Driving Dynamics Control of a Wheeled Mobile Driving Simulator Utilizing an Omnidirectional Motion Base for Urban Traffic Simulation

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ABSTRACT: The Wheeled Mobile Driving Simulator (WMDS) is a motion base that provides a driving experience by moving on wheels. The WMDS itself represents a vehicle performing omnidirectional x, y and yaw-motion. Thus, conventional rail systems are removed in order to reduce moving mass significantly. Compared to state of the art driving simulators, the new approach is promising to allow for mass and cost reduction while enlarging possible motion space. This work investigates the performance of four different open and closed-loop control setups for a WMDS. The performance is evaluated by acceleration error in x (a_x), y (a_y) and about z-axis (yaw, \( \psi \)). To do this, a virtual WMDS prototype is created as a multibody simulation in IPG CarMaker. The multibody model of the WMDS is embedded in a Matlab/Simulink environment and controlled via a virtual interface. For comparing the four control approaches, relevant test maneuvers are selected and conducted virtually. Best results, in terms of acceleration errors, are received when combining slip based algorithms for Motion Control and closed-loop approaches. The main outcome is that results show control setups that qualify the WMDS for application in driving simulation.

KEY WORDS: wheeled mobile driving simulator, driving dynamics control, urban traffic

1. Introduction

Driving simulators (DS) are an established and indispensable developmental tool in the automotive industry. Various areas of application all profit from the high degree of reproducibility, safety and economic efficiency of DS. One area of application is the development and validation of Advanced Driver Assistance Systems (ADAS). For analysis of safety critical situations, concerning driver behavior and human machine interaction, DS are adequate tools. Human error in common traffic situations such as turning, U-turning, pulling out and reversing is one of the main reasons for urban traffic accidents(1,2,3). The upcoming demands for ADAS, with respect to urban traffic situations, result in increasing DS requirements concerning motion envelope and system dynamics. The motion simulation of vehicle surge (x), sway (y) and yaw (\( \psi \)) easily exceeds the physical limits of conventional DS. To fulfill the increasing requirements, modern-day DS can have up to 10 degrees of freedom (DOF) and have reached remarkable quality in simulating real world driving experiences. These improvements are attained at the costs of complex systems with increasing moving mass of about 80 t(4). Beside the additional DOF, the main reason for large moving-mass results from the rail systems carrying the tilt system in order to enable sufficient translational motion as shown in Fig. 1. Hence, a link between moving mass and motion envelope is caused limiting motion envelope and system dynamics.

1.1 New Approach

Wheeled Mobile Driving Simulators (WMDS) solve the core problem of linked moving mass. The main idea is based on the assumption that a wheeled system, whose propulsion is limited by friction forces, is suitable to simulate the dynamics of vehicles that are also limited by tire friction forces. The idea of a WMDS is addressed by a patent held by Donges(6) and a reference by Slob(7) though the references don’t prove feasibility of WMDS. Requirements, such as workspace, power, energy and friction demand, of the new DS approach are not analyzed in the aforementioned references and neither is system latency. Therefore, a representative assembly of a WMDS is considered showing an omnidirectional motion base. The wheeled mobile platform, with three conventional, powered and active steerable wheels, allows translational motion and yaw. On top of the platform a tilt system has to be mounted to provide pitch, roll and heave. The chosen design removes the need for additional DOF and shows inbuilt stroke fitting real world vehicle motion. Avoiding the conventional rail systems, which mainly cause the moving mass increase, results in a light weight concept as shown schematically in Fig. 2.
1.2 Scientific Goal

The introduced assembly of the WMDS utilizes one drive and one steer motor for each wheel. In total, six motors are used to perform x, y and yaw-motion. Thus, the ambiguous characteristic of the system has to be solved by algorithms using additional constraints. Four different control setups are analyzed concerning the created driving experience. Based on the conducted analysis, the WMDS’s potential will be explored regarding performance of the created driving experience.

2. Methodology

This work deals with driving dynamics of a WMDS. In order to analyze the introduced scientific goal, a representative model for the simulator’s motion control is developed that transforms provided vehicle dynamics into the actuator task of the DS. The architecture of the Motion Cueing Algorithm (MCA) is designed to take advantage of the WMDS’s inbuilt motion capability(9). The developed, representative simulator’s Motion Control (MC) is connected to a virtual WMDS prototype which is implemented in IPG CarMaker. Based on this toolchain, open-loop and closed-loop control setups are analyzed concerning the created performance of the driving experience.

