Power, Energy, and Latency Test Drives with the Wheeled Mobile Driving Simulator Prototype MORPHEUS

Paul Wagner¹, Chris Zöller¹, Torben Albrecht¹, Hermann Winner¹

Abstract – This paper presents test drive results for power and energy demand as well as motion latency for the wheeled mobile driving simulator prototype MORPHEUS. Thus, this work further fills the mosaic of theoretical and practical evidence for the conceptual validity of wheeled mobile driving simulators. For evaluating the power demand, a straight-line manoeuvre is driven with MORPHEUS and the main accumulator’s output current and voltage are measured. The initial requirement is not met, because road surface excitations impede tire force transmission at high velocities, and because of the accumulator’s power limit. The energy demand is investigated by validating the virtual prototype’s energy model with measurement data from MORPHEUS, and finally calculating the overall energy demand for an unscaled, representative urban driving scenario with the validated simulation model. The results prove that the requirement can be met by state-of-the-art accumulator technology. Motion cue latency is researched by driving synthetic manoeuvres and measuring the time span from a target input value to certain acceleration thresholds, which are in accordance with state-of-the-art motion latency measurement methods from the automotive industry. The measured latency is below that of regular passenger cars and therewith meets the requirements.

Keywords: Wheeled Mobile Driving Simulator, Feasibility, Experiments, Simulation, Validation.

Motivation

“Wheeled Mobile Driving Simulators (WMDS) bear the potential to revolutionise driving simulation. By resolving the dependency between mass and range of motion, which is characteristic for state-of-the-art driving simulators (DS), a WMDS [can] represent low and high frequency accelerations with amplitudes close to 10 m/s² while still providing a lightweight concept and thereby reducing power and energy demands as well as costs.” [Wag16]

Nevertheless, the WMDS concept will only be accepted by the driving simulation community if an immersion is reached that is at least comparable to state-of-the-art DS and if acceptable experiment durations are enabled by the onboard energy supply. Betz [Bet15] identified five aspects (i.e. requirements) that must be fulfilled. These aspects are supplemented within this work by a sixth and seventh aspect:

1. Power demand
2. Energy demand
3. Friction coefficient
4. Motion control (MC)
5. Safety architecture
6. Motion cue latency
7. Control of vertical dynamics

The first five aspects have been proven feasible by Betz on a theoretical basis. So far, only the friction coefficient has been practically proven feasible for DS applications [Zoe16]. The safety architecture, MC, and the control of the vertical dynamics are currently researched, cf. Table 1.

Concluding, this paper aims at proving practical feasibility of the power demand, energy demand, and motion cue latency.

<table>
<thead>
<tr>
<th>Feasibility aspect</th>
<th>Theoretically proven</th>
<th>Practically proven</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power demand</td>
<td>[Bet15, Bet12b, Bet14b]</td>
<td>Present paper</td>
</tr>
<tr>
<td>Energy demand</td>
<td>[Bet15, Bet12a, Bet14b]</td>
<td>Present paper</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>[Bet15, Bet12a, Bet12b, Bet14b]</td>
<td>[Bet14b, Zoe16]</td>
</tr>
<tr>
<td>Motion control</td>
<td>[Bet15, Bet13, Bet14b, Wag15]</td>
<td>Future research</td>
</tr>
<tr>
<td>Safety architecture</td>
<td>[Bet15, Bet14a, Bet14b]</td>
<td>Future research [Wag16]</td>
</tr>
<tr>
<td>Motion cue latency</td>
<td>Unnecessary</td>
<td>Present paper</td>
</tr>
<tr>
<td>Control of vertical dynamics</td>
<td>Future research [Zoe 16]</td>
<td>Future research</td>
</tr>
</tbody>
</table>
Requirements Analysis

Power demand

The drive power must be sufficient to provide maximum acceleration within the friction limit of the tires in the velocity range necessary for the simulation of urban driving scenarios. Previous research has revealed that over 99% of urban driving scenarios are representable with a maximum DS velocity of 14 m/s and about 90% with a maximum velocity of 8.5 m/s [Bet12a].

Energy Demand

The energy supplied by the main accumulator is desired to be sufficient for a 2 h test drive, until the accumulator must be recharged or substituted by a fully charged accumulator.

Latency

Defining values for the acceptable latency emanating from the vestibular signals is rather difficult, because human perception is strongly dependent on ambient conditions, which makes it difficult to find consistent values in literature.

