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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe werden sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Real-time human in the loop MBS simulation in the Fraunhofer Robot-Based Driving Simulator

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Abstract

The paper encompasses the overview of hardware architecture and the systems characteristics of the Fraunhofer driving simulator. First, the requirements of the real-time model and the real-time calculation hardware are defined and discussed in detail. Aspects like transport delay and the parallel computation of complex real-time models are presented. In addition, the interfacing of the models with the simulator system is shown. Two simulator driving tests, including a fully interactive rough terrain driving with a wheeled excavator and a test drive with a passenger car, are set to demonstrate system characteristics. Furthermore, the simulator characteristics are of practical significance, such as simulator response time delay, simulator acceleration signal bandwidth obtained from artificial excitation and from the simulator driving test will be presented and discussed.

Introduction

The design and development of commercial vehicles has to satisfy requirements for cost, efficiency, safety, and durability. To analyse attributes like energy efficiency or durability, detailed models need to be simulated for variable transient manoeuvres. Additionally, the environment interaction and the work process are responsible for variations in the simulated results. The human influence is one of the major parameters for a complex mechatronic system like passenger cars, trucks or construction machines like excavators. This influence depends on numerous boundary conditions. The operator inputs in simulator should be as realistic as possible; these are essential for simulation of the dynamic behaviour, durability, and reliability of mechanical and mechatronic systems. This task can be effectively addressed by a human-in-the-loop system or a driving simulator. Commonly, simulators for commercial vehicles are used for training purposes or drivability investigations. Although there are a number of very complex and detailed vehicle models used to simulate durability, energy consumption, and dynamic behaviour for a widespread variety of commercial vehicles, human influence, which is a very sensitive factor for the validity of simulations, is often left under-investigated. In this context, RODOS® (**RO**bot-based **D**riving and **O**peration **S**imulator) developed and installed at Fraunhofer ITWM is a viable solution to include the human operator in the simulation, such that the virtual product model, e.g. of a commercial vehicle, can be experienced at a high level of immersion. Detailed dynamic models of the vehicle, co-simulations of tyres and a motion compression which can be adapted allow a motion feedback with comparably low motion errors.

Alongside with a wide variety of simulators for passenger vehicles, the simulators for commercial and special machinery have been far less looked into. This paper presents the results of tests of an operator-driven driving simulator for special machinery coupled with the real-time commercial vehicle model, e.g. an excavator model, harvester, wheel loader, and visual system. The simulator will be shown as a functional system with possibility to utilise standard simulation tools. Currently, the simulator is undergoing concluding stage of construction. This is the world's first motion simulator for interactive driving simulation, based on an anthropomorphic robot with up to 1000 kg payload.

Unlike RODOS® simulator, employing a serial kinematic system, most motion platforms for driving simulators are parallel kinematic systems of Stewart-Gough type. This manipulator type, compared to the serial kinematic system of the same power capacity, allows a higher payload and a wider motion bandwidth. On another side, the parallel system has a number of comparative disadvantages, i.e. smaller motion workspace, coupling between translational and rotational motions leading to mutual workspace reduction in the presence of the other, mechanical self-lock phenomenon [1].

Advanced hexapod simulators, belonging to the parallel kinematic system group, are enhanced with an additional linear travel system, usually of 20 metres in stroke and more, which permits reproduction of low frequency cues for restricted time duration. Prominent examples are the NADS (National Advanced Driving Simulator at University of Iowa), Daimler and Toyota simulators. However, the typical maximum tilt angle of 25 degrees and significantly reduced translational workspace at large endeffector tilt angles presents a significant limitation, especially for the simulation of off-road manoeuvres of SUV and commercial vehicles, requiring tilt angles exceeding maximum allowed by the hexapod system.

Given the focus of RODOS® simulator on commercial vehicle simulation, the expected manoeuvres are primarily off-road along with the driving and performing work in rough terrain - all of which require large rotational workspace. Furthermore, the exact reproduction of the cabin orientation increases human perception and reduces the risk of simulator sickness [2]. This suggests that a serial kinematic system is more suitable for the stated purpose.

Currently, only few simulators are using serial robots. All of them are based on one type of industrial robot, called Robocoaster® [3]. This robot, designed as an amusement ride installation, carries a payload of 500 kg. Since on average the off-the-shelf cabin exceeds 500 kg weight, a class higher heavy duty industrial robot was adopted as a motion platform.

This paper presents an overview of key modules of the simulator, with an emphasis on the hardware architecture, and carried out interactive driving tests. The simulator is a functional system open to co-simulation with the standard multi-body simulation tools. Section 1 describes the setup of the simulator. Translation of a vehicle motion to the robot motion is realised by a motion cueing algorithm presented in section 2. Requirements for real-time simulation applicable to simulators are outlined in section 3. In section 4, the architecture of the vehicle model and hardware is shown. In this section, the model details of the vehicle are not addressed and will be covered in the following publications. Interactive simulation of an excavator driving over rough terrain and a passenger vehicle model created by an industry standard multi-body simulation software are shown in sections 5 and 6 respectively. The key components of the simulator – visual system, motion feedback, audio system, motion cueing filter, safety system, and the vehicle model – were conceived, designed, and implemented by the simulator group at Fraunhofer ITWM.