3. Model

The toolchain contains four major elements that are introduced in the following subsections:

- Section 3.1 (Motion Cueing Algorithm) describes the transformation from vehicle dynamics into DS’s dynamics.
- Section 3.2 (Motion Control) shows the reduction of the ambiguous system characteristic which allows to determine the six control signals.
- Section 3.3 (WMDS Driving Dynamics) introduces the used software tool that creates the multibody representation of the virtual WMDS prototype.
- Section 3.4 (Control Setups) presents the four different control setups that are analyzed in this work.

3.1 Motion Cueing Algorithm (MCA) (9)

The so-called MCA is a transformation from real vehicle motion into the WMDS motion and thereby creates the task for the DS’s center of gravity (CG). Therefore, the 6 DOF motion information (accelerations in and about all directions in space) of the simulated vehicle dynamics is used as an input into the MCA. The block diagram of the used MCA is shown in Fig. 3. DS usually employ two principles to simulate acceleration for the driver – translational motion and tilting the driver with respect to the vertical direction (below human perception thresholds for rotational motion). Combining those principles allows the required motion space to be reduced. Because tilt coordination (TC) requires less workspace, the basic idea is to allow as much translational acceleration simulation from tilt as possible, while considering human perception thresholds for cabin tilt. The used thresholds for rotational rate are 0.1 rad/s and 0.1 rad/s² for rotational acceleration. Those values are determined by DS studies from literature(9). With the described “ideal MCA” method, an “ideal” motion simulation is reached, considering the usual adverse effects due to tilt. The so-called washout algorithm represents the DS behavior to return to the initial position in workspace, which is usually determined to allow for the biggest motion space in all directions. The washout takes advantage of superposing tilt coordination and translational motion. It is implemented into the MCA as a feedback gain of DS velocity (1/τ) and displacement from origin (1/τ).

The major outputs of the MCA are the translational (aₓ, aᵧ) and yaw (ᵦ) accelerations for the CG of the motion base. The translational accelerations are interpreted as a resulting acceleration vector in the horizontal plane that is demanded to perform the simulated vehicle dynamics. Further outputs like roll, pitch and heave acceleration are also important results of a MCA, but are neglected here since this work is focused on the major x, y and yaw-motions of the WMDS. The block diagram in Fig. 3 is slightly adapted compared to Betz(9). Here, sensor values are used as feedback for the washout (vCG, dCG) instead of ideally calculated values within the MCA as it was implemented before the toolchain was more comprehensive. The adaption became necessary since the presented toolchain operates on the fly and provides position and velocity feedback of the multibody simulation. For further details concerning the MCA see Betz(9).

3.2 Motion Control (MC)

The output of the MCA presents the demanded accelerations of the DS’s CG, but how would one control the DS’s actuators to perform the acceleration-based task? The so-called Motion Control transforms the acceleration-based task of the DS’s CG into the required DS’s actuator tasks. The algorithm is required to solve the ambiguous characteristic of the presented WMDS.
assembly. The schematic block diagram is presented in Fig. 4 and gives an overview about the relations of the following calculations.

![Fig. 4 Block diagram of the MC.](image)

The task of the DS’s CG is reduced to translational force and yaw moment demand (Fig. 5, left). The distribution of the wheel force for the three wheels of the motion base has to be worked out, in order to perform the introduced acceleration demands (Fig. 5, right).

![Fig. 5 DS task resulting from MCA output.](image)

The developed MC algorithm distributes the demanded traction forces, with the aim of minimizing differences between the utilized friction coefficients of the wheels, in order to realize equal friction reserve. Thus, the wheels remain, as long as possible, in the linear friction-slip characteristics of the tire. That is why the dynamic wheel load distribution has to be known and is derived by Newton’s first law of motion. For further details concerning the wheel force distribution see Betz(10).

So far the presented algorithm provides the demanded force vector for each wheel, but how would one perform this force vector by controlling drive and steer motor of a wheel? The wheel’s task is defined by longitudinal and lateral force. In total, these two forces have to match the previously derived force vector demand ($F_{\text{res,dem},i}$). The longitudinal force is performed directly by the drive motor torque and heads in the longitudinal direction of the wheel’s coordinate system (COS).

$$M_{\text{long},i} = F_{\text{long},i} \cdot r_{\text{wheel}}$$

The lateral force of a conventional wheel cannot be performed directly by a motor just like the longitudinal force. The lateral force of a conventional tire results from the slip angle and the tire’s cornering stiffness. Hence, the lateral force is controlled by the wheel’s steer angle. Furthermore, it has to be stressed that providing lateral force on a horizontal plane is only possible if and only if, the wheel hub is in motion. Otherwise there is no velocity vector and by that no slip angle is possible. These circumstances show that the velocity states of each wheel have to be known to solve the drive and steer motor task of the wheels (Fig. 6).

