Driving simulations for commercial vehicles- A technical overview of a robot based approach

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Abstract – *This paper gives a technical overview of the world's first motion simulator for interactive driving simulation, based on an anthropomorphic robot with up to 1000 kg payload, installed at Fraunhofer ITWM. First the applications and vehicle specific issues are discussed and presented. Some requirements of simulating commercial vehicle manoeuvres and off-road drives will be derived from measurements and simulations. This paper also describes the system architecture of the simulator and the interaction of the most important subsystems. This work delivers a deeper insight into the design of the moving platform, its control, the cabin concept and the safety features coordinated with the responsible Employer's Liability Insurance Association.*

Key words: Driving Simulation, Industrial Robot, Commercial Vehicles, Human in the Loop, Environment Interaction

Introduction and motivation

The design and development of commercial vehicles has to achieve the highest requirements regarding cost, efficiency, safety and durability. The extreme usage variability and versatility of commercial machinery in construction and agricultural applications leads to many restrictions and demands for such mechatronical systems. Human influence is one of the major parameters for a complex mechatronical system like an excavator or tractor etc., depending on many boundary conditions and on the driver's behaviour itself. To simulate the dynamic behaviour, durability and reliability of mechanical and mechatronical systems, it is necessary to provide the model with correct and realistic input data. The way a machine is operated and driven has a significant impact on its service life and durability and hence on the design and development process. A lot of very complex and detailed vehicle models to simulate durability, energy consumption, and dynamic behaviour for a widespread variety of commercial vehicles do exist. But the human influence, which is a very sensitive factor for the validity of simulations, is often covered poorly. To generate realistic stress profiles depending on human influences to a mechatronical system basically several possible approaches can be applied. If the system complexity allows the implementation of a driver model, then it is often possible to extract a limited set of data with this approach.

Another way to derive load cases is to use an invariant excitations method. The problem is that the derived load data depends on the complex interactions between the specific machine, the measured tasks and its operators.

Prototypes as an alternative way are very expensive. Especially for commercial vehicles the usage of prototypes, if existing at all, is extremely expensive.

If driver models are reaching their limits for certain simulations e.g. the task complexity is too high, the human influence has to be included into the simulation by an alternative way.

Therefore the solution is the use of an interactive simulator to support the development process of commercial vehicles. The human operator will be included into the simulation, such that the virtual product model, e.g. a commercial vehicle like an excavator, can be experienced at a high level of immersion.

Another aim is the implementation and test of driver / operator models. The interactive simulator can be useful in both directions. For the extraction of the operators behaviour on the one hand and for the multi-sensory representation of operator models on the other hand. The effects of assistant and safety systems can be examined without any risk for machine and operator in a realistic working scenario and much better than only on a scope or plot.

Applications

The ITWM simulator is designed for development purposes in the context of commercial vehicles. The system has to cover the requirements and expectations of experienced and expert operators of construction, forestry and agricultural machines and trucks. One of the major goals and long-term objectives is the generation of a special load case catalogue for various commercial vehicles. This catalogue is important to handle the extremely high variability and versatility of use of commercial machinery in construction and agricultural applications.

The user data which are the input for both, the interactive simulation and the subsequent detail simulations will be monitored online and stored. Another aim is to derive and validate driver models together with expert operators in the simulator. These models are useful for complex and non real-time simulations like tool-soil interaction or complex tires etc.

The analysis of possible applications and the derivation and definition of requirements for the motion platform is one important preliminary work. Most system parameters only can be defined after the mentioned tasks are analyzed.

