Control Engineering Practice 41 (2015) 98–112

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Nonlinear model-based track guidance of user-defined points at the vehicle front

Stefan Hahn [a,*], Klaus Zindler [a], Ulrich Jumar [b]

[a] University of Applied Sciences Aschaffenburg, Würzburger Str. 45, 63743 Aschaffenburg, Germany
[b] ifak - Institute of Automation and Communication, Werner-Heisenberg-Str. 1, 39106 Magdeburg, Germany

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
20 March 2015
Accepted 10 April 2015
Available online 22 May 2015

Keywords:
Nonlinear lateral vehicle control
Track guidance
Feedback linearization
Input–output linearization
Reproducible driving test
Automated testing

ABSTRACT

Preventive pedestrian protection systems are validated by means of fully automated driving tests reproducing safety-critical traffic situations on a proving ground. In order to assess these preventive safety systems, a precise and reproducible collision of a pedestrian dummy with a specific point at the vehicle front, e.g., the left corner of the vehicle, must be ensured. Hence, a track guidance of this specific point is required. Beyond the state of the art a new nonlinear model describing the lateral deviation of any point at the vehicle front to a predefined path is proposed in this paper. Based on this model the method of input–output linearization is used to design a flexible lateral guidance system for an easy application in different vehicles. Furthermore, the closed-loop stability is proven and experimental results are presented.

1. Introduction

1.1. Problem description and requirements

Preventive pedestrian protection systems (Coelingh, Eidehall, & Bengtsson, 2009; Darms et al., 2009; Gandhi & Trivedi, 2007; Keller et al., 2011; Köhler et al., 2013) are evaluated by means of driving tests reproducing safety-critical traffic situations with pedestrian involvement on a testing ground. The corresponding scenarios have been proposed by industrial working groups (e.g. vFSS, 2012 and AEB-Group, 2012) as well as public funded projects (e.g. AsPeCSS, 2014). These proposals also include the requirements and tolerances towards the velocities and positions of the Vehicle Under Test (VUT) as well as of the pedestrian, replicated by a movable dummy. More precisely, the maneuver has to be accomplished 10 times (vFSS) with a maximal lateral deviation of ± 0.1 m of the vehicle front's center—which corresponds to the proposed impact point—to the path (vFSS and AEB).

Extensive studies show that a human test driver is not able to fulfill these requirements (Zindler, Hahn, Zecha, & Juergens, 2012). Therefore, the maneuvers have to be accomplished fully automated. This automation implies that the VUT to be equipped with a lateral and longitudinal guidance system. In order to ensure an efficient testing, the control algorithms should be applicable in different vehicles without a complex and time-consuming redesign. Furthermore, it is necessary to synchronize the positioning of the pedestrian dummy to the vehicle movement (Heinlein, Hahn, & Zindler, 2015).

Since a collision with a pedestrian can occur at each point at the vehicle front, it is also advisable to validate the preventive safety system in situations where the impact point is located at the left or right half of the front (Ando & Tanaka, 2013; Wisch et al., 2013).

Fig. 1 illustrates this testing method on the example of a typical as well as critical turning maneuver. AsPeCSS classifies such a turning maneuver as an *enhanced test scenario* and recommends it to consider for validating the safety system. Both, the VUT as well as the pedestrian dummy, are moving with constant velocities v_{Veh} and v_{Ped} towards the collision point P_{Coll}. In this example, the collision shall occur at the left corner of the vehicle front.

In accordance with the proposals of the industrial working groups and public projects, the requirements to the needed lateral guidance system for validating preventive safety systems in these enhanced test scenarios can be summarized as follows:

- compliance of the desired impact point I and the actual impact point with a maximal lateral deviation of ± 0.1 m,
- equally high reproducibility (maneuver has to be driven 10 times) up to 60 km/h = 16.67 m/s,
- easy handling and application in different vehicles without complex redesign.

* Corresponding author. Tel.: +49 6021 4206 841.
E-mail addresses: stefan.hahn@h-ab.de (S. Hahn), klaus.zindler@h-ab.de (K. Zindler), ulrich.jumar@ifak.eu (U. Jumar).

http://dx.doi.org/10.1016/j.conengprac.2015.04.001
0967-0661/

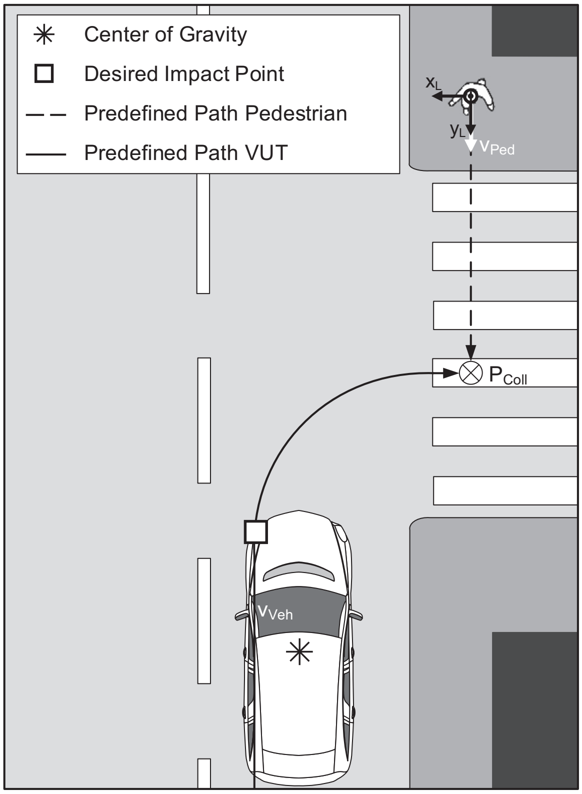

Fig. 1. Enhanced test scenario according to the working group AsPeCSS (see Wisch et al., 2013).

