Development of Active Steering Angle Control based on Electric Power Steering Systems

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***Abstract* - The number of electric power steering(EPS) applications continues to grow rapidly. EPS systems utilize electric motors to provide steering assistance when cornering. Because of the controllability of the EPS motor, it provides more and more possibility to help the driver in driving process actively. An automatic parking system(APS), one of the Advanced Driver Assist System(ADAS), is a typical application by controlling the EPS motor to assist drivers in parking vehicle automatically. In this paper, two approaches are proposed for active steering angle control based on EPS systems and the system dynamics was analysed to improve the angle control performance in APS. Furthermore, the active angle control algorithm was realized with an embedded-DSP and validated in a prototype vehicle.**

I. INTRODUCTION

An electrical power steering system utilizes an electric motor as an actuator to provide a suitable assist torque when the driver turns the steering wheel. Compared with the conventional power steering system, it is an on-demand system that operates only when the steering wheel is turned. Besides, because of its electromechanical structure, it has possibility of steering vehicle actively. By integrating the EPS system with other vehicle systems, advanced steering functions can be fulfilled. The most prominent example is the automatic parking system (APS)[1]. The APS takes advantage of the EPS system to help drivers automatically park in constrained environments where needs much attention and experience is required. The APS generates a stream of values for the steering angle when the vehicle reversing into a parking spot. These values are transformed into the motor torque commands at the steering angle control level by the EPS system.

In recent years, the research of the APS is a popular topic. Because of APS, parking is not a troublesome action. Many studies have been done on parking strategies. For instance Hsu et al.[1] provided the path planning and the path tracking strategy for the APS. Lin et al.[2] used ultrasonic sensors, camera vision and developed algorithm to decrease parking space for parallel parking. Besides, the commercial product of the APS has been first introduced by Toyota Motor Corporation in Toyota Prius/Lexus LS models.

However, little attention has been paid to steering angle control performance. The rotational motion of the steering wheel may make the driver feel dangerous and even more influence his/her confidence in the APS. The purpose of this paper is to propose the steering angle control algorithm which is suitable for the EPS system and capable of better performance for the APS. The path trajectory of the vehicle for the APS [1] is planned in advance and transformed into the steering angle commands. The response of the steering wheel will be discussed.

II. ELECTRIC POWER STEERING

The basic control of an EPS system is achieved by motor current control. The framework of an EPS system includes an electric motor and steering mechanisms. An EPS mathematic model is considered as below, and the schematic diagram of the EPS system is showed in Fig.1. The model is used to describe the system dynamics and to verify the accuracy and reliability of the steering torque control logic.

$$T_h - K_{tb}(\theta_{sc} - \theta_p) - B_{sc}\dot{\theta}_{sc} = J_{sc}\ddot{\theta}_{sc} \tag{1}$$

$$K_{tb}(\theta_{sc} - \theta_p) + K_m(\frac{\theta_m}{n} - \theta_p) + T_f - k_r(\theta_p - \frac{x_r}{r}) - B_p\dot{\theta}_p = J_p\ddot{\theta}_p \tag{2}$$

$$\frac{k_r}{r}(\theta_{sc} - \frac{x_r}{r}) - F_r - b_r\dot{x}_r = m_r\ddot{x}_r \tag{3}$$

$$T_m - \frac{1}{n}K_m(\frac{\theta_m}{n} - \theta_{sc}) - B_m\dot{\theta}_m = J_m\ddot{\theta}_m \tag{4}$$

where T_h is the torque that driver act on the steering wheel; K_{tb} is the stiffness of the torsion bar; J_{sc} and B_{sc} are the inertia and the damping constant of the steering shaft and column respectively; θ_p and θ_{sc} are the pinion shaft rotational angle and the steering column angle respectively; θ_m is the mechanical motor position of the rotor; n is the reduction gear ratio; K_m is the stiffness between the motor and reduction gear; T_f is the friction torque on the steering column and shaft; k_r is the stiffness between the rack and pinion; x_r is the displacement of the rack; r is the stroke ratio; F_r is the alignment force on the rack from the road wheel; m_r and b_r are the mass and the damping constant of the rack; T_m is the electromagnetic drive torque.

