Proceedings

Karsten Berns · Klaus Dressler
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# Commercial Vehicle Technology 2022

## Proceedings of the 7th International Commercial Vehicle Technology Symposium

Springer Vieweg

# Proceedings

Ein stetig steigender Fundus an Informationen ist heute notwendig, um die immer komplexer werdende Technik heutiger Kraftfahrzeuge zu verstehen. Funktionen, Arbeitsweise, Komponenten und Systeme entwickeln sich rasant. In immer schnelleren Zyklen verbreitet sich aktuelles Wissen gerade aus Konferenzen, Tagungen und Symposien in die Fachwelt. Den raschen Zugriff auf diese Informationen bietet diese Reihe Proceedings, die sich zur Aufgabe gestellt hat, das zum Verständnis topaktueller Technik rund um das Automobil erforderliche spezielle Wissen in der Systematik aus Konferenzen und Tagungen zusammen zu stellen und als Buch in Springer.com wie auch elektronisch in Springer Link und Springer Professional bereit zu stellen. Die Reihe wendet sich an Fahrzeug- und Motoreningenieure sowie Studierende, die aktuelles Fachwissen im Zusammenhang mit Fragestellungen ihres Arbeitsfeldes suchen. Professoren und Dozenten an Universitäten und Hochschulen mit Schwerpunkt Kraftfahrzeug- und Motorentechnik finden hier die Zusammenstellung von Veranstaltungen, die sie selbst nicht besuchen konnten. Gutachtern, Forschern und Entwicklungsingenieuren in der Automobil- und Zulieferindustrie sowie Dienstleistern können die Proceedings wertvolle Antworten auf topaktuelle Fragen geben.

Today, a steadily growing store of information is called for in order to understand the increasingly complex technologies used in modern automobiles. Functions, modes of operation, components and systems are rapidly evolving, while at the same time the latest expertise is disseminated directly from conferences, congresses and symposia to the professional world in ever-faster cycles. This series of proceedings offers rapid access to this information, gathering the specific knowledge needed to keep up with cutting-edge advances in automotive technologies, employing the same systematic approach used at conferences and congresses and presenting it in print (available at Springer.com) and electronic (at Springer Link and Springer Professional) formats. The series addresses the needs of automotive engineers, motor design engineers and students looking for the latest expertise in connection with key questions in their field, while professors and instructors working in the areas of automotive and motor design engineering will also find summaries of industry events they weren't able to attend. The proceedings also offer valuable answers to the topical questions that concern assessors, researchers and developmental engineers in the automotive and supplier industry, as well as service providers.

Karsten Berns · Klaus Dressler ·
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# Preface

Finally! … 2022 shall be the year after the pandemic in which we met again in presence for our 7th International Commercial Vehicle Technology Symposium!

The topics of this year's conference again addressed different aspects of commercial vehicle development and production at the pulse of time. Assisted and Automated Driving and Working, Alternative Propulsion Technologies, Innovative Development and Production Methods, Safety, Reliability and Durability as well as New Simulation Methods were the topics that we discussed. Contributions were, for example, in the fields of the handling of pedestrian behavior in autonomous driving scenarios, hydrogen-fueled direct injection systems, system integration applying Digital Twins, statistically proven load spectra for next generation e-truck platforms and the development of ADAS systems using driving simulators.

To guarantee the high quality and large impact, the program committee of the conference selected more than 35 very innovative contributions (talks and interactive poster presentations) out of all submitted papers. To ensure scientific innovation as well as practical benefit, 3 reviewers from academic and industry side evaluated each submitted paper and only the best were selected for the Proceedings.

The 7$^{th}$ International Commercial Vehicle Technology Symposium itself was originally planned for March 2022 but due to high infection rates it had to be postponed to September 13$^{th}$ – 15$^{th}$. However, we are confident, that we can continue our success story that began in 2010 with the 1$^{st}$ conference. This year, we had all the participants and speakers present again and, as well known from the past, several vehicle demonstrators and numerous exhibitions from industry and research institutions supported the Symposium. In addition, the international orientation was kept and all German contributions were simultaneously translated into English for our foreign guests. Furthermore, we again had interesting guests from industry and politics, especially from our sponsors and the Ministry of Economics, Transport, Agriculture and Viticulture of Rhineland Palatinate who gave their views to the future of commercial vehicle technology and business development.