1. Simulator setup

As presented in [4] and [5], the simulator represents a heavy duty industrial robot with the original excavator cabin mounted with a lightweight design flange on the robot. The cabin has original in-cabin interface including seat, steering wheel, pedals, joysticks. Besides original instruments, the cabin has additional active force-feedback attachment to the steering wheel, speakers and shakers for audio and high-frequency inputs respectively. The haptics of the cabin is one of the important aspects for increasing the level of immersion. Inside the cabin, the analogue signals of the off-the-shelf user interfaces are digitized and send to the real-time simulation system. Figure 1 shows the closed loop arrangement of the simulator motion and the visual simulation.

The operator signals are transferred to the simulation model executed on a real-time platform. This could be a steering angle, a pedal value or joystick positions. This model simulates dynamics of the vehicle and its subsystems subjected to the given operator inputs and vehicle interaction with the environment. The output quantities of the vehicle model are the cabin translational accelerations, rotational angles, and rate of angular rotation which are required to produce motion feedback to the simulator. The goal is to present the same motion inside the simulator cabin. It is obvious that due to limitations of the simulator workspace the motion cannot be identical to the vehicle and has to be compressed. This feature is provided by the "motion cueing" and "washout filter" algorithms reflected in Figure 1. Both algorithms take human perception mechanisms into account and are adapted to the new motion platform. After the required cabin position and orientation are found from the previous step, the individual command inputs to the robot 6 axes are calculated from the inverse kinematic transformation. The obtained command inputs pass through collision prevention filter and are sent to the robot in the form of increments at every sample time via communication network. With this step the motion feedback loop for the test driver closes. The complete hardware architecture and the motion calculation algorithms are developed in our group and implemented as white boxes to allow a full access.

The graphics system is responsible for the correct visualisation of the virtual scene. A spherical projection dome with a diameter of approx. 10 m is used with a projector array to display the vehicle and the environment. To get a field of view of 300° by 110° 18 projectors are installed inside the fixed screen. Each projector has a resolution of 1920 by 1200 pixels. Finally, the pictures are rendered by a computer cluster which also uses the tracking information of the simulator position and orientation for image correction. Every interactive object in the visual scene is coupled to the real-time vehicle simulation system. Position and orientation of each part, e.g. the parts of the excavator arm, are sent via network communication to the visual system in order to obtain a deterministic behaviour. Both the clustering code, and the software for warping and blending algorithms are developed in house; furthermore the access to the source code allows further improvement of the system. The installed automatic calibration of the visual system is also a product of Fraunhofer.

For the chosen elbow up operation point the first measured resonance frequency is about 12 Hz. It is obvious that this value depends on the mass of the cabin and the driver, so the filter frequency of the motion cueing algorithms was set to 6 Hz in order to ensure a feasible motion without resonance effects. This bandwidth is sufficient for the adequate representation of the vehicle handling of passenger cars and commercial vehicles. The body and seat motions in a passenger car vehicle are usually below 2.5-3 Hz [6]. Despite the limited dynamics of the motion, due to serial manipulator scheme, the higher frequency excitations are delivered by two shakers and an acoustics system (see block NVH simulation in Figure 1).

The acoustic system contains 10 channels for low frequency shakers (bandwidth from 5 Hz to 200 Hz) subwoofer (bandwidth from 20 Hz to 500 Hz), mid-range speakers and tweeters (bandwidth up to 20 kHz). In the examples presented in sections 5 and 6 only 7 channels are used and represent a 5.2 surround-sound system. The database for the sound generation uses measured samples for different operating points. The simplest way is to generate a “click-free” sound by using a microphone record taken inside the cabin of the real vehicle, cut and warp it with a short time blending. “Click-free” refers to a smooth endless repetition of sound samples. At runtime the sound engine algorithm interpolates within this field. The states are rpm and load of the engine and other systems, which shall be separately recorded. The advantage of in-cabin record is that the sound provided to the test person is realistic, including the effects like body vibrations and different sound transmission paths. The shaker signals are recorded by accelerometers together with the audio samples. The shaker system has another signal input in order to reproduce high frequency translational model motions (e.g. vibrations caused by the wheel rolling motion). A digital-analogue converter provides the signals for the mixer which combines this signal with the recorded samples.

A new safety concept for RODOS® was developed in house taking into account that the serial kinematic system can collide with the environment (e.g. floor) and itself. While Robocoaster®-based motion systems use deformable end-stops to limit the collision-free workspace, the presented simulator employed following safety features: redundant workspace limiting algorithms, running on safety PLCs and real-time systems, proximity switches, and a safety cage of the cabin in the worst case scenario.

