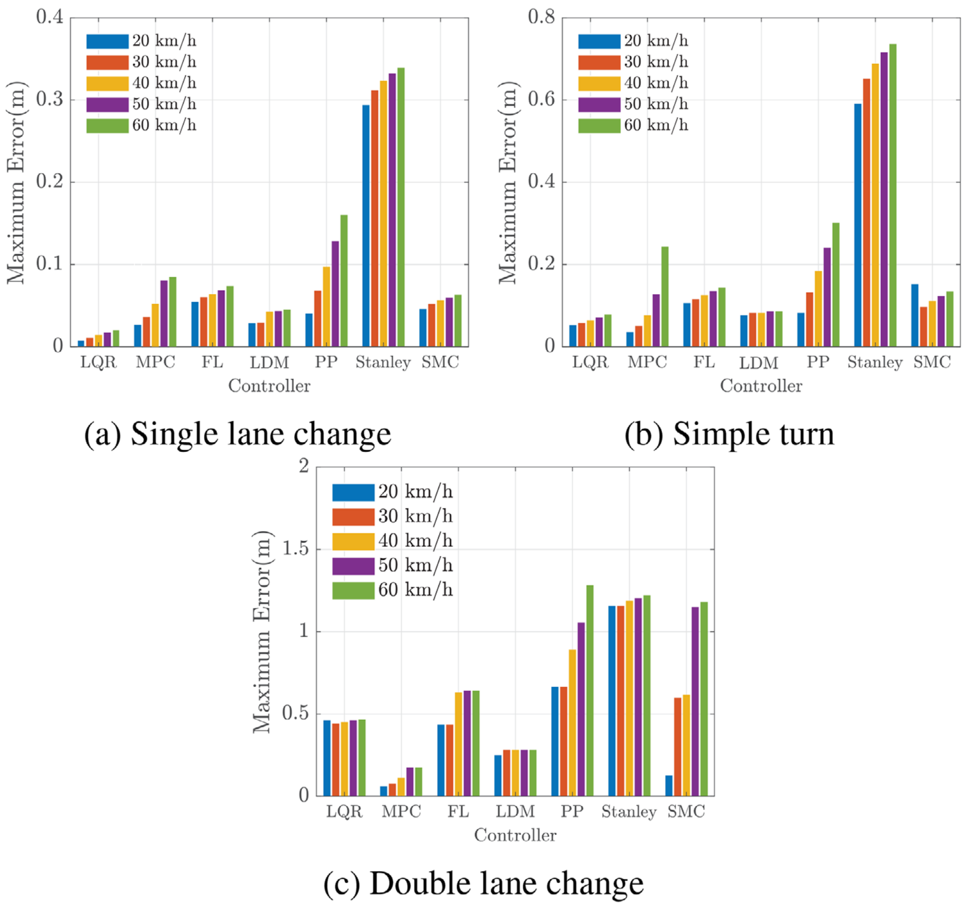

FIGURE 14 Maximum lateral error for different velocities (20–60 km/h) for (a) single lane change, (b) simple turn and (c) double lane change

TABLE 5 Summary of control techniques reviewed in the current study

Type	Advantages	Disadvantages
PPC	• Easy to implement • Low computational cost • Good performance at lower vehicle speeds • Good tracking performance when started on the reference path (low lateral and heading error)	• Does not consider the orientation of the vehicle at the target point. • Does not perform well in case of large initial lateral and heading error. • Performance depends on the proper tuning of look-ahead distance which may vary for different trajectories • Performance degrades at higher vehicle speeds
Stanley	• Easy to implement • Low computational cost • No look-ahead distance requirement • Performs well at varying path conditions	• Performance depends on proper tuning of parameters • Does not perform well in case of path discontinuity • Less robust thanPPC
FL	• Allows use of well-defined linear control techniques	• Lack robustness • Presence of internal dynamics (for input-output linearisation)
LDM	• Being stable for a large range of gain values	• Lyapunov candidate function is not easy to construct
LQR	• Control effort and system response can be optimised	• Use of linear model increases uncertainty • Not robust at the presence of uncertainty
SMC	• Robust performance against uncertainties and external disturbances • Reduces the order of the system dynamic • simple structure, fast response and transient performance • Convergence to the stable manifold in finite time	• Chattering can happen • Tendency to excite high-frequency unmodelled dynamics • Sensitive to the unmatched disturbances
Adaptive	• Good performance with parametric uncertainty • No prior information about dynamic parameter if an intelligent algorithm (NN,FLS) is used	• Not robust against non-parametric uncertainty • Parameter drifting problem
MPC	• Ability to handle multiple variables • Constraints can be included in states and control • Optimised performance based on a cost function	• Solves online optimisation problem which is computationally expensive

6 | CONCLUSION

This study has provided a critical review of several selected techniques used for the design of Path Tracking Controller (PTC) of AVs. These control strategies were chosen based on their popularity in the field of path tracking control and the applicability to car-like autonomous vehicles. These techniques include Pure Pursuit Controller (PPC), Stanley, Feedback Linearisation (FL), Lyapunov's Direct Method (LDM), Linear Quadratic Regulator (LQR), Sliding Mode Control (SMC), Adaptive Control, Model Predictive Control (MPC), and Neural Network (NN). The AVs were assumed to have limited controllability due to non-holonomic constraints such as car-like vehicles and differential drive mobile robots. Two common vehicle models were also discussed and their mathematical formulations were presented. A simulation study for urban path tracking tasks was also performed in order to evaluate the performance of the selected techniques. The simulation outcomes were discussed in detail and the pros and cons of each technique have been shown for the sake of implementation and improvement of state-of-the-art PTC.

From the extensive literature review and the simulation results of the controllers, NMPC seems to be most suitable for highway driving for an AV. The geometric controllers (i.e. PPC and Stanley) are not suitable for highway driving due to their poor performance at higher speeds. A similar conclusion can be made for FL and LDM based on their performances at different driving scenarios. On the other hand, the performance of the robust controller (i.e. SMC), degrades less than the other controllers for external disturbances; however, they are prone to chattering which affects the comfort of the passenger and may put a significant strain on the hardware. The optimisation-based controllers, such as LQR and NMPC, provide relatively lower lateral and orientation errors than the other controllers with disturbance. This finding justifies the application of these approaches when integrated into more intelligent learning-based techniques in order to establish a robust and adaptive controller that can act in real-time, irrespective of complexity in the vehicle dynamic model. The future step of the current study will be adopted to develop a PTC that can realise these qualities.

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