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IFAC-PapersOnLine 49-11 (2016) 182–189

Two-Degrees-of-Freedom Lateral Vehicle Control using Nonlinear Model Based Disturbance Compensation

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Abstract: Evasive pedestrian protection systems avoid imminent collisions with vulnerable road users via autonomous evasive maneuvers. For this purpose, a new lateral control scheme is presented in this paper. We propose a new two-degrees-of-freedom control structure consisting of a linear PDT_2 controller and a nonlinear model based disturbance compensation. By means of the latter component the highly nonlinear influence of the evasive trajectory's curvature (disturbance variable) to the lateral deviation (controlled variable) is compensated. In contrast to classical nonlinear control methods, the proposed control scheme does not require the measurement of the complete state vector.

Keywords: Autonomous Driving, Collision Avoidance, Two-Degrees-of-Freedom Control, Nonlinear Model Based Disturbance Compensation, Lateral Vehicle Guidance.

1. INTRODUCTION

1.1 Problem Description and Requirements

One focus of current research in the field of vehicle safety is on the development of evasive preventive pedestrian protection systems [Keller et al. (2011); Köhler et al. (2013); Jiménez et al. (2015)]. Such safety systems intervene in critical traffic situations, in which the resulting time to collision and thus the distance to the pedestrian is too short to avoid the accident by braking. An example of such a traffic situation is depicted in Figure 1. Here, a pedestrian unexpectedly crosses the street in front of an approaching car without paying attention to the vehicle. In order to avoid the collision, it is essential to perform an autonomous evasive maneuver.

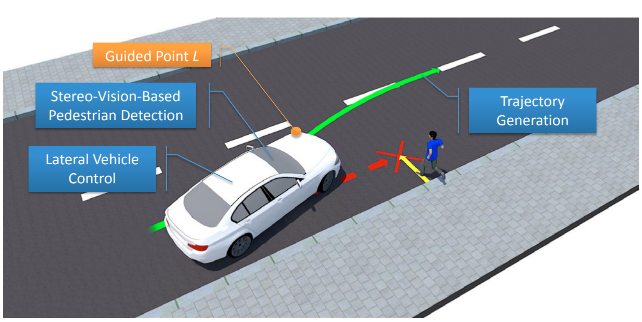

Fig. 1. Critical traffic situation and main components of an emergency steering system (blue parts)

In general, such emergency steering systems consist of three main components (blue parts in Figure 1). First, the detection of the pedestrian or even of the pedestrian's intention by means of, e.g., stereo-vision [Keller et al. (2011); Köhler et al. (2015)]. Second, the calculation of the evasive trajectory in order to maximize the distance to the pedestrian and, furthermore, to perform the evasive maneuver within the own lane. This is necessary in order to avoid an accident with the oncoming traffic. Note that unlike the green trajectory illustrated in Figure 1, the evasive trajectory is mostly planned for guiding the vehicle's center of gravity 'C' or a preview point 'P' located on the vehicle's longitudinal axis (see Section 1.2). The third component of an emergency steering assist corresponds to the lateral vehicle control to guide the vehicle autonomously on the generated trajectory.

The focus of this paper is on the development of a lateral vehicle guidance system for emergency steering assists fulfilling the listed requirements:

- In order to ensure a lane keeping evasive maneuver, the vehicle has to be precisely guided on the path.
- Since the vehicle is driving up to the nonlinear physical driving limits, the nonlinear tire characteristic has to be considered in the controller design.
- With regard to the application in series production vehicles, it is essential that the lateral vehicle control only depends on variables which can be measured by means of series production sensors.

1.2 Related Research

Numerous works in literature are dedicated to the design of lateral vehicle controllers. Most of these works propose the guidance of 'C' or 'P' by means of linear control methods. For instance, Katriniok et al. (2013) uses model predictive control, Saleh et al. (2010) applies an H_2 controller and Söhnitz and Schwarze (1999) as well as Heinlein et al. (2015) propose a two-degrees-of-freedom (2DoF) control

10.1016/j.ifacol.2016.08.028

structure. This structure consists of a linear disturbance compensation combined with an H_2 controller [Söhnitz and Schwarze (1999)] and, respectively, a PDT_2 controller [Heinlein et al. (2015)]. Both disturbance compensations are based on the inverted plant model and are, thus, subject to restrictions. Due to the linear plant model used for controller design, none of the mentioned controllers consider the required nonlinear tire characteristic. In consequence, an only insufficient control performance at the physical driving limits is achieved.

In order to precisely guide 'C' or 'P' even in highly dynamic maneuvers on the path, the control scheme has to take into account the nonlinear tire characteristic. To this, König et al. (2007) presents a lateral vehicle control by means of input-output linearization, Falcone et al. (2007) by means of nonlinear model predictive control and Saedodin et al. (2010) by means of variable structure control. However, these controllers have a major disadvantage in the view of the intended application in a series production vehicle: The nonlinear control methods require the measurement of all state variables, which can not be entirely provided by series production sensors.