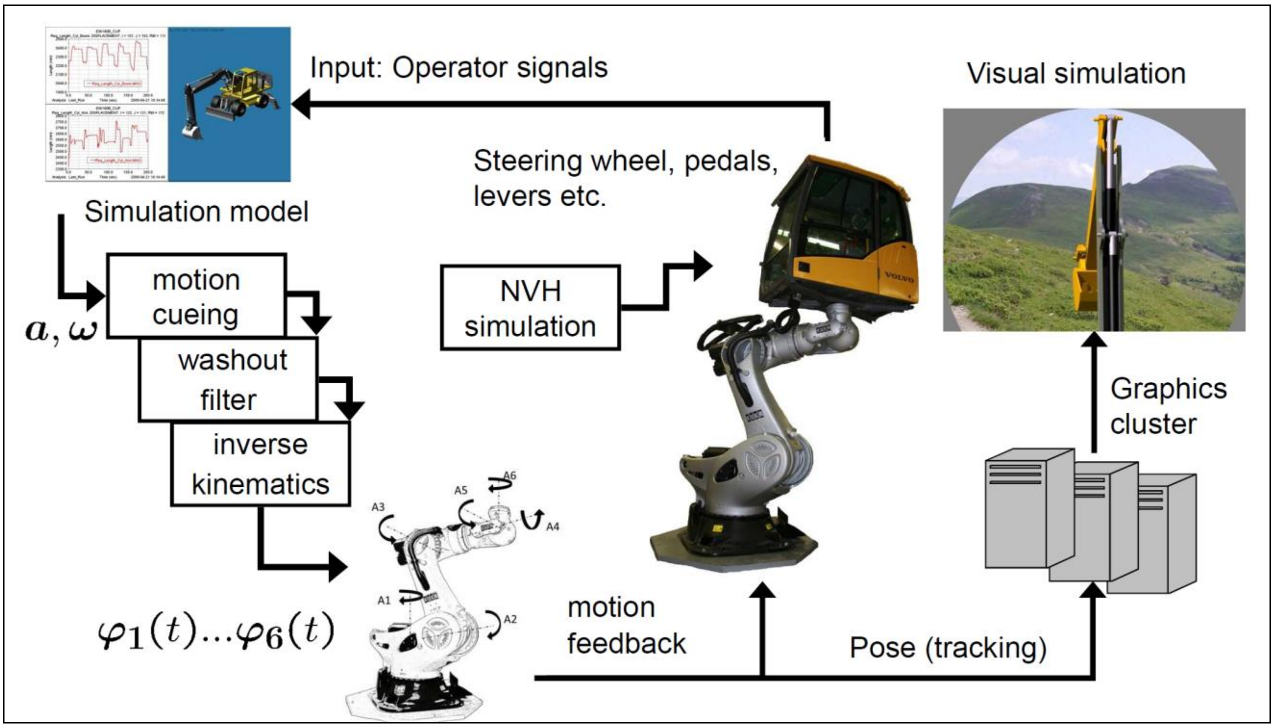

Figure 1. Principal system setup

2. Motion cueing algorithm considerations

One important aspect in the motion cueing context is the fact that the human operator can not distinguish between a tilt and a translational acceleration as long as the following conditions are fulfilled: the angular velocity of the tilt motion is lower than the sensation threshold (approx. 3 deg/s) [7] and the amplitude of the applied tilt angels is less than 20 deg [8]. Then translational accelerations can be simulated by tilting the test person. The resulting component of the gravity vector is used to present a long-lasting translational acceleration. The higher frequency translational accelerations should be presented by respective translational acceleration of the cabin. It is obvious that the visual simulation has to compensate the motion caused by the tilt coordination algorithm. With the motion cueing technique combined with an input scaling, the workspace of the virtual machine can be compressed to fit into the simulator workspace.

Human cognition mechanisms are considered to reduce the risk of kinetosis or better known as simulator sickness. To increase the fidelity and immersion, it is essential to have the possibility to modify the motion cueing algorithms depending on the scenario and on different vehicle models. For each case, the output of the motion cueing and washout filter algorithms are target positions of the robot in world coordinates referenced to the robot origin.

In the work presented here, the so-called classical motion cueing and washout algorithms are enhanced with some modifications. The classical washout approach goes back to REID and NAHON [7] and was originally developed for flight simulation applications on hexapod motion platforms. It is adapted to use with an anthropomorphic robot arm. The important parameters for the excavator simulation are the scaling of the input accelerations, the high-pass filter frequency which is responsible for translational motion cues, and the low-pass filter frequency which defines the tilt coordination algorithm. Common scaling settings are between 0.4 and 0.7 [10]. In our case, the filter parameters as well as the scaling values can be modified according to the simulation scenario. The specific settings are described below.

Generally, one of the most critical spurious effects introduced by linear time invariant motion cueing filters is the resulting time delay. This is one reason to modify the filters for different scenarios. Another important feature is the limiting of the translational and rotational cabin position to ensure a feasible and also safe simulator motion. Singular positions as well as collisions are important to prevent. So, yaw and roll motions are limited to a maximum angle of 90 deg. The maximum allowed pitch angle depends on the cabin position; additionally the robot arm is prevented from being fully stretched out.

The inverse kinematic of the motion platform is calculated analytically. By choosing only the practical relevant solutions and by using an “elbow-up” configuration. the calculation of the axis angles is straightforward (see e.g. [11]).