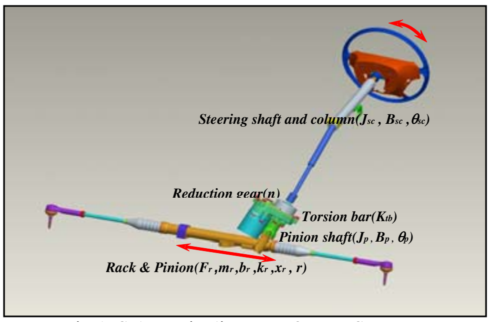

Fig.1. Schematic diagram of an EPS system

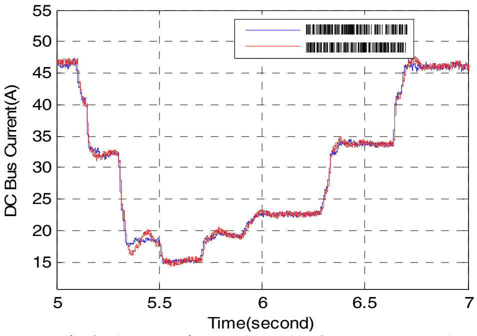

Fig.2. the experimental result of current control

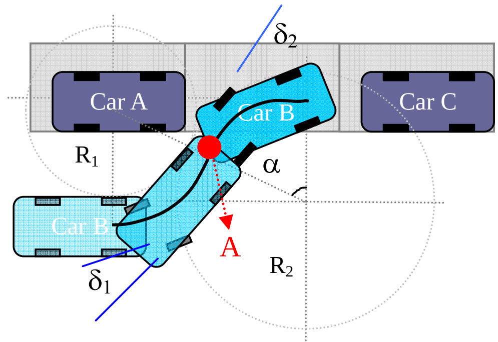

Fig.4. the sketch map of the APS path trajectory

The motor used for the EPS system in this study is a three-phase permanent magnet synchronous machine (PMSM). Here use the d-q frame through the rotation reference frame transformation to model the PMSM for achieving torque control by current control. The internal model control (IMC) method is applied to design the current control loop of the PMSM[3]. The controller was implemented by an embedded microprocessor. Fig.2 is the experimental result of the current response which was verified by a dyno.

III. AUTOMATIC PARKING SYSTEM

The APS is an auxiliary system which helps drivers having more convenience in parking. The major techniques of the APS system are parking trajectory planning and tracking. The APS framework is showed as Fig.3.

After the APS detects or the driver decides the parking space, the trajectory of the parking process is calculated, and the vehicle will follow it with the active steering control. The average front wheel angle will be first obtained by using the curvature of the path and the Ackerman steering equation showed as equation(5) where L is the wheelbase, R_i is the curvature of the partial path trajectory, δ_i and δ_{sw} is the steering angle of front wheel and the steering wheel angle at every curvature respectively, and k is the steering ratio. The sketch map is depicted as Fig.4, it is a two turn model for example, and point A is the reverse point of the steering wheel angle.

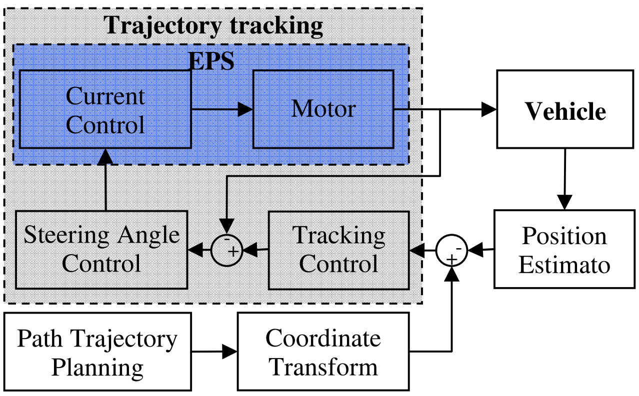

Fig.3. The APS framework

$$\delta_{sw} = k\delta_i = k(L/R_i) \tag{5}$$

While the front wheel steering angle is known, the steering angle control can be performed to achieve APS function. Because of the characteristics of the steering and suspension mechanism, the steering ratio is not a constant. In order to have precision steering angle of the front wheel, the relationship between front wheel steering angle and the steering wheel angle must be considered. The steering ratio of the experimental vehicle is showed as Fig.5.

