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Research Article

Application of an Integral-PID-Like-SMC (IPS) for Cruise Control

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Abstract

This study presents the application of an enhanced Proportional–Integral–Derivative (PID)-like Sliding Mode Controller (SMC), referred to as the Integral PID-like Sliding Mode (IPS) controller, for cruise control systems. Robustness remains a critical requirement in cruise control applications, particularly with the increasing use of automation and intelligent vehicle systems. During operation, cruise controllers must compensate for various uncertainties and disturbances, including changes in fuel weight due to consumption, variations in passenger and luggage loads, aerodynamic effects, frictional changes caused by road conditions, and variations in road inclination. As autonomous vehicle technologies continue to advance, improved control strategies are required to ensure smoother and more reliable system performance. Several control approaches have been proposed for cruise control systems. Although nonlinear control methods provide strong robustness and high precision, their implementation often involves significant computational complexity. The proposed IPS approach addresses this limitation by combining the robustness of sliding mode control with a PID-like structure and an additional integral component. The performance of the IPS controller was evaluated and compared with conventional PID control and standard SMC under disturbance conditions. The IPS control law contains fewer components than the standard SMC while maintaining comparable or improved performance. Simulation results demonstrate that the IPS controller achieves enhanced precision and robustness with reduced computational complexity, making it suitable for real-time implementation.

1. Introduction

Modern vehicles are equipped with cruise control systems, which are electronic circuits designed to regulate vehicle speed at predetermined levels. This ability is utilised by the person driving to maintain the desired vehicle speed without physically engaging the existing accelerator pedal, which is achieved after initiating the system and selecting a desired cruising speed. The driver can then move their foot off the accelerator pedal, and the vehicle's speed is automatically maintained at the desired speed [1-3]. This available feature in modern cars reduces foot stress and fatigue, especially during long-distance journeys [4-6]. Another desired advantage is improved fuel efficiency or reduced fuel consumption as a result of maintaining a steady speed during the ride. Accelerating and decelerating in an abrupt manner during travel causes engines to consume more energy (fuel). Records indicated that it can be suppressed to about 50% or even higher utilising cruise-control systems. This means that employing cruise systems provides easy avenues for automating vehicle speed regulation, in addition to reducing fuel consumption by remarkable amounts, which becomes an advantage to users [7-10].

Based on the literature, various control methods were investigated to enhance the smooth operation of cruise control systems. The studies conducted by [2] indicated that, despite the popularity of PID controllers and their extensive application in modern industrial control systems, their simplistic nature makes parameter tuning easy. The demerits they incur could be time-consuming to obtain suitable parameters, coupled with the low reliability of obtaining efficient parameters. In their studies, a linear model of the cruise system was used, and the PID and IMC controllers were realised by tuning using the 'Ziegler-Nichols' method, after which their performances were compared. The system performance indices utilised in the response analysis were rise time, settling time, and time to reach steady state. The results indicated that the system with the IMC controller showed better response performance than the PID control methods. The model predictive control (MPC) scheme was investigated by [6] for a cruise control system, together with the PID control method. It was simulated in MATLAB, showing improved system performance. The MPC system yields better outcomes.

The MPC, together with constraints on the inputs, was designed for cooperative "Adaptive Cruise Control (ACC)" among grouped moving vehicles and investigated [11]. It is a promising method for improving traffic capacity in moving streams of autonomous vehicles, which is a modern, popular practice. The method was shown to be effective and efficient, as evidenced by the study results. The PID control scheme with feed-forward loop was proposed by [12]. These scholars also mentioned the popularity of the PID and its simplicity. It was applied to the nonlinear form of the cruise control model and considered the effects of disturbances, such as gravity and wind. The C++ software was utilised and implemented using an AMR microcontroller for a mobile robot.