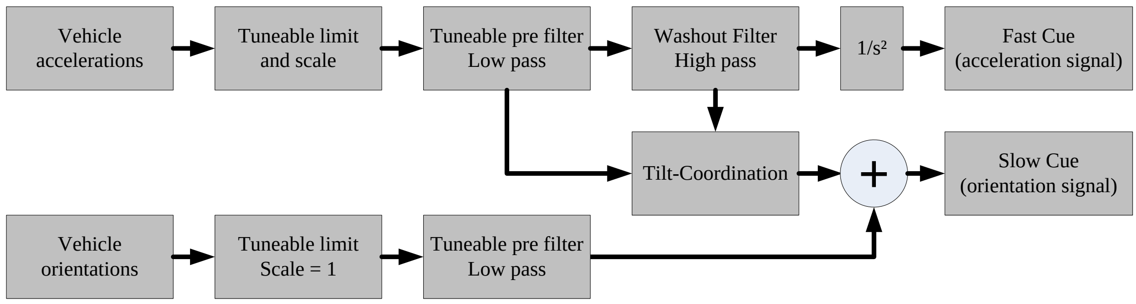

Figure 2. Motion compression algorithm, based on a classical washout filter

3. Requirement analysis for real-time simulation

Realistic operation of the driving vehicle simulator requires virtually delay-free operation of all key components responsible for sensory inputs to the operator. Although the hard real-time is not required by all of them, the consistency of some are critical for the realism of the simulator. As follows from the simulator setup shown in Figure 1, the real-time system simulating the vehicle and the vehicle interaction with the environment plays central role in this matter. Besides providing control inputs to the motion platform, the real-time system is also responsible for generating the signals for visualisation and audio systems, and thus affecting the timing of all operator sensory inputs. Requirements for the real-time system are outlined below.

Stimuli consistency, transport delay, and simulator dynamics
The importance of timing is described below. Since a test person expects an interactive response from the system, any inconsistency between expected and received responses of motion, visual, and audio systems might degrade realism and contribute to the motion sickness. It is difficult to determine required value for the sensational delay tolerance. For example, in [9] the author suggested maximum allowable transport delay of 50 ms, whereas for delays up to 130 ms the driver has the capability to learn and adapt to them. Furthermore, the inherent dynamic response delay of the motion platform to the command input can reduce perceived realism. In particular, any types of unwanted delays, either due to signal transport delay or sluggish dynamics of the motion platform, gain more weight in worsening the realism, especially for the usage cases when the driver expects to receive an immediate impact motion or jerk from the vehicle. To a certain extent, simulator response time is affected by the filter parameters and scaling factors of the motion cueing system, as shown in section 2.

Jitter
Another critical timing related task is the communication with the motion platform. The jitter, which is irregularity of sample periods of the real-time systems, usually leads to a non-smooth simulator motion or even a loss of a command signal increment. To prevent this, the computer system where the interfacing with the robot is calculated has to have acceptable real-time characteristics, i.e. turnaround time has to be less than the sample time. The introduced time delay has to be kept minimal; otherwise, large timing errors can lead to a degraded fidelity and poor level of immersion.

Parallel execution of complex models
Depending on the test objective, the model of the vehicle and subsystems can have varying levels of

detail and complexity. Simulations of complex systems such as tyre models, non-linear soil mechanics, hydraulics, flexible structures can require extremely high computational demand and may exceed real-time capabilities of the processor. Therefore, the model design should reflect maximum computational capacity of the system. Another approach to incorporate higher complexity is to employ parallel execution of the model, given that the model topology allows parallel execution of the model parts. Together with the multi-core systems and data exchange via network, different simulation tasks can be executed on different machines. As shown in example in the section 5**,** the parallel execution was done by running tyre models, MBS model, acoustics, visual simulation, the robot control and safety system on a multi-computer system. Time-critical tasks are executed under hard real-time conditions, whereas non-time-critical tasks run independently in parallel. Non-real-time applications are connected with zero order hold functions to ensure an independent timing of these systems.

<u>Integration with external vehicle control hardware</u>

Real-time system should be open for integration to the third-party vehicle control devices. A typical application scenario is the use of the simulator together with the vehicle ECUs (electronic control units); an ECU unit represents an embedded hardware system for the control of vehicle electrical system or subsystem. Integration could be implemented via any standard vehicle network communication system, e.g. CAN, LIN, FlexRay, etc.

<u>Model Stability</u>

The real-time simulation model has to be stable under any input condition. Instability or singularity of the model will result in safe abort of the test run.

4. Real-time simulation model and interfacing with the simulator

Although simulator was designed to be suitable for simulation of commercial vehicles, the range of applications also extends to other vehicle types, e.g. trucks, passenger cars, and potentially to motorbikes.