Motion cue latency ought to be comparable to what can be experienced when driving a real car. In a passenger car, for longitudinal motion, the time span from brake pedal actuation to the first incline in longitudinal deceleration (response time) and the time span from the first incline to 50% of the desired longitudinal acceleration (build-up time/2) are observed [Bre12]. Passenger cars usually need 200 ms from brake pedal actuation until 50% of the desired deceleration is reached (response time + build-up time/2) [Bre12]. This 50% target acceleration criterion will be referred to as the indicator for longitudinal acceleration cue latency (IACL_{long}). For lateral motion, the time span from steering wheel actuation to the first increase in the yaw velocity gain is used. This time span ranges between 82 ms and 138 ms for sports cars and between 100 ms and 190 ms for regular passenger cars [Pfe11]. Thus, 100 ms is used as the requirement for lateral motion latency, because the primary purpose of a DS is not to simulate sports cars. The criterion of an increase in the yaw velocity gain will be referred to as the indicator for lateral acceleration cue latency (IACL_{lat}).

Methodology

Research Tools

For researching the feasibility aspects, the MORPHEUS prototype [Wag14], Figure 1, is used. The three drive motors provide 100 kW each. The high voltage (HV) accumulator consists of 144 Lithium-Polymer-cells connected in series and has a nominal voltage of 532.8 V (DC), a minimum operating voltage of 432 V (DC), and a capacity of 10 Ah. The maximum current that can be drawn from the accumulator for at least 20 s is 200 A.

Motion quantities are measured by fibre-optic gyroscopes (angular velocities), inertial sensors (linear accelerations), and GPS/DGPS (3D position), and are merged and filtered into an overall 3D motion information by a GeneSys ADMA-G.3. Motor resolvers measure the electric motors’ position that is transferred to the motor controllers from where these values are tapped together with the signal of a current sensor that is positioned between each electric motor and its motor controller. Another current and voltage sensor is installed at the main accumulator for identifying the peak power, Eq. 1, and energy demand over a given time, Eq. 2.

\[ P = U \cdot I \]  \hspace{1cm} (1)

\[ E = \int P \Delta t = \int U \cdot I \Delta t \]  \hspace{1cm} (2)

Translational accelerations as well as rotational velocities are measured with a sampling rate of 500 Hz, electric current as well as voltage of the main accumulator with 200 Hz, and motor currents and revolutions with 100 Hz.

Acceleration signals are low-pass filtered in the post processing. Sensor noise, vibrations of the electric motors, and body vibration due to vertical excitation from the uneven road surface cause signal disturbance. The Power Spectral Density (PSD) of the discrete Fourier Transform (FFT) of a longitudinal acceleration signal is shown in Figure 2.
noise. In accordance with the values found in literature and a conducted sensitivity analysis (considering the standard deviation and variance of the motion cue latency of six trials of the identical manoeuvre, before filtering and after filtering with varied low-pass filter parameters), a low-pass filter with a passband frequency of 7 Hz and a stopband frequency of 13 Hz is chosen. Figure 3 shows the comparison between the unfiltered (orange line) and low-pass filtered (yellow crosses) measured longitudinal acceleration signal.

![Figure 3. Comparison of unfiltered and low-pass filtered measured longitudinal acceleration (90° steering angle input at \( v_{\text{total}} = \text{const.} = 2 \text{ m/s, trial 1} \))](image)

A classical motion cueing algorithm (MCA) is used [Bet15]. Scaling factors are chosen in dependence of the driving manoeuvre due to limited available driving area of the test track, the August-Euler-airfield in Darmstadt, Germany.

Furthermore, a virtual prototype programmed in Matlab Simulink and IPG CarMaker is available, using the same MCA and MC as the hardware prototype.

**Power Demand**

For measuring the power demand, a simple straight-line driving manoeuvre with maximum acceleration up to 9 m/s velocity is sufficient. This velocity is chosen for two reasons: Firstly, more than 90 % of all unscaled urban driving scenarios can be driven with that velocity and, secondly, the driving area provided at the test track will not allow for higher velocities.

The feasibility aspect power demand is considered valid if the hardware prototype can represent full acceleration up to 9 m/s.