During the automatic parking procedures, the steering wheel angle will vary with the vehicle position which can be obtained based on the accumulation as the equation(6) and (7).

$$x = x_0 + l\cos(\psi) \tag{6}$$

$$y = y_0 + l\sin(\psi) \tag{7}$$

where x and y are the current positions, x_0 and y_0 are the former positions, l is the distance travelled in the time interval, and ψ is the yaw angle which is calculated from the wheel speed signals of the two sides. The calculating equation is showed as equation(8) where L_w is the tread dimension, $\triangle l$ is the differential travelling distance between the left rear wheel

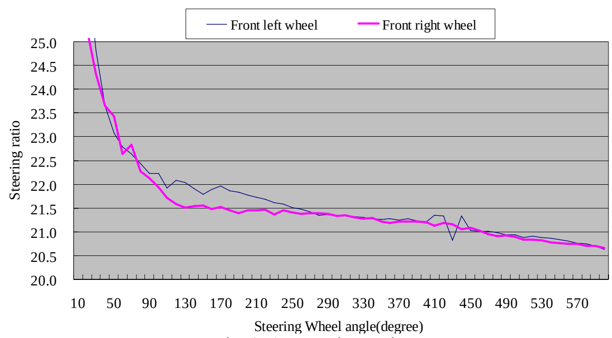

Fig.5. the steering ratio

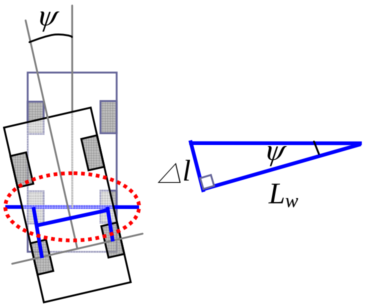

Fig.6. the geometric relationship of the yaw angle

and right rear wheel, V_l and V_r are the wheel speed of the left rear wheel and the right rear wheel respectively. The geometric relationship is showed as Fig.6.

$$\psi = \tan^{-1}(\Delta l / L_w) = \tan^{-1}\left[\left(\int V_l dt - \int V_r dt\right) / L_w\right] \quad (8)$$

In order to get the reverse timing of the steering wheel, the distance from the center of the rear axle of the vehicle to the reverse point of the steering wheel is necessary to monitor. The global coordinate is transformed to vehicle coordinate for the trajectory tracking algorithm of the reverse position works properly. The transformed equations are showed as bellow. Where x_g and y_g are the reverse point of the reversing of the steering wheel in global coordinate, x_{gv} and y_{gv} are the goal point in vehicle coordinate.

$$x_{gv} = (x_g - x_0)\cos(-\psi) + (y_g - y_0)\sin(-\psi) - l\cos(2\psi) \quad (9)$$

$$y_{gv} = (x_g - x_0)\cos(-\psi) - (y_g - y_0)\sin(-\psi) - l \quad (10)$$

IV. Steering Angle Control Strategy

The objective of the paper is to develop steering angle control strategies based on the current control loop to achieve the function of the parking trajectory tracking. In this section, the brief steering angle control algorithm (named as type1) will be discussed first, and a complete control algorithm (named as type2) will be proposed.

The type1 control algorithm is showed as Fig.7. It is simple to achieve the steering angle control with PI control strategy (C_{ap}) which doesn't consider the variation of the steering angle rate. The controller decides the motor current command according to the difference between the steering angle command and steering angle feedback.