A typical model for commercial vehicle has the following key components: engine, chassis with tyres, hydraulics, mechanical links, interaction with the ground, assistance and safety systems, etc. In many applications, the key part plays hydraulics which provides power for operating mechanical arms, lift and travel systems. The typical layout and interconnection of the vehicle submodels, on the example of an excavator, and the interface to external systems is shown in Figure 3. As it follows from the diagram, the hydraulic system receives inputs from the operator in the form of valve pilot pressures and translates them into respective motions of mechanical system. Hydraulic system is cross-coupled with engine model via two signals: engine shaft rotation speed and total load moment applied from the pump on the motor shaft. On the other side, hydraulics is connected to the mechanical links submodel in such a way that the latter receives force and moment inputs and sends either piston or hydraulic motor shaft position and velocity outputs. Tyres represent classical force element of the mechanical system, and, therefore, they require spindle positions and orientations as inputs, and feed back forces and moments applied on the spindle. And finally, NVH model converts the inputs from engine, hydraulics, and mechanical model to the sound signal. On the interface level, the vehicle model requires external inputs in the form of operator commands and sends two sets of outputs: the first is cabin acceleration, roll, pitch, and yaw rate signals to the motion cueing system, and the second is the sound model parameters to audio system which are used to pitch and merge corresponding recorded sound tracks. Note that for clarity reasons in the diagram depicted in Figure 3 the following parts are omitted: ECUs, assistance systems, and outputs to graphics system.

The commercial vehicle model and its subsystems can be implemented using commercially available multi-body simulation packages such as: MATLAB®, LMS Virtual.Lab Motion® of LMS® A Siemens Business, VI-CarRealTime™ and other products of VI-grade GmbH, SIMPACK®, CarMaker® and other products of IPG Automotive GmbH, etc.

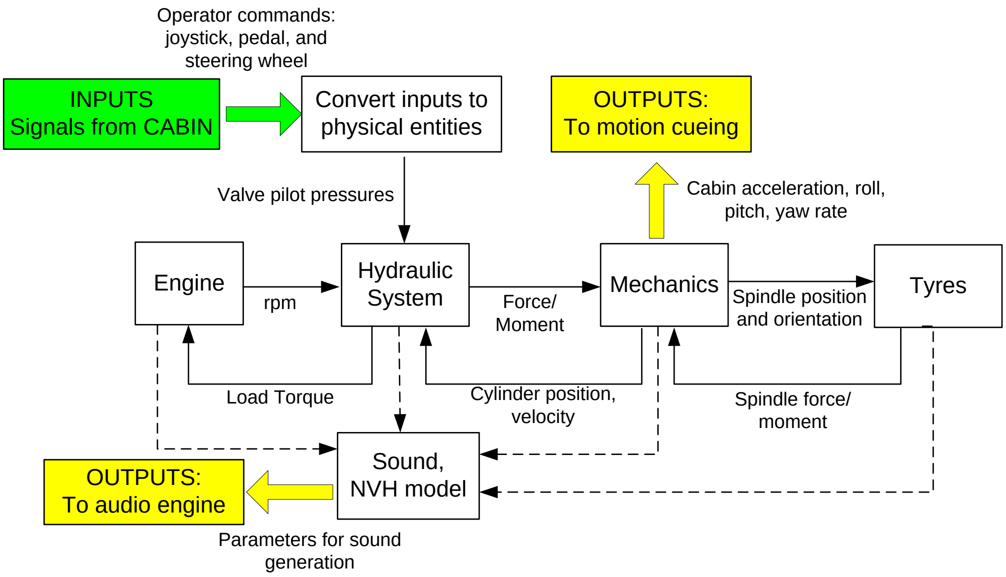

Figure 3 Relationship between submodels of an excavator model

As was mention before, the vehicle model is an inherent part of the real-time system which includes additional components such as: robot motion control system, consisting of motion cueing and washout algorithms, inverse kinematics, and finally cabin signal conditioning and robot motion limits observer. Concerning hardware implementation, the abovementioned components of the real-time system can be run either on the same platform or on the distributed hardware system as shown in Figure 4. A single platform layout of the real-time system is shown in Figure 4a, where the vehicle model and robot control components are run on the same hardware platform, and in the case of many-core system - each can be executed on an individual core. On another side, once complexity of the vehicle model increases it can be calculated on an additional many-core platform, as suggested in Figure 4b. Common application is the parallel execution of the vehicle and tyre models on individual cores of the high-performance real-time platform. By this means the separation of the platforms occurs on the physical level, thereby achieving scalability of computational resources for the vehicle model and avoiding bottleneck of having to run all components on the single platform with limited performance.

5. Excavator simulation example

As an example we present and discuss the interactive simulation of a wheeled excavator. The vehicle model is an integral part of the control loop between an operator and the robot.

For the demonstration purpose, the excavator model complexity is reduced to reflect rudimental characteristics, which allow the vehicle to drive across rough terrain and operate the excavator mechanics. Multi-body model of the excavator consists of the following elements: an undercarriage with the tyre-ground contact, the superstructure with boom, stick, attachment, and basic hydraulic and drive train model.