At this point, we would like to take the opportunity to thank all people who were involved in preparing this year's Symposium and in completing the Proceedings.

In addition, we would like to thank our gold sponsors

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for remaining loyal to us despite the corona pandemic and the postponements and cancellations of the recent years.

Furthermore, we would like to thank the university board and the government of Rhineland-Palatinate for their kind support and hope that we can further built on them for future conferences.

Stay healthy and enjoy the Proceedings of the 7th International Commercial Vehicle Technology Symposium 2022!

Prof. Dr.-Ing. Roman Teutsch
Speaker of the Commercial Vehicle Alliance Kaiserslautern
Kaiserslautern, September 2022

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## Assisted and Automated Driving and Working



## Innovative Development and Production Methods



## Safety, Reliability and Durability

## Alternative Propulsion Technologies

# Simulation Methods

# Simulator-based development of a stability assistant for wheeled excavators

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**Abstract.** Interactive simulator-based development has a great potential for product development in the automotive and commercial vehicle industry. In particular, test studies and validation steps can be performed during early development phases in a safe and reproducible simulator environment, leading to a decreasing need for real prototype building and testing. Furthermore, it enables engineers to explore features that would require major changes to the current machine generations. In this contribution we report about the simulator-based development of a stability assistance system for excavators. We show the complete toolchain from modeling over interactive simulator studies to a prototype environment and industrialization, closely following the exemplary case of a tip over warning assistant.

**Keywords:** Interactive Simulation, Assistance System, Tip Over Warning Assistant, Excavator.

## 1 Introduction

In recent years, market regulations, increasing awareness for safety on the construction site and the lack of experienced machine operators led to a rising demand for operator assistance systems. Safety plays a particularly important role with construction machines as an accident, such as a machine tipping over, can result in serious personal injury or capital damage to the construction site and the machine itself.

In particular, safety is a core value for the Volvo Group that is not only important for the final product, but also during the development process. Testing and verification of a stability assistance system on a physical prototype would require the test drivers or study participants to maneuver into dangerous situations close to the machine's tipping point. Since particularly inexperienced

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operators are a dedicated target group in a usability study, such an approach is out of scope.

In terms of requirements of the tip over warning assistant, the goal of the simulator-based development approach is to narrow down the scope of operator feedback with respect to operability and user experience such as specific visual or acoustic warning patterns. Additionally, the optimum trade-off between sufficient safety margin and maximized usable operation range of the machine shall be evaluated in usability studies. The targeted use cases of the assistance system shall be operations with rather low attachment speeds, like lifting tasks or heavy object handling.

The interactive driving simulator RODOS® [5,3] offers the possibility to test driver assistance systems in extreme situations in a safe environment. In particular, it allows to operate the machine in the tipping limit range and beyond without endangering the driver. Furthermore, a considerable part of the development steps on the simulator can take place without the presence of a physical demonstrator. This saves costs since less testing on expensive prototypes is required. In particular, many tests for the development of the intelligent machines of tomorrow would not even be possible based on current machine generations, for example due to the lack of required sensor technology. However, a successful simulator-based development requires a very high model fidelity, especially of the dynamic machine behavior. On the one hand, it is crucial to ensure high predictability, so that a later implementation on the physical demonstrator requires little additional tuning effort. On the other hand, it is essential to guarantee acceptance of this development approach by experienced operators who are used to evaluate the stability of their excavator through motion feedback.

Within this contribution we report about the simulator-based development of a tip over warning assistant for wheeled excavators. In particular, we introduce the driving simulator setup in Section 2. The development workflow showing the complete toolchain from modeling over interactive simulator studies to a prototype environment and industrialization is depicted in Section 3.