In another simulation-based study conducted by [13], the 'Linear Quadratic optimum control' method was employed for the 'adaptive cruise control system'. The gains of the controller for the virtual lead vehicle and the host vehicle were obtained, along with the varying weights applied in the quadratic regulator for the virtual vehicles. The results indicated smooth, continuous movements with good responses and fast enough operations. In [14], the focus was on the design of the well-known "adaptive cruise control system (ADAS)" features. The realisation and function evaluations of the control systems were achieved using

Petri Nets. The work focused on the development of an adaptive fault-tolerant controller for the cruise control system using Petri nets. System evaluations were conducted for several conditions. In [15], an H∞ controller was proposed for the cruise control of grouped autonomous vehicle movements. The challenges of stability for increased-density operation were investigated. Increasing the density of the vehicles in the groups reduces inter-vehicle distance during movement, creating constraints on stability, and this was addressed in the work by utilising a multi-objective and cooperative version of the control scheme. The results obtained in the study were promising. In another development, the fuzzy logic controller was investigated for similar systems mentioned above [16]. The system was regarded by the researchers as nonlinear, with high inertia and a complex nature. The fuzzy controller with 25 rules was proposed with the two inputs being the distance between adjacent vehicles and the speed, while the acceleration was the output. The simulated outcomes obtained were promising.

Hence, the literature has revealed that different control schemes proposed for cruise control systems can be categorised as linear (e.g., the PID), intelligent (e.g., the fuzzy logic), and nonlinear (e.g., the MPC). The linear schemes were known for their simplicity but may require more accurate sensors for real-world operations, which might not be readily available. Intelligent control systems have embedded intelligence; in some cases, they may lack readily available equations for more refined evaluations and proofs. The nonlinear would have been the best, but it would have required more time for computations. Therefore, the study sought to utilise the simplicity of linear schemes and the robustness of nonlinear methods. In that vein, an Integral-PID-like sliding mode control (ISC) scheme was presented for such systems, having the property of simple implementation of the normal PID and characterised by the inherent robustness associated with sliding mode controllers. Therefore, the study was an effort to reduce computations associated with the SMC, a nonlinear control method, by shortening the algorithm and implementing it similarly to how PID is done, thereby retaining the simplicity of linear control methods. Thereby, reducing the computational burden associated with the SMC, thereby hindering its real-time control practical applications.

2. Methodology

The simulation studies were executed utilising the SIMULINK/MATLAB software. An adapted mathematical model of the cruise control system and the starting parameters from [2] were used for the study. The proposed controller was an integral PID, like SMC, realised by utilising the integral part of a PID controller and the portion of SMC that contains the robustness properties, and the scheme was synthesised similarly to the PID approach. Examination was started by implementing the new approach and examining it alongside without any controller, using unity feedback. Comparison was then made with the other schemes, namely the PID and the SMC, both with and without disturbances. The wind with a magnitude of 40 km/hr and an inclination angle of about 40 degrees was the disturbance considered. It is expected that the reduced length/computation of the proposed algorithm would make it practically implementable on real systems.

2.1. The Control System Analytical Model

The adapted model was initiated according to the Newtonian law of motion, as illustrated by equation (1), which states that the resultant of forces on a system causes it to accelerate. The resultant of the forces F_R is therefore equated to the product of the vehicle mass including its content M and the acceleration A. The forces were FD, FA, and FG, which are the engine force, aerodynamic force, and gravity force, respectively. Their relationship was as revealed by equation (2). Equation (3) was an experimental approximation for vehicle engine dynamics, generating the force with K1 as the gain, τ as the delay time, and T as the time constant. The aerodynamic force details were as depicted by (4). The aerodynamic coefficient is KA, while V is the vehicle's speed, and Vw is the wind speed. The gravity effect was depicted by (5), with G being the gravity acceleration and the vehicle's inclination angle, θ. The various system parameters are shown in Table 1.

Table 1. System parameters for the study.