All excavator mechanical model bodies are implemented as solids with frictionless joints between them. Undercarriage is a body directly connected to tyres and has force and moment inputs from all 4 spindles. Wheel rims have spinning degree-of-freedom and front wheels are steered. Each tyre represents a spring and damper force element in vertical direction and has no slip in road contact. Wheel rims and mechanical arms are driven by moments and forces originated from simple hydraulic system model. Hydraulic model incorporates a fixed volume oil column resonance for each motor and each cylinder, and considers frictionless flow from directional valve to the cylinder or motor. The valve flow-pressure characteristic employs square root relationship and flow gain is linearly proportional to spool displacement. No dynamics are considered between operator joysticks outputs and relevant spool position. On the hydraulic supply side the supply pressure is considered to be constant and flow supply infinite. Load-sensing elements and pressure compensated flow control valves, which are used for excavator hydraulics, are ignored. Also bucket-ground interaction is not considered. Parameters of the excavator model are set to be representative of 20 ton wheeled excavator.

The accelerations and orientations of the vehicle model are arbitrary unknown while depending on the operators input. Even tip-over motions are possible when the operator provokes such situations. The motion compression algorithm has to generate a feasible motion profile such that the simulator can reach each desired pose with given speed, acceleration, and jerk.

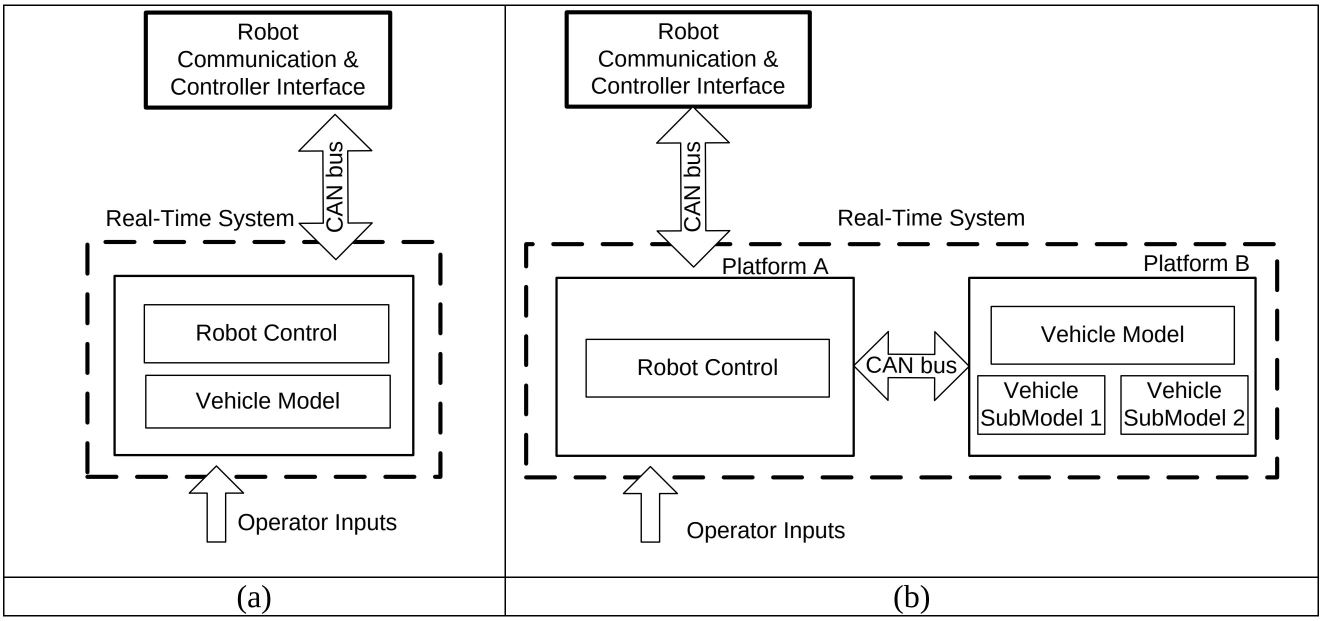

Figure 4 Hardware architecture of the real-time system: (left) single platform, (right) many-computer many-core platform

In this example, the motion cueing settings are the following: scaling factor is set to a value of 0.7.

The translational accelerations are filtered with a second order band-pass filter with a bandwidth from 0.5 Hz to 6 Hz. Rotational motions of the cabin are low-pass filtered (10 Hz corner frequency). Pitch- and roll-rates are critical because the inner ear as a part of the human perception system is very sensitive for spurious motions of this type. Especially if tilt coordination algorithms are used to manipulate the acceleration simulations, large tilt velocities can cause motion sickness. To solve this problem, for the excavator the tilt coordination algorithm is parameterized such that the signal is low-pass filtered with a corner frequency of 0.5 Hz. In combination with the comparably slow drive speed, nearly no tilt coordination algorithm is required.

In the first test, the operator has to drive with the wheeled excavator a predefined path on a terrain with constant speed. Generated accelerations and orientations of the vehicle model are the input signals for the subsequent motion simulation as already explained.

