Real-Time Simulation of Vehicle Dynamics: On-line Control and Handling Investigations

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1. Introduction

For improving car handling and safety, active vehicle control units become increasingly important. E.g., the new Mercedes A-Class subcompact is now being equipped with the "Electronic Stability Program" (ESP) for safety reasons, because it reduces the risk of flipping over during extreme maneuvers. The active control unit ESP makes the car more safe and comfortable in handling. Similar sensor controlled units are offered by most other car manufacturers such as BMW and Audi. Besides the stability programs many other active control units, as the well known anti-lock braking system (ABS) and active axle components are investigated [1].

Tests with real prototypes of cars are expensive and time consuming. Therefore development of cars, especially of active vehicle control components, requires numerical simulation of vehicle dynamics. Computer simulation can be used for various tasks, e.g., for suspension tuning or for ride comfort and handling investigations. A virtual prototype has to perform standard maneuvers as the ISO lane change, the ISO slalom test, or the now famous "moose test". Also, it can be guided along any test course. Effects at the driving limits as spinning, sliding or even flip overs have to be simulated correctly. Modern vehicle dynamics simulation tools are needed in order to make rapid prototyping possible.

Tests of vehicle components are performed in so-called Hardware-in-the-Loop (HIL) test stands, where only the unit to be tested is present as part of the hardware, whereas the full vehicle dynamics, the road and the driver are simulated by computer software *in real time*. The hardware, e.g., an ABS control unit, receives "sensor" signals from the simulated car ride in the same way as from a real one. The output and effect of the active control unit, e.g., brake pressures, are measured and provided as input to the simulation (cf. Fig. 1).

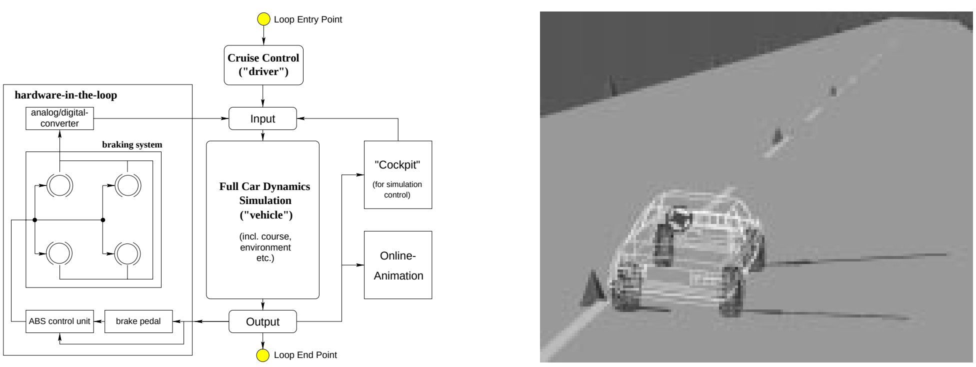

Figure 1: Scheme of a Hardware-in-the-Loop (HIL) test stand for an ABS system (left). Lateral forces in the numerical simulation of a BMW 325i car performing the ISO slalom test (right).

In this talk we will describe the real time vehicle dynamics simulation program *VEDYNA* due to Rill [4] and TESIS Dynaware GmbH [6] used in HIL test stands, and a new guidance scheme, which makes standard handling tests and general driveability investigations possible.

2. Numerical Simulation of Vehicle Dynamics

For dynamical simulations, cars are modeled as multi body systems (MBS), i.e., systems of rigid bodies, together with tire models, kinematic links, force elements (springs, dampers, etc.) and active components. General purpose methods for simulation of MBS like *ADAMS* [3] or *SIMPACK* [5] may be very time consuming, since the computation of one real time second of full car dynamics with *ADAMS* may take up to 8000 seconds CPU-time [7]. The real time simulation tool *VEDYNA* utilizes the structure of the vehicle MBS and a specially adapted, efficient integration algorithm and optionally a mulit-processor hardware. The model is divided into basically three parts: a system of nine rigid bodies for the car structure, a submodel for the drive train and a submodel for the steering system and the tires. The tire forces are computed by a semi empiric tire model [4].

