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Speed Control of Vehicle using Fractional Network based Controller

[1]Abida K, [2]Dr. Nafeesa K and [3]Labeeb M
[1-3]Department of EEE, MES CE kuttippuram, malappuram, kerala,india
[1]abida.06@gmail.com

***Abstract*—Vehicle dynamics plays an important role in driving systems, especially in congested traffic situations at very low speeds. In order to ensure safety during driving accurate controllers are needed. The design of a fractional PI controller for low speed control problem is attempted in this paper. A system to adapt the vehicles speed to avoid or mitigate possible accidents is developed. The performance comparison of various controllers like PI controller, fuzzy PI controller and fractional PI controller iscarried out. Results show that fractional PI controller gives better performance than the other controllers in terms of settling time, rise time, maximum overshoot etc.**

***Index Terms*— Fractional-order control; adaptive cruise control; gain scheduling; vehicle-to-infrastructure (V2I) communication; vehicle-to-vehicle (V2V) communication.**

I. INTRODUCTION

The idea of vehicles driving in an automatic way is a far aim. Tasks, such as parking assistance or keeping a safe distance from other vehicles is discussed in [1]. Most of these advances focus on improving the passengers and pedestrians safety. However, human failures remain the main cause of serious accidents.
The safety initiative includes research projects based on vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications designed to reduce the number of vehicle accidents. Intelligent cooperative systems based on wireless communications will play a key role in the development of new advanced driver assistance systems (ADAS). Indeed, the development of dedicated short-range communications (DSRC) as a reserved band for communications among vehicles reflects the importance of applying communication systems to increase road safety [2]. It is based on control stations to coordinate the traffic within a zone.
However, the main drawback of wireless communication systems is that they present delays that can cause failures in the control system, since information has to go from the vehicle and the infrastructure to a control station and then return to the vehicles and devices in the infrastructure to take the most appropriate action. Most road fatalities are due to excessive speed, so management of delays in the information exchange between a control station and the vehicles in its vicinity can be critical for collision avoidance. Number of vehicles driving in a common area and a control station capable of communicating with all of them through a wireless network is described in [3]. The control station will be responsible for sending each vehicle its specific target speed so as to avoid the possibility of collisions. Design and development of a fractional-order proportional integral (PI) controller to manage a vehicles speed in the common area at low speeds and designing a gain scheduler to make adaptations to the local speed controller from the control station will be a new venture. In this paper a local fractional PI controller capable of performing efficient networked control by modifying its gains with an external gain beta is designed. The gain beta is determined as an optimal function of the current network conditions.

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Among the various networked control strategies, gain scheduling technique is the most widely used one due to the frequent change in operating network conditions. Replacing a proper and widely used controller by a new one for efficient network-based capability may be costly and time consuming [4]. Gain scheduling can be considered as the simplest classical strategy of adaptive control. Several gain scheduling approaches have been applied successfully in network control systems.

Fractional-order control (FOC) is the generalization to non-integer orders of traditional controllers or control schemes. Its applications are becoming an important research field in recent years due to its adjustable time and frequency response of the control system, which gives robust performances.

II. System Description

The architecture is mainly based on local control stations towards traffic control of cooperating vehicles. These receive information from the vehicles in their domain, analyses it to determine when a situation of risk might arise, and modify the vehicles speeds in order to avoid an accident. Although control stations are capable of analysing traffic conditions in real time, delays caused by the wireless communications between each vehicle and the control station may cause inappropriate control signals to be sent to the vehicles [5]. This paper describes a controller that is capable of overcoming this problem.