![Fig. 6 Calculation of wheel’s velocity vector.](image)

As introduced, the wheel’s task is to provide lateral and longitudinal force matching the demanded overall force vector ($F_{\text{res,dem}}$). The most basic layout of the MC stays on the kinematical level and expects the wheels to orientate in direction of their predicted motion (Fig. 6). This method does not require knowledge of the tire properties and is commonly used in robotics(11) because it is valid for low dynamic motion where only low amount of slip that can be corrected by closed-loop approaches, occurs. The tire is modeled to behave as if it has infinite cornering stiffness. The method neglects slip effects and therewith obviously causes error for the demanded motion. This layout is named kinematic MC.

If there is knowledge about the properties of the used tire, a dynamic control approach is possible. A more plausible tire characteristics like real cornering stiffness ($c_\alpha$), are considered for predicting slip angle demand. This method represents a feed forward approach. The used relationship between lateral force and slip angle (equation 2) might be represented as detailed as necessary. For this work, a linear behavior is implemented using the same cornering stiffness as it is used later on in the driving simulation model. The required slip angle and the matching torque of the drive motor have to be identified regarding the DS states. This identification is done by a numerical root-finding algorithm. The wheel’s slip angle is varied in discrete steps without interpolation. As shown by equation 4, the lateral force (equation 2) resulting from the varied slip angles is compared to the lateral component (equation 3) of the demanded force vector with respect to the wheel’s COS. According to equation 5, the set of $\alpha$ is searched that satisfies equation 4.

$$F_{a,i} = c_\alpha \alpha_i$$

$$F_{y,dem,i} = |\vec{F}_{\text{res,dem},i}| \cdot \sin(\rho_i - \delta_i - \alpha_i)$$

$$F_{a,i} = F_{y,dem,i}$$

$$\{\alpha_i : F_{y,dem,i} = F_{a,i}\}$$

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After determining the required lateral force, the missing longitudinal force is calculated which results in the demanded force vector when superposed with lateral wheel force. The longitudinal component of the demanded force vector is calculated with respect to the wheel’s COS (equation 6 and Fig. 7).

\[ F_{\text{long},i} = |\vec{F}_{\text{res},dem,i}| \cdot \cos(\rho_i - \delta_i - \alpha_i) \]  

(6)

In the following this layout is named dynamic MC. It has to be considered that this approach represents a simplification of slip effects and neglects dependencies of longitudinal and lateral slip as it is considered by combined slip approaches. The steer angles for the two introduced layouts are calculated using a 4-quadrant function of arctangent (atan2) and are as follows:

\[ \delta_{\text{kin},i} = \text{atan2}(v_{\text{res},y,i}, v_{\text{res},x,i}) \]  

(7)

\[ \delta_{\text{dyn},i} = \text{atan2}(v_{\text{res},y,i}, v_{\text{res},x,i}) + \alpha_i \]  

(8)

3.3 WMDS Driving Dynamics

The driving dynamics behavior of the WMDS is simulated using IPG CarMaker\(^{12}\). CarMaker provides a parameter-based, multibody vehicle-model and is linked to MathWorks Matlab/Simulink\(^{13}\) by a control interface. Since CarMaker is mainly used for analysis of passenger cars, some workarounds have to be implemented to build a three wheeled motion base as it is required to represent the introduced WMDS. One wheel is suppressed by minimizing its size and placing it above ground without ground contact.

3.3.1 Tire

The simulation of the tire behavior is based on Pacejka’s Magic Formula (version 5.2). The tire data is provided as ADAMS tir-file of a conventional 195/65R15 tire\(^{14}\). The tire dimension is adjusted in order to fit the DS’s geometry. The relevant excerpt of the tire properties is presented in Table 1.