## 2 Driving Simulator Setup

In this work, the interactive "RObot based Driving and Operation Simulator" (RODOS®), one of the most powerful driving simulators of the Fraunhofer society, has been employed to carry out expert operator studies, aiming to support the advanced assistance system development process at Volvo CE. In contrast to most common driving simulators, the motion platform of RODOS® is based on an anthropomorphic industrial robot arm (Kuka KR1000). This motion platform is predestined for the generation of motion feedback for off-road vehicles such as tractors, SUVs and – in this particular case – excavators. Large inclinations up to the tipping point of a machine can be presented with a motion bandwidth ranging from 0 Hz to approximately 10 Hz. Due to the large translational and rotational workspace of RODOS®, no down-scaling of the motion signals is needed, hence enabling a realistic experience for the expert operators.

The employed motion cueing filters are based on a classical wash-out algorithm [8], modified to provide a 1:1 transmission of translational cabin accelerations as well as pitch and roll motions. The motion platform of RODOS® carries a standard Volvo excavator cabin. For weight reduction purposes, some heavier parts such as the roll over protection system have been removed or, in case of the windscreens, replaced by lighter counterparts, custom-made from polycarbonate. All control and user elements as well as the cabin interior were kept unmodified to provide best possible haptic experience.

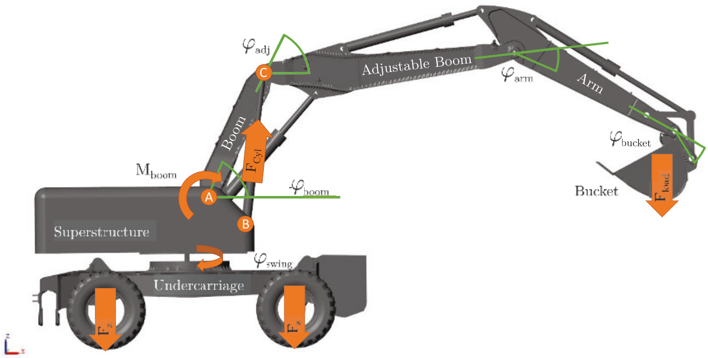


**Fig. 1.** CAD sketch [1] of employed wheeled excavator in side view. Nomenclature of movable parts, forces, angles and pivot points as applied in the article.

The interactive simulation model is a fully real-time capable combination of a Simulink-based hydraulic model and a Simscape/Multibody-based multibody simulation (MBS) model [1], depicted in Fig. 1. The operator controls hydraulic valves, connected to a dedicated hydraulics simulation model, which calculates the cylinder forces currently acting from the effective hydraulic flow through these valves. The cylinder forces are applied to the MBS model, calculating the current mechanical state of the excavator. While the positions and velocities are fed back into the hydraulic system to set the cylinder extension, the cabin motions are sent to the motion cueing algorithm, which controls the robot arm of RODOS® [5,4]. Visual feedback is generated by 18 Full HD projectors with a 120 Hz refresh rate, delivering a 300° image to a projection dome with 10 m diameter. The images generated by the single projectors are modified by a blending and warping algorithm [6], resulting in a bright and seamless image with a total resolution of 11.520 × 3.600 px. The image distortion originating from the dome curvature is corrected by a visual cues algorithm in dependence of the current cabin position in the dome, i.e. the operator head position.

The employment of the presented setup in the tool chain for the development of stability assistance systems will be described in the next section.

## 3 Development Workflow

The whole tool chain that is covered within the development process of the stability assistant for wheeled excavators is illustrated in Fig. 2.


**Fig. 2.** Toolchain in the development process of the stability assistant for wheeled excavators: From an offline predevelopment phase (Section 3.1) and online expert tests in the driving simulator RODOS® (Section 3.2) at the Fraunhofer ITWM to further expert tests in a prototype machine (Section 3.3) and the industrialization (Section 3.4) at Volvo CE.