S/No.	Parameter	Symbol	Value	Unit
1	Gain	K_1	5.34	
2	Delay time	τ	0.2	seconds
3	Time constant	T	1	seconds
4	Aerodynamics coefficient	K_A	1.23	$N/m/s^2$
5	Acceleration due to gravity	G	9.8	m/s
6	Engine force	FD	13000	N

$$F_R = MA \tag{1}$$

$$F_R = FD - FA - FG = MA \tag{2}$$

$$FD = \frac{K_1 e^{-\tau s}}{Ts+1} \tag{3}$$

$$FA = K_A(V - V_w)^2 \tag{4}$$

$$FG = MGsin\theta \tag{5}$$

2.2. The Control Law Formulations

The control system was realised by assembling the components in the appropriate order. The basic components are the desired speed, vehicle speed, feedback, controller and the vehicle. The desired speed in this work is the vehicle's desired speed/velocity, or reference; the vehicle's speed is the actual speed/velocity, or response. The vehicle is the plant and is the entire cruise system model. The feedback is basically the sensor loop that measures the response and passes it back to the controller for processing, and the controller makes adjustments to compensate for changes to maintain the reference in accordance with the error between the response and reference.

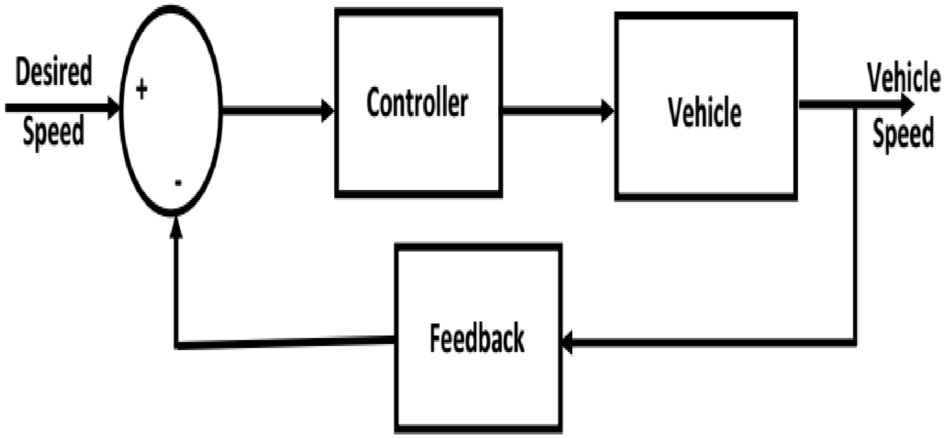

Figure 1. Block diagram of the system.

The control law of the PID controller is given by equation (6) [17], K_P, K_D and K_I are the proportional, derivative and integral constants, respectively.

$$U_{PID}(s) = K_P E(s) + K_D sE(s) + K_I \frac{E(s)}{s} \quad (6)$$

The sliding mode controller (SMC) implementation is shown below. Starting with the sliding surface in (7), then its derivative as given by (8). Equation (9) was obtained from (2), the plant dynamics. The error, its first and second derivatives, were given by (10), (11), and (12), respectively. The constant-rate-reaching law chosen was as depicted in (13). The control law with the normal SMC was obtained by substituting (12) and (13) into (9) and making U the subject, resulting in (14), which is the control law using the SMC [18].

$$p = C\,E(s) + sE(s) \quad (7)$$

$$sp = CsE(s) + s^2E(s) \quad (8)$$

$$s^2V\,M = U(s) - FA - FG \quad (9)$$

$$E(s) = V_D(s) - V(s) \quad (10)$$

$$s\,E(s) = sV_D(s) - s\,V(s) \quad (11)$$

$$s^2E(s) = s^2V_D(s) - s^2V(s) \quad (12)$$

$$sp = -zeta * sgn(p) \quad (13)$$

$$U_{SMC}(s) = FA + FG + M * zeta * sgn(p) + M * s^2V_D(s) + M * CsE(s) \quad (14)$$

To obtain the PID-Like SMC (PSC), the SMC was simplified and implemented similarly to a PID controller, reducing the number of steps as shown in (15)–(18) and, hence, the length of the algorithm as given by (20). The parameters C and zeta are constants, while sgn is the well-known signum function.

