A New Approach to Linear Motion Technology: 
the Wall is the Limit

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Abstract—Drive and control company Bosch Rexroth aims to develop a new approach to 6DOF motion technology for motion systems intended for driving simulators. Humans experience motion in no more than 6DOF. Hence a design concept is sought, which moves a payload in any direction and is driven in no more than 6DOF.

A design concept is found in a roll, pitch and heave mechanism driven and supported by 12 sets of wheels provided with in-wheel motors. The wheels provide the system with accelerations in the remaining three DOF’s: surge, sway and yaw. The wheel driven system moves unrestricted in these directions. The only limitation would be the size of the hall it is situated in. The system is designed such that accelerations in any direction can be applied instantaneously. The designed concept has a total mass of 11 t, including a 3.5 t payload.

Index Terms—Motion based driving simulation, mechanical design, motion cueing, instantaneous acceleration in 6DOF.

I. INTRODUCTION

The demand for motion based driving simulators is based on the success of flight simulators. The driving simulator differs from the flight simulator in its planar accelerations. Planar accelerations in a car are typically larger and hold longer than experienced in an aeroplane. Therefore many driving simulators have a separate system that actuates the simulator in x- and y-direction [1], [2], [3], [4].

A driver should feel the same accelerations as he visually perceives. This is true to a certain extent. Threshold values determine an indifference zone. These values vary as a function of DOF, frequency and workload [5], but are determined to be typically at an angular velocity of ±3°/s and a maximum acceleration of ±0.6 m/s² [6]. Staying within this zone and therefore below these values, allows the motion system to move without the occupant noticing it. Larger excursions allow a washout filter to act more subtle, with lower accelerations.

A. Previous Work

One of the latest hi-fi driving simulators developed by Bosch Rexroth is the UoLDS 2006 [3], shown in Fig. 1. Its motion system drives a payload of 2.5 t in 8 degrees of freedom, a so called 8DOF. Motion cueing algorithms assure that the driver experiences accelerations in all 6 DOF’s: surge x, sway y, heave z, roll (around x), pitch (around y), yaw (around z).

The motion system accelerates the payload with 0.5 g in x- and y-direction and is limited to excursions of 5 m in these directions. One of the issues with this type of motion system is noise. Gears and rack and pinion driven systems are relatively loud.

B. New Approach

A trend can be seen in designing a hi-fi driving simulator with as many DOF’s as possible; while one experiences not more than six DOF’s. Previously designed driving simulators are typically converted flight simulators. Additional systems are designed to meet the new requirements. This results in systems driven in eight DOF’s or even more. Additional, redundant DOF’s require additional equipment, which is expensive in a financial as well as a performance sense. The extension of an x,y-excursion requires an unproportionately amount of equipment.

That is why the research department of Bosch Rexroth seeks a new design, completely from scratch, for a driving simulator, which is driven in six DOF’s. The motion system is to accelerate a 3.5 t payload instantaneously at 7 m/s² in any
planar direction and at the specified accelerations in Table I in the other DOF’s.

II. REQUIRED PERFORMANCE

The required performance of the motion system is obtained using 2D car suspension models, measurements of typical manoeuvres and experience with previous designed and tuned simulators. The requirements are summarized in Table I.

<table>
<thead>
<tr>
<th>non-simultaneous</th>
<th>Accelerations</th>
<th>Velocities</th>
<th>Excursions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge (z)</td>
<td>± 7.0 m/s²</td>
<td>± 4.0 m/s</td>
<td>± wall</td>
</tr>
<tr>
<td>Sway (y)</td>
<td>± 7.0 m/s²</td>
<td>± 4.0 m/s</td>
<td>± wall</td>
</tr>
<tr>
<td>Heave (z)</td>
<td>± 5.0 m/s²</td>
<td>± 0.4 m/s</td>
<td>± 0.2 m</td>
</tr>
<tr>
<td>Roll (φ)</td>
<td>± 52 rad/s²</td>
<td>± 0.7 rad/s</td>
<td>± 0.4 rad</td>
</tr>
<tr>
<td>Pitch (ψ)</td>
<td>± 52 rad/s²</td>
<td>± 0.7 rad/s</td>
<td>± 0.4 rad</td>
</tr>
<tr>
<td>Yaw (θ)</td>
<td>± 14 rad/s²</td>
<td>± 1.1 rad/s</td>
<td>± 1.2 rad</td>
</tr>
</tbody>
</table>

Generally all degrees of freedom are controlled at a bandwidth of at least 10 Hz.

