

New Motion Cueing Algorithm for Improved Evaluation of Vehicle Dynamics on a Driving Simulator

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ABSTRACT

In recent years, driving simulators have become a valuable tool in the automotive design and testing process. Yet, in the field of vehicle dynamics, most decisions are still based on test drives in real cars. One reason for this situation can be found in the fact that many driving simulators do not allow the driver to evaluate the handling qualities of a simulated vehicle. In a driving simulator, the motion cueing algorithm tries to represent the vehicle motion within the constrained motion envelope of the motion platform. By nature, this process leads to so called false cues where the motion of the platform is not in phase or moving in a different direction with respect to the vehicle motion. In a driving simulator with classical filter-based motion cueing, false cues make it considerably more difficult for the driver to rate vehicle dynamics. A team with members from the University of Stuttgart, Cruden B.V., and AUDI AG developed a new motion cueing methodology for the use in a driving simulator dedicated to vehicle dynamics. The new algorithm is a track based approach that makes use of the vehicle's position on the track and does not use high-pass filters. It therefore allows minimization of false cues, thereby giving the driver the best possible information on the handling qualities of the car. In this paper, the basic principles of the algorithm are described, as well as the implementation in a driving simulator. Comparison with data from a handling track shows the advantages of the new methodology over the classical motion cueing approach.

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INTRODUCTION

Driving simulators have become a valuable tool in the design and validation process in the automotive industry. In the field of motorsport they are widely used for driver training, race preparation, as well as vehicle development. For investigations on human factors, such as ergonomics or also acceptance of driver assistance systems, simulators allow reproducible and cost efficient experiments. Yet, in the field of vehicle dynamics, most decisions are based on test drives in real prototype cars. Part of this can be attributed to the fact that driving simulators often do not allow the driver to evaluate the handling qualities of the simulated vehicle. The driver in the simulator perceives inconsistent or wrong information on the vehicle states compared to an evaluation in a real car.

Most advanced driving simulators use motion platforms which can improve the perceived realism and increase driving performance [1], [2], [3]. The generated motion cues can help the driver in understanding the vehicle behavior and thus, allow better control of the vehicle. The limited platform workspace however, does not allow a one-to-one representation of vehicle motion by the motion platform. Therefore, motion cueing algorithms were developed to derive a control input for the motion platform that approximates the vehicle accelerations, while maintaining the workspace limits. Depending on the use case for the simulator, different requirements for the motion cueing can be identified. The next section provides insight in a variety of motion cueing algorithms and discusses their suitability for the use in vehicle dynamics evaluation.

For many driving simulators the motion cueing algorithms used, are based on an algorithm known as “classical washout”. This algorithm has been known from flight simulation since the ‘70s [4], [5] and its basic structure can be seen in Figure 1. The classical washout uses high-pass filters on the translational and rotational motion of the vehicle to remove the large motion produced by steady-state vehicle movements. The high-pass filters in combination with appropriate scaling factors keep the platform motion within the platform limits. Additional washout filters aim at pulling back the platform to its center position below human perception thresholds.

For sensation of stationary lateral or longitudinal accelerations, the algorithm uses a technique known as tilt coordination where the low-pass filtered translational vehicle motion is transformed into platform tilt motion. As the human sensory apparatus cannot sense rotational orientation, the gravitational force in the tilted orientation is perceived as lateral/longitudinal acceleration. However, the vestibular organ can sense roll velocities above specific thresholds ranging from 1 °/s to 6 °/s [6]. Therefore the tilting rate of the motion platform should be limited such that it is not possible to sense the tilting process.