$$p = C\ E(s) + sE(s) \tag{15}$$

$$sp = CsE(s) + s^2E(s) \tag{16}$$

$$E(s) = V_D(s) - V(s) \tag{17}$$

$$s\ E(s) = sV_D(s) - s\ V(s) \tag{18}$$

$$sp = -zeta * sgn(p) \tag{19}$$

$$U_{PSC}(s) = M * zeta * sgn(p) \tag{20}$$

The integral PID-like SMC (ISC) was obtained by adding the integral component as follows: maintaining the PID-like structure, plus the integral component of the PID scheme, as depicted by steps (21)–(25), with the final control law given by (26).

$$p = C\ E(s) + sE(s) \tag{21}$$

$$sp = CsE(s) + s^2E(s) \tag{22}$$

$$E(s) = V_D(s) - V(s) \tag{23}$$

$$s\ E(s) = sV_D(s) - s\ V(s) \tag{24}$$

$$sp = -zeta * sgn(p) \tag{25}$$

$$U_{ISC}(s) = M * zeta * sgn(p) + K_I \frac{E(s)}{s} \tag{26}$$

3. Results

The results were presented in stages. Starting with implementing the proposed scheme, thereafter the comparison with and without disturbances.

3.1. Implementing the Proposed Controller

Implementation of the improved control law was as depicted in equations (21)–(26). Comparing the lengths of the algorithms and the numbers of evaluations were as explained: the PID has six evaluations in one step; making of approximately seven (7) executions in total, the SMC had 30 evaluations and eight steps; making it having a total of 38 execution steps, the PSC had eleven (11) evaluations and five (5) steps making it having a total of sixteen execution steps and the ISC had twelve evaluations with five steps; making a total of seventeen execution stages. Therefore, compared with the SMC, the proposed was about 50% shorter, and with the PID, they were closer than with ISC, with the SMC being 6 times, while the ISC is just around 2 times the control law with the PID. It means the ISC is the closest to the PID in terms of execution time and simplicity.

Figure 2 and Figure 3 show the response and error plots of the system with the proposed control scheme, which was successfully implemented alongside the system without a controller (i.e., using unity feedback). The responses of the system with the ISC controller revealed a settling time of 70s, no overshoot, and close to zero steady-state error. The response without the controller has a settling time of about 250s, with an undershoot of 74% and a steady-state error of 36 km/hr. The summation of the errors was 4984200 km/hr and 194260 Km/hr without and with the ISC, meaning that the amount without the controller was 26 times that with the controller.

