# Subjective Evaluation of Different Motion Cueing Algorithms Implemented on ATMOS Driving Simulator

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**Abstract –** The objective of this work is to compare a novel motion cueing algorithm based on the constrained linear optimal controller (CLOC) as introduced in [Alq1] to two established algorithms, namely the classical and adaptive algorithms [Neh11, Neh12]. A subjective motion cueing quality criterion was used to evaluate the fidelity of the ATMOS driving simulator and to assess the quality of the motion cueing algorithms. A group of test subjects attended three pre-simulated rides on the same track, each controlled by one of the different control strategies. The analysis of the subjective evaluation shows that the adaptive motion cueing algorithm provides the best impression in longitudinal direction. However, the subjects perceive that the CLOC strategy provides the most realistic impression in the lateral direction as well as the most comfortable and realistic feeling. None of the subjects experienced simulation sickness. All of them easily and quickly overcame any kind of discomforts.

**Key words**: Driving simulators**,** Motion cueing, CLOC, Subjective quality criterion, Real-time implementation.

## 1. Introduction

Any driving simulator aims to give a realistic impression of the vehicle motion to the driver. Typically, driving simulators are constructed from several subsystems that contribute to the overall replication of the senses felt in a vehicle. Driving simulators are mainly constructed from mechanical moving parts to provide inertial cues as well as a virtual reality system to provide the visual cues corresponding to the actual driving situation. Ideally, the driver perceives the same accelerations and rotational movements as he anticipates from the visual environment in order to give him a more realistic impression of the simulated driving maneuver. Due to the limitations of the workspace and the simulator motion systems' technological constraints, the vehicle's translational accelerations and angular velocities as generated by the vehicle dynamic model cannot be reproduced unaltered by the motion system. Therefore, the simulated vehicle's motion must be rendered in a specific manner in order to provide the simulator with admissible signals. Those signals should provide the driver with a feeling close to reality while keeping the simulator within its technological constraints and capabilities. Any kind of contradiction between the motion trajectories of the simulator and the trajectories generated by vehicle dynamic virtual reality models will have significant detrimental effects on the driving simulation and could provoke simulator sickness which is more likely to cause dizziness, headaches and nausea to the simulator driver. Therefore, the use of motion in simulators is still subject to debate and the implementation of motion control/cueing strategies is vital.

The motion control strategy that is used to render the vehicle accelerations and velocities is commonly called motion cueing algorithm. Several motion cueing algorithms which use frequency domain techniques to calculate the simulator's motion from the simulated vehicle's accelerations have been proposed for flight and driving simulators, such as classical motion cueing algorithms [Sch16, Gra9, Neh11, Neh12], adaptive motion cueing algorithms

[Par13, Rei14, Rei15], and optimal algorithms [Rei14, Rei15, Tel18, Siv17]. Furthermore, a few model predictive approaches have been developed for motion control of driving simulators [Dag6, Aug4].

Subjective and objective motion cueing quality criteria may be used out to evaluate the fidelity of driving simulators and to rate the quality of motion cueing algorithms to transfer vehicle accelerations and velocities to those in the actual simulator.

This work focuses on a subjective quality criterion to compare three different motion cueing approaches, namely the classical motion cueing algorithm, the adaptive motion cueing algorithm and the model based constrained linear optimal control (CLOC) strategy [Alq1], implemented on the ATMOS driving simulator. Several test persons were asked to participate in three simulated driving maneuvers and to rate their experiences afterwards.

## 2. ATMOS Driving Simulator

The driving simulator of the University of Paderborn (ATMOS driving simulator) serves a wide range of applications. Primarily, it is used as a virtual prototyping tool in the development of advanced driver assistance systems (ADAS). The simulator enables developers to test these systems under safe and reproducible conditions. Furthermore, it may be used to study the driver's behavior and to systematically train the driver for specific situations or in the handling of various driver assistance systems.