The driver assistance system is modeled in Simulink [1] and Simscape/Multibody (Section 3.1) and transferred to the interactive simulator RODOS®. Together with experts from Volvo CE, the assistance system is then parameterized and optimized in an interactive simulation workshop executed at the Fraunhofer ITWM according to the needs of experienced operators (Section 3.2). The assistance system at this stage is then further processed and compiled for integration in the existing prototype machine available at Volvo CE for further expert tests and validation steps (Section 3.3). After the stability assistant satisfies all criteria and verification levels in this environment, it is finalized and adapted for its industrialization (Section 3.4).

### 3.1 Offline Pre-Development

The RODOS® environment provides a flexible and realistic test laboratory, where engineers are able to access a manifold of quantities within the underlying mechanical multibody model without the need of installing sensors at the prototype machine. The perception of this virtual laboratory environment is increasing with the model fidelity. For the RODOS® environment, a high level of realism is reached due to a dedicated MBS and hydraulics model, which is parameterized using quantities from the real machine, as described more closely in Section 2.

For the present stability system, a tip over warning assistant, the vertical components of the four wheel contact forces have been extracted from the MBS model, see Fig. 1. In order to ensure a respective transferability and comparability for the test driver, particularly the load distribution needs to be validated with respect to the real prototype machine employed in the later development steps. Therefore, the wheel contact forces of the prototype machine have been measured for different static excavator positions, employing all accessible degrees of freedom and recording the angles of all attachment components using inertial measurement units (IMUs) that will be used as input by the assistance system later, see Section 3.3 for further details. For each static excavator position, the wheel contact forces have been recorded by a dedicated scale with four separated measurement zones.

The recorded IMU angles for each approached position have then been fed into the MBS model (observer), resulting in simulated wheel contact forces. The four wheels are represented by four point-to-point springs, whereby the wheel contact forces are defined via

$$F_{z,i} = \max\{(\vec{F_i})_z, 0\}, \tag{1}$$

where $(\vec{F_i})_z$ denotes the $z$-component of the $i$-th wheel force. Only non-negative wheel contact forces are considered to indicate a loss of contact in case the machine is tipping over. For each data point, we compute the load ratio

$$\frac{F_{z,i}}{G_{\text{excav}}} \tag{2}$$

with the excavator's gravitational force absolute value $G_{\text{excav}} = \|\vec{G}_{\text{excav}}\|$. These load ratios are plotted in Fig. 3. Note that $G_{\text{excav}} = \sum_{i=1}^{4} F_{z,i}$ for each set excavator position. A high agreement between simulation model and prototype on scale was shown with the deviation being less than 5 %. To gain such high accuracy of all the movable excavator parts within the model parameterization, all parts have been carefully checked to the level of masses and positions of hydraulic hoses and bearing pins.

The choice of the actual algorithm, calculating a tip over warning indicator $w(F_{z,i})$ depending on the wheel contact forces, has been made in a first workshop at Fraunhofer ITWM by experienced operators. Different possible implementation schemes for the warning assistance function have been evaluated. Intuitivity, simplicity and predictability of the warning have been rated superior to calculation complexity of the function $w$. The best rated algorithm in this pre-study has been implemented further and qualified for the online test session. This algorithm consists of a two-step process, first sorting the four wheel contact forces according to their magnitude, with $F_{z,1} \leq \cdots \leq F_{z,4}$, followed by a calculation of the intuitive tip over warning function $w(F_{z,i})$ indicating the excavator stability with respect to the machine's tipping load, see also Fig. 4:

$$w(F_{z,i} \mid i = 1, \ldots, 4) = \frac{F_{z,1} + F_{z,2}}{F_{z,3} + F_{z,4} + 1}. \tag{3}$$