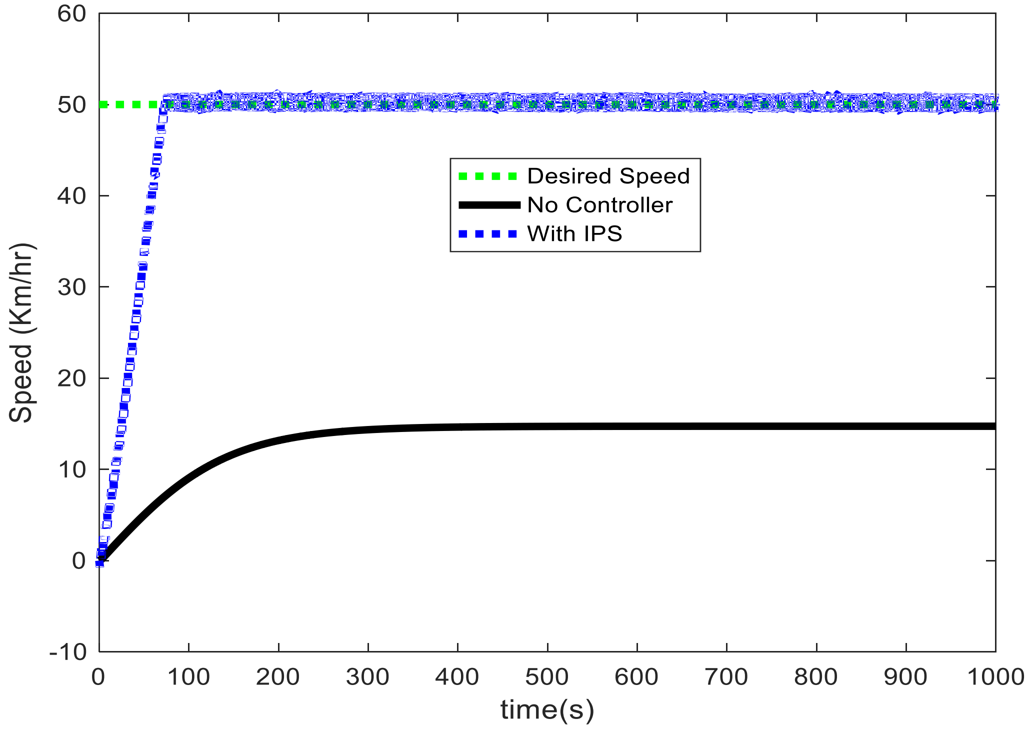

Figure 2. Response of the system with the proposed controller.

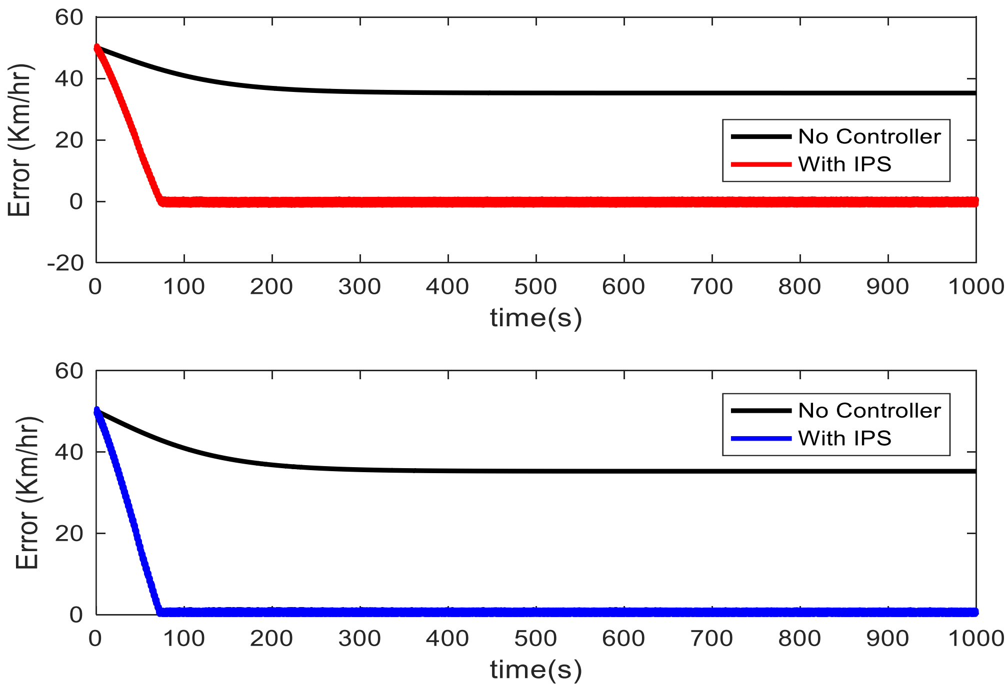

Figure 3. The error plots of response of the system with the proposed controller.

3.2. Comparison without Disturbances

The system responses with the different control schemes, as well as the estimates of their errors without considering disturbance effects, are shown in Figures 4 and 5. The responses with the IPS, SMC and PID were accordingly: settling time of 70s, no overshoot with close to zero steady state error, settling time of 120s, no overshoot with close to zero steady state error, but not as that with the ISC, settling time of 120s, an overshoot of 22% with close to zero steady state error. The cumulative errors with the PID scheme were 387235 km/hr, with the SMC 271880 km/hr, and with the ISC 194260 km/hr.