The mathematical description of the MBS results in a system of 24 first order ordinary differential equations (ODE) for the vehicle body and the axles (6), (7) and 8 differential equations for the tires (1). A model of the power train is given by 19 differential equations including four equations for the angular velocities of the wheels (4), (5). Five differential equations describe the dynamics of the steering system (2), (3).

$$
\begin{aligned}
D\,\dot{y}_T(t) &= F_{stat} - C\,y_T(t) && (1)\\
M_S\,\dot{z}_S(t) &= Q_S(y_S(t), z_S(t)) && (2)\\
\dot{y}_S(t) &= V_S(t)\,z_S(t) && (3)\\
M_P\,\dot{z}_P(t) &= Q_P(y_P(t), z_P(t)) && (4)\\
\dot{y}_P(t) &= V_P\,z_P(t) && (5)\\
M_V\,\dot{z}_V(t) &= Q_V(y_V(t), z_V(t), y_S(t), z_S(t), y_P(t), z_P(t)) && (6)\\
\dot{y}_V(t) &= K_V^{-1}(y_V(t))\;z_V(t) && (7)
\end{aligned}
$$

Here, $y_T : \mathbb{R} \to \mathbb{R}^8$ are eight coordinates for the lateral and longitudinal deviations of the tires, D, C denote diagonal matrices of damping and stiffness coefficients and F_{stat} are forces computed by a statical, semi empiric tire model. We have generalized, minimal coordinates $y_S : \mathbb{R} \to \mathbb{R}^2$ (steering), $y_P : \mathbb{R} \to \mathbb{R}^7$ (power train), $y_V : \mathbb{R} \to \mathbb{R}^{12}$ (vehicle) and generalized velocities $z_S : \mathbb{R} \to \mathbb{R}^3$, $z_P : \mathbb{R} \to \mathbb{R}^{12}$, $z_V : \mathbb{R} \to \mathbb{R}^{12}$. Some simplifications of the equations (6), which utilize the structure of the vehicle, and a specially adapted semi implicit Euler algorithm make numerical integration of the system *in real time* on a multi-processor hardware equipped with five TI C40 processors possible. This allows usage of the vehicle dynamics simulation in HIL test stands, e.g., at Audi AG. *VEDYNA* is now also used for fast, realistic simulation of vehicle dynamics at several other companies, such as BMW, Ford and Denso. For *VEDYNA* an advanced road model has been developed recently which is easy to use and able to provide almost any realistic road situation [8]. Also a first version of a guidance scheme for the virtual car [8, 9] has been investigated.

3. Online Control of Cars and Handling Investigations

The simulation program *VEDYNA* provides a virtual "driver", which is able to guide the virtual car along a nominal track on a virtual road at high speed and in extreme maneuvers where skidding and sliding effects take place. This first version of a synthetical driver is basically a nonlinear position control law, which controls the position of the center of gravity of the car. The input of the control law is the current position and velocity of the center of gravity and the position of a set point ("target"), where the center of gravity is supposed to be [2, 8, 9]. The output of the control law are values of the front lateral

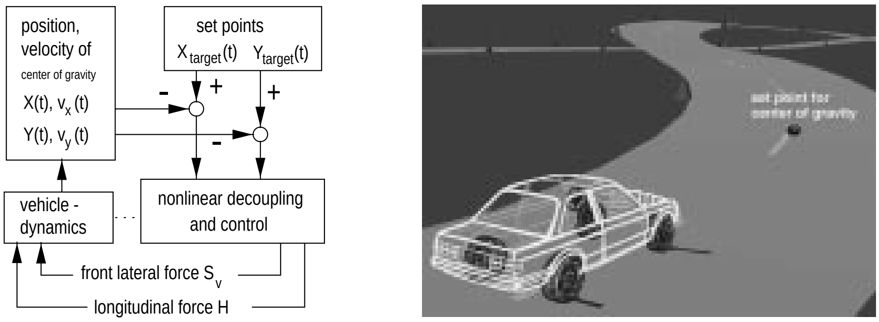

Figure 2: The closed loop control with nonlinear control law (left). The set point for online guidance of full car dynamics simulation and the actual position of the virtual car (right).

force S_V and the longitudinal force H which have to be achieved by choosing appropriate steering angles and brake/gas pedal positions in the virtual car.
The set point for the center of gravity travels along a nominal track with certain speed, which can be prescribed or computed online depending, e.g., on the data of the car and the curvature of the road. The purpose of this guidance scheme is not to simulate specific human driver behavior rather than to investigate objective dynamical car properties. Nevertheless, a performance close to human test drivers is desired, e.g., to guide a car accurately along a nominal track even at high speed. First results demonstrate that the guidance scheme, the "virtual driver", keeps the center of gravity near the nominal track in various situations at the driving limits.
This allows the guidance scheme to be used for handling investigations as the ISO lane change, the ISO slalom test or the "moose test".

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