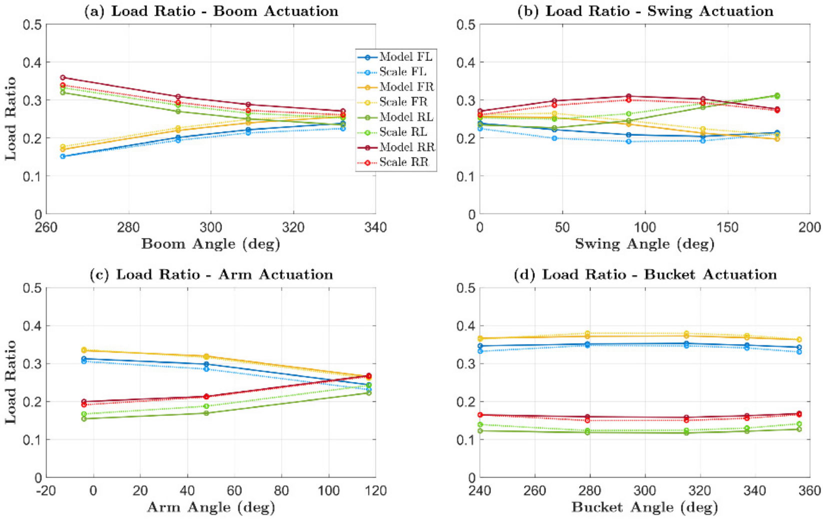


**Fig. 3.** Validation data of load ratio on scale (prototype) versus load ratio of model (simulation model) for different excavator states and all wheels (front left (FL) to rear right (RR)). For each state, the sum of the four load ratios of model and scale equals to one. For each position, the agreement between model and prototype deviates less than 5 %. Measurement traces (a) and (b) were performed without working tool, (c) and (d) with attached load bucket ($m = 1500\,\text{kg}$).

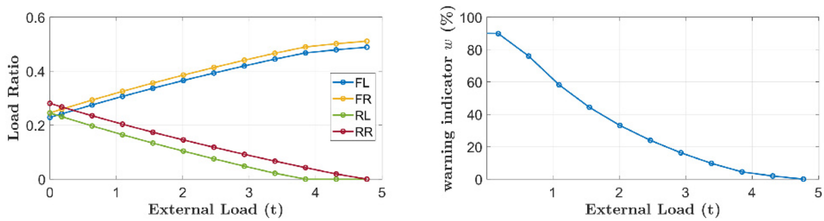


**Fig. 4.** Load ratios (*left*) for all excavator wheels and tip over warning indicator $w$ (*right*) for a successively added external load.

This definition of $w$ is well-defined satisfying $0 \leq w \leq 1$, since $F_{z,i} \geq 0$. If the excavator is tipping over, thereby losing ground contact with two wheels, the two smallest ground contact forces yield $F_{z,1} = F_{z,2} = 0$, resulting in a stability value $w = 0$. In the other extreme, $F_{z,1} = \ldots = F_{z,4}$, i.e. the excavator is in a stable condition, $w$ calculates to $w \approx 1$, as $1 \ll F_{z,i}$ for all $i = 1, \ldots, 4$.

The actual progressiveness of the tip over warning indicator $w(F_{z,i})$ in the human-machine interface (HMI), as plotted in Fig. 4, is held adaptable during online simulation. Furthermore, a single-sided hysteresis functionality has been implemented within the warning indicator, allowing to hold local minima for a short amount of time. These functionalities allow for decent tunability of the warning message during the online test sessions at RODOS® and on the prototype, see Sections 3.2 and 3.3.

### 3.2 Online Verification

In this phase the pre-developed algorithms for calculating the tipping point as prescribed in Section 3.1 have been implemented by the ITWM and the Volvo CE development team and made tangible in the interactive simulator RODOS®.

Experts from Volvo CE were able to explore three different HMI design concepts – visual bar display and acoustic warning tone output depending on the current machine stability – in each of two different maneuvers. The interviews and surveys conducted following the simulation runs provide the basis for subsequent design decisions. The best rating was given to a bar display that is integrated into the existing display system and activates automatically depending on the situation, thereby maximizing the display area for other information while the machine is in stable condition. This bar display enables the driver to assess the stability of his machine intuitively.

