Performance optimization of a hexapod on a lateral rail with force feed forward compensation

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***Abstract** – The 7-dof driving simulator at Daimler AG uses the lateral rail for all cues in Sway (T_y). This implies that no cues in T_y are generated by the hexapod. Still movements of the hexapod in the other 5 DoF generate disturbances in T_y. Why are there disturbances if the dome is not moving in T_y direction by the hexapod? This is due to the fact that a cue in one of the other directions does change the cog (center of gravity) location in y direction. If the mass is accelerating in T_y it causes a reaction force of the lateral rail. If the disturbance reduction of the control loop of the lateral rail is not good enough to withstand these inertia forces, the lateral rail will move and thus generate a false cue. Since, these inertia forces are very predictable (we know in advance what motion is demanded from the hexapod).they are suited for feed forward. From the demanded accelerations of the dome, an inertia force in T_y can be computed. This signal is used as feed forward to the demanded T_y accelerations. The effect of the feed forward compensation becomes very clear from measurements of the position error of the lateral rail.*

An extra motion system like a lateral rail with the matching software controls is a leap forward to the Stewart platform to overcome the limited workspace for a specific direction. The extended workspace is essential for evaluating vehicle dynamics in a driving simulator. The feed forward compensation of the inertia forces are a key element to get the optimal performance out of the complete motion system, leading to maximum accelerations and minimal false cues.

***Key words:** driving simulator, vehicle dynamics, feed forward control, Moog, Daimler AG*

Introduction

Driving simulators

Stewart platforms, also known as hexapods, have been used to generate motion cues for driving simulators for many years now. Driving simulators have been used for various purposes like human machine interface (HMI) testing and design and more recently also for testing and designing driver assistant systems. In these later applications, where drivers' reaction to an active driving assistant system is tested, the realism of the motion cues dictates the quality of the test result.

The recent use of a driving simulator for vehicle dynamics development sets the demands of the motion system to the next level. For testing, evaluating and designing vehicle dynamics, the motion cues are key to the test and they require a state-of-the-art motion system.

The purpose of the driving simulator, or better to say the role of the motion cue, has a significant influence on the design of the driving simulator motion system. Based on a long experience providing high-performance flight simulation and leading-edge testing systems to the automotive and aerospace markets, the current performance of the Moog electric actuators makes it possible to build driving simulators that allow realistic vehicle dynamics testing to support the latest generation of test, research and assessment.

As a starting point for a motion base design, the Stewart platform is chosen as it has a very compact design to generate 6 DOF motion cues that offer many advantages over alternative solutions. When evaluating vehicle dynamics, one specific direction may need much more excursion than the other directions; the limited excursions of a Stewart platform are no longer sufficient to make the required sustained accelerations. This challenge is addressed by mounting the Stewart platform on a moving base, like an x-y table or a lateral rail. However, a moving base underneath the hexapod results into a challenging control problem. Movement of one mass is considered a disturbance for the movement of the other mass. It is essential to have an optimal disturbance reduction without losing performance, to make effective use of the extra stroke of a lateral rail or x-y table. If the construction or control of additional degrees of freedom introduces disturbances or bumps in the simulator, the additional value is negative instead of positive.

The play and friction free lateral rail of the driving simulator at Daimler AG, together with the nature of the moving mass disturbances or inertia disturbances makes the system very suitable for feed forward compensation. This paper discusses the control problems and applied solutions by Moog implemented at this 7-dof driving simulator.

Driving simulator system description

The motion system of the Daimler driving simulator consists of a base frame that can move in lateral direction. On this frame a hexapod with a dome on top. The total moving mass in lateral direction is 23 tons. The dome with car and equipment has a mass of 7200kg. The hexapod has a stroke of 1.5m per actuator. The motion system is depicted in Fig. 1.

Fig. 1. The motion system of the Daimler driving simulator.

Problem description

The high level problem description is “One can feel unwanted bumps while driving”. If we translate this to a more technical problem definition, it becomes “While making the commanded accelerations, the motion system makes extra disturbance movements”. The disturbances can be quantified in either position error or measured acceleration. The base frame is standard equipped with an accelerometer. This accelerometer is used as feedback sensor in the control loop of the base frame. In more detail, the base frame is controlled by a cascaded control loop of current, acceleration, velocity and position, see Fig. 2.