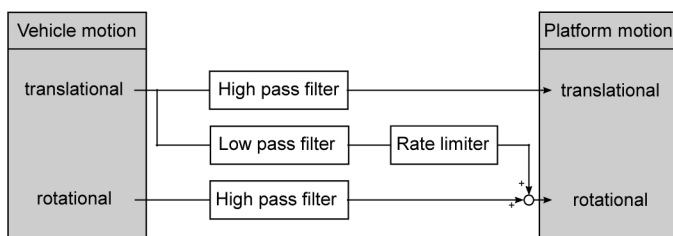


Figure 1. Schematic of the classical washout algorithm

While the classical washout algorithm is easy to implement and does not necessarily require specific tuning for each track or maneuver, it also has shortcomings. The classical washout algorithm has to be tuned for the worst case as there is no feedback loop from the platform to the algorithm. Therefore, most of the time, it only makes poor use of the available workspace. In addition, it is not ensured that the washout motion does not exceed the perception thresholds. This is critical especially with professional and acceleration sensitive test drivers.

To overcome those shortcomings, some algorithms model the motion cueing task as optimization problem, where the simulator motion tracks the vehicle motion [7]. The cost function of the linear quadratic regulator contains terms for the simulator motion limits, as well as for the perceived error between simulator motion and vehicle motion. Newer developments also propose the use of model predictive control (MPC) to calculate the desired motion signals, while simultaneously maintaining the platform limits and minimizing the perceivable error [8], [9], [10]. While the MPC based algorithms reduce the amount of false cues, they introduce nonlinearity in the platform behavior. This means that the same vehicle acceleration input can lead to different platform motion, depending on the system state. E.g. when driving multiple curves in the same direction, the platform approaches its actuator limits and the motion slows down. Therefore, the motion response in the first curve will be different to the motion response in

the last curve. These nonlinear responses can make it considerably more difficult for the test driver to assess the vehicle’s handling quality.

Another algorithm is a vehicle sideslip based algorithm, presented in [13]. It makes use of the fact that in most driving situations, the vehicle sideslip angle does not exceed platform limits. Using the sideslip angle as motion platform input signal for the rotation about the vertical axis, the washout motion for this degree of freedom can be omitted. In addition it can be seen as suitable for race driving, as the sideslip angle is a good measure for the lateral stability of the car. On the other hand, the sideslip angle is not linearly related to the car’s yaw behavior, and may therefore not be accepted as cue for yaw response by test drivers.

As the limited platform workspace is the biggest constraint in the motion cueing process, some algorithms make use of prepositioning techniques. GRANZOW et al. describe a maneuver based algorithm where e.g. before a fast lane change to the left, the platform is prepositioned to the right, allowing an enlargement of the available workspace for this specific maneuver [20]. While the larger workspace is of great use, it comes at the cost of inflexibility in the maneuvers. Most test drivers have different maneuvers to assess the handling qualities of a vehicle and also want to drive on circuit tracks. Due to the high dynamics and uncertainty of the driving style of the test driver, translational prepositioning techniques are not of great help for those cases.

This paper describes a new motion cueing approach, specifically designed for the evaluation of vehicle dynamics on circuits or predefined tracks. This new approach makes use of the vehicles position on the track for prepositioning. In Section 2, the framework for this work is described, such as the used simulator and the designated use case for the algorithm. The new algorithm is described in Section 3, as well as its exemplary implementation. A comparison between a classical washout and the new algorithm is presented in Section 4. The last Section draws conclusions and gives an outlook for future work.

PROBLEM BACKGROUND

The simulator used in this research project is a Cruden simulator displayed in Figure 2. It features a mid-size hexapod with 640 mm cylinder stroke. Table 1 shows the excursion limits of the hexapod. The hexapod is placed in the center of a floor mounted screen with 4 m height and 8 m diameter. The system is equipped with 7 LED projectors running 120 Hz in WUXGA resolution (1900 x 1200). The cockpit of an Audi A6 is placed on the top frame of the hexapod featuring the throttle pedal from the production car and a passive hydraulic brake pedal. Steering feedback to the driver is provided by a fast and accurate control loader. Additionally a fully functional dashboard is integrated for driver information.



Figure 2. Cruden simulator used in this project

The simulator is equipped with a MatLab/Simulink UDP block interface that allows to integrate different vehicle models and other models, such as motion cueing. The current setup uses a VI-CarRealTime [14] vehicle model, which runs at a fixed step size of 1.2 ms. The output of the motion cueing model must consist of position, velocity, and acceleration for each of the six degrees of freedom to serve as an input for the kinematics model and motor controller of the hexapod. Further information, also including a full dynamic analysis of the system, can be found in BREMS et al. [11].