Besides guiding 'C' or 'P' on a predefined path, Hahn et al. (2015) propose a new lateral control scheme for guiding the vehicle's front left corner 'L' (orange parts in Figure 1) on an evasive trajectory (green line in Figure 1) ending up on the center line of the road. Based on a new model of sixth order considering the nonlinear tire characteristic as well as the highly nonlinear dynamics and kinematics of 'L', the method of input-output linearization is applied and a precise track guidance of the vehicle is achieved. The main advantage of this approach is that the free space within the own lane is optimally exploited during the evasive maneuver. However, this is also associated with the requirement of measuring the complete state vector.

Another approach is to use a nonlinear observer to estimate the vehicle dynamics state variables which can not be measured by means of series production sensors. However, due to the complexity of calculation and, furthermore, due to the problem of proving closed-loop stability caused by the violation of the separation theorem in the resulting nonlinear control loop [Adamy (2014)], this approach is not further considered.

1.3 Proposed Solution and Main Contributions

As shown in Subsection 1.2, commonly known nonlinear control methods require the measurement information of the complete state vector, which is disadvantageously for the intended application of an emergency steering system for series production vehicles. In contrast, by using a linear output feedback control based on the linearization of the plant, crucial nonlinearities are neglected. Hence, a new control scheme has to be developed in order to fulfill the requirements listed in Section 1.1.

We propose a new 2DoF control structure consisting of a linear output feedback controller extended by a nonlinear model based disturbance compensation, which is designed referring to the linear model based feedforward control presented in Roppenecker (1990). The main idea is to realize an own control loop inside the disturbance compensation. I.e., within the compensator the nonlinear model of the plant is controlled by means of a nonlinear control method. Hence, the control signal of the compensator is determined in dependence on the *calculated* states of the plant model, not on the measured ones. In order to parametrize the internal plant model with regard to the current operating point, only the velocity of the vehicle and the curvature of the evasive trajectory have to be measured. In case of lateral vehicle guidance, the curvature is, in general, assumed as disturbance variable [Söhnitz and Schwarze (1999); Saleh et al. (2010); Katriniok et al. (2013); Heinlein et al. (2015); Hahn et al. (2015)].

Since a lane keeping evasive maneuver has to be performed, we also propose the guidance of the front left corner 'L' in order to exploit the free space within the own lane optimally [Hahn et al. (2015)]. Hence, the plant model inside the disturbance compensation includes not only the nonlinear tire characteristic, but also the highly nonlinear dynamics and kinematics of 'L'.

In the next section, the proposed 2DoF control structure is explained in detail. Afterwards, the plant model comprising the dynamics and kinematics of 'L' is derived and analyzed in Section 3. Based on this model the linear output feedback controller as well as the nonlinear disturbance compensation is designed (Section 4).

Furthermore, Section 5 contains the implementation of the proposed control structure in the prototype vehicle and its validation on a testing ground by means of the safety critical traffic scenario with pedestrian involvement (replicated by a pedestrian dummy) shown in Figure 1. Additionally, the performance of the control concept is compared to the performance of the nonlinear state controller presented in Hahn et al. (2015) and to the performance of the linear 2DoF control scheme proposed in Heinlein et al. (2015).

The paper ends with a summary and an outlook on future research objectives (Section 6).

2. TWO-DEGREES-OF-FREEDOM CONTROL STRUCTURE

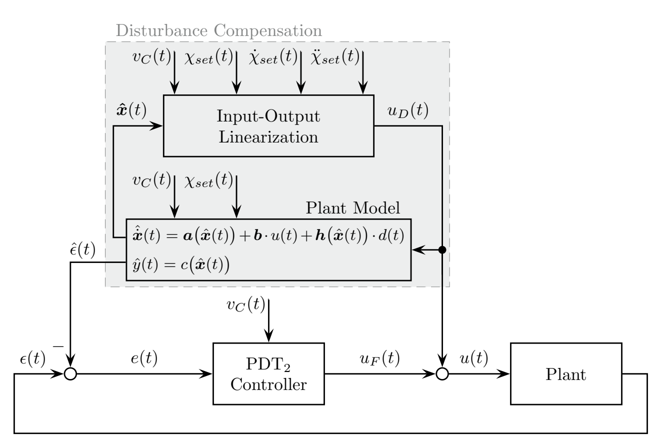

Fig. 2. Structure of the proposed lateral vehicle control

As depicted in Figure 2, the 2DoF control consists of a linear PDT_2 controller (Section 4.1) and a nonlinear model based disturbance compensation (Section 4.2). The latter component serves to compensate the influence of the