**Energy Demand**

Energy is consumed by the platform, the hexapod and auxiliaries (visualisation, measurement technology etc.). Because the available driving area is not sufficient to drive unscaled urban driving scenarios [Gra11, Bet12a], with MORPHEUS – which constitutes the most realistic application with maximum energy consumption – the virtual prototype is used to determine the platform's energy consumption. Therefore, a Matlab Simulink based energy model is integrated into the virtual prototype, taking four effects into account:

1. Power demand calculated from wheel hub torques and electric motor speeds in combination with an electric motor speed-dependent efficiency map
2. Constant power demand of motor controllers
3. Driving speed-dependent power demand from driving resistances
4. Power demand from steering and self-aligning torque

These effects were parameterized by conducting synthetic manoeuvres with MORPHEUS and measuring the platform’s energy consumption. The power demand of the model integrated over time yields the overall energy demand (Eq. 2).

Finally, the maximum energy consumption of a full-scale WMDS platform can be calculated by simulating an unscaled, representative urban driving scenario with the validated energy model. Adding the measured energy consumption of low voltage (LV) auxiliaries (e.g. safety system, power electronics, measurement technology) and the estimated consumption of the hexapod and visualisation, yields the overall energy demand.

The feasibility aspect energy demand is considered valid if the results from the validated energy model prove that unscaled urban driving simulation is allowed for at least 2 h of operation with state-of-the-art accumulator technology.

**Latency**

For identifying the latency in the motion system, synthetic manoeuvres are used with MORPHEUS. Because of the omnidirectionality of WMDS, the latency requirements cannot be clearly divided into longitudinal and lateral motion. Even more, latency is expected to depend on the wheels’ orientation and to behave identical for lateral and longitudinal motion. In contrast, a passenger car has a distinctive orientation, hence latency is different in lateral and longitudinal motion. Furthermore, in passenger cars, different measurement indicators are used for lateral and longitudinal motion latency. When it comes to simulating a passenger car with a WMDS, the dilemma worsens, illustrated by the following example: The virtual car is driving in a straight line when the driver executes an emergency braking while the WMDS is not travelling in its longitudinal but in its lateral direction due to the washout. Then, the WMDS’ wheels would have to turn about 90° to provide a longitudinal motion cue. This 90° wheel turn scenario constitutes the worst case for longitudinal and lateral acceleration representation, because the time for the wheels’ reorientation is added to the time needed for providing the desired motion cue.

Concluding, the worst case for providing a motion cue – longitudinal, lateral, or a combination of both – are wheels that are misaligned by 90° to the desired direction of motion, and, therefore, the worst case
motion latency is the same in every direction of a WMDS. Only the real-life measurement methods differ, which is why two motion latencies will be determined for WMDS. Because these two motion latencies correspond to the longitudinal and lateral motion latency of the virtual car – and NOT to the longitudinal and lateral motion latency of a WMDS – they are referred to as longitudinal and lateral acceleration cue latency ($ACL_{long}$ and $ACL_{lat}$).

**Longitudinal Acceleration Cue Latency**

$ACL_{long}$ is determined by comparing lateral acceleration step inputs to the resulting lateral acceleration of MORPHEUS, whereas the wheels are misaligned by 90°. Another test scenario would be to provide a longitudinal acceleration step input with misaligned wheels; the results would be the same. $ACL_{long}$ is then calculated by subtracting the manoeuvre initiation time (acceleration step input) from the time when 50% of the set acceleration is reached (cf. requirements analysis). In order to quantify the impact of driving velocity, an experiment design from 0 to 6 m/s in 1 m/s increments is chosen at an exemplary step input amplitude of 5 m/s². To evaluate the impact of the step input amplitude, a variation from 1 m/s² to 8 m/s² in 1 m/s² increments for driving velocities of 0 and 1 m/s is driven, resulting in a total of 21 experiments. Driving velocity may have an influence due to the relaxation length of the tire and relating thereto delayed tire force build-up. The step input amplitude provides insight to the control behaviour of the motor controllers.