Table 1. Excursion limits of the used Cruden Simulator

	Position	Velocity	Acceleration
Surge	± 0.63 m	0.8 m/s	15 m/s^2
Sway	± 0.66 m	0.8 m/s	15 m/s^2
Heave	± 0.41 m	0.6 m/s	15 m/s^2
Roll	$\pm 29^\circ$	$35^\circ/\text{s}$	$600^\circ/\text{s}^2$
Pitch	$\pm 28^\circ$	$35^\circ/\text{s}$	$700^\circ/\text{s}^2$
Yaw	$\pm 29^\circ$	$40^\circ/\text{s}$	$900^\circ/\text{s}^2$

The main application for the simulator used in this research, is in the subjective evaluation of vehicle dynamics at AUDI AG. With the simulator, different chassis variants can be evaluated in an early development stage when no prototype vehicles are available.

While non-professional drivers in their everyday driving only produce small magnitude accelerations, professional test drivers fully exploit the capabilities of the vehicle: They evaluate the vehicle response, ranging from very small steering input, to the limit handling qualities. Additionally they are very sensitive to small changes in vehicle response, and thus also motion response. This makes the motion cueing task difficult but critical, as the drivers rely on specific motion cues and the consistency of e.g. visual and motion cues.

On the other hand, working with professional test drivers also has advantages. In studies with non-professional drivers (e.g. in the development of driver assistance systems), it is crucial that the drivers' behavior in the simulator is comparable with their behavior in the normal car [12]. For the participants, the experience in the simulator should be the same as in the car. This is not necessary when working with professional drivers. They are aware of being in a simulator with reduced possibilities of representing reality. Therefore, they can tolerate a lack of realism and accept that, for example, longitudinal cues are not displayed very realistic in a setup dedicated to evaluation of lateral dynamics.

THE NEW TRACK BASED ALGORITHM

In the following section, the new track based algorithm will be described.

Basic Idea behind the Track Based Algorithm

The problem with prepositioning techniques for motion cueing is the uncertainty of the future. There is always a tradeoff between workspace exploration and flexibility in the maneuver, if lateral and/or longitudinal prepositioning shall be used. The approach of GRANZOW [20] focuses on full workspace exploration and therefore, only allows a very specific maneuver (e.g. fast lane change) within a very limited time window for the maneuver start. Another implementation described by FANG et al. [15] is less strict in the maneuver starting time and also the execution of the maneuver. Nevertheless, the maneuver is restricted to, for example, a double lane change, the prepositioning time is given with 7-15 s and a simulator with several meters of translational workspace is needed.

The challenge is to find a balanced set of workspace exploration and maneuver flexibility. The constraints in the current project can be seen in the use case (evaluation of vehicle dynamics) and the simulator platform (mid-size hexapod). Most test drivers prefer free driving over specified maneuvers. In this situation, a closed track, e.g. a handling track on a proving ground, can be seen as compromise between the full uncertainty of the chosen trajectory in free driving and strictly specified maneuvers. With the possibly large magnitudes of accelerations on a handling track, it was decided to not investigate prediction for lateral and longitudinal motion, as the hexapod workspace is too small. Instead, the prepositioning focus is on rotation around the vertical axis and on vertical motion.

For the evaluation of lateral dynamics, the rotation of the vehicle around the vertical axis, known as yaw motion is a very important measure. The vertical motion on the other side is important in the evaluation of the vertical dynamics of the vehicle (ride comfort). On a given track the vertical position of the car only depends on the car's position on the track. For the yaw angle, a small corridor can be defined depending on the car's position on the track, where the yaw angle of the car is nearly parallel to the heading angle of the track, only slightly varying with the driven line. Therefore, the yaw angle (corridor) and the vertical position can be used for track based prepositioning.