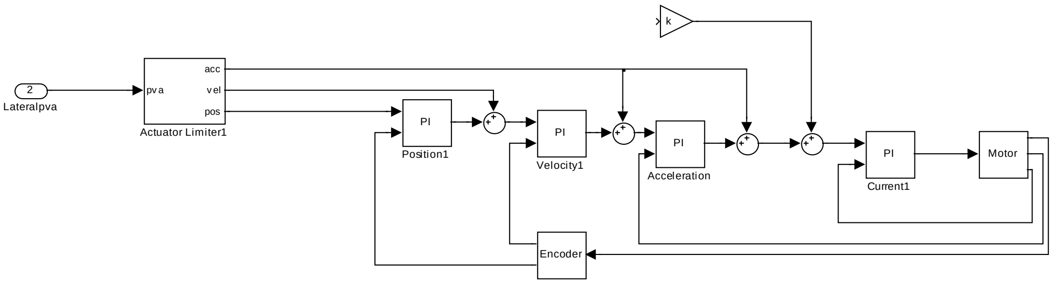

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Fig. 2. Lateral rail Control loop without Force calculation.

The current loop has a high bandwidth. The acceleration loop has a relatively low gain, not to introduce any noise disturbance from the accelerometer into the system. The velocity and position loop have an even lower gain. Their purpose is just to remove the steady state offsets. The performance of the base frame with this control loop is very good. The current loop is able to make the demanded accelerations. The feedback is hardly used. This becomes different if the disturbance behaviour is investigated. Here it becomes clear that the relatively low control gains are not strong enough to take out the disturbance effects. It is this disturbance reduction that can explain the main problem description. The base frame is not a rigid mass that is moving. The hexapod with dome is moving as well. The hexapod movements introduce disturbances to the base frame movement.

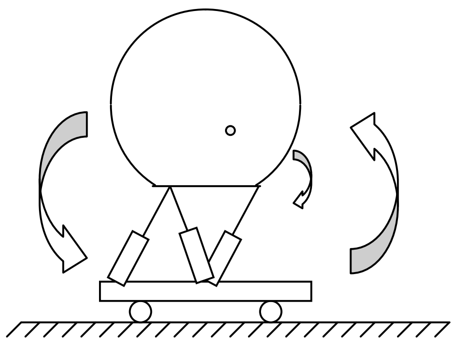

Fig. 3. Interaction between hexapod and base frame, between base frame and hexapod and between dome and hexapod actuators.

As said in the introduction, Daimler uses the lateral rail for all cues in T_y direction. The disturbance for the lateral rail is the T_y component of the 5 other DoF accelerations of the dome mass. Acceleration in Roll (R_x) has the largest contribution to this effect. Let us demonstrate how acceleration in R_x causes acceleration in T_y of the dome mass.

In Fig 4 the black dot represents the location of the Centre of Gravity (CoG). As the dome moves from -16 deg (blue) to +16 deg (black) the CoG has moved in y direction. This acceleration in T_y causes a reaction force of the lateral rail, which needs to be generated by the lateral rail control.

Instead of using feedback control, which is rather weak in this particular system we can use this acceleration in T_y as feed-forward for the lateral rail control. The advantage of using feed forward is that it is faster and thus gives a better disturbance rejection. The disadvantage is that it relies on a good estimation of the disturbance or that disturbances that are not modelled by the feed forward algorithm are not taken into account. So feed forward improves the disturbance rejection for the known disturbances, but not in general.

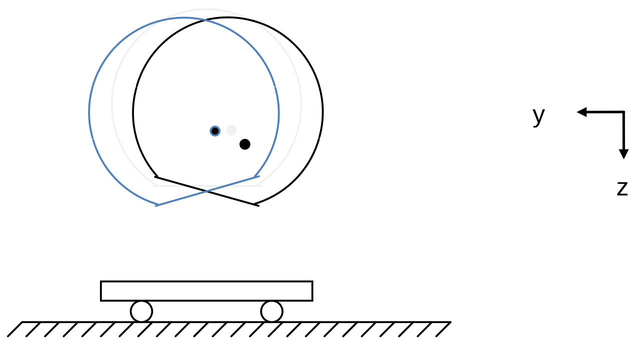

Fig 4. Moving CoG introduces lateral forces.

Force feed forward compensation

Lateral force computation

The positive effect of the feed forward compensation depends heavily on the quality of the force prediction. In the previous paragraph, the force prediction was briefly introduced. In this paragraph we will elaborate the force computation in more detail. Additionally the way how the computed forces are used in the control loop will be described.

Platform force calculation

The platform accelerations are known in the Rotation Reference Point (RRP). As the CoG is not located in the RRP, additional forces are required to follow the commanded trajectory. These forces are generated by the six hexapod actuators and their reaction forces are supported by the lateral rail. The force component in T_y is supported by the lateral motor.

To compute the forces in the RRP, the position vector between RRP and CoG is needed as well as the mass, I_{xx}, I_{yy} and I_{zz}. With some precise straight forward vector algebra the forces are known. This force is directly injected after the acceleration loop of the lateral rail control.

Implementation in control loops

In Fig. 2 the control loops without force feed forward are depicted. In Fig. 5, the calculation of the platform forces is added. Also in this picture it is made clear that the T_y component of the forces is used in the feed forward path of the lateral control.