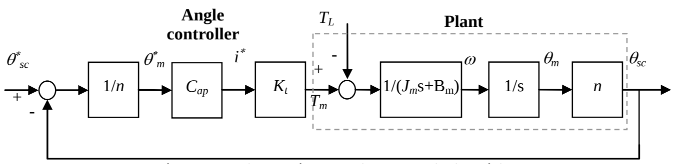

Fig.7. type1 steering angle control algorithm

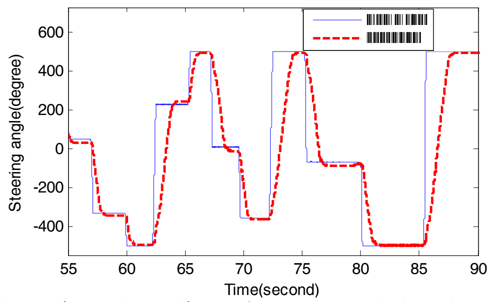

Fig.8.the steering angle tracking performance on asphalt road(type1)

$$C_{ap} = K_p + K_I / s \quad (11)$$

After the controller designed, the control algorithm was implemented in the EPS system to achieve the active steering angle control. The steering angle tracking performance is showed as Fig.8. It has good tracking performance at the large angle variation, but bad at the slight variation. If it has good performance at the slight varying interval, it will track badly at the large varying interval. The type1 control algorithm can't have the same tracking performance at the different angular degree varying interval.

Based on type1 control algorithm, the type2 control algorithm adds the steering angular velocity control into the loop. The type2 algorithm is showed as Fig.9. It is a complete steering angle control loop, which includes the steering angular velocity control loop and current control loop inside. C_{ap} and C_{av} are the controller for steering angle control and steering angular speed control respectively. *Sat* is the saturation of the steering angular speed command to restrain the maximum steering angular speed.

$$C_{ap} = K_{pp} + K_{Ip} / s \quad (12)$$

$$C_{av} = K_{pv} + K_{Iv} / s \quad (13)$$

The PI control strategy is also be utilized to design the controller as showed in equation (12) and (13). The performance is showed as below.

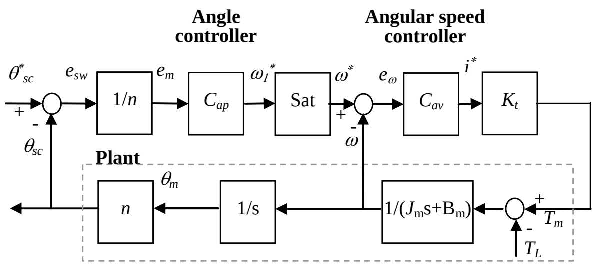

Fig.9. type2 steering angle control algorithm

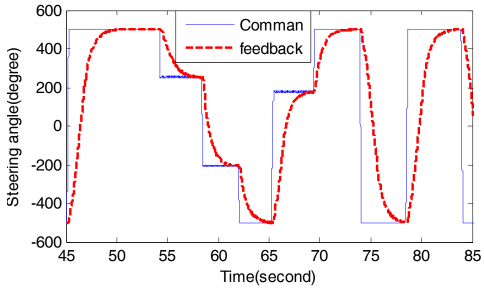

Fig.10. the steering angle tracking performance on asphalt road(type2)

Fig. 10 shows that the type2 control algorithm had good performance at different steering angle variation.

V. Experimental Result

The proposed steering control strategies were achieved on the experimental vehicle showed in Fig.11 equipped with Pinion EPS to compare the performance of those steering angle control algorithms which were applied to APS function. The two-turn model[1] was used for trajectory planning of parallel parking. The parameters of the experimental vehicle are showed as table1.

Taking the parameters of the vehicle into consideration, the path trajectory was planned as Fig.12. The different active steering strategies were utilized to achieve APS function with the trajectory, and the results of path tracking and some vehicle characteristics were compared as bellow.