By slow driving on the rough test terrain, the simulator orientations mostly follow the vehicle model orientations. Figure 5 shows the cabin orientations of the simulated excavator and the measured orientations of the simulator cabin depending on the manoeuvre on the terrain. Tilt angles up to 30 deg are possible, for this application the robot based motion system is very useful because translational motions can be reproduced simultaneously. In addition to the absolute value encoders, the motion is also recorded by an inertial measuring system attached to the driver’s seat and shown in Figure 5. The comparably low motion errors are only caused by the phase shift of the motion filters and the robot system.

The high frequency excitation as well as the acoustics is presented with the NVH simulation hardware inside the cabin. For this purpose, the measured sound samples are prepared as described in section 1.

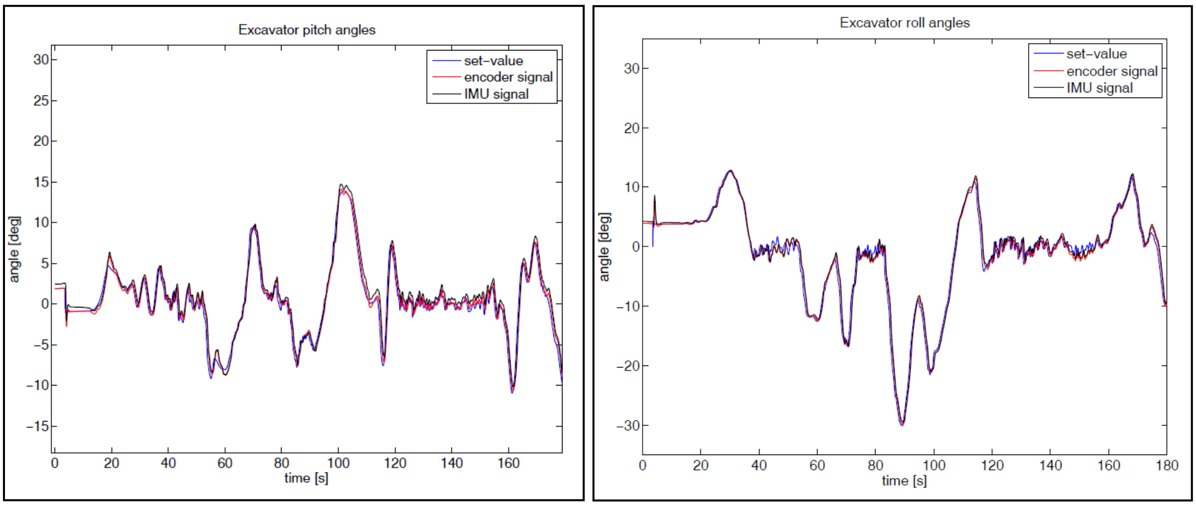

Figure 5. Pitch (left) and roll (right) angles reproduced by the simulator

The visual simulation has the goal to give a realistic visual feedback to the test person. This is possible with the already-mentioned dome projection system. In this virtual environment, a comparable small scene, the test person has to drive the machine along a defined path. Figure 6 shows a panoramic all round view during this simulator drive. The distance from the operator to the screen is about 5 m, which is very similar to the real machine. This reduces accommodation errors of the eye and a realistic convergent angle between the two eyes is guaranteed. In the foreground, one can see the steering wheel; in the background virtual objects are displayed.

Figure 6. Drivers view during the interactive excavator simulation

During these tests, performance values like drive speed, timing, steering effort, working performance and others are monitored and stored. The reproducibility and the fact that every state of the machine and every in- and output is observable with a rate of 1 kHz allows a complete consideration of the process and the drivers reaction. These objective values in combination with questionnaires are used for the evaluation of test person's performance or for the development or improvement of assistant systems. Beside these methods it is possible to attach online monitoring devices such as heart rate, respiration rate, skin conductance and cameras. An eye tracking device helps to find hot spots, where the test person spends most concentration.

6. Passenger car simulation example

The test of a passenger vehicle on the simulator is aimed at demonstrating two objectives: (a) integration of the simulator with the commercial product of a state-of-the-art real-time car model, (b) integration of the real-time tyre model developed in-house by Fraunhofer Institute with a commercial real-time car model on external many-core real-time hardware platform as proposed in section 4.

The passenger car model is created using the software of one of the major multi-body simulation software suppliers. The model has 189 degrees of freedom and is designed to be run in parallel on 3 CPU cores. The tyre model is the commercial product CDTire/Realtime, currently being developed in Fraunhofer Institute. The tyre has 150 degrees of freedom and is represented by the tyre model with the flexible belt and brush-type contact formulation [12],[13]. Each tyre is run on a dedicated CPU core in parallel to the vehicle model.

The hardware architecture is presented in Figure 7, where only the vehicle model and robot control systems are shown. The robot control system is run on a single core real-time platform, while the vehicle model and tyres are executed a multi-core system with real time capabilities. The total number of cores used by the vehicle and tyres is 7; furthermore, an additional 1 core is used for the scheduler and CAN bus communication. The master/administrator process is established to control data exchange between vehicle and tyres. A predictor scheme is incorporated into the data exchange between the vehicle and tyres with the purpose to improve co-simulation stability of these model elements. With respect to the type of data exchanged between two computers - the computer with the vehicle model receives operator inputs, such as steering wheel angle, pedal signals; and returns signals required by motion cueing filter, including cabin accelerations, roll, pitch, yaw rate, as well as steering wheel feedback force.