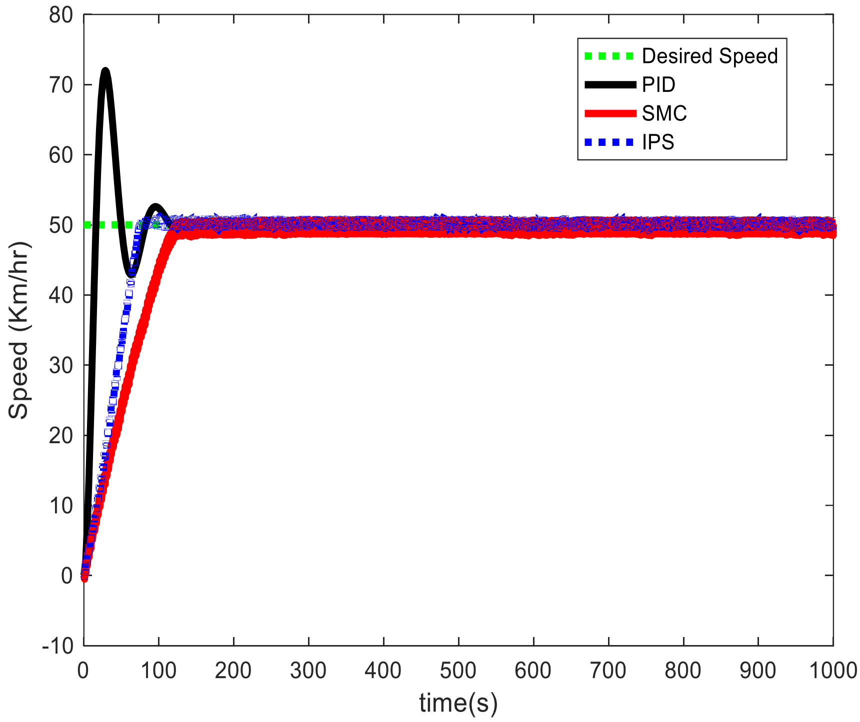

Figure 4. Response of the system with the different controllers without disturbance.

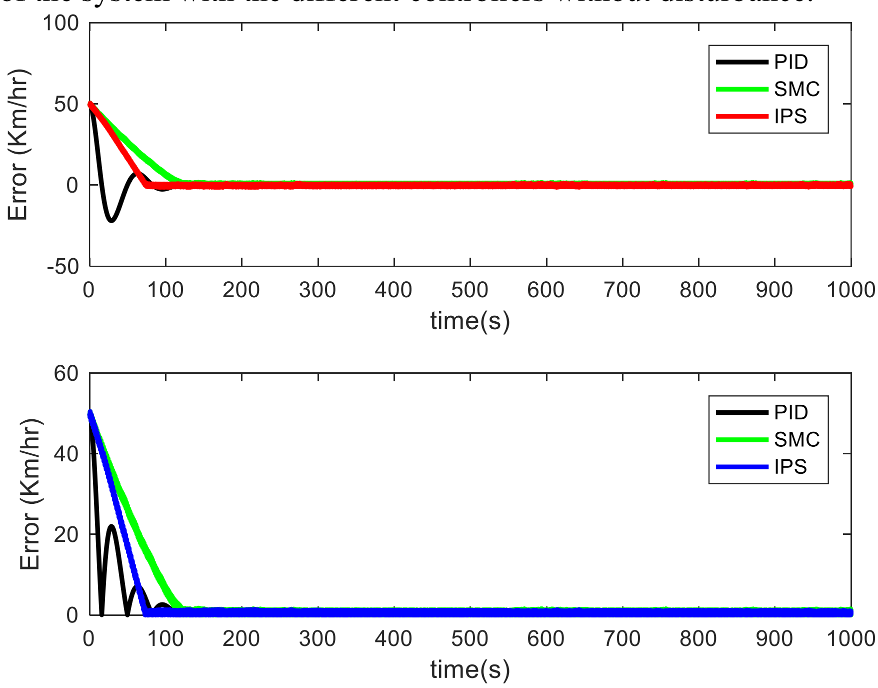

Figure 5. Error plots of the system with the different controllers without disturbance.