**Fig. 1. ATMOS Driving Simulator.**

The ATMOS driving simulator (Fig. 1) is a modular system. It grants high flexibility by offering the ability to replace the driving cabins not only as a hardware component, but also with fully parametrisable software [Has10]. The simulator consists of two main components: a visualization system and a motion system.

The visualization system includes a 240° circular projection wall with eight identical projectors. Each projector has a resolution of 1400 x 1050 pixels, covers 30° and a 128 pixel edge-blending zone with neighboring projectors.

The motion system provides five independent degrees of freedom (DOF). This is accomplished by two dynamical components. The first one is the motion platform which can be tilted around the lateral as well as the longitudinal axis with maximum angles of 13.5° and 10.0° respectively. Two belt drives in each direction perform these movements in arbitrary combination. The platform is used to simulate the vehicle's longitudinal and lateral acceleration. The other three DOF are provided by the second dynamical component: the shaker platform. It is actuated by crank drives and is used to simulate the vehicle's roll velocity, pitch velocity and vertical acceleration.

The computations of the underlying vehicle model and the motion cueing algorithms are carried out by a dSPACE real-time simulator. It has several IO-ports which are connected to the simulator's vehicle mock-up interface, an inertial measurement unit (IMU) and the inverters controlling the electrical drives of the motion system (Fig. 2). A controller area network (CAN) interface is used for transmitting the appropriate signals such as the desired actuator actions.

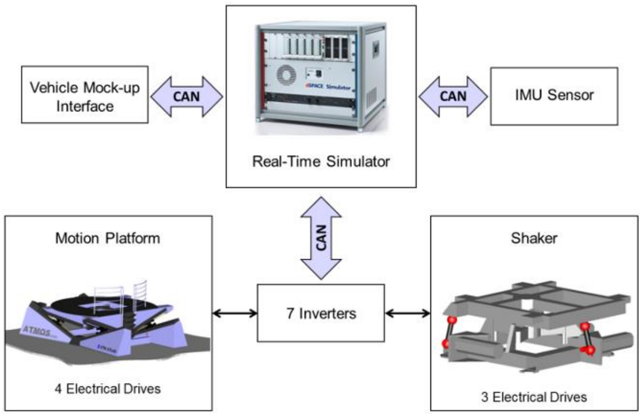


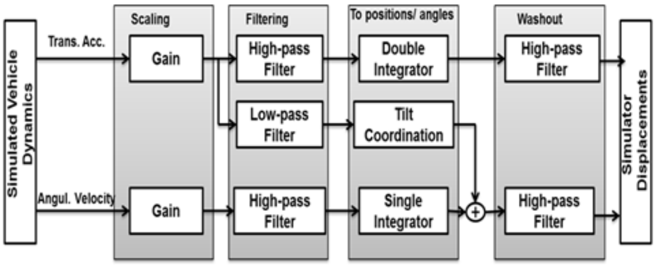

**Fig. 2. Hardware components of the motion system.**

The vehicle mock-up provides the driver's inputs such as the steering angle, accelerator and brake pedal position and current gear. It receives the calculated vehicle velocity and the engine speed from the real-time simulator and displays these values on the vehicle's dashboard. The IMU is located near the vehicle's center of gravity to compare the measured and desired vehicle accelerations and angular velocities.

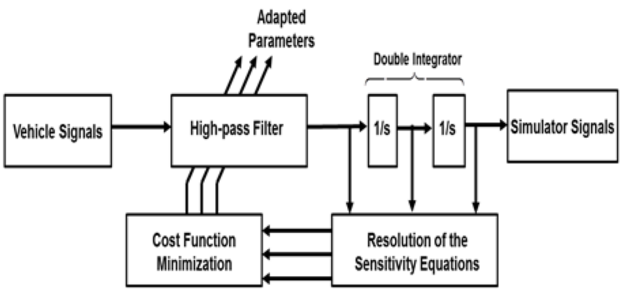
## 3. Motion Cueing Algorithms

Traditionally, motion cueing algorithms were derived experimentally. However, the most common fundamentals of these algorithms are scaling, tilt coordination and filtering. Combinations of these techniques are necessary to meet the performance and fidelity requirements of motion simulators.

