Potentials and Limitations of Hexapods in Wheeled Mobile Driving Simulators

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Abstract – This paper deals with the benefits and drawbacks of hexapods in Wheeled Mobile Driving Simulators. Therefore, a large and a small hexapod are considered and investigated in regard to their potential to reduce power, energy, and workspace demand of a Wheeled Mobile Driving Simulator. This is done by employing the hexapod for representing horizontal acceleration cues. Furthermore, the hexapod may contribute to overcoming characteristic problems of wheeled mobile robots like singularities in wheel orientation while still providing the correct acceleration cues to the user. A potential field algorithm with compensation of acceleration through the hexapod has been investigated. Still, the inertial forces of the hexapod have to be supported by the wheeled mobile platform. When inertial forces of the hexapod are supported by the wheels, the acceleration potential of the whole driving simulator is reduced. It is shown that translational forces have the largest influence on the wheel load – up to 19 %, whereas translational and rotational displacements as well as torques have no significant influence.

Keywords: Hexapod, Wheeled Mobile Driving Simulator, Potential Analysis, Dynamics, Simulation.

Introduction

A dynamic Driving Simulator (DS) is a tool that can be used for research, development, and also entertainment purposes. Due to the representation of acceleration cues, a higher immersion is reached with dynamic DS than with static DS. In order to reduce the space demand of such a system scaling, Tilt Coordination (TC), and washout algorithms are used.

Scaling describes the process of proportionally reducing the amplitude of those acceleration signals that would occur in a real vehicle. TC takes advantage of the human perception by tilting the user relative to the gravity vector. As a result the user perceives the sine portion of the gravity vector as horizontal acceleration (in the user’s coordinate system). Washout is the attempt to bring the simulator back to its initial position in order to provide maximum workspace in all directions. Since the user must not notice any of those processes, they have to be carried out below human perception thresholds.

The three methods above are applied to almost all dynamic DS. To implement TC and washout – especially when both methods are combined, i.e. increased washout due to increased tilting angle (unwanted resulting accelerations cancel each other out) – hexapods are primarily used. Thus resulting inertial forces can be easily supported for systems comprising only a hexapod as well as for systems combining a hexapod with sledges for horizontal acceleration – the so-called advanced dynamic DS.

The institute of automotive engineering (FZD) at Technische Universität Darmstadt (TUD), Germany has been researching the concept of a Wheeled Mobile Driving Simulator (WMDS) since 2010. The approach is to use a self-driving platform to overcome the disadvantages of advanced dynamic DS as they are nowadays used with sledges for providing adequate horizontal accelerations: The large moving mass contributes to high energy and power demands as well as costs. This dilemma has been recognized by the automotive industry, as attested by Zeeb in 2010, former head of Driving Simulators at Daimler AG: “To induce a much better longitudinal motion sensation with a scaling factor close to 1:1 for all possible acceleration and deceleration scenarios even a several ten meter long sledge would not be sufficient, but would increase the technical and financial effort tremendously, especially when the [...] mandatory requirements for drive dynamic experiments have to be fulfilled.” [Zee10].

The non-holonomic, self-driving platform of the WMDS provides two Degrees of Freedom (DOF): surge, sway, and yaw. In order to fulfill the demands forTC, pitch and roll must be provided by an additional tilting system. Heave is needed when tilting causes vertical movement of the user’s head. Since this linking is characteristic for most tilting...
systems, a Tripod with three DOF is generally sufficient and was suggested in the previous research [Bet12b].

Heave then may also be used to represent road surface unevenness and therefore contributes to a higher immersion. Currently a hexapod is used in the WMDS prototype. Then the redundant DOF (surge, sway, and yaw) may be used to gain advantages over non-redundant systems.

Especially for the class of WMDS it has to be stressed that all inertial forces from the hexapod have to be supported by the wheels and therefore have an influence on wheel force transmission and rollover stability.

Previous publications that covered the research topics such as control [Bet13], feasibility [Bet12a, Bet12b, Bet14b], the safety system [Bet14a], and the design of the WMDS prototype [Wag14] can also be found summarized in the dissertation of Betz [Bet15].

**Methodology**

The overall project goal is to demonstrate feasibility of the WMDS concept. The approach is to try to falsify the feasibility hypothesis. Thus, investigations into limitations of the concept are carried out.

Since a hexapod is used instead of a tripod, redundant DOF may be used to improve performance of the WMDS. On one hand compensation measures can be taken; this is especially interesting for masking shortcomings of the wheeled mobile platform. On the other hand new methods for representing acceleration cues may be provided: Since the mass of the upper part of the hexapod with the cabin and user are much lower than that of the whole system, the same acceleration would result in lower forces at the wheels.