**Lateral Acceleration Cue Latency**

For researching $ACL_{lat}$, two drive control methods are investigated. Firstly, a steering angle step input of 90° is applied at constant, total driving velocities of 1 m/s to 6 m/s in 1 m/s increments. Secondly, a lateral acceleration step input is applied. Conveniently, the data from the $ACL_{long}$ experiments can be used for the latter experiment, thus resulting in a total of only 6 experiments. For calculating $ACL_{lat}$, an indicator is needed to determine the time when the system is reacting to the control input. Latency is then calculated as the difference between the time of indication and the time of manoeuvre initiation, the latter being a steering angle or lateral acceleration step input. With passenger cars, an increase in the yaw velocity gain is used as an indicator for the vehicle’s reaction to the control input (cf. requirements analysis). Because lateral motion in a driving simulator is not necessarily connected to yaw motion, it is not advisable to use yaw velocity gain as an indicator, but rather lateral acceleration. This assumption is eligible because in a car yaw motion and lateral acceleration occur almost simultaneously. Since the overall aim is to represent acceleration to a human test person, it is obvious to use the human perception threshold of 0.2 m/s² [Bet15] as an indicator.

Each experiment is carried out 6 times, yielding 162 data sets for evaluating $ACL_{long}$ and $ACL_{lat}$.

The feasibility aspect motion cue latency is considered valid if the hardware prototype reaches 50% of any acceleration step input within 200 ms and 0.2 m/s² after any acceleration or steering angle step input within 100 ms at any velocity.

### Test Drive Results

#### Power Demand

Figure 4 shows the set (red solid line) and measured (blue stars) longitudinal acceleration, measured longitudinal velocity (yellow dots), and the accumulator’s power output (purple circles). The maximum acceleration cannot be maintained throughout the manoeuvre. At velocities above approximately 3 m/s the acceleration amplitude decreases and starts oscillating heavily above 6 m/s. The acceleration’s oscillation coincides with an accumulator output power of about 70 kW.

![Figure 4. Exemplary acceleration, velocity, and power signals for maximum longitudinal acceleration up to 9 m/s](image)

#### Energy Demand

**Motion energy consumption (HV)**

The validation (cf. Table 2) of the energy model is done by comparing the virtual prototype’s and MORPHEUS’ energy consumption during a 90° turning manoeuvre ($a_y = const. = 1$ m/s², averaged over 6 trials), a figure eight manoeuvre ($a_y = const. = 1$ m/s², averaged over 6 trials), and a 10 min urban driving scenario with a scaling factor of 0.3 (scenario #3, averaged over 10 trials), whereas $s$ is the standard deviation of the trials conducted with MORPHEUS.

**Table 2. Results of the validation of the energy model**

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>$t_{sim}$ in s</th>
<th>$E_{sim}$ in Wh</th>
<th>$E_{MEASURED}$ in Wh</th>
<th>$s_{MEASURED}$ in Wh</th>
<th>$\Delta$ in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° Turn</td>
<td>31</td>
<td>17.3</td>
<td>17</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Figure 8</td>
<td>66</td>
<td>38.6</td>
<td>36</td>
<td>0.8</td>
<td>7.2</td>
</tr>
<tr>
<td>Urban</td>
<td>600</td>
<td>348.7</td>
<td>358.8</td>
<td>14.2</td>
<td>2.8</td>
</tr>
</tbody>
</table>
The higher standard deviation in the urban scenario arises because of environmental conditions like winds or temperature and measurement inaccuracies, which lead to not exactly reproducible measurements. Regarding the validation results, the energy model is valid for the purpose of estimating the platform’s energy demand.

Four unscaled, representative, urban driving scenarios [Gra11] are simulated with the validated energy model of the virtual prototype and a WMDs mass of 1,200 kg for determining the maximum energy consumption. The results are presented in Table 3:

<table>
<thead>
<tr>
<th>Urban driving scenario #</th>
<th>$t_{\text{sim}}$ in s</th>
<th>$k_{\text{sim}}$ in Wh</th>
<th>$\phi P_{\text{sim}}$ in W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.500</td>
<td>8,391</td>
<td>8,631</td>
</tr>
<tr>
<td>2</td>
<td>3.100</td>
<td>7,057</td>
<td>8,195</td>
</tr>
<tr>
<td>3</td>
<td>2.900</td>
<td>6,234</td>
<td>7,739</td>
</tr>
<tr>
<td>4</td>
<td>3.500</td>
<td>6,337</td>
<td>6,518</td>
</tr>
</tbody>
</table>

For the evaluation, the worst case energy consumption of urban driving scenario #1 will be used.

