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Autonomous Vehicle Steering-based Feedback Linearization and Sliding Mode Control

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Abstract

This study proposes a robust control approach for vehicular dynamic system speed control. The proposed method combines a sliding mode controller with a feedback linearization technique. Considering the high nonlinearity of the vehicle dynamic system model, feedback linearization is used to transform the vehicle dynamic system into a linear system. A Lyapunov theorem is used to approve the stability of the proposed controller. Moreover, a proportional integral derivative (PID) controller with genetic algorithms is used for comparison. The integral absolute error (IAE) is used as the performance comparison index between controllers. Simulation results show that the proposed method can achieve excellent performance with high robustness against external disturbance and system uncertainty. In the tracking case, the IAE value of the proposed controller is 2.3, whilst that of the PID is 15.2. Under external disturbance, the IAE values are 3.1 and 19.1 for the proposed controller and PID, respectively.

Keywords: Feedback Linearization; Robust control; SMC.

1. Introduction

In recent years, automotive and road safety has become a crucial focus in the development of vehicle control, monitoring systems and driving assistance technologies. All Advanced Driver Assistance Systems (ADASs) aim to improve driving safety and vehicle control by facilitating human–machine interaction [1, 2]. ADAS includes various types, including adaptive cruise control (ACC), blind spot detection, automated parking, pedestrian safety systems, and anti-lock brakes [3, 4]. ACC is one of the important assistance systems, as it enhances driver and passenger comfort by reducing driver fatigue. Moreover, ACC enhances safety by using sensors for monitoring [5]. ACC maintains the vehicle speed as set by the driver without requiring throttle input whilst also ensuring a safe distance from other vehicles or obstacles. The ACC system consists of two-sub control systems: speed control and distance control. The transition between these two sub system must be smooth and comfortable [6]. PID control is widely used in various control systems [7]. A PID controller adjusts the control inputs based on the proportional, integral and derivative components of the error signal to maintain a constant vehicle speed or following distance, regardless of uncertainties in the system dynamics [8]. Given the ability of model predictive control (MPC) in handling complex constraints and predict future vehicle states, it is used to maintain the desired speed and safe distances from obstacles, ensuring comfort and safety [9]. Fuzzy logic control can approximate complex systems using fuzzy rules [10], which has motivated a number of researchers to use it in designing ACC systems that adapt to various driving conditions through flexible control strategies [11]. Artificial neural networks have been used to model the dynamics of complex vehicles using real-time data [12]. This adaptive neural network can enhance the performance of the ACC system by effectively responding to various cases, such as changing traffic conditions and diverse driving environments [13]. This adaption makes the ACC system highly robust against varying conditions and disturbances [14]. Pratama Mahadika et al. [15] used an ANN in the inner loop of an ACC system using model predictive control. The ANN is used to model the vehicle dynamics, whilst the MPC minimises the errors between the estimated outputs and the future reference trajectories. Victoria Oguntosin and Jamiu Olasina [16] utilised root locus and frequency domain methods to analyse the proposed linear cruise control system. The proposed control method was designed to meet the following specifications: a steady-state error of less than 1%, an overshoot of less than 5% and a rise time of less than 1.5 s. The results showed that the proposed control method successfully satisfied these criteria. Trieu Minh Vu et al. [17] proposed a control method that integrates neural networks with the MPC, taking into account the hard and soft constraints to determine control actions whilst ensuring system stability. The simulation results demonstrated the excellent performance of the proposed control method across various trajectories.

This study aims to present a reliable control system for regulating vehicle speed. The proposed control method combines feedback linearization and SMC to simplify the control of the vehicle's nonlinear dynamics. Feedback linearization is used to obtain a linear dynamic system. Thereafter, SMC is applied to control the linear system. The stability of the proposed control method is verified using Lyapunov's second method. Finally, the performance of the proposed control method is evaluated and compared with that of a PID controller using Matlab/SIMULINK software.

2. Dynamic Model

Newton's second law is used to model the longitudinal dynamics of the vehicle, where the net tractive force, aerodynamic drag, rolling resistance and road grade determine the vehicle's acceleration. The vehicle's dynamic system can be modelled using Newton's second law, which relates the vehicle's acceleration to the net force acting on it (Fig. 1) [18].

