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Active disturbance rejection control in steering by wire haptic systems

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ABSTRACT

This paper introduces a steering by wired haptic system based on disturbance rejection control techniques. High gain Generalized Proportional Integral (GPI) observers are considered for the estimation of tire and steering wheel dynamic disturbances. These disturbances are on line canceled to ensure tracking between the commanded steering wheel angle and the tire orientation angle. The estimated disturbances at the steering rack are feedback to the steering wheel to provide a haptic interface with the driver. The overall system behaves as a bilateral master-slave system. Very few sensors and minimum knowledge of the dynamic model are required. Experimental results are presented on a prototype platform that consists on: (1) half of the steering rack of a beetle VW vehicle, (2) a steering wheel.

1. Introduction

The basic design of the automobile steering system has changed little since the steering wheel invention. The driver commanded direction is transmitted by a column or steering shaft, including universal joints and gearboxes, to the front tires. A major advanced on such system was introduced in 1950, with the hydraulic power steering system. Since then, the assistance unit has become standard in modern steering systems. Based on hydraulic pressure, the steering system complements the effort required by the driver to steer the vehicle. More recently, electrical assisted steering systems have been introduced, which eliminate the requirement of a hydraulic pump or diminished the required effort provided by the hydraulic power, giving rise to electro-hydraulic or electrical assistance to the rack [1,2].

As the automobile dynamics, safety and comfort are taking a major role on vehicle design [3], the steering system, or rather the interface between the driver and the vehicle, is becoming one of the most important parts of automobile design tasks [4–6].

Actually, the steering systems can be classified into three main groups:

1. Mechanical steering systems [7].
2. Hydraulic power and electro-hydraulic power systems.
3. Electric Power Assisted Systems (EPAS) [8–10].

Among the EPAS, there is a new technology called steering by wired (SBW), which main characteristic is to completely do away with as many mechanical components (steering shaft, column, gear reduction mechanism, etc.) as possible [11], see Fig. 1. Completely replacing conventional steering system with steer-by-wire exhibits several advantages, such as:

1. The absence of steering column simplifies the car interior design.
2. The absence of steering shaft, column and gear reduction mechanism allows much better space utilization in the engine compartment.
3. The steering mechanism can be designed and installed as a modular unit.
4. Without mechanical connection between the steering wheel and the road wheel, it is less likely that the impact of a frontal crash will force the steering wheel to invade into the driver's survival space.
5. Steering by wired system characteristics can easily be adjusted to optimize the steering response and driving feeling [12,13].

In general SBW systems allow better structures for crash energy absorption [14], as well as benefits related to passengers

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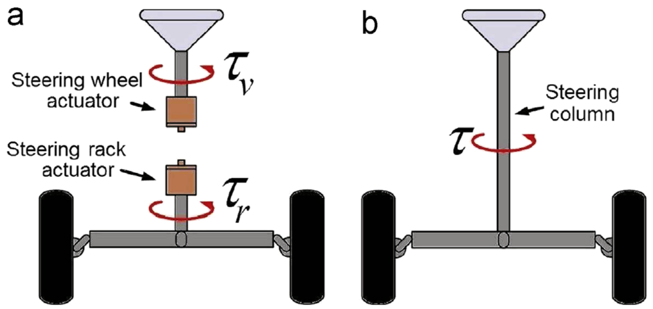

Fig. 1. (a) SBW; (b) conventional steering system.

comfort and driver feeling. In spite of all the advantages of SBW over conventional steering systems, there is a major issue related to what the driver feels through the steering wheel. The forces, torques and driving conditions transmitted by the steering wheel to the driver are important for a proper and safe vehicle driving. Therefore, the SBW must provide the driver the opportunity to "feel" what the road driving conditions are. As a consequence, the SBW mechanism must also behave as a haptic device [13,14].

There exist several dynamic models related to haptic SBW systems in the literature, [13–15]. In these models, uncertain and disturbance terms appear which affect the dynamics and the behavior of the SBW. Those terms include phenomena such as friction, damping, inertia, realigning forces, among others. The influence of those uncertain and disturbance terms is rather important to guarantee a good performance of the SBW and to provide a reliable feedback of the road and driving conditions to the driver. The previously mentioned phenomena can be regarded as perturbations since they are difficult to be known with certainty due to the changing conditions on the road and the driving, e.g., speed, roadway texture, tire wear, tire air pressure, rain, etc. For the purpose of determining the effects of such unknown disturbances, the use of observers has been proposed [11,16]. The implementation of such observers often requires the used of specialized sensors, such as GPS and INS, measurement of lateral acceleration [12], current and torque motors measurements [15]. On the other hand, most of the proposed observers highly rely on dynamic models of the phenomena that are present at the steering system, which usually are complicated models.