Unfortunately, the hexapod was not operable and therefore no energy consumption could be determined. Betz identified a Tripod’s average energy demand for tilt coordination in an unscaled, representative urban driving scenario simulation based on the actuators’ lengths and velocities to be 32 W [Bet12a]. The average energy required for holding the load was neglected in simulation, but estimated to be 100 W [Bet12a]. Adding an estimate for the power electronics’ average energy consumption yields a total power consumption of 200 W for the hexapod’s tilt coordination task.

**Auxiliary energy consumption (LV)**

A 12 V (DC) and a 24 V (DC) auxiliary electrical system with separate LV accumulators are used on MORPHEUS. Because the aim is to replace the LV accumulators with a DC/DC converter to solely use the HV accumulator, every auxiliary energy consumer is measured, resulting in an overall power consumption of 266.9 W:

- IPG Roadbox: 30.3 W
- Wireless emergency stop: 2.3 W
- Programmable logic controller: 3.5 W
- Magnetic clamps (safety system): 121.7 W
- Status LEDs: 0.6 W
- Wireless router: 4.8 W
- Power electronics: 78 W
- Battery management system: 4 W
- High voltage contactors: 3.6 W
- ADMA-G: 18.1 W

Still, the main auxiliary energy consumer is expected to be the simulation computers. Because no measurements were possible, their power demand is estimated (after consultation with a provider of simulation computers) to be 600 W, resulting in a total average LV power consumption of 866.9 W.

**Latency**

**Longitudinal Acceleration Cue Latency**

Recalling the methodology for measuring latency, lateral acceleration signals are used to validate this requirement. Figure 5 shows an exemplary lateral acceleration step input (red point-dashed line) and MORPHEUS’ lateral acceleration response (blue stars). Additionally, the IACL$_{\text{Long}}$ (i.e. 50 % of set acceleration) is shown (black solid line).

![Figure 5. Exemplary acceleration time signals for a 4 m/s$^2$ lateral acceleration step input at 0 m/s for identifying IACL$_{\text{Long}}$ (trial 1)](image)

50 % of the set acceleration is reached after approximately 155 ms for this exemplary test drive.

The variation of the acceleration step input amplitude yields variable results, Table 4, because the IACL$_{\text{Long}}$ (50 % of set acceleration) is dependent on the step input amplitude itself. For example, in a trial with a step input of 2 m/s$^2$, the latency measurement time ends as soon as 1 m/s$^2$ are measured, whereas with a step input of 8 m/s$^2$, an acceleration of 4 m/s$^2$ has to be measured.

<table>
<thead>
<tr>
<th>a in m/s$^2$</th>
<th>$\text{IACL}<em>{\text{Long}}$ in ms, caused by lateral acceleration step inputs, calculated with the IACL$</em>{\text{Lat}}$, and initial longitudinal driving velocities of 0 and 1 m/s (values are averaged over 6 trials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>123 134 145 150 155 159 157 157</td>
</tr>
<tr>
<td>1</td>
<td>81 93 101 113 122 127 134 139</td>
</tr>
</tbody>
</table>

Thus, acceleration cue latency increases with the acceleration step input and yields a maximum latency of 159 ms at 7 m/s$^2$ and 0 m/s. Still, the results are rather dependent on the IACL$_{\text{Lat}}$ than the input variation itself. Nevertheless, the input amplitude’s influence is evaluated for these test drives using the IACL$_{\text{Lat}}$ (0.2 m/s$^2$) in the next section of this paper.

The variation of the driving velocity also yields variable results, Table 5, because of the relaxation length of the tire. Thus, IACL$_{\text{Long}}$ increases with decreasing driving velocity (and therewith decreasing tire relaxation length over time).
The average of the relative mean signed deviation (MSD) of each ACL_long set of 6 trials (Table 4 and Table 5) is 4.4%, proving the robustness of the IACL_long. Concluding, the maximum ACL_long is found at standstill (due to drilling torque and no relaxation length in the tire) and close to the maximum acceleration step input (due to the IACL_long): 159 ms.

**Lateral Acceleration Cue Latency**

Figure 6 shows an exemplary lateral acceleration step input (red dot-dashed line) and MORPHEUS' lateral acceleration response (blue stars). Additionally, the IACL_lat (0.2 m/s²) is shown (black solid line).