A. Local station

A local control station is responsible for detecting traffic risk situations in its control area and then modifying the speeds of the vehicles involved so as to avoid or mitigate possible accidents. A wireless access point is used to detect any vehicle in its vicinity, establishing a Vehicle-2-Infrastructure (V2I) communication following the Wi-Fi standard. Although Vehicle-2-Vehicle (V2V) solutions have been proposed for several automotive applications including adaptive cruise control (ACC) [6], V2I communications play a key role for the management of driving areas, since they significantly reduce the number of communication channels required. One of the major concerns in the V2I communication field is the ability of the infrastructure (control station) to manage the information coming from hundreds of vehicles in real time with minimum delay. To obtain a suitable intelligent infrastructure management system, it will be vital to deal with the effects of traffic density on the communication requirements. The vehicle is able to send its current position and speed to the control station, which will take into account the vehicle's proximity to a curved stretch of road, an intersection or a traffic merging segment, and the measured condition of the network to determine the reference speed. It then sends this data together with the measured network delay to the vehicle for it to adapt its speed to the road's layout.

B. Vehicle

The vehicle has been modified to permit actions on the brake by means of control commands. For the brake automation, a brake-by-wire system was installed in the trunk of the vehicle. It consists of a pump attached to a dc motor that permits different pressures to be applied to the brake shoes. The vehicle is equipped with an on-board control unit which is responsible for receiving the control commands to be applied to the vehicles actuators. It is impossible to obtain the exact dynamics that describe the vehicle, this paper uses a simplified model developed in [7] based on the vehicles experimental response. The model is implemented in the MATLAB environment and by taking a chirp signal as the input to the vehicles throttle, the transfer function is obtained as,

$$G(s) = \frac{K}{s^2+2\delta\omega_n s+\omega_n^2} \tag{1}$$

Where K=7.8473 x 104 , δ=160, and ωn=55.87. The poles of (1) are p1 = 0.1746 and p2 = -1.7878 x 104, so the vehicle dynamics will evidently be given by p1, being the greater time constant. As a result, (1) is reduced to a first-order function as

$$G(s) = \frac{K}{s+p} = \frac{4.39}{s+0.1746} \tag{2}$$

III. V2I COMMUNICATIONS

Point-to-point communications cause an exponential number of opened communication channels in case number of vehicles are driving in the same area. Wide area architecture based on five levels to reduce the number of communication in order to perform a safety and efficient system is presented. Following points must be considered while developing a wide area control system to improve the local area control [8],

1. A central unit of control must exist inside every local area which manages everything that happens inside it.
2. Every vehicle must know the information of the vehicles in the local area.
3. Existence of a common zone among local stations to assure the commutation of one zone to another one without loss of information.
4. Communication of the unit of local control with the local surrounding units in order to exchange the information of the vehicles in the common zones.

The V2I architecture is divided into five steps as shown in Fig. 1

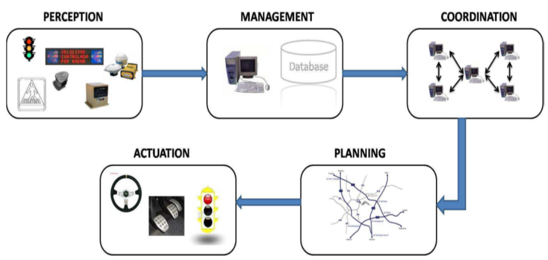

Fig. 1 V2I architecture

1. Perception:- All the sensorial information is sent from the vehicles (car, trucks, motorbikes, etc.) and the infrastructure (traffic signals, light panels, etc.) to the local control station (LCS). From the vehicles standpoint, these information can come from Global Navigation Satellite Systems (GNSS), Inertial Measurement Unit (IMU), compass or any sensor that can be used (CAN bus) in the vehicles. From the infrastructure standpoint, sensors can be used to obtain extra informations. The LCS is limited by the area that can be covered by the local communication system.
2. Management:- All the sensorial information received by the LCS is analysed and efficiently sorted to find the best way to solve the risky traffic situations
3. Coordination:- All the information of the vehicle that are driving in common areas are send to the LCSs. Taking into account this information, the LCS will send the data information to the vehicles and the infrastructure in order to permit safety manoeuvres.
4. Planning:- With the information coming from the LCSs, the vehicles and the infrastructure evaluate the conditions and choose the best alternative in order to improve the traffic flow.
5. Actuation:- The options selected in the previous stage are sent to the actuators. In case of a traffic light, it can be to change the light or in case of a vehicle, it can be to modify the speed.