### Table 1: Excerpt of relevant tire properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel radius</td>
<td>m</td>
<td>0.15</td>
</tr>
<tr>
<td>Cornering stiffness</td>
<td>kN/rad</td>
<td>67</td>
</tr>
<tr>
<td>Nominal wheel load</td>
<td>kN</td>
<td>4</td>
</tr>
<tr>
<td>Vertical stiffness</td>
<td>kN/m</td>
<td>200</td>
</tr>
<tr>
<td>Vertical damping</td>
<td>Ns/m</td>
<td>50</td>
</tr>
</tbody>
</table>

3.3.2 Geometric Specifications

The WMDS is designed as an equilateral triangle with point masses in the center of the platform and in each wheel center. The relevant specifications are listed in Table 2.

### Table 2: Geometric specifications of the WMDS.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge length of equilateral triangle</td>
<td>m</td>
<td>2.54</td>
</tr>
<tr>
<td>Height of CG</td>
<td>m</td>
<td>0.48</td>
</tr>
<tr>
<td>Total mass</td>
<td>kg</td>
<td>1,200</td>
</tr>
<tr>
<td>Total inertia torque about z-axis</td>
<td>kgm²</td>
<td>945</td>
</tr>
<tr>
<td>Inertia torque about z-axis of steer units</td>
<td>kgm²</td>
<td>1.09</td>
</tr>
</tbody>
</table>

3.3.3 Chassis Geometry

The chassis geometry differs from conventional passenger cars. The WMDS has only three wheels. They are designed to be fully steerable (infinite rotation about vertical axis). The stiffness of the body spring has 25 kN/m and the constant of the body damper has 2.5 kNs/m (compression and rebound). Further chassis properties like camber, toe, kingpin inclination and offset are designed to be zero. These properties do not vary with wheel lift.

3.3.4 Motor Models\(^{15}\)

The drive and steer motors are implemented according to Scholz\(^{15}\) using differential equations of the electric circuit. The maximum torque output of the motors is limited. Maximum rotational speed of the motors does not need to be limited since the operational field of the motors stays below the field weakening. The part beyond the field weakening is not of interest, because the WMDS does not have a friction brake thus, the motor torque must be sufficient to provide full acceleration up to maximum operational velocity. The electric machines are parameterized accordingly to Table 3.

### Table 3: Specification of electric motors.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance</td>
<td>mΩ</td>
<td>19</td>
</tr>
<tr>
<td>Inductance in q axis</td>
<td>mH</td>
<td>0.18</td>
</tr>
<tr>
<td>Torque constant</td>
<td>Nm/A</td>
<td>0.673</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>kNm</td>
<td>1.125</td>
</tr>
</tbody>
</table>

3.3.5 Control Interface

The input signals for CarMaker are three steer angles and three torques of the wheel hubs. The steer angles are calculated in Matlab/Simulink using differential equations about the wheels’ vertical axes. For the differential equations, the steer and the aligning torques are considered.
3.3.6 Numeric Solver
The first order Euler method is used with a fixed step-size of 1 ms. This simulation parameter is required by CarMaker.

3.4 Control Setups
This work analyzes the performance of open-loop and closed-loop control setups of the WMDS. The control’s aim is to provide driving experience to a test person sitting on top of the platform. Since humans do not perceive velocity directly, the driving experience in DS is represented by acceleration simulation. Therefore, the presented control setups are implemented on acceleration level and differ from common control setups which are usually trajectory based. In the following, four different control setups are presented in order to analyze their performance for acceleration based motion simulation.

3.4.1 Kinematic Open-Loop Control (kinOLC)
As described in section 3.2 the kinematic-based control neglects tire slip. The wheel is expected to move only in its longitudinal direction without any slip angle. The kinematic open-loop control is implemented accordingly to the introduced kinematic MC, as it also neglects slip angles and shows no signal feedback beside yaw orientation.

3.4.2 Dynamic Open-Loop Control (dynOLC)
As described in section 3.2 the dynamic MC differs from the kinOLC by enhancing the MC with linear characteristics of lateral force and slip angle. According to the kinOLC there is no signal feedback besides yaw orientation.

3.4.3 Kinematic Closed-Loop Control (kinCLC)
The kinematic closed-loop control is based on the kinOLC from section 3.4.1, but shows feedback of the actual control signals – \(a_x, a_y\) and \(\dot{\psi}\). The feedback control of those signals is implemented as shown in Fig. 8 and represents a disturbance rejection approach. The choice of the control parameters for the WMDS depends on a trade-off between system dynamics and stability. The iteratively chosen parameters (PI-controller) are found in Table 4. The proportional gain is set to be zero for the presented results. A small proportional gain might be suitable for increase of system dynamics but easily reaches stability limits. Since the goal of the controller is to reduce acceleration error, the control-loop differs from similar applications like TNO VEHL\(^{(16)(17)}\) that use trajectory-based control.