Table 5. ACL_long, caused by a 5 m/s² lateral acceleration step input, calculated with the IACL_long, and varied driving velocity (values are averaged over 6 trials)

<table>
<thead>
<tr>
<th>$v$ in m/s</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL_long in ms</td>
<td>155</td>
<td>122</td>
<td>100</td>
<td>97</td>
<td>78</td>
<td>83</td>
<td>78</td>
</tr>
</tbody>
</table>

The average of the relative mean signed deviation (MSD) of each ACL_long set of 6 trials (Table 4 and Table 5) is 4.4%, proving the robustness of the IACL_long. Concluding, the maximum ACL_long is found at standstill (due to drilling torque and no relaxation length in the tire) and close to the maximum acceleration step input (due to the IACL_long): 159 ms.

**Figure 7.** Exemplary acceleration and steering angle time signals for a 90° steering angle step input at 1 m/s longitudinal velocity (trial 1) IACL_lat is reached 52 ms after the set steering angle has been ramped to 90°.

Table 8 shows that ACL_lat decreases with increasing driving velocity.

Table 8. ACL_lat, caused by a 90° steering angle step input, calculated with the IACL_lat, and varied driving velocity (values are averaged over 6 trials)

<table>
<thead>
<tr>
<th>$v$ in m/s</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL_lat in ms</td>
<td>65</td>
<td>48</td>
<td>53</td>
<td>52</td>
<td>48</td>
<td>44</td>
</tr>
</tbody>
</table>

The average of the relative MSD of each ACL_lat set of 6 trials (Table 6, Table 7, and Table 8) is 14.6%, showing that the IACL_lat is more sensitive than the IACL_long. Concluding, the maximum ACL_lat is found at standstill (due to drilling torque and no relaxation length in the tire) whereas the acceleration step input amplitude plays a minor role: 104 ms.

**Conclusion**

**Power Demand**

The requirement for the power demand was not met. Three possible reasons are identified:

Firstly, the HV accumulator's output power is limiting the overall propulsion power (3 x 100 kW electric motor power), as can be seen when Eq. 1 is calculated with the accumulator’s parameters for minimum voltage. The minimum operating voltage is used because measurements show that the accumulator’s output voltage drops to this value when the maximum current is drawn from the accumulator.

$$ P_{\text{accumulator}} = 432 \text{ V} \cdot 200 \text{ A} = 86 \text{kW} \quad (3) $$

The required mechanical propulsion power for the conducted manoeuvre is calculated by Eq. 4:

$$ P_{\text{mechanical}} = F \cdot v = m_{\text{MORPHEUS}} \cdot a_{\text{max}} \cdot v = 1.056 \text{ kg} \cdot 8 \text{ m/s}^2 \cdot 9 \text{ m/s} \quad (4) $$

$$ = 76 \text{kW} $$

Still, the calculated mechanical power does not account for rolling and air resistance and losses in electrical components. Thus, the conducted manoeuvre is close or likely even above the capability of the HV accumulator.
Secondly, measurement data showed that vertical excitation in combination with the stiff body and the lack of a proper suspension disturbs the tire-road contact so that increased driving velocities come along with a reduced force transmission potential at the tires. Although the measurement data from the electric current and voltage sensor suggest that the power is sufficient for fulfilling the requirements, a sophisticated control of the vertical dynamics is required to achieve this goal.

Thirdly, the accumulator’s measured average output power of 70 kW at velocities between 6 m/s and 9 m/s suggests that the accumulator’s cells—in that have been manufactured in 2013—have aged and therefore provide deficient performance due to increased internal resistance.

Concluding, the feasibility aspect power demand is currently considered to be practically invalid.

Energy Demand

The worst case average power demand for an unscaled, representative urban driving scenario is 9,698 W, which results in an energy demand of 19,396 Wh for a 2 h simulation run. Thus, the initial requirement for the energy demand is not met for the currently installed accumulator (532.8 V · 10 Ah = 5,328 Wh). Nevertheless, adding three further HV accumulators (mass 34 kg each) is reasonable, especially when a DC/DC converter is compensating for the three LV accumulators (mass approx. 20 kg each). Thus, the updated requirement for four HV accumulators is a 2 h energy demand below 21.3 kWh, which is met when considering the simulation data. Also, when considering the energy demand for the 0.3 scaled urban driving scenario, a simulator runtime of 1 h 41 min is enabled with the current accumulator.

Thus, the feasibility aspect energy demand is considered to be valid when applying state-of-the-art accumulator technology.