III. DESIGN CONCEPT

The payload consists of a dome mounted on a platform and has an assumed total mass of \( M_1 = 3500 \) kg. Within the dome a virtual environment is created by multiple projectors generating a 360° projection on the dome shell. The body and interior of a car is fixed in the centre of the dome on a sled, which allows to exchange cars easily. The car is equipped with an audio system, force feedback steering, monitoring equipment, etc. The motion system has an estimated mass of \( M_2 = 7500 \) kg, resulting in a total mass of the driving simulator of 11 t.

As it is required to have a design that has its centre of gravity (COG) as close to the ground plane as possible, in order to drive the system close to its COG, the following approach is used. The design is split up in a part that describes motion within the ground plane (surge \( x \), sway \( y \) and yaw \( \theta \)) and a part describing motion perpendicular to that plane (heave \( z \), roll \( \phi \) and pitch \( \psi \)).

Each DOF is required to meet the specifications mentioned in Table I. A concept, which fulfils these requests, is found in a motion system driven in inner-plane directions by wheels (Paragraph IV) and in outer-plane directions by a 3-crank mechanism (Paragraph V-A) [7].

IV. WHEEL DRIVEN

The motion system is supported and driven by 12 sets of two wheels (see Fig 3), fixed in wheel frames inspired by [8]. Steering is realized by a different setpoint for each wheel in a pair. When driving the frame with the wheels, the system is easily extensible for larger excursions. The sound production is minimized. No gears are used, nor any other form of metallic contact is made.

A. Traction

Due to wheelbase filtering the lowest normal force is found at the front wheels, for positive accelerations and vice versa for negative accelerations. This minimal normal force is calculated as

\[
F_{N,\text{min}} = \frac{1}{12} \left( \frac{1}{2g} - \frac{x}{l} \right) (M_1 + M_2)
\]

with \( h = 1 \) m the height of the COG and \( l = 6.5 \) m the length of the wheelbase. A similar relation holds for lateral accelerations \( j \).

Initially a motor torque \( T_m \) is applied to the wheels, with radius \( R \), without the wheels slipping in longitudinal direction. Hence the following equation should hold

\[
\frac{\mu F_{N,\text{min}}}{24} \geq \frac{T_m}{R}
\]

requiring a friction coefficient of the wheel-floor contact of \( \mu = 0.9 \). The rims are provided with solid rubber tyres, which can withstand the traction forces and the required friction coefficient. Because the floor is relatively flat and the wheel sets (see Fig. 2) are designed such that they can tilt, absorbing 2/3 of the excitation. Hence the motion system doesn’t require a suspension. Vibrations applied to the system through the wheels will be damped or filtered out.

The requirements of the floor are relatively low. It should be rough and flat. Roughness should be such that the required friction coefficient can be attained. This can be done using a commercial off-the-shelf special coating. Flatness should be similar to industrial floors in factories. The maximum wheel
B. Surge, Sway and Yaw Unlimited

All performance requirements are met with the wheel driven concept. The length of the excursion can even be extended far beyond the required specification. The surge and sway excursion will be limited to the size of the hall. The yaw excursion however is has no limits at all. The wheel sets can turn more than 360°, allowing rotations about any (virtual) vertical axis.

C. How to Accelerate Instantaneously?

Wheels do not move in lateral direction without full slip, which is difficult to control. Therefore a mechanism has been designed which allows the motion system to accelerate instantaneously in any given planar direction. The steering axis is shifted a distance \( L = 80 \text{ mm} \) away from the wheel axle (Fig. 3 and Fig. 4). Fig. 4 shows a top view of the wheel set. The grey areas represent the wheels and the axle connecting them. Pivoting point \( P \) represents the shifted steering axis. Rotating the wheels in opposite direction initiates a rotation of the wheel set around point \( A \), called the steering axis. Pivoting point \( P' \) will instantaneously accelerate in lateral direction. Combined steering and driving allows \( P \) to follow any given trajectory \( S \).

Offset Calculation: The attainable lateral acceleration has an optimum as a function of the offset \( L \). This optimum is found because the lateral acceleration is a non-linear function of \( L \):

\[
\dot{y}(L) = \dot{\theta}L = \frac{T}{J + J(L^2)}L
\]

Here \( \dot{\theta} \) represents the angular acceleration around the \( z \)-axis and \( J \) represents inertia and \( T \) steer torque. The required acceleration of 7 m/s\(^2\) is met with an offset of \( 48 \leq L \leq 98 \text{ mm} \) and is chosen at the optimum, \( L = 80 \text{ mm} \).