Fig.11. the experimental vehicle

TABLE I

The parameters of the experimental vehicle

Items	value	unit
Length	4090	mm
Width	1570	mm
Height	1950	mm
Weight	1260	kg
Wheelbase	2610	mm
Tread(rear)	1395	mm
Tire size	165R13	
The resolution of the wheel speed sensor	1000	pulses/cycle
The steering angle of the steering wheel	-580~580	degree
The reduction gear ratio of pinion EPS	15	

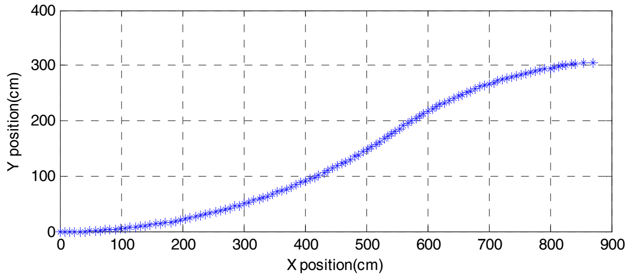

Fig.12. the path trajectory of the APS

The experimental vehicle performed automatic parking on the road surfaces with different friction which included the asphalt, cement and mix friction road.

Fig.13 demonstrates that, the type1 control algorithm has bad tracking performance on the different friction of the road surfaces with the same controller gain. The controller gain used in the asphalt road could get good performance, but when the road type is different, there were obvious tracking error at the end of the trajectory. If the tracking error wants to be eliminated, the controller gain needs to be retuned, or a complex control strategy needs to be used which has the function of self retune, like the adaptive control.

On the other hand, the type2 control algorithm using the same controller gain has the same performance on the road surfaces with different friction, showed as Fig.14. Without retuning the controller gain, the tracking performance is similar.

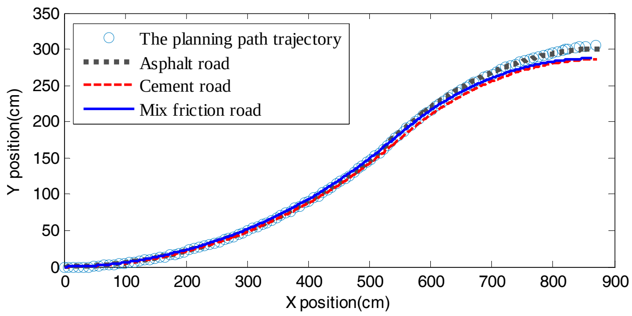

Fig.13. type1 control on different types of the road

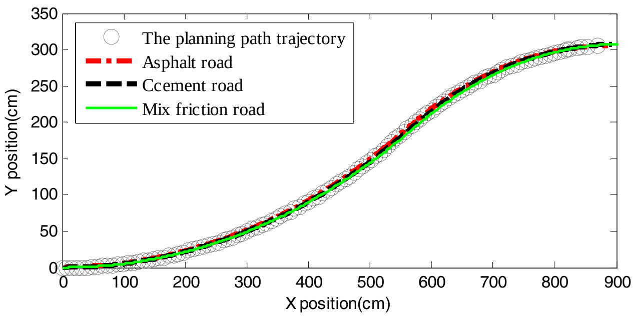

Fig.14. type2 control on different types of the road

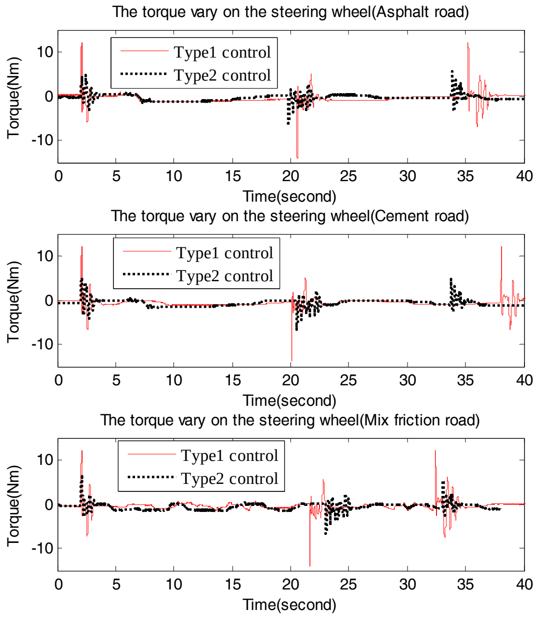

Fig.15. the torque varies acts at the steering wheel on different road types

The results show that the type1 algorithm can not handle the load variation. Therefore, the performance of the APS will be inconsistent in different environments.