3.3. Comparison with Disturbances

Figure 6 and Figure 7were the response of the system and graphical representations of the errors on the system considering the effects of inclination angle and wind disturbances. The system with the ISC showed a settling time of about 72s, with no overshoot and close to zero steady-state error. The system with the SMC had a settling time of about 130s, no overshoot, and close to zero steady-state error, but not as good as with the ISC. The PID system showed a settling time of 310s, with 80% overshoot and close to zero steady-state error, but not as good as that with the ISC. The PID had an integral error of about 408100 km/hr with the SMC, and with the ISC it was 371400 km/hr. These showed changes of 368%, 130%, and 86% when comparing the amounts of errors without and with disturbances; these indicated the superiority of the ISC, then SMC, and the PID in terms of robustness.

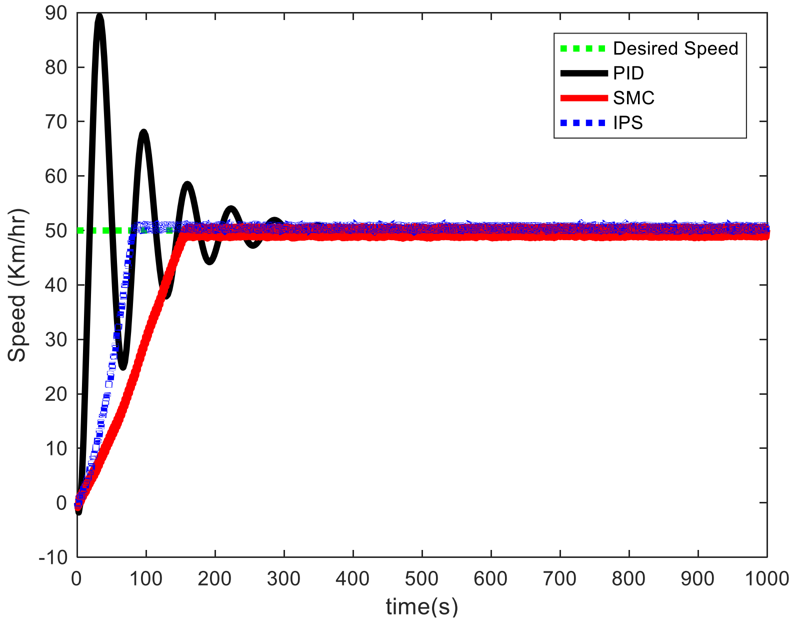

Figure 6. Response of the system with different controllers with disturbance.

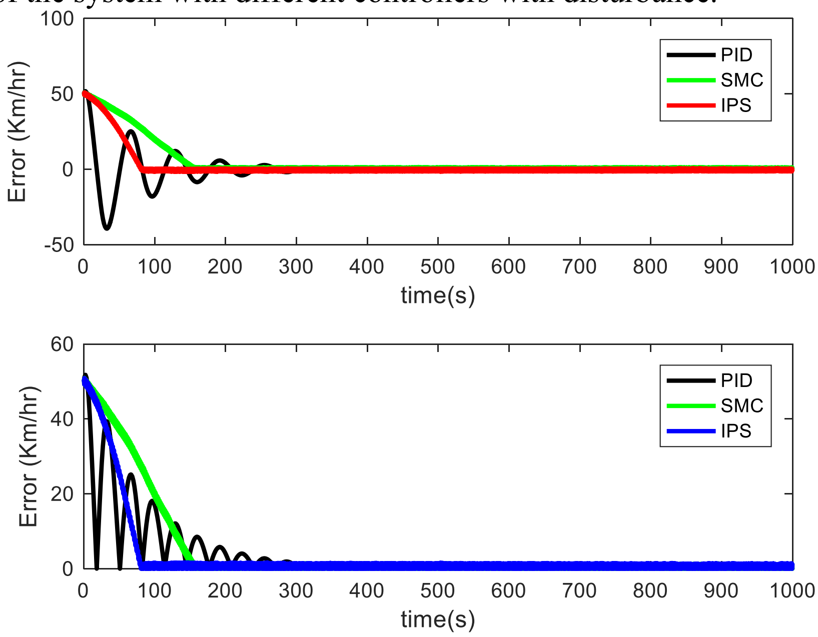

Figure 7. The error plots of response of the system with different controllers and disturbance effects.