1.2. Evaluation of existing solutions

The lateral control concepts known from literature used for the automated testing as well as for further applications can be divided into two sections: first, the control of the vehicle center of gravity (see, e.g., Falcone, Borrelli, Asgari, Tseng, & Hrovat, 2007; Fukao, Aoki, Sugimachi, Yamada, & Kawashima, 2013; Hurich, Luther, & Schöner, 2009; Katriniok, Maschuw, Christen, Eckstein, & Abel, 2013; Meier, Roppenecker, & Wurmthaler, 2004; Schorn & Isermann, 2006; Söhnitz & Schwarze, 1999; Schöner, Neads, & Schretter (2009, 2011); Watts & Pick, 2008; Zindler et al., 2012) and second, the control of a so-called *preview point* located on the vehicle longitudinal axis to a predefined path (see, e.g., Benine-Neto, Scalzi, & Mammar, 2011; Enache, Mammar, Glaser, & Lusetti, 2010; Guldner et al., 1999; Hahn, Heinlein, & Zindler, 2012a Hahn, Heinlein, & Zindler, 2012b, 2013; Heinlein et al., 2015; Hernandez & Kuo, 2003; Kessler, Hakenberg, Deutschle, & Abel, 2010; König, Neubeck, & Wiedemann, 2007; Moon, Kim, & Lee, 2011).

In the following it will be examined, if these concepts comply with the aforementioned requirement to establish a collision with an impact point located at the left corner of the vehicle front.

For this purpose, the experimental results of an automated test drive (see Fig. 2) of the maneuver shown in Fig. 1 are analyzed. Here, the vehicle center of gravity C (dark dashed line) is controlled on the predefined turning path (solid line). The VUT drives with a constant velocity of $v_{Veh}=20$ km/h$=5.56$ m/s, while the dummy moves with $v_{Ped}=10$ km/h$=2.78$ m/s. Although the lateral control guarantees the guidance of C with only minimal deviations to the path, the desired impact point I (square) does not comply with the actual impact point. More precisely, the analysis reveals an offset of $dx_L=0.18$ m and $dy_L=-1.07$ m in the local coordinate system. Note, that the origin of this coordinate system lies at the starting point of the pedestrian.

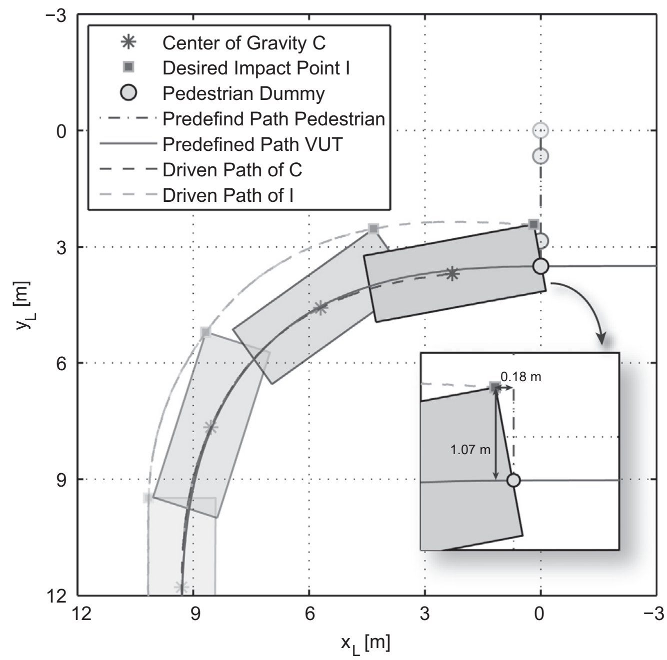

Fig. 2. Experimental results of guiding the vehicle center of gravity, using a PDT$_2$-controller (Hahn et al., 2012a, 2013; Heinlein et al., 2015).

Moreover, the ordinate corresponds to the walking direction of the dummy whereas the abscissa points to the right of the dummy.

Furthermore, it has to be stated that the offset dx_L and a major part of dy_L are caused by the yaw angle of the vehicle. Since such offsets would also occur in case of guiding the vehicle front center on the path, the secondly mentioned approach of guiding a preview point would also not ensure the consistency of the desired and actual impact point.

Hence, the lateral guidance systems known from the literature cannot be used without modifications for the validation of preventive pedestrian protection systems in enhanced test scenarios.

1.3. Proposed solution and paper outline

One obvious approach would be shifting the predefined path calculated with regard to C according to the identified lateral and longitudinal offsets. However, these offsets depend on the geometry of the trajectory itself, to the location of the desired impact point, to the vehicle dimension and to its dynamic behavior (which depends, in turn, on its velocity, see Section 2.2). In consequence, for *each* individual test of a preventive safety system accurate closed loop simulations, preferably real world measurements, ought to be performed in order to determine the offsets precisely. Since various vehicles have to be tested in different scenarios with also different velocities, a redesign of the predefined path according to the mentioned parameters would be complex, time-consuming and thus expensive. Consequently, this approach does not comply with the requirement of an easy handling (see Section 1.1).

A more useful approach is to calculate the predefined path with regard to I and, furthermore, to guide this specific point on the trajectory. Hence, the lateral control system itself has to ensure the guidance of any desired impact point on the predefined path.

This paper presents a new method for the automated validation of preventive pedestrian protection systems in enhanced test scenarios. The proposed solution consists of a new model describing the lateral deviation of the freely definable impact point I at the vehicle front to a predefined path. This model comprises the dynamics of I, which differ substantially from those of the vehicle