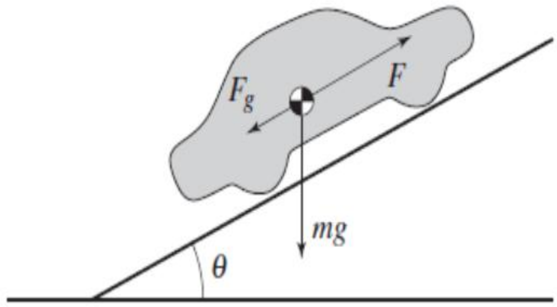

Fig. 1. Gravitational forces

$$m\frac{dv(t)}{dt} = F_{tr}(t) - F_r(t), \quad \ldots(1)$$

where m is the vehicle mass (kg), $v(t)$ the vehicle speed (m/s), $\frac{dv(t)}{dt}$ is the vehicle acceleration (m/s^2), $F_{tr}(t)$ is tractive force (N), and $F_r(t)$ is the resistive force (N).

The resistive force $F_r(t)$ consists of three main components [18]:

$$F_r(t) = F_{\text{drag}}(t) + F_{\text{roll}}(t) + F_{\text{grade}}(t), \quad \ldots(2)$$

where:

$$F_{drag}(t) = \frac{1}{2}\rho C_d A_f v^2(t), \quad \ldots(3)$$

$$F_{\text{roll}}(t) = C_{rr} mg, \quad \ldots(4)$$

$$F_{\text{grade}}(t) = mq\sin(\theta). \quad \ldots(5)$$

$F_{drag}(t)$ is the aerodynamic drag force, ρ is the air density (kg/m^3), C_d is the drag coefficient, and A_f is the frontal area of the vehicle (m^2).

$F_{\text{roll}}(t)$ is the rolling resistance force, C_{rr} is the rolling resistance coefficient, and g is the gravitational acceleration $\left(9.8 \downarrow^{1/s^2}\right)$.

$F_{\text{grade}}(t)$ is the grade resistance force, and θ is the road grade angle (radians).

$u(t)$ represents the ACC system's control input, representing the combined throttle and brake commands.

3. Proposed Control Method

The nonlinear dynamic model of a vehicle can be transformed into a linear system through feedback linearization, without compromising the accuracy or generality of the system [19].

The control signal is selected as follows (Fig. 2):

$u(t) = \frac{1}{\alpha T}\left(\bar{u} + \frac{1}{2}\rho C_d A_f v^2(t) + C_{rr}mg + k\, sgn(e)\right),$ ...(6)

where $\bar{u}$ represents an auxiliary controller. The dynamic model of the vehicle system can be expressed as follows:

$m\frac{dv(t)}{dt} = \bar{u} + k\, sgn(e) + d,$ ...(7)

where $d = -mg\sin(\theta)$ can represent the disturbance signal.

Lyapunov function can be selected as follows:

$V = \frac{1}{2}e^2,$ ...(8)

$e = \dot{v}_d - v,$ ...(9)

$\dot{V} = e\dot{e} = e(\dot{v}_d - \dot{v}) = e\left(\dot{v}_d - \frac{1}{m}(\bar{u} + k\, sgn(e) + d)\right).$ ...(10)

If the auxiliary controller $\bar{u}$ is selected as follows:

$\bar{u} = m\dot{v}_d,$ ....(11)

then,

$\dot{V} = e\left(-\frac{k}{m}\, sgn(e) - \frac{d}{m}\right) = -\frac{k}{m}|e| - \frac{d}{m}e,$ ...(12)

$\dot{V} \le (D - k)|e|.$ ...(13)

If we select $k \ge D$, then

$\dot{V} \le 0.$ ...(14)

Thereafter, the final control law will be:

$u(t) = \frac{1}{\alpha T}\left(m\dot{v}_d + \frac{1}{2}\rho C_d A_f v^2(t) + C_{rr}mg + k\, sgn(e)\right).$ ...(15)