Giving a universally valid dimensioning method would go beyond the scope of this work. Nevertheless the mentioned manoeuvres have some similarities, which can be used in the design process. Especially agricultural and construction vehicles mostly drive off road during a standard working scenario and large tilt angles of the cabins are possible. Depending on the vehicle parameters, its velocity and the test track the resulting accelerations varying in amplitude and bandwidth. One example shown in this work is a cross country drive of a SUV vehicle. These all terrain vehicles are lighter than most agricultural or construction vehicles so they usually allow higher movability and stronger excitations in a wide field of use.
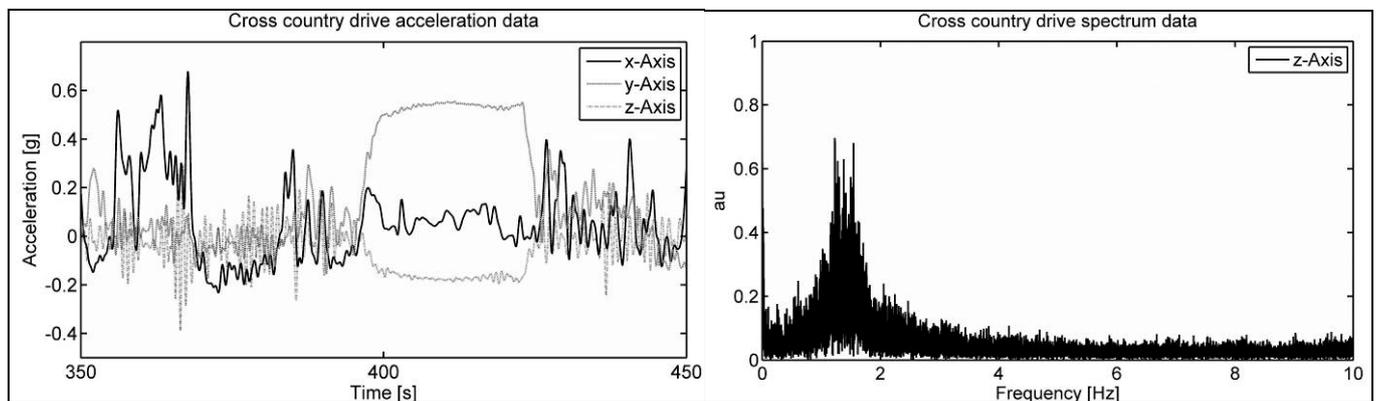
Fig. 1: Time domain (left) and frequency domain (right) of a cross country drive with an all terrain vehicle

Trucks have to be analyzed separately because the demands on the motion system are a bit different for this load case. Looking especially to the accelerations, a heavy duty distribution vehicle has more similarities to a passenger car than to a construction machine.

Detailed researches are done by Evers [Eve1] for a DAF XF 95 which is analyzed as an example (see Fig. 2).

Other manoeuvres e.g. obstacle passing require significant smaller translational displacements. On the other hand the sustained driving situations like breaking or accelerating over a long time or constant cornering could not be presented without a scale or tilt coordination.

With the analysis of different manoeuvres in combination with the vehicle specific motions like the turn of the upper-carriage of an excavator one can derive the major requirements as follows:

- Maximum translational travel: +-1.5m
- Tilt angles up to 180° for yaw and roll
- Translational acceleration min. 5 m/s²
- Min. payload 1000kg
- Interactive simulation with less than 15 ms latency
- Modular simulator setup
- Electrical actuators
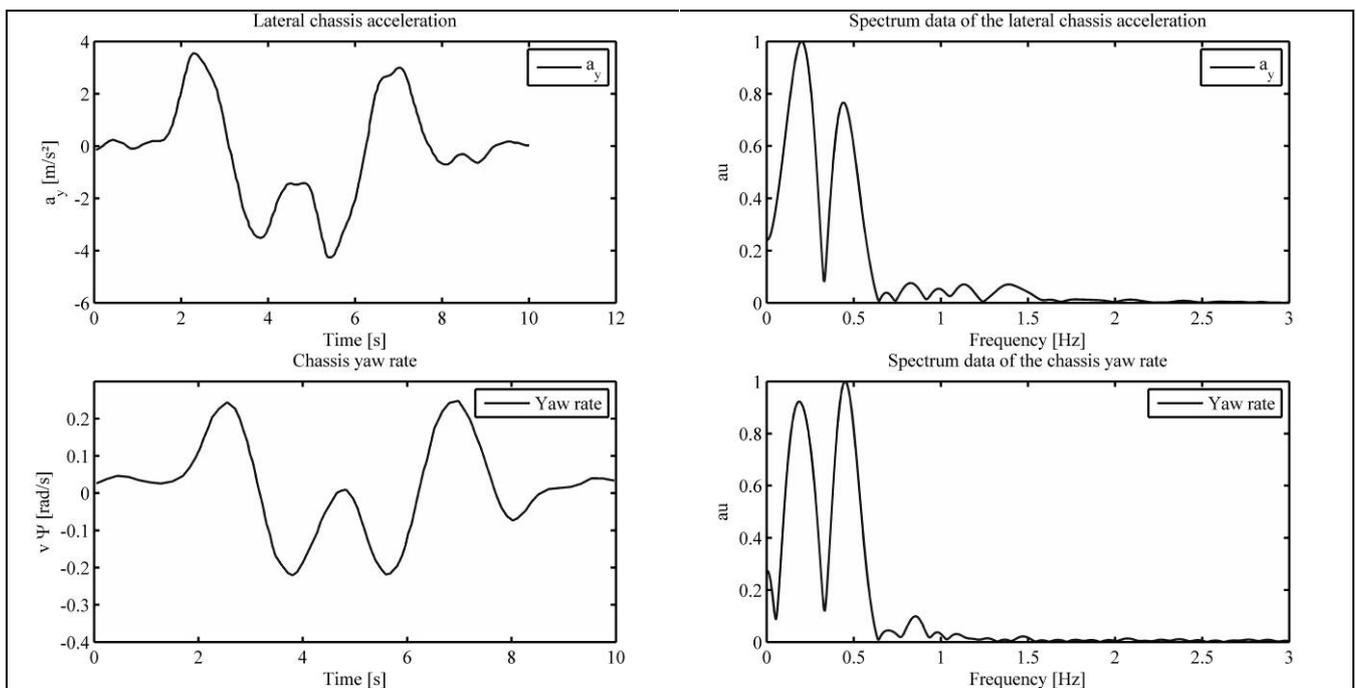
Fig. 2: ISO lane change manoeuvre of a DAF XF 95 truck at 60 km/h with measurement data (left) for lateral acceleration and yaw rate. The calculated frequency response for the manoeuvre (right) (see [Eve1]).