IV. BRAKING SYSTEM

The main prerequisite of a vehicle system is to obtain a brake by wire system in coexistence with the original braking system. The solution is to design a hydraulic system equipped with electronic components to permit handling by computer generated signals through an input/output device. It is also necessary to determine the maximum braking pressure in order to avoid excessive system stress.This data is experimentally determined by means of a manometer. A wheel is removed, and a manometer is connected in lieu of the brake shoe. A pressure of 160 bars is measured when the brake pedal is completely pressed down [9].

Fig. 2 shows the design scheme of the braking system. The hydraulic system consists of a one-litre capacity brake fluid tank that includes a gear pump and coupling to a 350-watt, 12-volt supply, and dc motor. A pressure limiter tube whose value is fixed at 160 bars is added in order to protect the vehicle elements involved in the braking process. This system permits one to obtain the maximum pressure that the original braking system is able to apply on the wheels. Electronic components are needed to regulate this pressure as

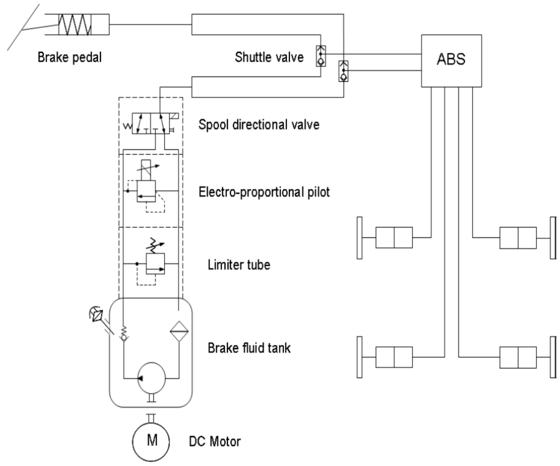

Fig. 2 Braking system design

required by the computer. Two electronic components are included, one is used to regulate the pressure between 0 and the maximum value, and the other to transmit this pressure from the pump to the wheels. In order to regulate the flow of the pressure, an electro-proportional pilot is installed with a nominal pressure between 12 and 250 bars. The control voltage varies between 0 and10 volts. The electro-proportional pilot yields a non-null minimum pressure, and hence will always exert some small pressure on the wheels. The second element, pool directional valve, is used to resolve this problem. It is normally open, and is only closed when the proportional pilot is actuated.

These two elements cause delays that cannot be disregarded if good behaviour of the system is desired. At the first sampling period after brake actuation is requested, a signal is sent simultaneously to both valves, and the actual delay corresponds to that of the slower element, the spool directional valve, whose switching time is about 30 ms. For subsequent sampling periods, the spool directional valve is already closed and the delay corresponds only to that of the electro-proportional pilot, being even in the worst case at most10 ms.

Following the design of the hydraulic and electronic components, the system needs to be plugged into the existing vehicle braking system. To this end, a shuttle valve is installed to form the junction between the two systems. This valve permits flow from either of two inlet ports to a common outlet. A free-floating metal ball shuttles back-and-forth according to the relative pressure at the two inlets. Flow from the higher pressure inlet through the valve moves the ball to close the opposite inlet. This valve is thus responsible for the switching between the two braking systems. The model selected is the Hydraulic WV 6-S. It is chosen because the smallness of the flow through a braking system permits one to select the valve of least diameter which also has the smallest floating ball, thus minimizing the switching time. The valve is mounted so that the ball under gravity maintains the standard braking system open, when the electro-hydraulic system is switched off.