Latency

Two influencing factors (driving velocity, step input amplitude) and two control methods (acceleration step input, steering angle step input) were researched. It was shown that the step input amplitude does not affect latency, whereas the driving velocity does. Increasing the driving velocity decreases the acceleration cue latency because of the tire’s relaxation length. The differences between the acceleration and steering angle input are marginal, so that the MC and the motor controllers seem to have no influence on the acceleration cue latency.

The IACL_{long} proved to be very robust, whereas the IACL_{lat} is less robust. This is partly caused by the resolution of 2 ms of the time signal, but also by signal disturbance, whose influence is greater on signals with low amplitudes (IACL_{lat} < IACL_{long} for set amplitudes above 0.4 m/s^2).

For the identified maximum ACL_{long} of 159 ms, the requirement of staying below 200 ms is met. The requirement of staying below 100 ms is not met for the identified maximum ACL_{lat} of 104 ms. For driving velocities of 1 m/s or more, the maximum ACL_{lat} is found to be 66 ms. Given the average relative MSD of 14.6 % for ACL_{lat} measurements and since the control approach is to keep the simulator in motion at any time so that the driving velocity will never become 0, the feasibility aspect of motion cue latency is considered to be valid.

Outlook

Further effort must be put into the control of MORPHEUS. This will help to improve the accuracy in following the set signals and reduce motion cue latency even further.

The vertical excitation due to the road surface is a major problem at the current state of research. A normalized cross-correlation of the vertical and lateral acceleration signal from the same test drive as in Figure 3 is calculated and plotted in Figure 8.

Figure 8. Normalized cross-correlation of equally low-pass filtered vertical and lateral acceleration signal (90° steering angle input at \(v_{\text{init}} = \text{const.} = 2 \text{ m/s, trial 1, from manoeuvre initiation to end of manoeuvre (i.e. } a_{\text{lat}} > 0)\))

The lateral and vertical acceleration signals are dependent on each other between ±200 ms lag, whereas the lateral acceleration signal follows the vertical acceleration signal. This suggests an influence of vertical acceleration, and therewith vertical excitation, onto horizontal acceleration. Reducing the vertical excitation of MORPHEUS’ self-driving platform is expected to reduce acceleration signal disturbance and to improve the tires’ force transmission potential at increased velocities.

The safety architecture remains in the research focus as well, so that the concept may be applied widely in automotive development and research, therewith increasing the safety of vehicles even further.

For a future, full-scale prototype, the energy supply must be increased so that simulator runs of up to 2 h are enabled and that the power output of the accumulator is increased, which is compatible with the state-of-the-art in accumulator technology.

The possibility to do the simulation off-board and then sending the platform’s control input and visual and acoustical cues wirelessly to the simulator should be investigated. This would reduce mass and
energy consumption likewise. Still, latencies will have to be observed closely.

Acknowledgements

The results issued in this paper were researched in the project “Potential Analysis of a Self-Driving Motion Base for Driving Simulators”, which is funded by the German Research Foundation (DFG) under the reference number WI 3153/8-1.

References


List of Symbols and Indices

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>m/s²</td>
<td>Acceleration</td>
</tr>
<tr>
<td>E</td>
<td>J / Wh</td>
<td>Energy</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
<td>Electric current</td>
</tr>
<tr>
<td>m</td>
<td>kg</td>
<td>Mass</td>
</tr>
<tr>
<td>P</td>
<td>W</td>
<td>Power</td>
</tr>
<tr>
<td>s</td>
<td>.</td>
<td>standard deviation</td>
</tr>
<tr>
<td>t</td>
<td>s</td>
<td>time</td>
</tr>
<tr>
<td>U</td>
<td>V</td>
<td>Electric voltage</td>
</tr>
<tr>
<td>v</td>
<td>m/s</td>
<td>Velocity</td>
</tr>
</tbody>
</table>

Abbreviations

ACL_{lat} lateral Acceleration Cue Latency
ACL_{long} longitudinal Acceleration Cue Latency

DS Driving Simulator
FFT discrete Fourier Transform
HV High Voltage
IACL_{lat} Indicator for lateral Acceleration Cue Latency
IACL_{long} Indicator for longitudinal Acceleration Cue Latency

LV Low Voltage
MC Motion Control
MCA Motion Cueing Algorithm
MORPHEUS Mobile Omnidirectional Platform for Highly Dynamic and Tirebound Driving Simulation

MSD Mean Signed Deviation
PSD Power Spectral Density
WMDS Wheeled Mobile Driving Simulator