In order to investigate these aspects, research tools, namely the hardware, the virtual prototype, and the control algorithms, are presented.

Potentials in the form of representing acceleration cues with the hexapod as well as masking shortcomings of the wheeled mobile platform are investigated analytically and by simulations. The influence of the hexapod motion on the wheeled mobile platform are calculated and discussed.

Finally, the conclusion and outlook summarize the results and give an insight towards future research.

**Research Tools**

Two prototypes have been set up at FZD: A hardware prototype, as shown in Figure 1, and a virtual prototype comprising Matlab Simulink and IPG CarMaker. Thus, new approaches may be researched with the virtual prototype before being validated with the physical prototype.

The control for both prototypes consists of a Motion Cueing Algorithm (MCA) and a Motion Control (MC).

![Figure 1: WMDS Hardware Prototype](image)

![Figure 2: "ideal" MCA of the WMDS [Bet15]](image)

The MCA transforms either the driver’s input or the accelerations of a real vehicle into the acceleration demand of the platform and the hexapod. The MCA
is based on a classical washout algorithm, complemented by an acceleration feedback from the TC. The so-called “ideal” MCA is depicted in Figure 2. The MC calculates the needed steering angles and wheel hub torques for the wheeled mobile platform. For doing so, a kinematic model is used that also takes slip angles into account [Bet13].

Data measured from four test drives of a representative urban driving cycle is used for investigating the research questions [Bet15].

In order to analyze the full potential of a hexapod in WMDS two different off-the-shelf hexapods are examined: The hexapod currently used at FZD that is provided by Mevea (6DOF 1200E) [Mev13] and a larger hexapod that is sold by Bosch (e-Motion 1500) [Bos15]. Subsequently the hexapods are denominated as Hexapod A (Mevea) and Hexapod B (Bosch). The relevant parameters of the two hexapods are listed in Table 1:

<table>
<thead>
<tr>
<th>DOF</th>
<th>Hexapod A</th>
<th>Hexapod B</th>
<th>Hexapod A</th>
<th>Hexapod B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge (x)</td>
<td>7 m/s²</td>
<td>7 m/s²</td>
<td>0.13 m</td>
<td>0.62 m</td>
</tr>
<tr>
<td>Sway (y)</td>
<td>7 m/s²</td>
<td>7 m/s²</td>
<td>0.12 m</td>
<td>0.51 m</td>
</tr>
<tr>
<td>Heave (z)</td>
<td>10 m/s²</td>
<td>10 m/s²</td>
<td>0.09 m</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Roll (φ)</td>
<td>170 °/s²</td>
<td>250 °/s²</td>
<td>15°</td>
<td>24°</td>
</tr>
<tr>
<td>Pitch (θ)</td>
<td>170 °/s²</td>
<td>250 °/s²</td>
<td>17°</td>
<td>28°</td>
</tr>
<tr>
<td>Yaw (ψ)</td>
<td>200 °/s²</td>
<td>500 °/s²</td>
<td>20°</td>
<td>27°</td>
</tr>
</tbody>
</table>

**Table 1: Maximum Accelerations and Displacements of the Hexapods [Mev13, Bos15]**

**Potentials and Limitations of Hexapods in WMDS**

**Potential: Representing Horizontal Acceleration Cues with the Hexapod**

To benefit from the redundant DOF (surge, sway, and yaw) of the hexapod and the motion platform the MCA shown in Figure 3 is introduced. It enhances the “ideal” MCA shown in Figure 2 by a high pass path to filter accelerations with high frequencies. These acceleration tasks are performed by the hexapod and subtracted from the overall horizontal acceleration demand to maintain the “ideal” characteristics of the previously introduced MCA. Another scaling factor ensures that the hexapod stays within its workspace limitations. A 3rd order high pass filter is implemented and designed to return the hexapod to its initial position [Fis09] while considering presumed human perception thresholds of 0.2 m/s² [Bet15].

**Figure 3: Enhanced “ideal” MCA of WMDS**

Due to the lighter mass of the hexapod with the user and its cabin compared to the whole system, all accelerations performed by the hexapod result in an overall lower energy and power demand as well as reduced friction forces in the tires. Furthermore there is a potential of decreasing the motion envelope.