The shuttle valve introduces a delay associated with the movement of the metal ball between the two inlets. The delay time calculated for the selected model is less than 1 ms for the minimum pressure of 10 bars. The connection between the shuttle valve and the electro-hydraulic braking system is through the output of the spool directional valve which is connected to one of the inputs of the shuttle valve. Therefore, two shuttle valves are used to switch between the conventional and the electro-hydraulic braking systems. The outputs of the two shuttle valves are connected to the ABS (Anti-lock Braking System) inputs. Finally, the ABS performs the distribution of the braking.

V. Controller Design

The design process of the local controller and its network based efficient adaptation is described. Use of fractional-order strategy is a new perspective in longitudinal control at low speeds in the automotive field, because of its capacity to provide time and frequency responses that are more adjustable [10].

For low speed control purposes, the most important mechanical and practical requirements of the vehicle to be addressed during the design process is that the vehicle response has to be smooth so that its acceleration will be less than the well-known comfort acceleration, that is, less than $2m/s^2$. Apart from the inherent vehicle issues, the controller will have a twofold purpose: 1) robustness against non-modelled dynamics and imprecision in measurements and 2) the desired closed loop response with a value of overshoot M_p close to 0% and a rise time $t_r \approx 4s$, or equivalently, a phase margin and a crossover frequency around 90deg and 0.45rad/s, respectively (it has been tested that higher values of both parameters cause worse system performances) [11]

In previous works, some traditional PI controllers have been designed with non-significantly good results. As fractional order controllers have been applied in several fields with better results in comparison with the traditional ones, a PI controller, given by (3), is designed to fulfil the desired system specifications. The use of a PID controller instead of the proposed PI might introduce problems with high frequency noise, since the derivative action is sensitive to measurement noise.

$$C(s) = k_p + \frac{k_i}{s^{\propto}} = k_p\left(1 + \frac{z_c}{s^{\propto}}\right), with\ z_c = {k_i}/{k_p} \quad (3)$$

Here the gain crossover frequency is given by ω_c, the phase margin is specified by φ_m and the output disturbance rejection is defined by a desired value of a sensitivity function S(s) for a desired frequencies range. For meeting the system stability and robustness, following specifications are considered.

A. Phase margin specification

$$\mathrm{Arg}[G_{0l}(j\omega_c)] = \mathrm{Arg}[C(j\omega_c)G(j\omega_c)] = \pi + \varphi_m \quad (4)$$

B. Gain crossover frequency specication

$$|G_{ol}(j\omega_c)| = |C(j\omega_c)G(j\omega_c)| = 1 \quad (5)$$

C. Output disturbance rejection for $\omega \leq \omega_s$= 0.035rad/s

$$|S(j\omega)|_{dB} = \left|\frac{1}{1+C(j\omega)G(j\omega)}\right|_{dB} \leq -20\ dB \quad (6)$$

The phase and magnitude of the open-loop frequency response $G_{ol}(j\omega)$ of the system can be written as

$$Arg(G_{ol}) = -tan^{-1}\left[\frac{z_c\omega^{-\alpha}sin\phi}{1 + z_c\omega^{-\alpha}cos\phi}\right] - tan^{-1}\left[\frac{\omega}{p}\right] \quad (7)$$

$$|G_{ol}| = \frac{Kk_p\sqrt{(1 + z_c\omega^{-\alpha}cos\phi)^2 + (z_c\omega^{-\alpha}sin\phi)^2}}{\sqrt{\omega^2 + p^2}} \quad (8)$$

where $\Phi=\alpha\pi/2$,

specification (1) leads to

$$-tan^{-1}\left[\frac{z_c\omega^{-\alpha}sin\phi}{1 + z_c\omega^{-\alpha}cos\phi}\right] - tan^{-1}\left[\frac{\omega}{p}\right] = -\pi + \varphi_m \quad (9)$$

In accordance with specification (2)

$$\frac{Kk_p\sqrt{(1 + z_c\omega^{-\alpha}cos\phi)^2 + (z_c\omega^{-\alpha}sin\phi)^2}}{\sqrt{\omega^2 + p^2}} = -1 \quad (10)$$