Furthermore, besides uncertainty on the dynamics phenomena, there exists also the problem of the model changes in accordance with the driving conditions. This makes it difficult to determine a precise mathematical model and control for the SBW strategy. Therefore, model free observers are suitable for estimating unmodeled dynamics and perturbations effects on SBW.

In this work a high gain Generalized Proportional Integral (GPI) observer [17] is considered for an Active Disturbance Rejection Control approach to the underlying trajectory tracking problems on the perturbed interconnected subsystems (steering wheel, steering rack subsystems). For background on Active Disturbance Rejection Control (ADRC) the reader is referred to [18,19]. The high gain GPI observer helps in determining the effects of uncertain dynamics phenomena and additive perturbations on the steering rack and tire, such as continuous and discontinuous friction, aligning forces, inertia effects, damping. The purpose of the high gain GPI observer is twofold: firstly to help a PD controller to actively reject dynamic perturbations, and secondly to provide the forces and torques that are fed back to the driver through the steering wheel, therefore closing a haptic loop. The proposed approach requires only the input gain of the systems, and it is robust against uncertainty on such gain, thus the knowledge of the SBW dynamic model is minimal. The proposed SBW behaves as a self-contained sensor for tire forces, since such forces directly influence vehicle dynamics. Although all uncertainties and dynamic perturbations are lumped into an estimated linear term, the approach shows a good performance and a proper estimation of the combined dynamic effects that are present at the SBW system. Different to other observer based approaches, as the previously mentioned, where full vehicle state feedback is required, the proposed approach is based only on angle position feedback, therefore, it can be implemented with common low cost encoder sensors as at the experimental platform here considered.

Experimental results on a real platform show a good agreement with the theoretical results that allow concluding convergence of the tracking and estimation errors to a small vicinity around zero.

2. SBW dynamic model

For modeling, control and implementation purposes the SBW system might be viewed as a bilateral master–slave system [20]. In such approach, the steering wheel acts as a master subsystem, and the steering rack is seen as a slave subsystem. Then both subsystems are interconnected through a PD controller with active disturbance rejection provided by a high gain GPI observer.

The dynamics of the master subsystem, in this case the steering wheel (Fig. 2), is affected by physical phenomena that are presented in its three fundamental components: the wheel, the reduction gearbox and the DC motor (Fig. 3). In particular the DC motor is in charge of reflecting to the driver the forces that are estimated by the high gain GPI observer from the dynamical phenomena presented on the steering rack and tire (slave subsystem). Uncertain dynamic effects and perturbation on the wheel subsystem are estimated by another high gain GPI observer and canceled through a PD controller with disturbance rejection. Dynamic effects on the steering wheel include discontinuous Coulomb friction, other works such as [12,20] considered that Coulomb friction phenomena affect only the steering rack and tire subsystem. However the used of a reduction gearbox induces discontinuous friction phenomena, even dead zones may occur depending on the reduction gear. Inclusion of Coulomb friction phenomena is in accordance with the experimental parameter estimation reported in this paper.

Fig. 3 shows an equivalent mechanical–electrical diagram of the master subsystem. It is shown how the dynamics of its three components are interconnected. For the electrical part the relevant parameters are, V_v the input voltage, L_v armature inductance, R_v armature resistance, i_v armature current, i_f current through the winding field, e_v electromotive force, k_2 electromotive force constant gain. Meanwhile, the mechanical relevant parameters are, ϕ_v output angle of the motor, J_1 inertia moment at the reduction input, B_1 damping coefficient at the reduction input, F_1 Coulomb friction coefficient at the reduction input, k_1 motor torque constant gain, τ_v' motor torque, F_{Tv} Coulomb friction coefficient at gearbox, B_{Tv} damping coefficient at gearbox, J_2 inertia moment at the reduction output, B_2 damping coefficient at the

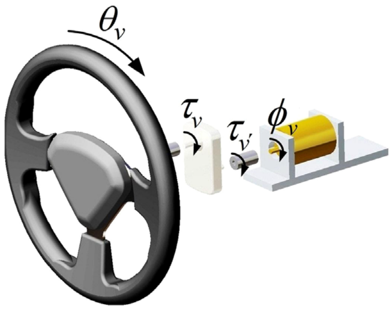

Fig. 2. Master subsystem: steering wheel, reduction and DC motor.

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