System architecture

Motion Base

One of the most important and challenging parts of the simulation system is the motion base. The motion system has to support the simulation by representing the filtered vehicle accelerations to an experienced operator, which is driving a virtual machine. Critical features are motion clearance, payload, the maximum of the reachable accelerations and their duration and the reachable orientation angles and angular velocities. Other restrictions like maintenance intervals, acquisition and working costs, modularity and the allocated space in the laboratory have to be considered too. A motion platform based on an anthropomorphic industrial robot covers all these features well. It combines large motion envelopes to present relative long lasting cues with relative low costs compared with parallel kinematics systems of the same size. Since the Robocoaster ® has been turned into an interactive motion simulator by several research groups see e.g. [Gio1, Gio2, Kec1, Bel1, Nel1] the system has shown its capacities.

One of the main drawbacks for simulating commercial vehicles with off-the-shelf cabins is the payload of the Robocoaster ® (only 500kg see [Kuk1]). Other restrictions are the fixed end stop limits which only allow a relative small translational workspace.

To solve both problems an industrial robot with larger payload was modified for simulation purposes. After a market analysis the most suitable system was selected as the motion platform. The maximum payload of this structure is about 1300 kg depending on the inertia; the translational workspace volume reaches up to nearly 80m³ (see [Kuk2]).

The off the shelf cabin is connected to the robot with a modular flange. The design of the flange has to handle two opposite demands. It should be a light weight construction to increase the maximum usable payload. On the other hand its stiffness has to be as high as possible to cover the safety demands and to minimize the negative influence of oscillations. The resonant frequencies of the flange have to be significant higher than the robots structure to prevent excitations which will lead e.g. to motion illness. For the first approach, a total weight of the flange below 100kg and an eigenfrequency higher than 20 Hz (fully-equipped with driver) was measured. The mounting position of the cabin was chosen similar to an inverse palletizing robot to increase the lateral workspace. This mounting position is suitable for ground vehicles where vertical displacements are below 0.5 m for the most application cases. To use a large workspace for simulating vehicle accelerations, the end stops for each axis are calculated online with fail safe hardware. This feature allows an orientation dependent deceleration or emergency stop function if a defined clearance is too small. For more details concerning the design process see [Kle1].