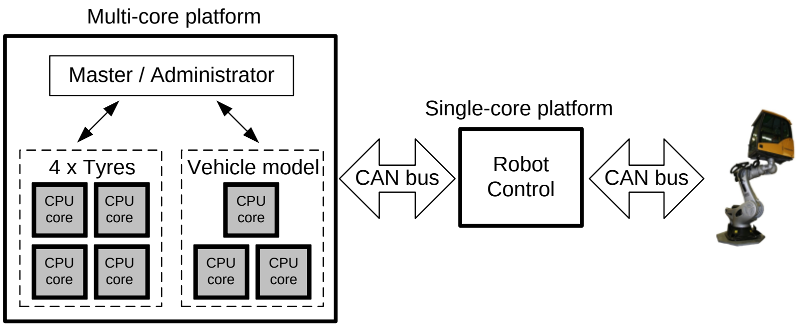

Figure 7 Relationship between submodels of an excavator model

Carried out tests included driving of the vehicle with a number of standard manoeuvres, like accelerating, braking, cornering, as well as cleat tests. A cleat test is commonly used for characterisation of tyre dynamics, since it causes a substantial transient dynamic response of the tyre. Figure 8 presents target and calculated measured cabin vertical accelerations together with target and measured cabin pitch angles obtained during the run over a cleat, of 20 mm height, of a vehicle moving at 5 km/h. Shown cabin target vertical acceleration and cabin pitch angle are the outputs of the motion cueing algorithm. The response acceleration is numerically obtained from measured position. All shown signals were filtered with 20 Hz phase-compensated filter. The observed delay between target and response is due to the transport delay, conservatively tuned robot input signal filter, and robot dynamics, and as the plots suggest it stays within allowable sensational delay limit.

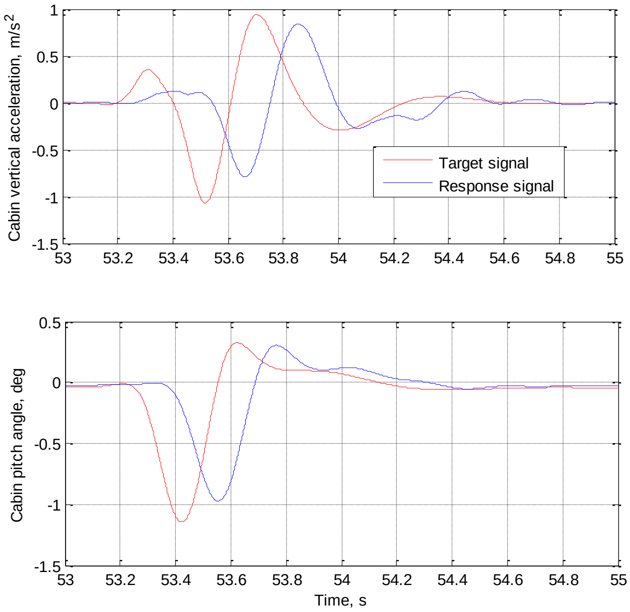

Figure 8 Robot vertical acceleration command and response for cleat run.

Concluding remarks and future work

All core components such as the vehicle model, the motion compression, the NVH simulation, the interfacing as well as the graphic engine are in-house developments with the full access to the source code. Commercial engines or simulation tools are also applicable as far as they allow a real-time simulation. The motion feedback requires a real-time response to have a smooth simulator motion without excessive filtering. For the visual feedback there is no need for a hard real-time, a frame rate of 120 Hz allows an optimal performance and guarantees a low motion blurring. On the other hand, commercial simulation solutions allow an efficient state-of-the-art model coupled with the simulator.

The future work presents an opportunity to include the interaction with a deformable environment, which is crucial for the simulation of earth moving machinery. To achieve this goal the real-time soil simulation is essential. Only if the correct forces can be determined, as well as a realistic soil movement, the simulator can reproduce realistic energy and efficiency estimations. The coupling to the graphical system is another big task in order to obtain an immersive simulation. A deformable ground model enables many simulations in the area of off-road driving. This is an issue for forest and agricultural machinery as well as for off-road passenger cars. Together with high sophisticated tyre models the quality of excitations by these manoeuvres is much better than in the simple non-deformable soil case. Also energy consumption can be calculated with such soil model.

The integration of flexible bodies is also the scope of the future work. Many commercial machines, such as excavators, cranes or trucks, contain many flexible large-sized structures. They show a strong influence on the motion characteristics during a working process. In general, the question of enhancement of the multi-body model complexity plays long-term central role for the simulator; on the one hand, the calculation speed is essential and, therefore, the model complexity should not exceed a certain degree, on the other hand, all relevant motions and machine typical effects should be presented to the driver in the simulator. It is obvious that a neglected physical effect is not visible in the simulator and would decrease the fidelity of the system.

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