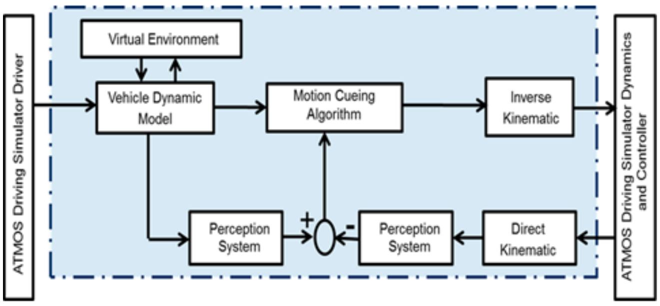
One of the oldest and most commonly used in driving simulators is the classical motion cueing algorithm. It renders the translational vehicle accelerations using a combination of linear high-pass and low-pass filters. However, only high pass filters are used to render the vertical vehicle acceleration since the tilt coordination can only be used to render the sustained longitudinal and lateral accelerations. The outputs of the tilt coordination are then fed into the channel of the rendered angular velocities. Afterwards, the combined generated angles are used to drive the simulator in pitch and roll cues. The classical algorithm implemented in this work is shown in Fig. 3(a).




(a) Classical motion cueing algorithm.




(b) Scheme of the adaptive washout filter.




(c) Model based motion control strategy (CLOC).

**Fig. 3. Implemented washout algorithms.**

Unlike the classical approach, adaptive motion cueing algorithms use the steepest descent technique to carry out a minimization of a cost function consisting of the acceleration errors subject to the constraints regarding the velocities and displacements of the simulator. For that reason, the resulting filter parameters are variable in real-time and are computed at each time step of the simulation. Fig. 3(b) shows the general scheme of the adaptive high-pass washout filter.

In the constrained linear quadratic optimal controller (CLOC) strategy as introduced in [Alq1], an optimization problem is solved online over a finite time horizon. This approach minimizes the difference between the accelerations anticipated by the driver and the actual perceived motions generated by the motion system while keeping the simulator within its technological constraints. The parameters of the model based approach are chosen by trial and error to guarantee the best tracking of the perceived movements in the vehicle and to ensure the stability of the constrained linear quadratic optimal controller implementation. Fig. 3(c) shows the block diagram of the model based motion control strategy in the ATMOS driving simulator.

To implement the CLOC strategy, it is necessary to solve a quadratic programming problem [Alq1]. There are many software tools with integrated solvers available [And3, Cga5, Ger8]. However, these tools use operating system specific precompiled files and, thus, cannot be used to generate code for the employed dSPACE real-time simulator. One possibility to use the CLOC algorithm for the generation of motion signals in real-time (for so-called active driving scenarios) is to reimplement it using the Model Predictive Control Toolbox by The MathWorks. The toolbox supports C-code generation for embedded systems such as dSPACE real-time hardware.

## 4. Motion Cueing Quality Criterion

The main goal of motion cueing algorithms is to produce admissible motions within the driving simulator's physical boundaries. The simulated vehicle's motion is reproduced in order to provide a high degree of realism in a computer generated virtual environment. Subjective and objective motion cueing quality criteria may be used to evaluate the fidelity of driving simulators and to measure the quality of motion cueing algorithms.

The objective motion quality criterion is used to evaluate different motion cueing algorithms offline and without time consumption [Alq2].