D. Inverse Kinematic Algorithm

To see if the chosen wheel motors can handle the required acceleration for an instantaneous acceleration in any planar direction with a magnitude of 7 m/s\(^2\) an inverse kinematic algorithm has been developed, which calculates the required wheel angle, velocity and acceleration for the left and right wheel, with the coordinates presented in Fig. 4. The kinematics involved can partially be described as a wheeled planar mobile robot [9], describing a two-wheeled robot with its base, point \( A \), as point of interest.

The input of this algorithm is any given trajectory \( S \) in the \( xy \)-plane as a function of time.

\[
u = S(x, y, t) = \begin{bmatrix} x_S(t) \\ y_S(t) \end{bmatrix}
\]

The states of the system, a single wheel set, are defined as the coordinates of the wheel set \( (x, y)_A \) and its orientation \( \theta \). From these states the wheel angle, velocity and acceleration can be calculated.

\[
\begin{bmatrix} x_0 \\ y_0 \\ \theta_0 \end{bmatrix} = \begin{bmatrix} x_{A,0} \\ y_{A,0} \\ \theta_0 \end{bmatrix}
\]

The new state is calculated as a function of the current state at time interval \( k \) and the new trajectory coordinates at \( k + 1 \). The position \( P \) is calculated as

\[
r_{APk} = \begin{bmatrix} 0 \\ L \end{bmatrix} \begin{bmatrix} \sin(\theta_k) & -\cos(\theta_k) \\ \cos(\theta_k) & \sin(\theta_k) \end{bmatrix} \epsilon^3
\]

and

\[
r_{OPk} = \begin{bmatrix} x_{P_k} \\ y_{P_k} \end{bmatrix} \epsilon^3
= \begin{bmatrix} x_{A_k} \\ y_{A_k} \end{bmatrix} \epsilon^3 + r_{APk}
\]

To get to the following point on trajectory \( S, r_{OPk} \) rotates over an angle

\[
\Delta \theta_k = \angle(S_{k+1} - P_k)
\]

\[
= \arctan\left(\frac{y_{S_{k+1}} - y_{A_k}}{x_{S_{k+1}} - x_{A_k}}\right)...
\]

\[
= \arctan\left(\frac{y_{P_k} - y_{A_k}}{x_{P_k} - x_{A_k}}\right)
\]

and its new position becomes

\[
r_{OPk} = r_{OPk} + \begin{bmatrix} \cos(\Delta \theta_k) \\ -\sin(\Delta \theta_k) \end{bmatrix} \epsilon^3
\]

The error between trajectory and \( P' \) now is

\[
\Delta r_k = |S_{k+1} - P'_k|
\]

\[
= \sqrt{(x_{S_{k+1}} - x_{P'_k})^2 + (y_{S_{k+1}} - y_{P'_k})^2}
\]

Update the states for the next iteration

\[
\theta_{k+1} = \theta_k + \Delta \theta_k
\]
\[ \vec{r}_{OA_{k+1}} = \vec{r}_{OA_k} + \Delta r_k \angle \theta_{k+1} \]  
(16)

\[ k = k + 1 \]  
(17)

and continue to do so till the end of the trajectory.

The wheel motor angles \( \Delta \phi_L \) and \( \Delta \phi_R \) required to follow the trajectory can be extracted from the steering angle \( \Delta \theta \) and driving distance \( \Delta r \).

\[ \Delta \theta = \arcsin \left( \frac{R (\Delta \varphi_R - \Delta \varphi_L)}{2d} \right) \]  
(18)

\[ \Delta r = \frac{R (\Delta \varphi_R + \Delta \varphi_L)}{2} \]  
(19)

\[
\begin{cases}
\Delta \varphi_L = \frac{\Delta r + d \sin (\theta)}{R} \\
\Delta \varphi_R = \frac{\Delta r - d \sin (\theta)}{R}
\end{cases}
\]  
(20)

This algorithm is tested on a shape 8 trajectory and the results are shown in Fig. 5. From the initial conditions the planar robot rotates and translates to the initial condition and the tip, point \( P \), follows the trajectory closely. The movement of the wheel base is enforced by the trajectory of the point \( P \) and the initial condition. The required wheel rotations are shown in Fig. 6.

E. Additional Required Systems

Because the motion system is to operate autonomously and is not fixed to a rail or other type of guiding system, a positioning system is required. Several commercial off-the-shelf local positioning systems (LPS) exist and will suffice for this application.

Power is supplied to the system using cables hanging on an active tracking system. This system is carried out as an overhead travelling crane. Communication can be performed through cables, but is also possible using wireless applications making use of the UDP/IP protocol.