4. Discussions

The ISC was successfully implemented for the cruise control system with a relatively shorter algorithm, which was expected to have up to 50% lower computation than the normal SMC. The implementation was also simple; similar to what is obtainable in the case of PID. This was shown by comparing the execution steps, approximated as five (5), thirty-eight (38), and twelve (12), with the PID, SMC, and ISC, respectively. Hence, the SMC system had 6 times the duration and the ISC around 2 times the duration compared to the PID, making the ISC the closest to the PID in terms of simplicity. The system response with the ISC controller upon successful implementation showed a settling time of about 70s, no overshoot, and close to zero steady-state error, whereas without the controller, the settling time was about 250s, with an undershoot of 74% and a steady-state error of 36 km/hr. This revealed that a compensator is highly required for the smooth operation of the cruise system due to the large steady-state error; without the controller, the system would not be able to reach the desired steady state for the desired system operation.

The response without considering disturbances effects for the different control schemes viz: IPS, SMC and PID accordingly revealed settling time, overshoot and steady state errors of; 70s, no overshoot, close to zero steady state error, then 120s, no overshoot, close to zero steady state error and 120s, an overshoot of 22%, close to zero steady state error respectively. The total amount of errors with the PID controller was 387235 km/hr, with the SMC it was 271880 Km/hr, and with the ISC it was 194260 Km/hr. The ISC revealed the best responses in terms of settling time, overshoot, steady-state error, and total error, as it showed the lowest values.

Upon considering disturbance effects, the system response with the ISC had a settling time of about 72s, with no overshoot and close to zero steady-state error. The system with the SMC had a settling time of about 130s, no overshoot, and close to zero steady-state error. The system with the PID had a settling time of 310s, an overshoot of 80%, and close to zero steady-state error. The ISC controller maintains its status as the best again. The PID had an integral error of about 408100 Km/hr, and with the SMC and ISMC, 627280 Km/hr and 371400 Km/hr, respectively. Upon comparison with the case without disturbances, increases of 368%, 130%, and 86% were observed. Hence, indicating the robustness superiority of the ISC, because it had the lowest amount of increase/change, followed by the SMC and then by the PID.

5. Conclusions

The integral proportional-derivative (IPD) sliding mode controller (ISC) was successfully applied to achieve smooth operation of a cruise control system. Cruise control systems automate the regulation of speed/velocity in moving vehicles at a constant value, allowing the driver to be free from manipulating the accelerator pedal. The system has the advantage of reducing fatigue while driving and reducing fuel consumption during a journey. The literature presents several control schemes, which are basically linear, intelligent, and nonlinear. The true nature of the system might work best with nonlinear schemes, but the resulting complexity becomes a major shortcoming. In that view, a simplified and improved version of the sliding mode controller (SMC), a nonlinear control method, was proposed. It was implemented and compared with the PID and SMC controllers, with and without disturbance effects. The disturbances considered were an inclination angle of about 4 degrees and a wind speed of about 40 km/h. Results revealed a reduction of computational burden by about 50%, making it more suitable for real-time or near-real-time control applications, as it requires half the initial computational burden of SMC. Others are improving the settling time by 300%, undershoot by about 74%, and steady-state error by about 74% compared to without a controller upon implementing the proposed controller, that is, the ISC. Upon comparing the ISC with the PID and the SMC, apart from improvements in the responses, it was found to be 4.3 times and 1.5 times more robust than the PID and SMC, respectively. Therefore, it implied that the proposed control system had 50% lower computational time, faster system response (about 50% reduction), better robustness (about 1.5 times), maintained response without overshoot, reduced the likelihood of wear and tear, and therefore reduced maintenance costs. Hence, the ISC had the best performance across almost all the indices considered; this suggests that, with more rigorous analysis, it could be enhanced and applied not only to similar systems but also to others. As part of further research, other error indices would be considered, such as mean square error (MSE), integral square error (ISE), and integral time absolute error (ITAE), for evaluating the controller performance.

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