To create a realistic and plausible environment for the assistance system evaluation, two new 3D scenarios have been set up, using the Unity3D engine [2]. The scenarios are designed in a way to make the interaction between operator and assistance system happen unconsciously. In this regard, the existing excavator real-time model has to be updated and extended by the following functionalities:

- *Implementation of a freely suspended load model with respective scenario for handling a heavy load*: For a realistic specification of the work task, a scene is implemented in which a trench box has to be lifted off a truck and placed inside a trench, see Fig. 5. After inserting the trench box into the trench, it has to be pulled out again. To bring the excavator closer to its tipping point and to increase the demand to the operator, friction between soil and trench box is enabled once the latter remains set within the trench for three seconds. The soil closing is also presented in the visual scene. The operators are given visual feedback when they succeed in the task.
  Lifting the box from the trailer adds a heavy weight far from the excavator's center of gravity (COG), forcing the driver to operate the machine close to its tipping point. RODOS® is able to depict this situation with high accuracy, allowing for actual cabin pitch and roll angles, limited to 30° in the presented scenario.
  In addition, an implemented reset logic allows the test person to subsequently repeat the scenario. The reset is performed by putting the trench box onto a trailer, see Fig. 5 (*middle*). Again, successful completion of the task is visually signaled to the operator.

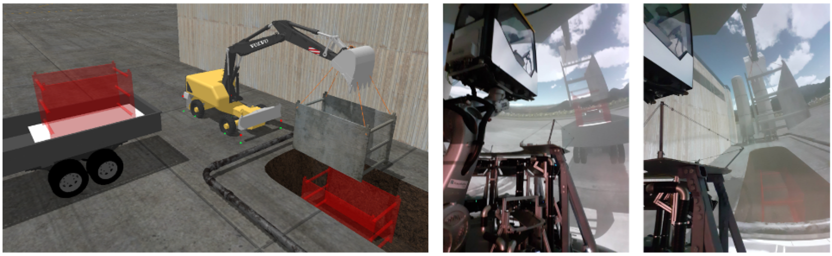

**Fig. 5.** Freely suspended load scenario: Visualization of wheeled excavator with trench box attached to load hook, trailer and trench (*left*). The operator needs to lift the trench box from a trailer (*middle*) and place it into a trench (*right*).

– *Implementation of a mulcher model with respective scenario*: This scenario has been developed to evaluate potential disturbance of the operator by the assistance system when working with heavy implements. A surrogate model for calculating the cutting forces during the mulching process is implemented based on [7]. Moreover, a 3D-mulcher model for visualization as well as a parameterizable mulcher scenario is developed. To increase immersion, a particle model and a sound simulation are added to the visualization. The scene can be parameterized at run time, enabling an online-variation of positions and cutting forces.

A group of expert operators was given time to experience the new assistance system in a workshop at Fraunhofer ITWM to tune the available parameters, thereby optimizing its intuitivity and responsiveness and collect hands-on experience with the HMI, evaluating and classifying different implementations in terms of helpfulness versus distraction from the actual operation.

Once the assistance system has passed this online session, the selected assistance system has to be modified to enable it for field-tests on the prototype excavator at Volvo CE in the following development step.

### 3.3 Transfer to Prototype Machine

After successful completion of the offline pre-development and the online testing, the assistance system is transferred to the demonstrator machine. Within this task, the qualified assistance system is shaped to comply with the limited accessible quantities on the real machine at run time compared to the MBS model.

For the present case of a tip over warning assistant, the relative distance of the two horizontal components of the vehicle's COG to the closest tipping edge needs to be calculated for each time step. Therefore, the knowledge of the current COG of each of the machine's movable parts is a minimal requirement. With knowledge of the machine's kinematics, i.e. its constraints to movement and the parts' relative distances, their masses and inertia tensors, this relative dynamical COG can be calculated from the sensed absolute angles. In total, five IMUs on the machine provide information about the actual configuration of the superstructure, the lower and upper boom, the arm and the bucket assembly. Additionally, the slewing ring between undercarriage and superstructure is equipped with a sensor. From the superstructure IMU, the roll (rotation $x$) and pitch (rotation $y$) angles with respect to the gravity normal vector $\vec{g}$ are used together with the swing angle sensor value to calculate the undercarriage tilt. All following moving parts only have the pitch degree of freedom. The relative position of the part $i$ can therefore be directly calculated from the measured pitch angles $I_{y,i}$ via $\varphi_i = I_{y,i} - I_{y,i-1}$, compare to Fig. 1. These values are fed into a reduced RODOS® MBS model (observer), adapted to accept direct angle inputs for all joints relevant for the calculation of the COG.