**MCA Parameterization**

Based on the representative urban driving cycles the parameters of the MCA are iteratively tuned to gain a maximum use of the hexapod’s workspace. Table 2 shows the used parameters for the different hexapod configurations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hexapod A</th>
<th>Hexapod B</th>
</tr>
</thead>
<tbody>
<tr>
<td>kHexapod</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>kDS</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hexapod B (1)</th>
<th>Hexapod B (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{TC,max}$</td>
<td>2.2 m/s²</td>
<td>4 m/s²</td>
</tr>
<tr>
<td>$\omega_{washout}$</td>
<td>1.071 1/s</td>
<td>0.502 1/s</td>
</tr>
<tr>
<td>$\omega_{low pass filter}$</td>
<td>0.5585 1/s</td>
<td>0.5585 1/s</td>
</tr>
</tbody>
</table>

**Table 2: Parameterization of the MCA**

Due to the limited tilting angle of Hexapod A the saturation for accelerations represented by TC has to be lowered from the presumed human perception thresholds of 4 m/s² to 2.2 m/s² [Bet15]. The excessive use of the TC by the motion platform’s washout limits the potential of representing translational acceleration cues through the hexapod. Therefore a scaling factor of $k_{\text{Hexapod}} = 0.05$ is introduced for Hexapod B to stay within the given workspace (configuration (2)). Since the workspace of Hexapod A has already been exploited by TC, a scaling factor of 0 is used. The same scaling factor is used for configuration (1) of Hexapod B for reasons of comparability.

**Results**

The calculations of power and energy demand are carried out according to equations (1) and (2) without regards to efficiencies or real actuator behavior.
Table 3 shows the average translational energy, power, and workspace demand of each hexapod and motion platform with the used MCA parameterizations. Representing translational acceleration cues through the hexapod results in a decrease of power, energy, and workspace demand. Due to the scaling factor, however, the achieved savings are very low. No scaling of the WMDS has been applied for Hexapod B.

\[ P_{\text{trans}} = a_{\text{trans}} \cdot v_{\text{trans}} \cdot m_{\text{acc}} \]  \hspace{1cm} (1)

\[ E_{\text{trans}} = \int P_{\text{trans}} \, dt \]  \hspace{1cm} (2)

The saturation threshold for accelerations that are represented by TC directly affects the magnitude of the motion platform’s washout. A higher saturation leads to a faster washout, which will decrease the overall workspace demand (Figure 4) but comes with a higher energy demand although the motion platform has to represent lower acceleration cues. An average decrease of 7.8 % on workspace is achieved by increasing the saturation threshold for TC. Representing translational acceleration cues through the hexapod leads to small decreases in energy (1.5 %), power (2.4 %), and workspace (0.6 %) demand. Compared to the translational accelerations cues, the saturation of the TC shows a greater impact on the workspace demand.

The large workspace demand accounts for the unscaled MCA parameterization. Nevertheless, representing translational acceleration cues with the hexapod will also lead to a workspace decrease with scaled acceleration cues.

Potential: Masking of the Platform’s Shortcomings with the Hexapod

The WMDS with its three independently steerable wheels is a non-holonomic, omnidirectional platform. This means that it cannot instantaneously change its driving direction without re-orientating its wheels. The kinematic model of the MC calculates the steering direction of each wheel through the ratio of the horizontal velocity components [Bet13]. Due to this, singularities occur when both of the velocity components are close to zero. A small variation of these components implies a fast rotation of the wheels. These singular configurations require a fast re-orientation of one or all three wheels of the WMDS. The time for re-orientation (and with this the step size in discrete simulations) has a major influence on the steering power \( P_{\text{steering}} \), as can be seen from equation (3).

\[ P_{\text{steering}} = (\theta_{\text{steering}} \delta + M_{\text{drill}}) \delta \]  \hspace{1cm} (3)

\( M_{\text{drill}} \) is the drilling torque in standstill, \( \delta \) the steering angle, and \( \theta_{\text{steering}} \) the moment of inertia of the steering unit.

Thus, enormous steering power demands are generated, although they occur very rarely.

Instantaneous Center of Rotation (ICR)

One way to describe the motion of the WMDS is the ICR [Con08] (Figure 5). This approach offers a descriptive representation of the singular configurations of the wheels. Those singular configurations are characterized by a fast re-orientation of the wheels that results in a high peak power demand of the steering motors.

A sensitivity analysis with the representative urban driving cycles and the existing MCA has been per-
formed, revealing two categories of situations with large peak steering power demands:

1. Peak steering power occurs at all wheels at low yaw rate
2. Peak steering power occurs at a single wheel at high yaw rate

Both situations have low velocity components in x- and y-direction of the affected wheels in common.