In figure 3 the principal setup for the different sensory feedback channels is presented:
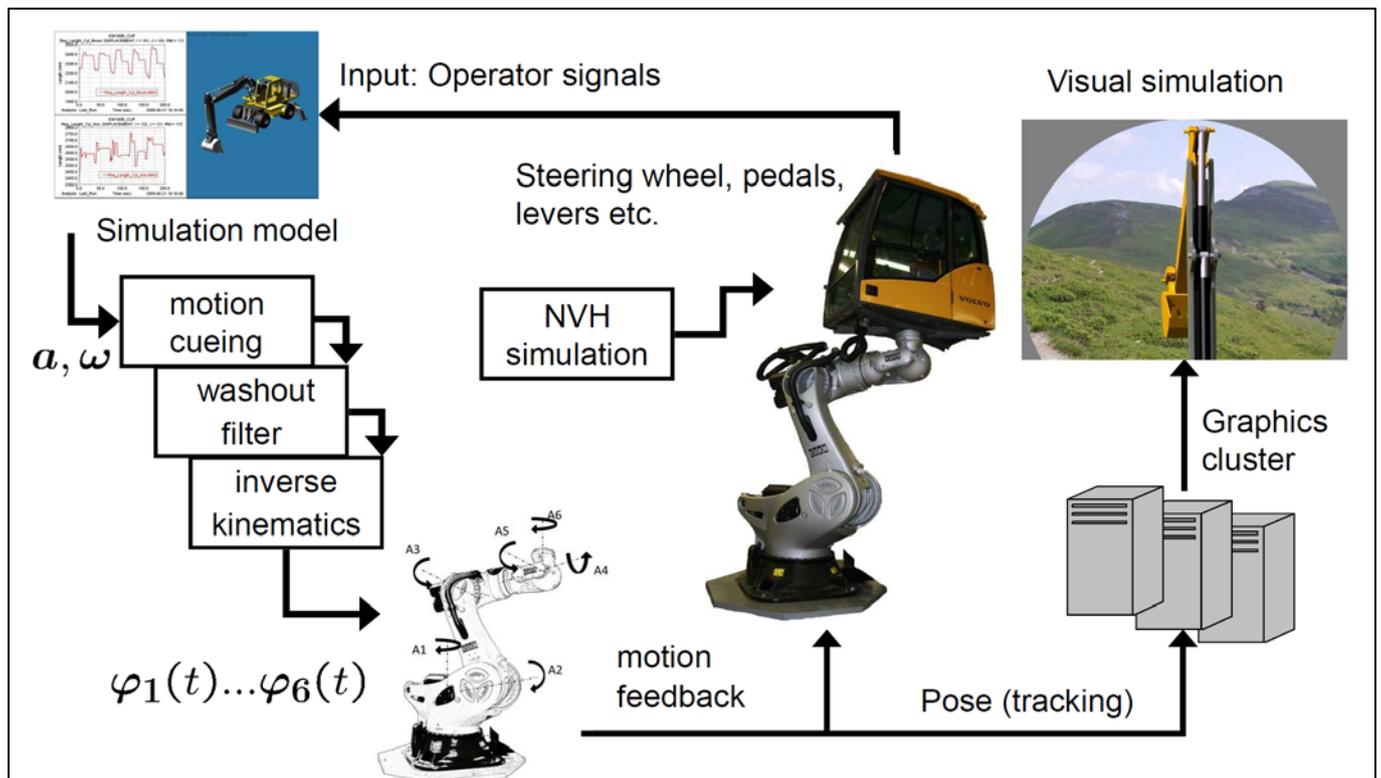
Fig. 3: Principal system setup

Motion simulation and vehicle models

The test person in the simulator cabin solves an interactive working task e.g. driving a passenger car or digging a trench with an excavator. The resulting lever positions, steering angles etc. are the actions of the test operator and will be digitized and transferred to the real-time computer via CAN communication.

Realisation of realistic motion is one of the most important challenges for any simulator. The robot obtains the motion inputs every 12 ms by an interface program executed on a real-time computer. These values, 6 angular velocities and 6 angles, are the output of the motion cueing algorithm (MCA), the washout filter and the inverse kinematics will be transferred to the robot controller hardware via network communication.

Most of the user interfaces in commercial vehicles are electronic devices but in case of conventional hydraulics, the lever or pedal motions have to be digitized. The control actions of the operator are the input data for the vehicle model.

Due to the modular setup it is possible to design the vehicle model with different software systems. Currently the code export is executed with Matlab / Simulink ® to generate a real-time executable model but different sources are possible. Simulink ® is used as a middleware to integrate the different signal sources and models and to manage the signals of the user interfaces. Once deployed, the real-time model generates a set of vehicle accelerations and orientations every time step. The model complexity can vary and it will be possible to scale the real-time calculation system. Currently a simplified vehicle model with a simple tire model (see [Pac1]) runs on one real-time computer.

The resulting accelerations, orientations and rotations of the vehicle model are the input values for the motion cueing algorithm. One of the implemented algorithms is a well known classical washout which dates back to Nahon & Reid [Rei1]. Another MCA is similar to the spherical washout algorithm, running at the MPI Motion Simulator at the Max Planck Institute for Biological Cybernetics in Tübingen (see [Gio1, Gio2]). In contrast, the presented system solves the inverse kinematics of the robot structure analytically. For a special set of manoeuvres the motion cueing algorithm can be adapted to minimize the sensation errors.

