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Investigation of vehicle motion control process due to the linearization of the lateral dynamics reference model used in the controller

Mirosław Gidlewski[a,*], Dariusz Żardecki[b]

[a] University of Technology and Humanities in Radom, Automotive Industry Institute (PIMOT), Poland
[b] Military University of Technology (WAT), Automotive Industry Institute (PIMOT), Poland

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ABSTRACT

Automatic control of vehicle motion often requires applying simple reference mathematical models in the controllers. Of those the so-called "bicycle model" is the simplest and most popular for the description of lateral dynamics of a two-axle motor vehicle. This one-mass linear model describes velocity relationships in the local coordinate frame (attached to the vehicle body). Calculation of the trajectory in the global coordinate frame (connected to the road) requires trigonometric transformations, and the model of the vehicle motion is in fact nonlinear. Applying classical control theory, developed for linear systems, is impossible unless the linearization of the nonlinear model is permissible. Implementation of the linearized system model in the synthesis of the control algorithm requires detailed studies, as well as the sensitivity analysis.

A similar problem had to be solved in the project on automation of the lane change manoeuvre. The controller was built on the basis of the linearized vehicle model. This article reports the most important details of the solution, and especially some results of simulations of the control process based on the linearization of the vehicle "bicycle model" in the global coordinate frame. The virtual object to be controlled was a lorry of medium load capacity modelled as a detailed multibody nonlinear system.

1. Introduction

Contemporary vehicles become more and more automated. Various driver assistance systems, facilitating vehicle driving in road traffic conditions or even automating the execution of certain vehicle manoeuvres carried out at low speeds, e.g. parking, are frequently offered as a standard feature. Studies of control systems developed to automate traffic manoeuvres at high driving speeds, such as vehicle passing or obstacle avoidance, are being carried out at many research centres. The manoeuvres of this kind are difficult to be automated, because in this case the vehicle is a challenging dynamic system. Its lateral dynamics is unstable and susceptible to changes in many parameters, and its trajectory is strictly limited.

The lane change manoeuvre is one of the basic manoeuvres out of which sequences of complex manoeuvres can be composed, e.g. vehicle passing or obstacle avoidance manoeuvre. Note that obstacle avoidance may occur in a very critical situation, when an object appears suddenly ahead at the distance shorter than the estimated distance needed for stopping the vehicle. For these reasons, automation of the lane change manoeuvre seems to have fundamental significance for automation of vehicle driving and is already a subject of numerous research [3,5,12–14], as well as technological projects.

Publications on automation of the lane change manoeuvre usually refer to a concept of automatic control including automatic determination of the desired path of travel, and then automatic execution of the assigned trajectory as a problem of tracking and control (regulation). Then, planning a trajectory is sometimes treated as a problem of parametric optimization for heuristically assumed form of a shape function of the desired path (segments of linear and sinusoidal function, composition of arcs, etc.). Such optimization of the path should take into account not only short manoeuvre duration, desired smoothness of the trajectory,

* Corresponding author.
E-mail addresses: miroslaw.gidlewski@gmail.com, miroslaw.gidlewski@uthrad.pl (M. Gidlewski), d.zardecki4@upcpoczta.pl, dariusz.zardecki@wat.edu.pl (D. Żardecki).

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limitation of side jerk sign, but also take into consideration the goal of acceptable execution of the tracking process (choice of the travel path shape has an impact on the tracking errors). Tracking and control systems proposed in the published literature are based on structures and algorithms that are known from control theory. Certainly, parameters of analysed vehicle, therein also parameters of its steering system, have significant influence on the choice of optimal path of travel as well as the choice of tracking and control systems.

Within the research project NN509568439, extensive analytical studies have been undertaken on application of the active steering system EPS (Electric Power System) in automatic driving of a vehicle in traffic situations threatening an accident because of a suddenly appearing obstacle. As a case study, a lorry of medium load capacity was chosen, equipped with typical elements of ECS (Electronic Stability Control) system and obstacle detectors, as well as road monitoring systems.

The authors' concept of the control system for active steering system is based on the "bicycle model" transferred to the global coordinate frame and then linearized and simplified by omitting small dynamical terms in the transfer functions. This model is used in the generator of set point trajectories as well as for the synthesis of linear regulators. Because of the simplicity of the algorithms they can be executed in real time. The controller's algorithms were tested in many simulations involving the model of a lorry of medium load capacity which had been modelled with details as a multibody nonlinear system. The control system and preliminary investigations were presented at several international conferences [7–9].

The general information on the control system, and especially new and more comprehensive results of its investigations for various conditions of vehicle operation (various loading, etc.) are presented in this article.

2. Concept of the control for the lane-change manoeuvre

The control strategy is based on the decomposition of the lane-change manoeuvre into two phases (Fig. 1).