Specification (3) gives

$$|S| = \left|\frac{1}{1 + k_p[1 + z_c\omega^{-\alpha}cos\phi - jz_c\omega^{-\alpha}sin\phi]\left(\frac{K}{j\omega + p}\right)}\right| \quad (11)$$

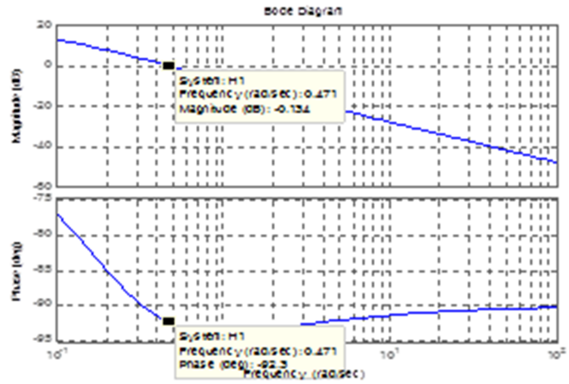

Fig. 3 Bode plot for designed controller

Solving the above set of equations, the values of the controller parameters obtained are: $k_p = 0.09$, $k_i = 0.025$ and $\alpha = 0.8$. Fig. 3 shows the Bode plot of the controlled system by applying the designed controller. As it can be observed, the cross over frequency $\omega_c = 0.46$ rad/s and the phase margin $\varphi_m = 87.79$ deg, which roughly fulfills the design specifications.

D. Networked Control

The future trend in the automotive field is to develop ADAS to ensure safe driving within a zone by using communication network for traffic control. For this the local station has to be able to adapt each vehicles speed according to the circumstances. In this sense, the previous local speed controller has to be moved towards a networked speed controller, taking into account the network effects [11].

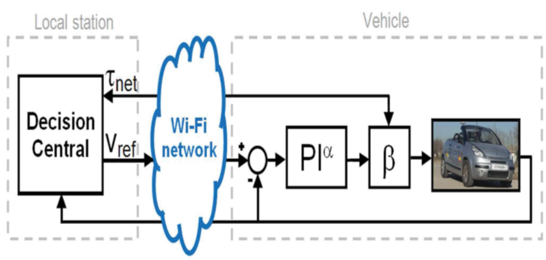

Fig. 4 Scheme for gain scheduling

This section presents the adaptation of the fractional controller for networked control by minimizing the effects of network induced delays. The idea is to enable the designed local controller to perform efficient networked control by means of an external gain. This is based on the approach proposed in [12]. It allows controller gains to adapt β ($\beta > 0$) with respect to the current network condition by estimating the current network delay. Thus, β will be a function of $\tau_{network} = f_{op}(\tau_{network})$, which will optimally adapt the vehicles speed according to the current network conditions, enabling the local controller to perform efficiently over the network. A scheme of this fractional gain scheduling strategy is shown in Fig. 4. There are three basic components in this scheme.

1) The central decision unit, whose function is to measure or estimate the current network condition. This measurement is then utilized by the gain scheduler and also to determine the reference speed.

2) The gain scheduler, which modifies the controller output with respect to the current network condition. It is determined by an offline optimal study of the system.

3) The remote system in this case is a production vehicle.

In [13], the authors solve the stability of the system roughly using the root locus, so that an approximation is needed for delays. On the contrary, here the Nyquist stability criterion is applied to calculate the maximum value of β that guarantees the systems stability. Hence, the structure of the gain scheduling and the form of tuning β ensure closed-loop stability for any given $\tau_{network}$. [14]. The application of the gain scheduling to the PI^{α} controller, referred to as a fractional gain scheduled controller (FGSC), is presented for networked vehicle speed adaptation at low speeds.

VI. PERFORMANCE COMPARISON

Comparing the step response of the system to various controllers, it is observed that fractional PI controller gives better performance than the others. The system response to ordinary PI controller, fuzzy PI controller and fractional PI controller is shown in Figs. 5, 6 and 7 respectively. An overshoot occurs in fuzzy PI and ordinary PI, but it is not present in fractional PI controller. So it can inferred that fractional PI is a better controller which gives better performance than the others in which many parameters can be adjusted to get better results.