Figure 4 shows the setup of the MCA. The low frequency motion is represented directly by the robot's motion. The spectrum from 5 Hz to 200 Hz of the motion signal is reproduced by two electro-dynamic shakers attached to the cabins floor structure. The high frequency band above 200 Hz is generated by an 8-channel audio system, where 4 speakers are inside and 4 outside the cabin.

The development of more suitable MCAs especially for robot-based simulators is one of the important future works.
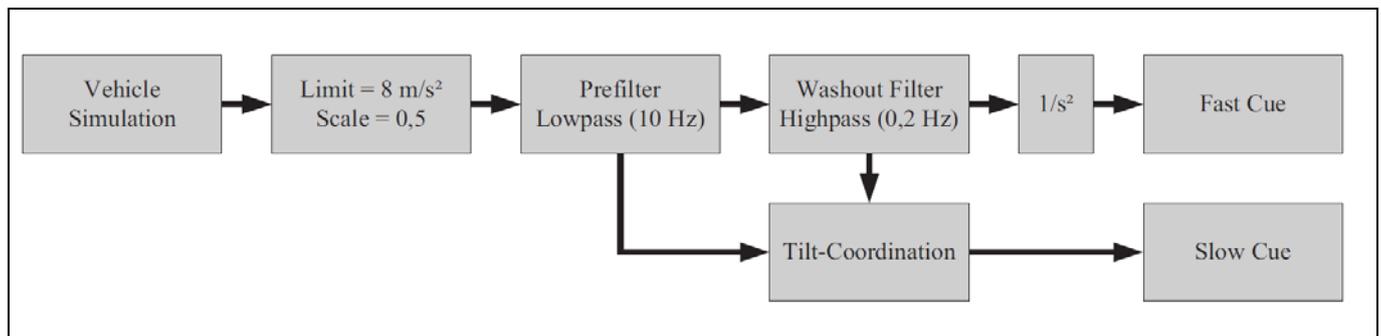
Fig. 4 Principal structure of the motion cueing algorithm

Visualization

The visualization system, designed for the simulator, is a fixed screen system with a spherical dome. The demand of a high resolution combined with a seamless field of view comparable to commercial vehicle cabins is a big challenge. Various possible solutions have been considered against the background of weight, acceptance and modularity of the setup. The planned concept covers the needs and restrictions, especially the limited payload of the robot, very well. The set up uses a modified drywall installation with deformable plasterboards and a steel skeleton with a spherical shape. The finishing of the visible surface has to fulfil the highest demands especially to prevent negative grazing light effects. The visible part of the screen is designed without any joint of dilatation to prevent disturbances during the simulation. The top of the projection dome can be removed for cabin change or maintenance. A displacement of the robot system is necessary to shift the drivers head into the centre of the sphere (see figure 5 right). The field of view (FOV) will be about 110° for the vertical and 300° for the horizontal direction. This corresponds to the FOV in the excavator cabin extended by the tilt, pitch and yaw angles of a motion cueing and tilt coordination algorithm to present a realistic scene for every relevant robot configuration. The distance to the screen in this setup allows that the driver's accommodation is similar to the reality. To allow all feasible robot motions without collisions, a diameter of the spherical projection dome of at least 10 m is necessary. Other side conditions are the shadowing effects, if the cabin structure intersects the optical path of a projector.
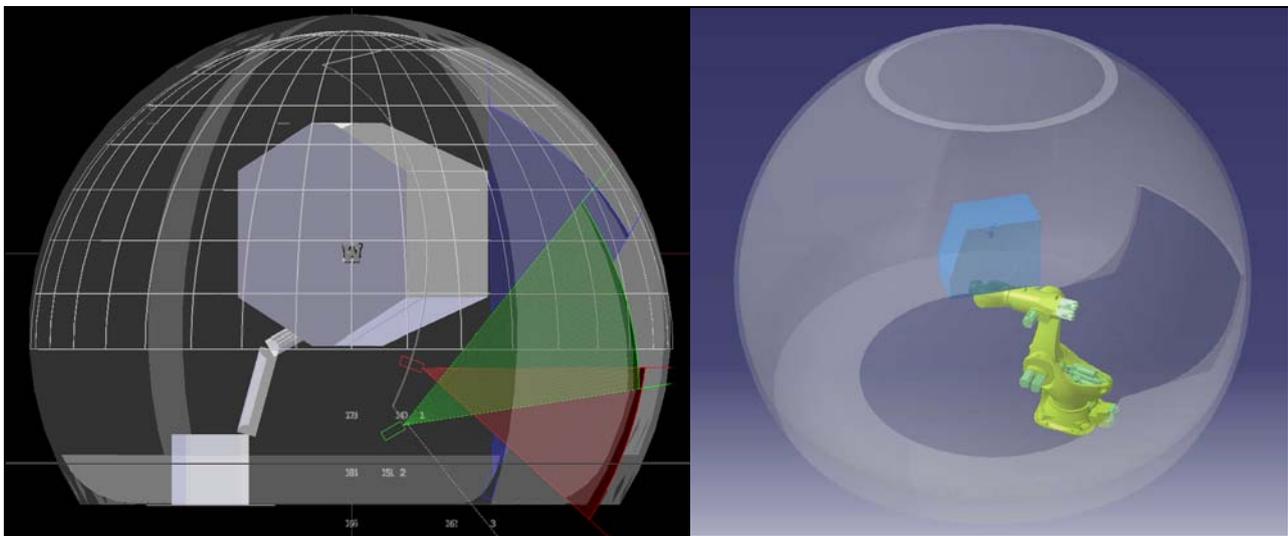
Fig. 5: Visualization setup with one of the 6 projector arrays (left) and the CAD model of the motion system and the projection screen.