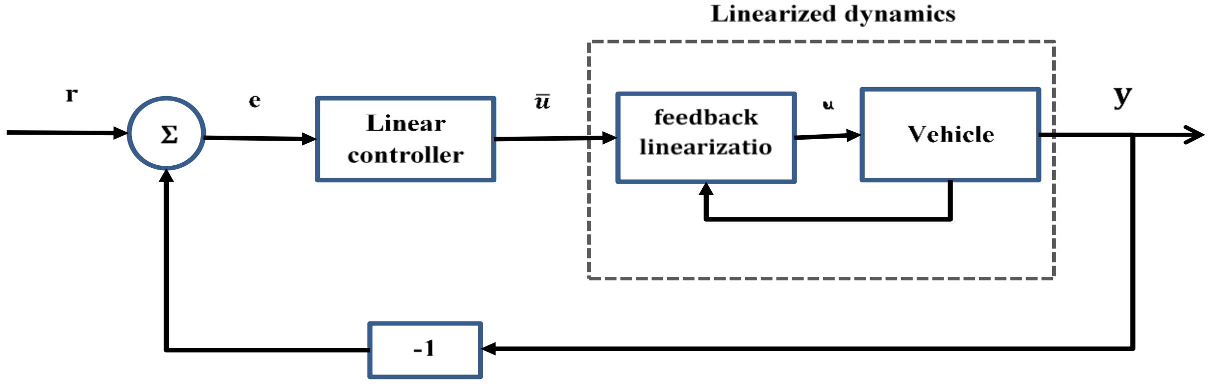

Fig. 2. Proposed control method

4. Simulation Results

MATLAB 2023 was used to simulate the dynamic model of the vehicle system and demonstrate the effectiveness and robustness of the proposed controller in terms of speed control. In addition, the PID controller, tuned using a GA, is simulated to enable a comparison with the proposed controller in terms of transient specification and steady-state error (Fig. 3). The GA parameters used for tuning are the values of gains of the PID controller obtained through GA: Roulette wheel selection crossover probability=0.7 and mutation rate=0.06.

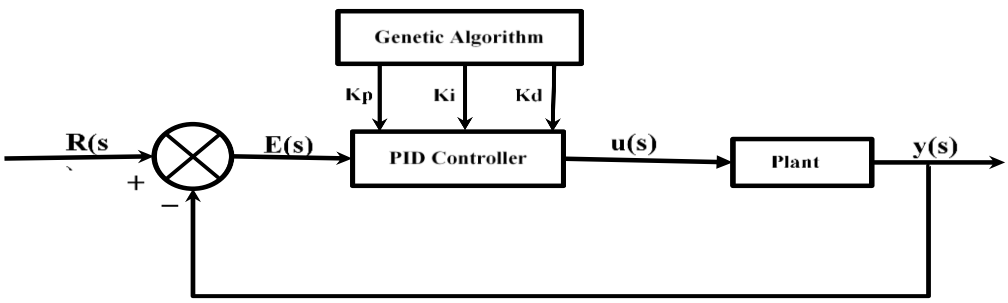

Fig. 3. PID tuning

$K_p = 1.1, K_i = 0.002, K_d = -0.51$

The gains of the proposed controller are selected as follows:

K=10.

The vehicle dynamic parameters are listed in Table 1:

Table 1,
Parameter values [19]

Parameter	*Value*
m	1600kg
C_{rr}	0.01
g	$9.8m/s^2$
C_d	0.32
ρ	$1.3kg/m^3$
A_f	$2.4m^2$
v	30m/s
k	10

4.1. Reference Tracking

In this test, a step input was used as a reference speed to compare the performance of the proposed controller with that of the PID controller. The simulation results are shown in Figs. 4 and 5. This figure highlights the superior performance of the proposed controller over the PID controller. Table 2 lists the transient specifications, including rise time, settling time and overshoot. The proposed controller achieved the shortest rise and settling times with zero overshoot. Moreover, the integral absolute error (IAE) is used as a performance metric and is be expressed as follows:

$$IAE = \int_0^t |e(t)|\, dt. \quad \ldots (16)$$

The IAE values for the two controllers are shown in Fig. 5. In particular, the IAE values demonstrate the superior performance of the proposed controller compared with the PID controller.