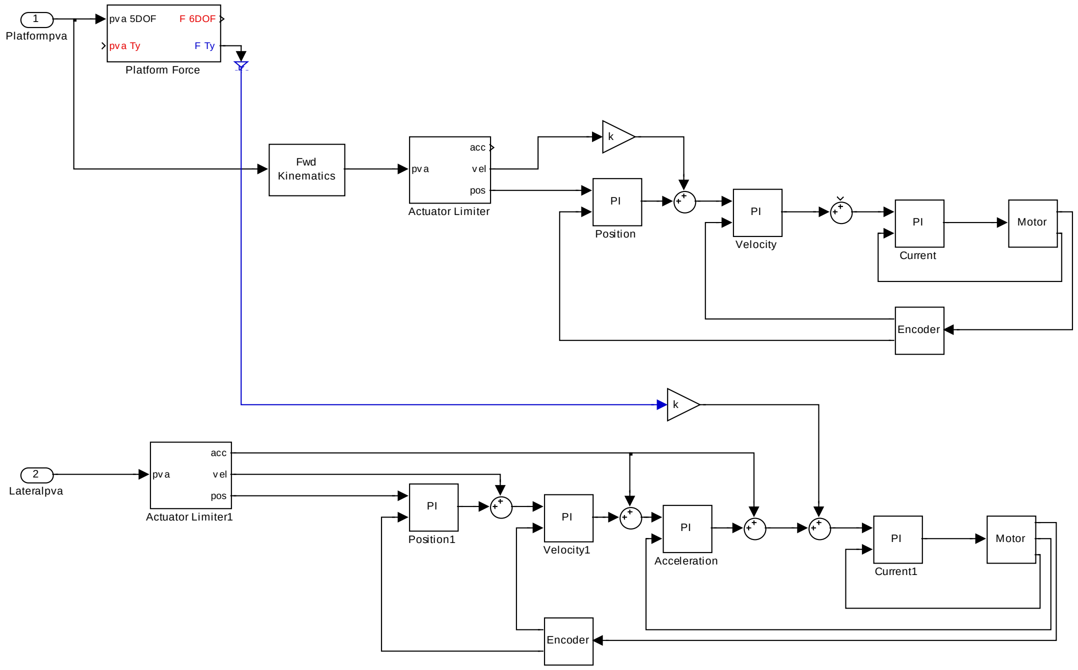

Fig. 5. Control loop with force feed forward to the lateral rail.

Disturbances from the base frame to the hexapod

Now that we realize that the moving dome disturbs the base frame, we can reason in the same way that the moving base frame disturbs the hexapod movement. Although the control strategy of the hexapod is different and its disturbance rejection by itself is much better, a feed forward injection of the known disturbances must have a positive effect. With the force computations needed for the lateral rail feed forward, we are already half way done with computing the actuator forces. In fact, if we are able to reduce the disturbances of the hexapod, we are improving the force prediction used in the lateral rail feed forward.

Actuator force calculation

The majority of the mass is obviously the dome and its content. However the six actuators do contribute to a significant extent. Let us zoom in to the actuator forces. The motion of the dome starts by a rotation of the motor axis. The motor axis and spindle are one part. Due to the rotational speeds, its inertia force cannot be neglected.

$$T_{act} = I_{act} *(a_{act} / (2\pi * spindle\ ratio)) \qquad (1)$$

Further, the moving parts of the actuator have mass and thus contribute.

$$F_{act} = m_{act\_moving} * a_{act} \qquad (2)$$

Finally, the complete actuator rotates in 2 degree of freedom around the bottom joint.

Friction and Pneumatic support

Now that the ideal motion and forces are described, two more components are required to model the actuator forces as accurate as possible.

First, the actuators have pneumatic assistant system, lifting the wait, and so reducing the current.

$$F_{pneu} = m_{dome} * g \qquad (3)$$

Secondly, a friction force must be modelled. Modelling friction could be an article in itself. A simplified vicious model seems a good starting point.

$$F_{friction} = c * v_{act} \qquad (4)$$

Implementation in the control loops

In Fig. 6 the control loops with force feed forward to both the hexapod and the lateral rail are depicted.