The primary concern is the resolution of the presented image and the distance to the screen. The projectors will be arranged in 6 groups with 3 projectors for each group; one of these groups is shown in figure 5. The blue projector is located below the screen and outside the driver's field of view. The red and the green projectors are located below the simulator system. The octagon area in the centre of the picture is the representation of the workspace where no shadows occur. Due to the fact that the screen is fixed in the lab the driver's position has to be tracked. This tracking calculates the position and orientation of the cabin relative to the dome centre by using the encoder values of the robot's axis. After the forward kinematics calculation, the position and orientation of the driver's head is known, which is supposed to be fixed inside the cabin. By removing tilt coordination effects, the tracking of the
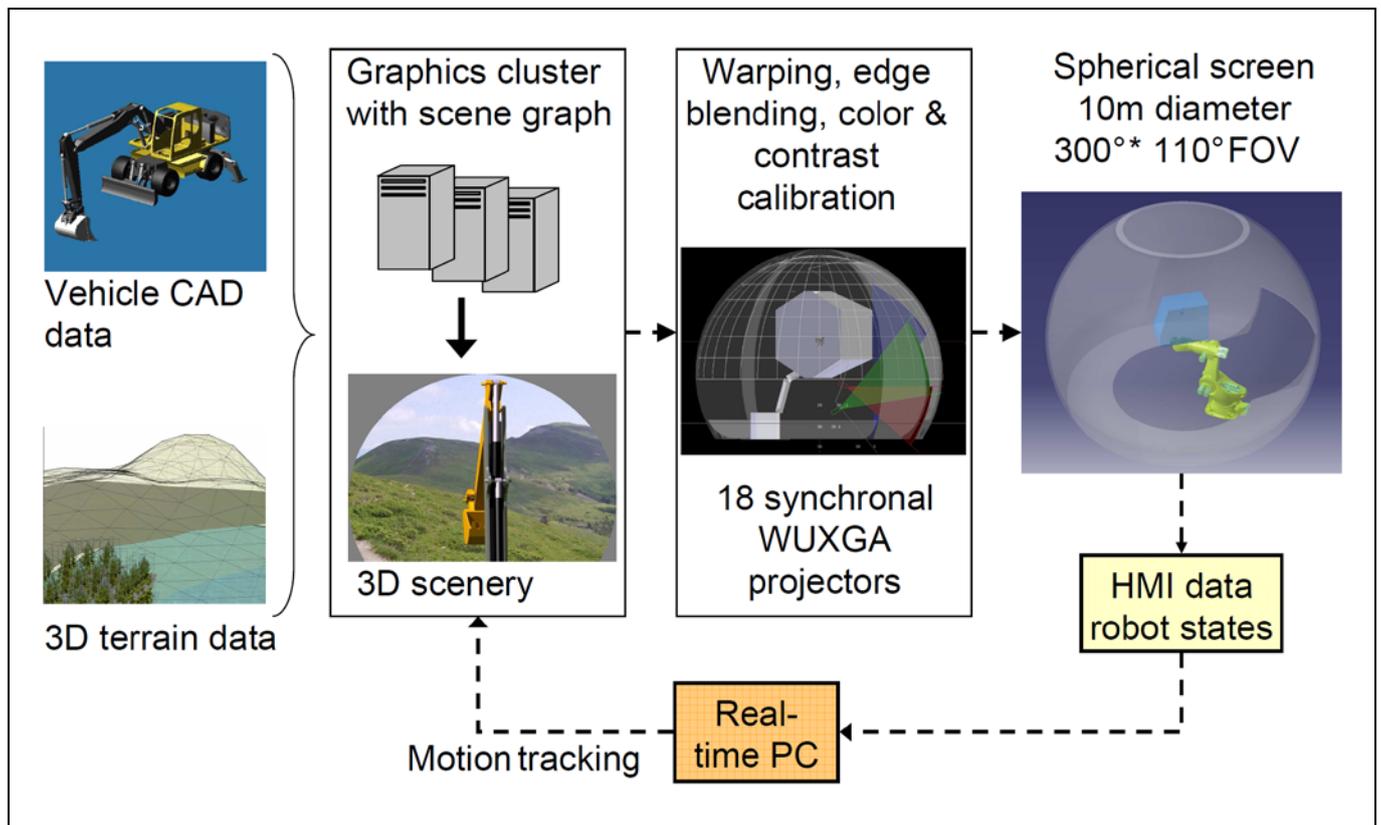
Fig. 6: Setup of the graphical simulation and digital content creation.