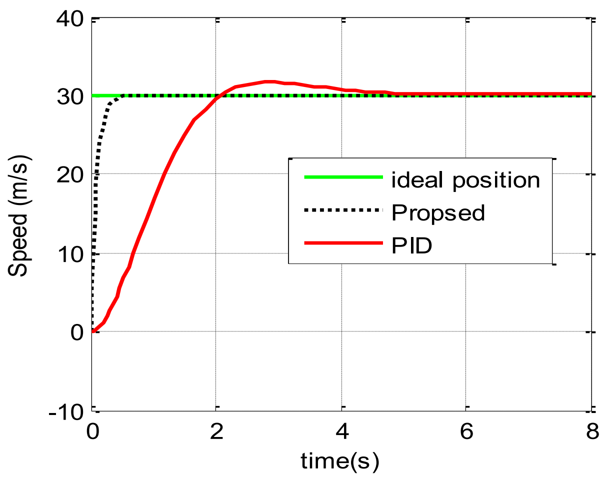

Fig. 4. Step response

A ramp function is used in this comparison to evaluate the performance of the controllers against another reference. The simulation results are shown in Fig. 6, demonstrating the excellent performance of the proposed controller.

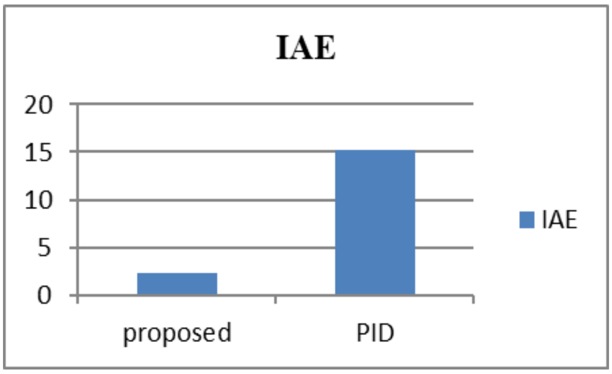

Fig. 5. IAE for step tracking

Table 2,
Transient specifications

Method	M_p	t_r (sec)	t_s (sec)
Proposed	0	0.2104	0.3751
PID_GA	4.8949	1.3823	3.9354

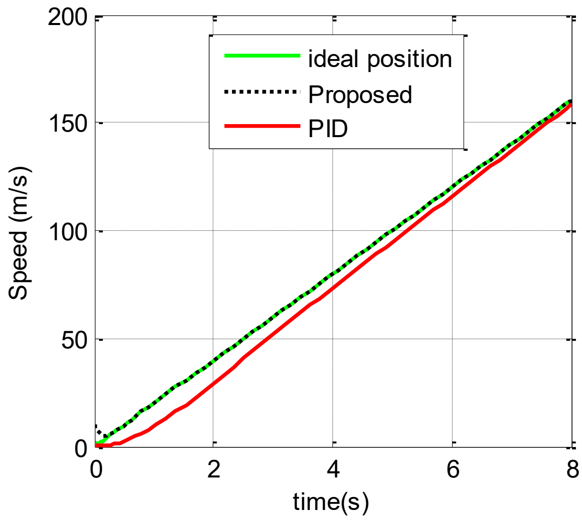

Fig. 6. Ramp response

4.2. Robustness

This study examines the robustness of the proposed controller by applying a disturbance signal lasting 1 s, beginning at 8 s. Fig. 7 shows the response of the proposed and PID controllers within a closed loop system. This figure demonstrates the superior robustness of the proposed controller in the presence of external disturbances. Moreover, the proposed controller is the least affected by the disturbance and requires only a short duration to return to steady state compared with the PID controller. Fig. 8 shows the IAE for the two controllers. The proposed controller achieves the lowest IAE value, indicating its superior performance.