**Potential Field Algorithm**

In order to avoid this singularity a potential field algorithm [Con09] is chosen. Since the existing kinematic model should be maintained, an approach as described by Dietrich et al. [Die11] is used. Three repulsive potential fields around the wheels of the WMDS are defined in order to push the ICR away from the wheel contact patch and thereby reduce steering velocity. The axially symmetric repulsive potentials are defined by equation (4).

\[ u_{rep,ax} = \begin{cases} \frac{k_{rep}}{3d(x)^2}(d(x) - d(x_0))^3 & \text{for } d(x) \leq d(x_0) \\ 0 & \text{for } d(x) > d(x_0) \end{cases} \]  

with \( k_{rep} \) as an amplification factor, \( d(x) \) as the radial distance from the center of the potential field (equates to the wheel contact patch) to the ICR, and \( d(x_0) \) as the radius of the potential field.

The necessary accelerations of the WMDS, which are required to change the position of the ICR, constitute a deviation in the acceleration representation to the user. These deviations may surpass the thresholds of human perception in certain driving situations and therefore corrupt the acceleration cues. The hexapod is used to compensate these deviations; nevertheless the hexapod’s workspace limits the compensation capability. TC has been taken into account for this investigation and limits the compensation capability since less workspace is available for compensation. Figure 6 schematically shows the implementation of the potential field algorithm as well as the compensation by the hexapod with the relevant signal flow.

![Figure 6: Implementation of Potential Field Algorithm and Compensation by Hexapod](image)

**Results of the Implementation of the ICR and the Potential Field Algorithm**

A repulsive potential for each wheel contact patch has been applied with the parameters \( d(x_0) = 1 \) m and \( k_{rep} = 80 \). An exemplary trajectory of the ICR with the parameters described above is shown in Figure 7:

![Figure 7: Exemplary ICR Trajectory in the Potential Fields](image)

The application of one big potential field around the center of the WMDS instead of three potential fields around the wheel contact patches has been investigated but is dismissed: No advantages are found but additional steering power peaks occurred due to significant changes in translational accelerations of the platform.

All four representative urban driving cycles have been simulated in Matlab Simulink with a step size of 10 ms and analyzed in regard to their peak steering power with and without the potential field algorithm described above. The results for each wheel are presented in Table 4:

<table>
<thead>
<tr>
<th>Urban driving cycle</th>
<th>Steer motor</th>
<th>Without potential field algorithm</th>
<th>With potential field algorithm</th>
<th>Relative steering power reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (t = 3600 s)</td>
<td>1</td>
<td>3218.6</td>
<td>3167.3</td>
<td>1.6 %</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3057.7</td>
<td>2816.1</td>
<td>7.9 %</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3134.1</td>
<td>2696.2</td>
<td>14 %</td>
</tr>
<tr>
<td>2 (t = 3200 s)</td>
<td>1</td>
<td>3041.9</td>
<td>543.5</td>
<td>82.1 %</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1003.6</td>
<td>642.5</td>
<td>36 %</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1303.2</td>
<td>2259.5</td>
<td>-73.4 %</td>
</tr>
<tr>
<td>3 (t = 2900 s)</td>
<td>1</td>
<td>721.9</td>
<td>58.4</td>
<td>91.9 %</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>66.7</td>
<td>55.2</td>
<td>17.2 %</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>56.9</td>
<td>56.1</td>
<td>1.4 %</td>
</tr>
<tr>
<td>4 (t = 3500 s)</td>
<td>1</td>
<td>577</td>
<td>71.7</td>
<td>87.6 %</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3751</td>
<td>239.9</td>
<td>93.6 %</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>236.9</td>
<td>64.71</td>
<td>72.7 %</td>
</tr>
</tbody>
</table>

An up to 93.6 % reduction in peak steering power is achieved. In the first urban driving cycle no significant reduction can be seen. This is caused by a singular wheel configuration, in which all three
wheels have to re-orientate very fast at the same time because the ICR moves with high velocity and close to the Center of Gravity (COG) of the WMDS. The applied repulsive potentials showed limited effect on improving this situation. For the third wheel in the second urban driving cycle even an increase of the peak steering power of 73.4 % can be observed.

The workspace of Hexapod A is exceeded by the compensation and TC in all representative urban driving cycle, whereas the workspace of Hexapod B is mostly sufficient. Thus, a larger hexapod would bear the potential to mask false cues due to the potential field algorithm.