V. Detail Design

A. 3DOF Crank Mechanism

The remaining 3 DOF’s in outer-plane direction: roll, pitch and yaw are actuated using a 3-crank mechanism with forked connecting rods mounted on a circle underneath the dome, inspired by a motion system designed and built by Bosch Rexroth for the Prater “Flyboard” (see Fig. 7) in Vienna. This system is known to be extremely silent, smooth and compact. It can be fitted inside the carrier frame, resulting in a relatively low design, with its overall height of 1250 mm.

The main differences between this design and the one applied at this driving simulator are the planar accelerations. The design in Fig. 7 is fixed to a concrete floor, while the driving simulator accelerates at 7 m/s². Due to these accelerations, additional reaction forces act on the cranks and the gears. All three motions have extensively been analyzed in a 2D approach and the geometry is adjusted such that the required, maximum motor torque of all motors is the same.

B. Wheel Sets

The wheel set consists of a wheel motor, attached to one half of a drum stub-axe (Fig. 3). The other side of the motor is bolted to the rim, which is provided with a solid rubber tire. Both halves of the drum stub-axe are screwed together and locked with bolts. Two halves are clamped around the axle and a steering axis is fixed on top of it.

C. Wheel Frame

The wheel sets are connected to each other and the carrier frame using the wheel frame. The wheel sets can rotate (steer) freely around their \( z \)-axis. To achieve an equal normal force distribution and to compensate for leaning, the wheel frame is allowed to rotate around the \( x \)- and \( y \)-axis. The carrier frame is
supported by a spherical plain bearing, which allows pivoting of the wheel frame with respect to the carrier frame. The bearing has its pole on the ground, where the tubular struts intersect.

**D. Carrier Frame**

The carrier frame is designed to support the payload and not to interfere with its workspace. It is built from box girders with square cross section (100x100) and length of 6.5 m. Stiffness is added to the frame using a bottom plate underneath the square cross in the middle. The triangular boxes are covered with steel plates on top and sides, to create a torsionally stiff box (Fig. 10).

A model is made using FEM software tool Algor. This model shows a maximum displacement of 1.7 mm due to maximum vertical loading at the three points where the three cranks will be mounted.

**VI. MOTION CUEING AND CONTROL**

Traditional motion cueing algorithms can be applied to the new 6DOF design. In fact the cueing is less complicated, as only six DOF’s are actuated and standard user tuneable software can be used. At lower speeds the linear motions can be applied without a washout filter and excursions can be applied 1:1 to the vehicle. Typical manoeuvres are parking, urban driving, etc.

The 12 wheel sets require control effort. The motors of a wheel set drive the carrier frame like an inverse pendulum. To achieve stability the orientation of the steering axis is measured using an encoder on the wheel frame.

**VII. PERFORMANCE & VALIDATION**

The designed motion system for the driving simulator is shown in Fig. 10. Throughout the design process a total system mass of 11 t is assumed. The actual mass of the entire system amounts 11.1 t, therefore this assumption is justified. The mass of the payload is 3.5 t and the mass of the motion system is 7630 kg.

The COG of the simulator is situated at 1000 mm from the ground. The height of the COG of the payload lies 1500 mm higher at 2500 mm. With a height of the motion system of 1250 mm, the system is relatively low built. At the maximum heave position the height of the motion system is 1650 mm and 1050 mm at the minimum heave position. The assumed COG-height of the simulator of 1 m is therefore achieved.

**VIII. CONCLUSIONS**

A demand for driving simulators with higher payloads and longer excursions is expected, as customer demands increase over the last decades. The mechanical design of the motions system of a driving simulator accelerating a payload of 3.5 t in six degrees of freedom is presented. The requirements of
7 m/s² in x- and y-direction, 5 m/s² in z-direction and similar rotary accelerations are met.

As a result of the wheel driven concept, the urge to have the system’s excursions for surge and sway easily extensible is attained. With a COG-height of the payload at 1000 mm from the ground and a height of the motion system of 1250 mm, the system is relatively low built. Hence the aim to build a compact simulator, i.e. to drive the payload close to its centre of gravity, is achieved.

The frames that carry the payload and connect the sub-systems of different degrees of freedom are designed based on stiffness. This allows the system to be controlled on a bandwidth as high as possible, which increases the sensation of motion to reality.

### IX. Future Work

The system is designed to a conceptual level. It is recommended to run several tests before getting to the actual production of the driving simulator. Traction tests should be applied to the designed wheel sets on different kinds of surfaces, seeking for the required amount of friction.

The number of 24 driven wheels requires a lot of control effort. It is suggested to perform tests on a single wheel frame with various dummy loads. This will prove if the suggested mechanism for instantaneous acceleration in x- and y-direction is successful and will give insights to what the actual control effort of the entire system will be like.

### References