3.4.4 Dynamic Closed-Loop Control (dynCLC)
The dynamic closed-loop control is based on the dynOLC (section 3.4.2) and shows the same feedback control as introduced for kinCLC in section 3.4.3 (Fig. 8).

4. Results
For the conducted tests, the tilt coordination and the washout of the MCA is disabled, since the reference input would be different for the analyzed control setups and a direct comparison would be complicated.

4.1 Test Maneuvers
The identification of the created driving experience is done for two test maneuvers. The first maneuver represents a T-junction as it occurs frequently in urban areas. The driver decelerates from initial velocity to standstill before having a short stop and then turning 90° to the right and reaccelerating to initial velocity. This maneuver presents a longitudinal deceleration and accelerated cornering. The boundary conditions of this maneuver are shown in Table 5. The second maneuver is a horizontal-8. This maneuver is conducted with constant velocity. Lateral dynamics and the transient change from cornering from left side to right side are presented. The boundary conditions of this maneuver are shown in Table 6.

Table 5 Specification of T-junction test maneuver

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner radius</td>
<td>m</td>
<td>25</td>
</tr>
<tr>
<td>Deceleration before</td>
<td>m/s(^2)</td>
<td>4</td>
</tr>
<tr>
<td>Acceleration after</td>
<td>m/s(^2)</td>
<td>4</td>
</tr>
<tr>
<td>Initial velocity</td>
<td>m/s</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 6 Specification of horizontal-8 test maneuver

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner radius</td>
<td>m</td>
<td>25</td>
</tr>
<tr>
<td>Constant velocity</td>
<td>m/s</td>
<td>12.2</td>
</tr>
</tbody>
</table>

4.2 Simulation Results
Best results are achieved by the setup of the introduced dynamical closed-loop approach. Thus, the following time plots of the two test maneuvers are shown for the dynOLC setup. Fig. 9 and Fig. 10 show the reference and actual signals of \(a_x, a_y\) and \(\dot{\psi}\). These plots provide first orientation for the best setup that was analyzed.
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Fig. 9 shows the time plot for the described T-junction maneuver with the dynamic closed-loop control. The longitudinal acceleration reaches peak values of ±4 m/s² as described for this maneuver. At about \( t = 21 \) s the virtual test driver declutches in order to prepare for stopping at the T-junction. Thus, an interruption of traction is found as a steep gap in \( a_x \). The lateral acceleration reaches a peak value of about 3 m/s². The simulation follows the reference input with a small latency but leaves no offset in amplitude. The behavior of yaw acceleration is similar. The peak at about \( t = 29 \) s results from the virtual test driver who operates the clutch in order to prepare for a gear shift while cornering.

Fig. 9  Time plot of dynCLC for T-junction.

In order to compare the four analyzed control setups, the error in \( a_x \), \( a_y \) and \( \ddot{\psi} \) is observed. The errors are presented as cumulative distribution functions (CDF) allowing for a comprehensive comparison of the different control setups. The plots are provided for both test maneuvers that are already shown above (Fig. 9 and Fig. 10).

\[
\Delta a_x = a_{x,ref} - a_{x,sim} \quad (9)
\]
\[
\Delta a_y = a_{y,ref} - a_{y,sim} \quad (10)
\]
\[
\Delta \ddot{\psi} = \ddot{\psi}_{ref} - \ddot{\psi}_{sim} \quad (11)
\]

Fig. 10 shows the time plot for the described horizontal-8 maneuver with the dynamic closed-loop control. The maneuver lasts for 60 seconds and contains several steer maneuvers. The behavior of the simulated WMDS is similar to the already described T-junction. This maneuver shows that the system behavior is no subject to simulation time or combined maneuvers. No drift is identified for the analyzed dynCLC.

Fig. 10  Time plot of dynCLC for horizontal 8.