However, subjective motion cueing quality criteria offer various advantages such as the possibility to get a subjective evaluation of experienced and inexperienced drivers. The driving impressions of the test drivers can be collected by a questionnaire, which includes technical questions as well as questions about the perception of motions or realism of the simulator in particular. This human-in-the-loop evaluation method is considered as a straightforward and consistent method to assess the fidelity of a driving simulator. Furthermore, different motion cueing algorithms are evaluated and compared to each other based on subjective ratings of realism regarding the rendered vehicle motions. The questionnaire focuses on different aspects and situations including the feelings during braking, acceleration and cornering maneuvers, simulator sickness, opinion of realism, visual environment and hardware evaluation.

Moreover, these evaluation tests can be conducted to study the fidelity of the simulator response to specific driver inputs (active mode) or by applying the simulator with pre-specified trajectories generated by different motion cueing algorithms (passive mode).

After the experiments, subjective reactions are collected to evaluate the behavior validity, quality of various motion cueing techniques and the driving simulator behavioral fidelity in general.

## 5. Implementation and Results Analysis

The driver's perception of motions depends on several factors such as the virtual environment, the acoustic system as well as the vehicle motion. Hence, to attribute the subject's perception of motions solely to the underlying motion cueing variant, a precalculated driving scenario was used during the experiments (passive driving). All test persons took part in the same ride three times except for the fact that the simulator's motion was computed by different motion cueing algorithms.

In the present case an actual track in a non-urban area of Northrhine-Westphalia with a length of 3 km, several curves and various velocities was used as testing scenario. Thereby, a wide range of lateral and longitudinal accelerations is included in the ride. The simulated vehicle's accelerations were calculated by an ASM-dSPACE [dSP7] vehicle model. The results have been used as reference inputs for the three motion cueing algorithms. Afterwards, the three different control strategies for the driving simulator were computed.

The test subjects attended these three precalculated rides on the same track. Altogether, 23 subjects took part in the evaluation. The participants, aged from 25 to 56 years, owned a valid driver's license and were of varying driving experience. The experience criterion is based on the test subject's driving experience concerning simulators and real vehicles. The evaluations of each group are multiplied by a suitable weighting factor. The subjects were asked to evaluate the driving simulator while being passive drivers in the cabin, i.e., they did not control the motion of the car.

At the end of the experiments, each subject was asked to fill out a survey on the realism and quality of the rides. This questionnaire served as the subjective evaluation of the ATMOS driving simulator performance based on the participant's experience. The participants were asked to evaluate the three algorithms based on the following criteria: i) perceived motion in the simulator compared to the reality, ii) simulator sickness, iii) comfort and iv) realism of the whole driving test. Each subject had to evaluate his/her driving experience on a scale of 1 to 5, where 1 denoted the worst performance and 5 denoted the best performance. Fig. 4 shows the results of this evaluation.

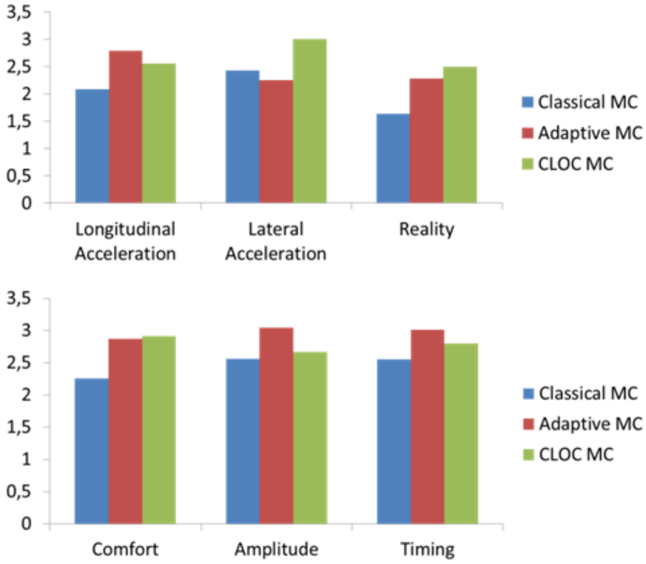



**Fig. 4. Subjectives' performance evaluation of ATMOS Driving Simulator.**

The analysis of the evaluation results shows that the adaptive motion cueing algorithm provides the best impression in longitudinal direction. Obviously, many subjects prefer low acceleration gain scaling compared to high scaling. However, the subjects perceive that the CLOC strategy provides the most realistic impression in the lateral direction as well as the most comfortable and realistic feeling. None of the subjects experienced simulation sickness. All of them easily and quickly overcame any kind of discomforts.