The decomposition of the control process is consistent with vehicle driving practiced by experienced drivers. In the first phase, the control can be done in a partly-open system ("blindly", "quickly") by generating an appropriate turn of the steering wheel. The precision of this phase of the manoeuvre should be ensured by an earlier identified reference model. Corrective error compensation will also take place during this phase of the control process. Within this correction, the steering wheel turning angle is adjusted based on the principle of regulation. The regulation error is defined as the difference between the vehicle lateral position according to the reference model and its actual measured value. In the second phase, the control process is run in a closed loop, on the principle of regulation based on comparing the values representing the desired and actual angular orientations of the vehicle. Note that the general idea of decomposition of the control process into several phases has a solid theoretical background in the Bellman's principle of optimality [2].

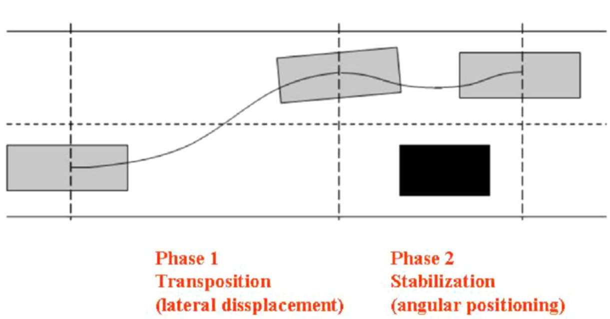

Fig. 1. Concept of decomposition of the lane-change manoeuvre into time-related phases.

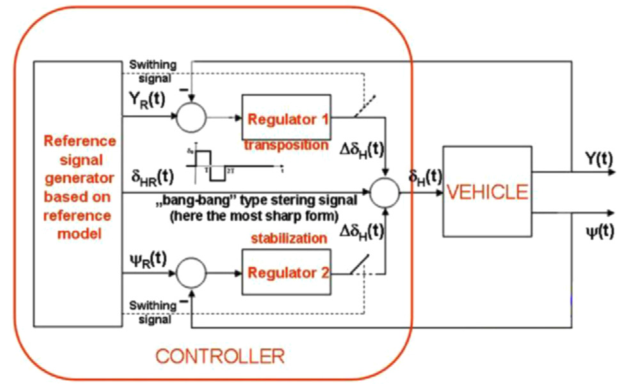

Fig. 2. Block diagram of the automatic control system.

According to the adopted concept, the two-phase control process (trajectory shift and angular stabilization) is carried out in one switchable control system (Fig. 2).

The block diagram of the control system shows its main components. Based on the reference model, the generator unit generates reference signals, which represent time histories of the steering wheel turning angle $\delta_{HR}(t)$, the lateral displacement of the vehicle relative to its initial position $Y_R(t)$, and the vehicle yaw angle relative to the road centre line $\psi_R(t)$. The signal of primary importance is the "bang-bang"-type control signal $\delta_{HR}(t)$ [1], applied as an input to the vehicle system and, in its simplest form, representing a combination of Heaviside step functions. The reference curves $Y_R(t)$ and $\psi_R(t)$ are inputs to the regulator used for correcting the vehicle path. Note that the "bang-bang"-type form of the control signal $\delta_{HR}(t)$ can be formally defined as the solution of the "minimum time" problem for a single-mass object on the basis of Pontriagin's "maximum principle" theorem [2].

In the first phase of the control process, the lateral displacement system is on (activated) and the angular stabilization system is off (deactivated); in the second phase, those roles are reversed. The switching over takes place when the vehicle mass centre reaches the lateral position which ensures obstacle avoidance.

The curve representing the reference lateral displacement $Y_R(t)$ is determined by generating the control signal $\delta_{HR}(t)$ ensuring that the acceleration and velocity calculated from the reference model would be within acceptable limits and that the final state could be achieved before the acceptable maximum time. In the case when the reference model has the form of a system of linear equations of motion (obtained by appropriate linearization of the initial reference model), the control parameters can be determined in a relatively simple way—thanks to the Laplace transformation and properties of the transforms. That ensures that the calculations can be carried out in real time. The reference curve of the vehicle yaw angle is represented by the relation $\psi_R(t) = 0$.

Let's note that the algorithms of Kalman regulators [2] are also based on the knowledge of the reference model in its linear version [1,7,16].

The algorithms generating the reference signals and the corrective signals of vehicle wheel steer angles constitute a basis for the active steering system controller. In the simplest design, the steering wheel turning angle $\delta_H(t)$ can be treated as a scaled value of the vehicle wheel steer angle $\delta(t)$. In more sophisticated versions, corrective terms can be introduced to account for the dynamics of the steering system.

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