Limitation: Hexapod Motion vs. Driving Simulator Dynamics

The movement of the Hexapod on top of the self-driving platform results in two essential influences on the platform’s dynamics:

- Inertial forces and torques due to the acceleration of the hexapod. These forces are applied to the self-driving platform and have to be supported by the tires horizontally and vertically.
- Translational and rotational movements between the platform and the upper part of the hexapod carrying the mockup, resulting in a change of geometry and therefore in a change of the COG as well as moments of inertia.

The forces and torques that are applied to the platform by the hexapod - depending on the direction - result in wheel load changes as well as in an acceleration of the platform (assuming that the forces are not supported by the wheels of the platform).

The relative movement between the hexapod and the platform results in wheel load changes (due to a change of the COG) and changes of the moments of inertia.

In summary, it can be stated that the motion of the hexapod has two impacts on the platform: The first one being a change of the wheel loads due to forces, torques, translational, and rotational movements of the hexapod, and the second one being an acceleration of the platform due to forces and torques applied by the hexapod. The upcoming investigation will focus on each individual effect respectively.

Two methods are used to investigate the influence of the hexapod on the self-driving platform. The first one is an analytical approach. The second one uses a simulation in IPG CarMaker based on MATLAB/Simulink. For the simulation approach, the forces created by the hexapod are calculated and applied to the virtual prototype in IPG CarMaker. By using the ‘virtual forces’ gateway in IPG CarMaker any forces and torques can be applied to the COG of the prototype.

Influences on the wheel load

The mechanical properties of the WMDS and Hexapod A that are used for the simulation are given in Table 5.

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge length of the WMDS</td>
<td>2.3 m</td>
</tr>
<tr>
<td>Height of the force application point</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Mass of the upper part of the hexapod, the mockup, and the passenger</td>
<td>233 kg</td>
</tr>
<tr>
<td>Mass of the platform and the lower part of the hexapod</td>
<td>967 kg</td>
</tr>
<tr>
<td>Moment of inertia of upper part of the hexapod, the mockup, and the passenger in z-direction</td>
<td>116.5 kgm²</td>
</tr>
<tr>
<td>Moment of inertia of the platform and the lower part of the hexapod in z-direction</td>
<td>864 kgm²</td>
</tr>
<tr>
<td>Height of the COG of the upper part of the hexapod, the mockup, and the passenger</td>
<td>1.19 m</td>
</tr>
<tr>
<td>Height of the COG of the platform and the lower part of the hexapod</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Maximum acceleration of the platform in x- and y-direction</td>
<td>10 m/s²</td>
</tr>
</tbody>
</table>

Table 6 shows three different results for the maximum relative wheel load change due to forces, torques, and translational and rotational movements of the hexapod. The first two rows of the table show a comparison of the wheel load changes between using the analytical approach and the simulation. Both are calculated based on the maximum accelerations $a_{\text{max}}$ of Hexapod A (Table 1). The translational and rotational motion is not part of the simulation model, and therefore the corresponding wheel load changes are not calculated.

As stated in the section ‘MCA Parameterization’ a scaling factor of $k_{\text{MCA}} = 0$ is used for the current MCA with Hexapod A. Therefore, no translational acceleration cues are represented by the hexapod. The rate limiter, as a part of the MCA (Figure 2, Figure 3), limits the rotational acceleration to the presumed human perception threshold of $6°/s²$ [Bet15]. The maximum wheel load changes for these accelerations are summarized in the third row of Table 6.

An investigation of the wheel load changes caused by a larger Hexapod like Hexapod B would require a scaling of the whole platform including geometry, propulsion, battery and safety system and therefore was not conducted since rough estimations would corrupt the results.
The values in brackets are valid for the case that the platform is accelerated with its maximum acceleration of 1 g. The differences between the results of the simulation and the analytical results arise because the end of the motion envelope is reached before the wheel load is built up completely. This means that due to the limited motion envelope of the hexapod, the maximum wheel load change of 19% does not occur.

The basic “ideal” MCA does not use translational acceleration of the hexapod and limits the rotational acceleration to the human perception threshold. In this case, the maximum relative wheel load change is 6%, caused by the rotational movement of the hexapod regarding the MCA parameterization for Hexapod A as given in Table 2.

### Influences on the acceleration of the platform

The motion of the hexapod results in forces and torques that have to be supported by the platform. If the horizontal forces and the yaw torque cannot be supported by the wheel forces, they will contribute to accelerating/decelerating the WMDS.