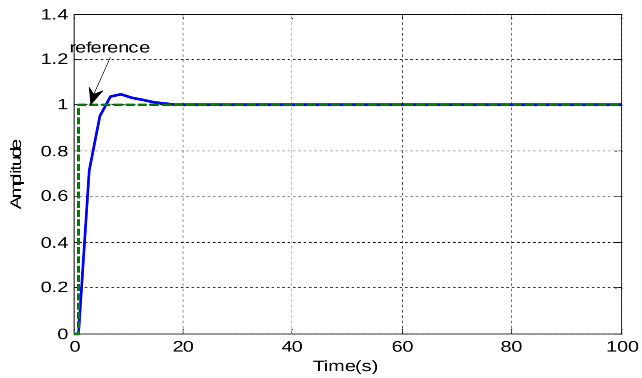

Fig.5 Response of PI controller

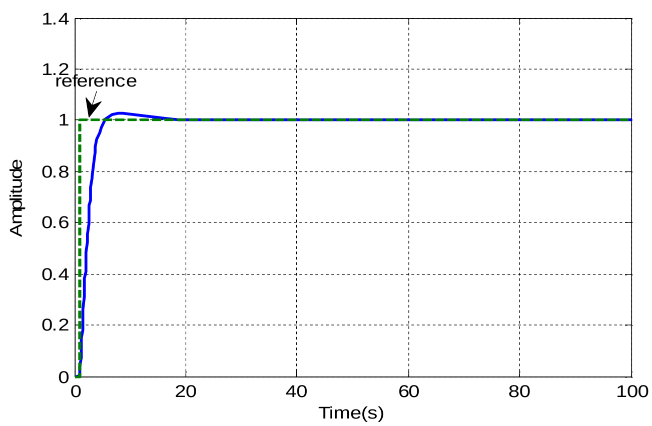

Fig.6 Response of fuzzy PI controller

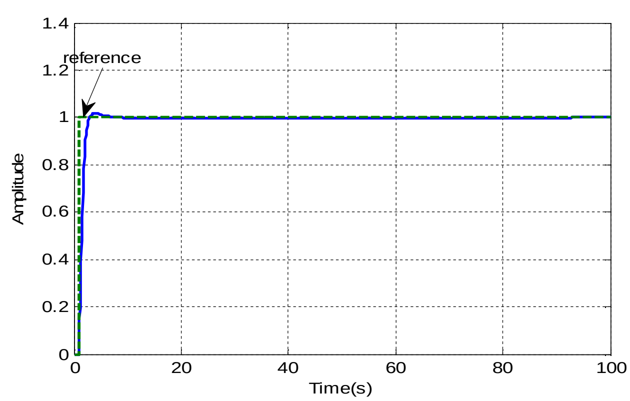

Fig.7 Response of FOPI controllerFig.7 Response of FOPI controller

TABLE I. PERFORMANCE COMPARISON WITH VARIOUS CONTROLLERS

Controllers	Rise time(sec)	Settling time(sec)	Overshoot (%)
PI	4.74	18.72	4.7
Fuzzy PI	4.12	18.57	2.3
FOPI	1.75	7.53	0.5

Table 1 shows the values of rise time, settling time and maximum overshoot for three different controllers from which it is analysed that fractional order controller is the better one.

VII. CONCLUSIONS

A fractional-order proportional integral (PI^{α}) controller to manage a vehicles speed in the common area at low speeds is designed and simulated. A gain scheduler is designed to make adaptations to the local speed controller from the control station, to compensate delays in system. Comparison of the system performance with various controllers like ordinary PI controller, fuzzy PI controller and fractional PI controller are done and it is found that fractional PI controller gives better results than the others in terms of settling time, rise time and percentage overshoot.

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