driver's head will be calculated. So the viewpoint inside the sphere is updated every frame and the subsequent warping, soft edge blending and colour calibration can be done.

The projector configuration planning and preliminary projector tests and measurements to determine the latencies, delays, colour space, contrast and depth of sharpness was done by Fraunhofer FIRST in Berlin.

Figure 6 shows the setup of the visual system. Starting with a CAD model of the vehicle and a model of the work area, a 3-dimensional scene is created. During the development process different engines have been compared in terms of threading model and clustering capabilities. Currently, the open SG graphics engine, developed by Fraunhofer IGD in Darmstadt [OSG1] renders the images.

The scene graph is rendered on the nodes of a computing cluster, equipped with high end graphic cards to render the different viewports. A master node distributes the content to the render nodes. The synchronous output of every frame is very important and a critical objective. Therefore the scene graph render loop is synchronized on the different nodes. Additionally, the video signals of the graphic cards on the different render nodes are synchronized by means of an add-on card per node. To limit the length of video signal cables and to avoid the use of range extenders, the render nodes are placed next to the projectors.

Safety concept

In comparison to the widespread Steward Gough platforms serial kinematics does not always have a secure final condition in case of errors. Parallel kinematics systems move to their lower end stops and dangerous situations usually do not lead to extensive damages.

The security system of the well known Robocoaster ® is designed conform to the DIN EN 13814 "Fliegende Bauten" (see [DIN1] for details) to allow human interaction, but the industrial version of a robot has no approval to move a person. So a detailed risk analysis and extensive modifications are necessary. The following multistage concept is implemented:

- Offline control of all possible robot motions in a preliminary step:
  The possible accelerations of a vehicle model are known. Together with the filter settings of the washout and motion cueing algorithms and the axis limits, a maximum travel range can be defined.

- Implementation of software limits:
  As closer one of the robot axes reaches their limit the higher priority function will slow down the robot

motion. If the remaining travel is large enough and no dangerous situation is detected then the working point of the washout algorithm will be modified without affecting the simulation. If the motion exceeds the first security distance level a penalty factor will slow down the simulator motion for this direction. In this case the safety concept leads to a motion error but the simulation is still active. By overshooting a maximum travel range a PLC will trigger the emergency stops. This function terminates the simulation and a manual reset is necessary. The software limits use data from the encoders installed in the robot links – not the data extracted from the controller.

- Implementation of proximity switches:
  For the very last possible clearance e.g. the critical areas at axis 3, where the cabin flange could touch the structure, proximity switches trigger a hard stop. In this case the break system will decelerate as fast as possible. This also terminates the simulation.

- Usage of a safety cage for the test subject:
  If a collision between the cabin and the robot structure or the ground is unpreventable e.g. in case of a gear box failure, a safety cage will protect the operator from serious injury.

- Organizationally arrangements and provisions:
  This means, that a procedure for safety checks, inspections and supervisions for both the operator and the test driver are done frequently. Another procedure is the monitoring of all cabin motions for durability calculations of the support structure.

All these safety features were developed in coordination with the responsible Employer's Liability Insurance Association.