Thus, the acceleration of the hexapod can possibly result in an acceleration of the platform reduced by a factor $D$. The factor $D$ for translational and rotational movement can be found using Equation (5) and (6), respectively. The results for Hexapod A are calculated within these equations:

\[
D_{\text{translation}} = \frac{a_{\text{platform}}}{a_{\text{hexapod}}} = \frac{m_{\text{hexapod}}}{m_{\text{platform}} + m_{\text{hexapod}}} = 0.19
\]

\[
D_{\text{rotation}} = \frac{\dot{\phi}_{\text{platform}}}{\dot{\phi}_{\text{hexapod}}} = \frac{\theta_{z,\text{hexapod}}}{\theta_{z,\text{simulator}}} = 0.13
\]

The acceleration perceived by the user is the sum of acceleration of the platform and hexapod:

\[
a_{\text{subject}} = a_{\text{platform}} + a_{\text{hexapod}} = (1 - D) \cdot a_{\text{hexapod}}
\]

As shown in equation (7), the acceleration of the user is smaller in magnitude than the acceleration generated solely by the hexapod, which has to be considered in the MC of the WMDS.

### Compensation of the influences of the hexapod

Due to the change of the wheel load caused by the hexapod, the wheel force distribution has to be adapted. This can be realized by expanding the MC with the hexapod influences on the wheel load.

As stated before, the acceleration of the user is alleviated due to the acceleration of the platform caused by the hexapod. One possible solution is to compensate this reduction by representing a hexapod acceleration raised by the factor $1/(1 - D)$. Nevertheless, this compensation would counteract the initial approach to reduce the platform’s motion envelope. Thus another compensation method is recommended that would avoid the platform's acceleration. To achieve this, a feed-forward control can be implemented, which uses the propulsion of the platform to generate a force that counteracts the hexapod forces. With this method, the hexapod forces are supported by the wheels. Nevertheless, this method reduces the wheel's residual coefficient of friction for other maneuvers.

### Conclusion

It has been shown that the redundant DOF of a hexapod in a WMDS bear the potential to reduce power, energy, and workspace demand as well as to mask shortcomings of the wheeled mobile platform. Presumably, hexapods with larger displacement also bear a larger potential, although the relation is not proportional.

Especially for characteristic problems of WMDS, like singular wheel configurations, a great contribution can be made by the hexapod: Methods aiming at avoiding those singular configurations lead to a corruption of the acceleration cues that can be masked by the hexapod. Those corrupted acceleration cues are also called false cues. Investigations have revealed that the hexapod that is currently used at FZD is not sufficient for masking most of the false cues.

The potential field algorithm seems promising for avoiding singular wheel configurations and thereby reducing the peak steering power demand drastically. Thus, latency in acceleration representation can be reduced and future hardware prototypes may be equipped with smaller and lighter steering motors.

In contrast to conventional advanced dynamic DS, the class of WMDS has to cope with reduced force transmission potential when the hexapod is moving. The effects on the wheel load as well as tire friction force potential have to be taken into account, espe-
cially for large hexapods. It was demonstrated that translational hexapod forces have the most significant influence.

**Outlook**

It has to be stressed that all investigations have been carried out individually and cross-linkages have been neglected. TC, however, was taken into account for all considerations. Therefore it is essential to prioritize and weigh the different tasks of the hexapod, namely TC, translational acceleration cues, and masking of false cues of the wheeled mobile platform.

The limitations of the press-on band tires are not known yet. Currently undergoing investigations are focusing on the properties of the tires in order to adapt the developed methods to the maximum transmittable tire forces.

To avoid singular wheel configurations – especially in combination with the potential field algorithm – a prediction of short-term acceleration demands could be useful.

The dynamics of the actuators of the hexapod have not been researched yet but need to be taken into account for analyzing the potential of reducing latency in the WMDS.

Finally, the potential field algorithm has to be further investigated. The chosen parameters have been adapted iteratively and should be optimized in a sensitivity analysis. Although the peak steering power demand is reduced in most situations, new singularities occur and have to be investigated. The data used to analyze the algorithm is representative for urban driving scenarios, but does not necessarily contain all situations with singular wheel configuration. Furthermore, the algorithm itself is prone to singularities: The ICR can get stuck in the middle of the WMDS surrounded by the potential fields of the wheels or is pushed towards another potential field. The first case would cause a longer acceleration masking demand that could possibly exceed the hexapod’s workspace. In the latter case the repulsive potential would not be able to push the ICR away in time, which would cause high steering velocities, i.e. steering power.

**References**