Fig. 11 shows the CDF plot for the errors occurring in the described T-junction maneuver. It occurs that the open-loop control setups show bigger error than the closed-loop control setups. The performance of the dynamic algorithms is hardly better than the kinematic approaches. This observation changes in Fig. 12 for the horizontal-8 maneuver. Still, the closed-loop control setups create smaller errors yet the dynamic algorithms show better results than the kinematic approaches.
To investigate the drawbacks shown in Fig. 12 of the kinematic approach Fig. 13 is introduced comparing kinOLC and dynOLC for the horizontal-8 test maneuver in a time plot. The kinematic approach shows drift. It cannot be stated from Fig. 13 if the dynOLC is also subject to drift but it is obvious that if there is drift, the effect is significantly smaller. One reason for the observed drift of the kinematic approach could be from the DS states that are used for the MC algorithm ($\gamma_{CG}$ and $\dot{\psi}$). Those states are calculated and observation error might rise over time. The observed drift is not solved yet but will be examined in further research. It has to be stated that the dynCLC does not seem to drift and creates good results.

In order to analyze the influence of the maneuver’s dynamics onto the created driving experience, a comparison for the horizontal-8 maneuver is conducted using different constant velocities. The aforementioned test maneuver was done with a constant velocity of 12.2 m/s (maximum $a_y = 6$ m/s²). Those results are compared in Fig. 14 with a less dynamic horizontal-8 maneuver using the same trajectory but only 7.1 m/s (maximum $a_y = 2$ m/s²). The comparison is provided for two of the analyzed control setups for the sake of readability. The best (dynCLC) and worst (kinOLC) control setup are selected. The results of Fig. 14 show that the driving experience in terms of acceleration errors suffers from increased dynamics but the dynCLC especially provides promising results.
4.3 Tire Analysis

Applications of omnidirectional robot structures, as they are used for the WMDS, are rare considering dynamics up to 10 m/s² acceleration for wheel loads similar to passenger cars. Since it is unknown what tire characteristic is suitable for such a WMDS, the simulation is used to gain first knowledge about tire requirements. Neglecting cornering stiffness showed major influence in the aforementioned subsections. Thus, different cornering stiffnesses are analyzed. The changes are implemented in the multibody dynamics as well as in the MC algorithm. Increasing cornering stiffness up to 140 % (93.8 kN/rad) of the initially used 67 kN/rad does not show influence on the created driving experience. When reducing cornering stiffness it is found that 40 kN/rad is capable for closed-loop approaches but results in problems for open-loop setups. When reducing to 16 kN/rad, even closed-loop approaches fail.

Analyzing longitudinal characteristics is not conducted, since the longitudinal force is controlled directly by the wheel hub torque. Thus, no major influence is expected.

5. Conclusion

Even the implementation of linear cornering stiffness behavior brings major improvements concerning drift behavior of the acceleration simulation. Further improvement is reached when using closed-loop control setups. The analyzed setups show best performance when combining the dynamic algorithm and closed-loop control (dynCLC). Since the introduced control parameters are found by iterative methods, it is not proved that kinCLC shows a conceptual disadvantage compared to dynCLC. Even so it becomes apparent that the tuning effort of the control setups is reduced when providing physical information of the simulated system. The introduced disturbance rejection approach profits from physical comprehension of the controlled system. Thus, the created driving experience benefits and the driving simulator performance increases.

The observed drift of the kinematic approach seems to be compensated by dynamic algorithms especially when combining with closed-loop controls. It has to be analyzed if the calculated DS states, which are used in the MC, affect drift as assumed. If the assumption is attested, results could be improved using measured sensor data of the DS states in combination with observers like a Kalman filter.

Considering tire requirements, it is identified that cornering stiffness affects the driving experience if chosen too low. Further research will be done in this field to determine suitable tires for the hardware prototype of the WMDS.

The dynCLC setup shows promising results considering qualification for driving simulation as it is used in the automobile industry. For the next step, the simulation results will be validated using a hardware prototype.
Abbreviations

ADAS  advanced driver assistance systems
CDF  cumulative distribution function
CG  center of gravity
COS  coordinate system
dem  demand
DOF  degrees of freedom
DS  driving simulator
dyn  dynamic
dynCLC  dynamic closed-loop control
dynOLC  dynamic open-loop control
e  earth fixed
FZD  Fachgebiet Fahrzeugtechnik
kin  kinematic
kinCLC  kinematic closed-loop control
kinOLC  kinematic open-loop control
long  longitudinal
MC  motion control
MCA  motion cueing algorithm
ref  reference input
res  resulting
sim  simulation output
TC  tilt coordination
trans  translational
WMDS  Wheeled Mobile Driving Simulator

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