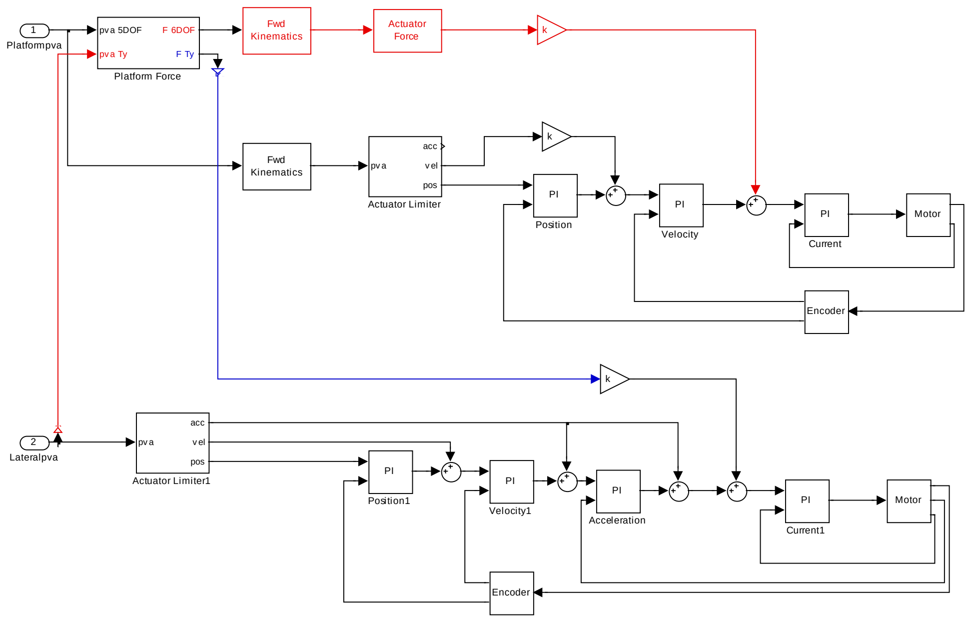

Fig. 6. Control loop with force feed forward to both lateral rail and hexapod.

Results

The effect of the feed forward compensation on the motion of the dome and on the lateral motion (T_y) can be illustrated by measurements. To simplify this proof, we apply a single frequency sinusoid to one of the other DoFs and we measure the position error of the lateral rail. In Fig. 7 the results are plotted. In T_x and T_z a 1m/s^2 sinusoid of 1Hz is applied. In R_x, R_y, R_z a 1rad/s^2 sinusoid of 1Hz is applied. The blue line is the position error with feed forward compensation; the green line is the position error without feed forward compensation.

From this figure it becomes clear that feed forward compensation does have a huge impact when the dome is moving in R_x and R_z. For the other directions, the effect is less which can be explained by a lower contribution in lateral disturbance.

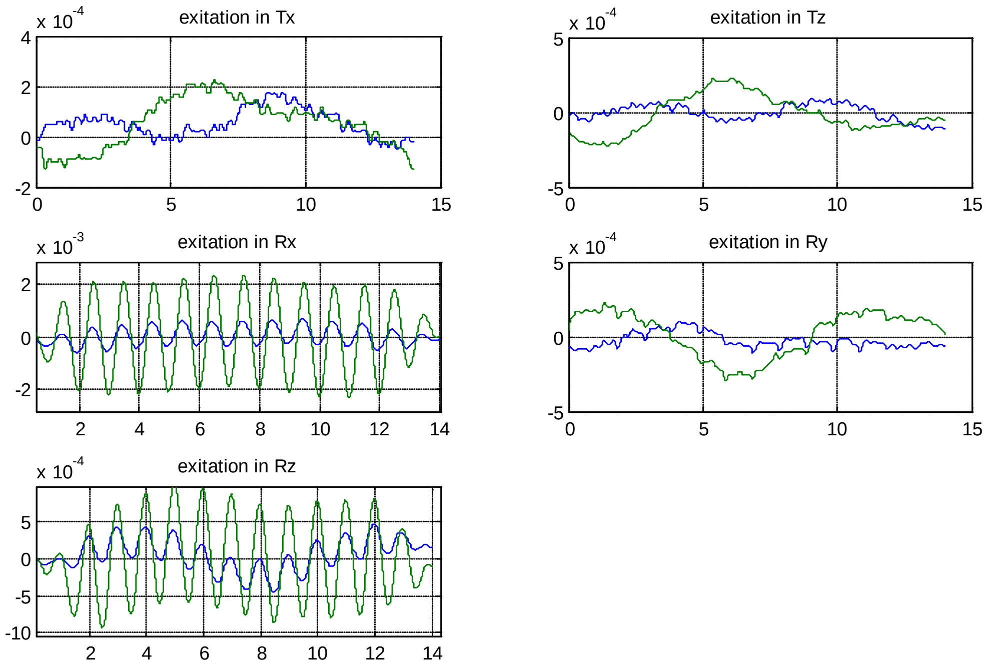

Fig. 7. Position error due to dome motion with (blue) and without (green) force feed forward.

Conclusion

For vehicle dynamics evaluation a next level driving simulators is required. Only a stiff and reactive motion base that has enough stroke in critical directions like T_y and R_z is able to support the development of virtual testing with a human in the loop.

For combined motion systems in which a hexapod is moving on a lateral rail or yaw table, it is crucial to cope with reaction forces that independent motion systems create.

With the Moog feed forward algorithms the reaction forces are under the threshold of human sensitivity.

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