Operational modal analysis

The first important experiments are the determination of the robots mechanical eigenfrequencies to ensure that the systems bandwidth is larger than the bandwidth of the vehicles handling dynamics. For this analysis, different robot motions in various configurations are recorded with an inertial measurement unit (IMU) sensor. The measurement results are used to set the bandwidth boundaries for vehicle model dynamics. The test setup is the following:

The robot eigenfrequencies are measured first without any payload and later with the fully-equipped simulator cabin and a driver to determine the maximum possible and typical limit frequencies. Starting with a motion for axis 1 and blocking all other axes, a full stop breaking manoeuvre leads to a characteristic oscillation which is measured by the IMU attached to the robot flange. The same measurements are done for other axes consecutively. The normalized power spectrum plots are shown figure 7.

The corresponding eigenfrequencies for a typical operation point are 8.65 Hz for the robot without a cabin and 4.8 Hz for the configuration with the flange (100 kg), the cabin with force feedback devices (700 kg) and a operator (90 kg). As shown in the figure 7 the above-mentioned eigenfrequencies appear to be dominant compared to others.

A likely reason for this behaviour could be due to the compliance in the joint of axis 1. The stiffness of the bearings in joint 1 leads to a characteristic oscillation for excitation of any robot axis.

Carried out tests suggest that the bandwidth of the fully-equipped robot has enough room to accommodate typical vehicle dynamics as shown in figure 1 and 2 (about 1.5 Hz) while the higher frequency parts have to be excited by the electro-dynamic shakers which are installed at the cabin floor.
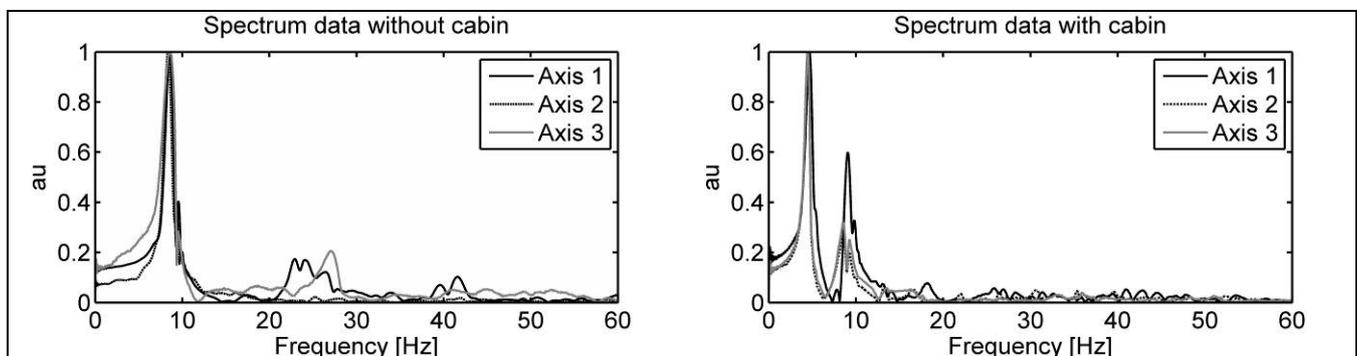
Fig. 7: Normalized frequency spectrum data of the Simulator without (left) and with the fully-equipped cabin (right).

Conclusions and future work

For complex tasks and machines in combination with a versatile user interaction, the interactive driving simulation is a suitable tool to analyse human-machine interaction. The real-time calculation of a vehicle model, in combination with the possibility to present realistic accelerations and tilt angles to a test person, solving a virtual task in an off-the-shelf simulator cabin allows a detailed analysis of typical working scenarios. These results allow predictions of handling, operability and the analysis of the effects of safety and assistant systems. Ad hoc design variations are possible without modifying a hardware system.

On the other hand an improved development of driver models is possible. For example, an expert operator can evaluate the realism and quality of an operator model driving the simulator while being a passive observer in the cabin.

The next task is the evaluation of the simulator system by experienced and expert drivers. This allows a tuning of system features by including the needs and demands of experts to improve the immersion for this user group.

More complex simulations like energy consumption, durability, service time, e.g. of a commercial vehicle usually cannot be executed in real-time. Also the computationally complex simulation, e.g. the tool-soil interaction, is done with the realistic user input data in a subsequent calculation step. The interactive simulation is computed with the help of a simplified model.

One of the future works is the implementation of sophisticated real-time soil interaction models, which are currently part of research projects in our department. These models will be calculated at interactive speed on a computing cluster. The improved results of the tool-soil and tire-soil interaction will increase the simulators level of immersion.

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