Beside of the performance of the path tracking, the vehicle dynamic characteristics are also discussed. The characteristics include the torque varying on the steering wheel and the variations of the steering angle and steering angular velocity.

Fig.15 shows the steering torque detected by the EPS torque sensor during the experiments. The type2 control algorithm has the smaller torque variation on the steering wheel which is about half of the torque variation of the type1 control algorithm. The smaller torque variation on the steering wheel is better, because the torque variation represents the impact and the inertia effect acts on the steering mechanism and the torsion bar. The bigger torque variation may cause the vibration and even the damage of the steering mechanism.

As far as the steering angle rate is concerned. Fig. 16 shows the type1 control algorithm has sharp variation at the steering angle rate. The sharp variation also caused bigger torque variation on the steering wheel. And the level of the variation is not controllable on different road type. The type2 control algorithm take the steering angle rate control into account. As a result, the variation of the steering angle rate is not so sharp, and has the smooth characteristic at the point of the steering angular velocity returning to zero. It is like the damping effect, and the situation doesn't cause any overshoot or oscillation at steering angle control on any type of road.

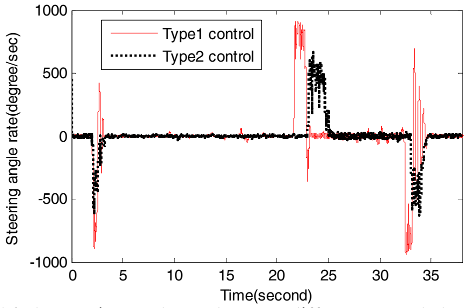

Fig.16. the steering angle rate between different control algorithms

Both two types of control algorithms are tuned on the asphalt road. There are no oscillation at steering angle tracking, showed as Fig.8 and Fig.10, but when the vehicle performed APS function acts on the different road, like the cement road, of which friction is smaller than the friction on the asphalt road. Some difference happened. The results showed in Fig. 17 and Fig. 18 reveal that although type1 has faster response time than type2, oscillation appeared before the steady state. In fact, the APS is enabled at low speed, normally less than 10 km/hr; therefore, the difference caused by response time is not significant. The other issue is that the steering wheel rotates too fast would make the driver feel scared, so the suitable steering angular speed of the steering wheel is needed to be considered. The trajectory tracking is more important if the multi-turn model is used in steering control of the APS function in the future. The good tracking ability will achieve good performance in multi-turn model.

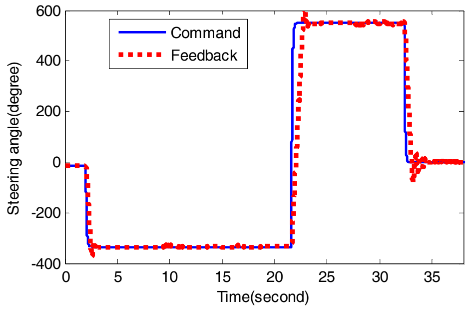

Fig.17. the angle tracking of the type1 control on cement road

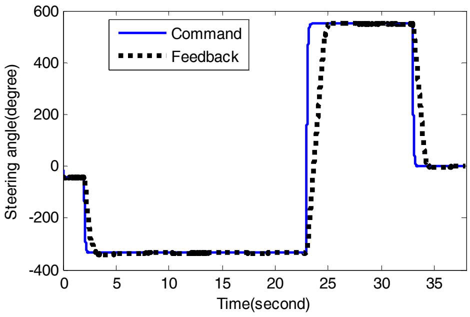

Fig.18. the angle tracking of the type2 control on cement road

VI. CONCLUSIONS

This paper has compared two types of steering angle control algorithm. The strategy which includes steering rate control has better performance of the APS in varing environment. It also has the advantage of compact code size which is crucial for embedded systems. In addition, controllable steering wheel angular velocity will be easier to satisfy drivers' feeling, which can let the APS become more friendly.

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