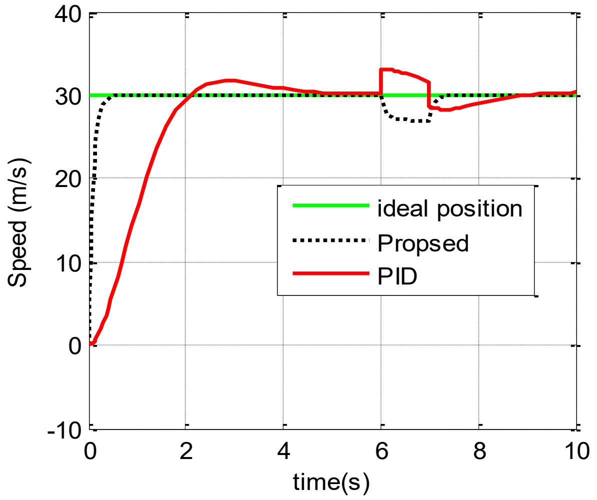

Fig. 7. Robustness against disturbance

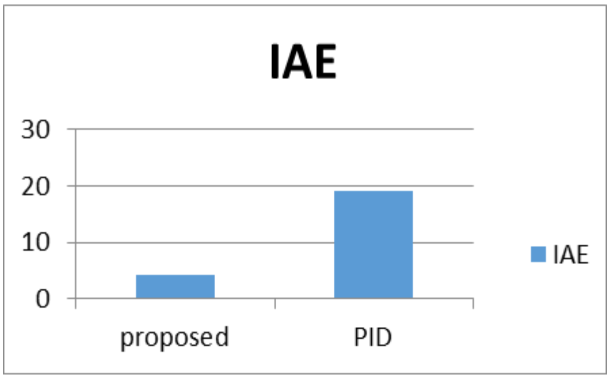

Fig. 8. IAE for external disturbance

5. Conclusions

This study proposed a robust control method based on SMC for the speed control of vehicle dynamic systems. First, a feedback linearization technique is used to transform the nonlinear dynamics of the vehicle system into a linear system. Thereafter, Lyapunov stability is used to verify the stability of the proposed controller. Thereafter, the performance of the proposed controller is compared with that of the PID controller, whose gains are tuned with GA. Two cases are discussed to demonstrate the effectiveness of the proposed controller. The first case involves tracking step and ramp reference inputs using the nominal model. Meanwhile, the second case evaluates the robustness of the proposed controller by introducing an external disturbance. The simulation results indicate that the proposed controller efficiently performs in tracking step and ramp reference inputs. Moreover, the robustness of the proposed controller is evident in the second case, where it rejects external disturbance faster than the PID controller. In future work, the proposed controller can be improved by using reinforcement learning to estimate the dynamic model of the controlled system.

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التوجيه المستقل للمركبة على أساس ردود الفعل الخطية والتحكم في وضع الانزلاق

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المستخلص

اقترحت طريقة التحكم القوي في سرعة النظام الديناميكي للمركبات. تجمعُ الطريقة المقترحة بين متحكم الوضع المنزلق، وتقنية خطية التغذية الراجعة ؛ لعدم الخطية العالية للنموذج الديناميكي لنظام السيارة، فيتم استخدام خطية التغذية المرتدة لتحويل النظام الديناميكي للمركبة إلى نظام خطي تم فيه استخدام نظرية اليابونوف للموافقة على استقرار المتحكم المقترح. فضلاً عن ذلك، استخدمت وحدة التحكم المشتق التكاملي التناسبي (PID) مع الخوارزميات الجينية (GA)باستخدام الخطأ المطلق المتكامل (IAE) كمؤشر أداء للمقارنة بين أداء وحدات التحكم، فيما تشير نتائج المحاكاة بوضوح إلى أن الطريقة المقدمة يمكن أن تحقق أداءً جيدًا بمتانة عالية ضد الاضطرابات الخارجية، وعدم اليقين في النظام. فوحدة التحكم المقترحة هي ٢,٣ بينما PID هو ١٥,٢. في حالة الاضطراب الخارجي، يكون IAE 3.1 و ١٩,١ لوحدة التحكم المقترحة و PIDعلى التوالي.