Jerky movements were observed in each of the three rides, but most significantly, they appeared within the ride based on the classical motion cueing algorithm.

Fig. 5 shows a physical trajectory comparison between the perceived signals in the simulator and the perceived signals in the vehicle. The perceived signals in the simulator are the simulator translational acceleration and angular velocity measurements filtered by a model of the human perception system. The comparison shows that there is a noticeable difference between the signals rendered by the classical or adaptive algorithms and those rendered by the CLOC strategy.

The results show a very good matching between the two perceived signals in the driving simulator generated by CLOC approach and the simulated vehicle. This good matching is a result of integrating human perception models in the optimization problem and considering the constraints of the simulator in the optimization problem instead of using gains scaling and limiters. Moreover, using the adaptive motion cueing algorithm provides a slightly better performance compared to the classical motion cueing algorithm. Nevertheless, the classical algorithm has an advantage of simple parameter tuning compared to the adaptive algorithm.

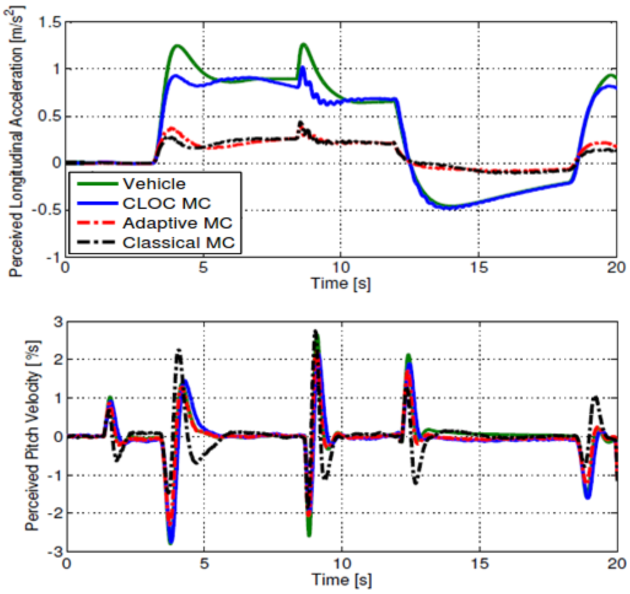



**Fig. 5. Physical trajectory comparison.**

## 6. Conclusion

In this work, three different motion cueing algorithms were investigated, designed, implemented and tested in the simulation environment of the ATMOS driving simulator. The performance of the model based strategy was compared against the classical and adaptive algorithms. The classical and adaptive motion cueing algorithms represent conventional approaches commonly used in driving simulators. The performance and quality of the three control strategies were subjectively evaluated.

The subjective quality evaluation was based on subjective impressions of a group of experienced and inexperienced drivers. The subjects rated the driving simulation while being passive drivers in the cabin, i.e., they did not control the motion of the car. Then, each subject was asked to fill out a survey on the realism and quality of the ATMOS driving simulator. The subjective evaluation results show that the model based strategy (CLOC) provides significantly the most realistic impression in the lateral direction. However, the subjects preferred the adaptive motion cueing algorithm in the longitudinal direction due to its low gain scaling. Moreover, the CLOC approach provides the most comfortable and realistic driving feeling without any simulator sickness.

## 7. Acknowledgement

This work, as part of the project TRAFFIS (German acronym for "Test and Training Environment for Advanced Driver Assistance Systems"), is funded by European Union and the Department for Economy, Energy, Industry, Trade and Craft of North Rhine-Westphalia, Germany.

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