Following this procedure, the dynamic COG of all excavator parts can be determined. The only unknown quantity is the COG of the working tool and a potential load, such as soil or some load on the load hook. This variable delivers a particularly important contribution to the excavator stability, having distinct changes in value during operation and being amplified by a large leverage, i.e. distance from the pivot bearing of the attachment. Here, we propose an approach to the topic of load estimation, adapted from [9], the calculation of a dynamic load equivalent, resulting in an effective additional torque to the attachment. This effective torque can be derived from the torque equilibrium around the bearing A between attachment and superstructure via

$$\begin{aligned}\vec{0} &= \sum_j \vec{M}_{\mathrm{A},j} \\ &= \vec{d}_{\mathrm{A,C}} \times \vec{F}_{\mathrm{Cyl}} - \sum_i \vec{d}_{\mathrm{A,COG}(i)} \times \vec{G}_i - \vec{d}_{\mathrm{A,COG(bk)}} \times (\vec{G}_{\mathrm{bk}} + \vec{G}_{\mathrm{load}})\end{aligned} \tag{4}$$

and we obtain

$$\left(\vec{G}_{\mathrm{bk}} + \vec{G}_{\mathrm{load}}\right)_z = \frac{\left(\vec{d}_{\mathrm{A,C}} \times \vec{F}_{\mathrm{Cyl}} - \sum_i \vec{d}_{\mathrm{A,COG}(i)} \times \vec{G}_i\right)_y}{\left(\vec{d}_{\mathrm{A,COG(bk)}}\right)_x}, \tag{5}$$

with the torque equilibrium summands $\vec{M}_{\mathrm{A},j}$, the distances $\vec{d}$ between defined points, the cylinder force $\vec{F}_{\mathrm{Cyl}}$ and distances $\vec{d}_{\mathrm{A,COG}(i)}$ and gravitational forces $\vec{G}_i$ of the adjacent parts, refer to Fig. 6.

Note that the physical significance of the resulting force does not correspond to a static load and thus should not be interpreted without context. Here, this force includes the contributions of the unknown distance between pivot point and COG of working tool and load, thereby even working for freely suspended loads attached to the load hook.

The cylinder force $\vec{F}_{\mathrm{Cyl}}$ has been derived from the measured cylinder pressures $p_a$ and $p_b$ on piston and rod side and the respective cross-sectional areas

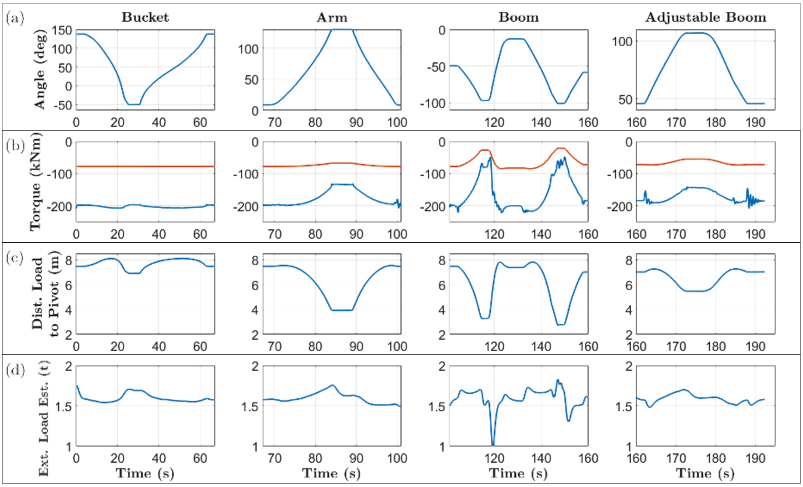


**Fig. 6.** (a) Angles of attachment parts as defined in Fig. 1. (b) Simulated torque (red) and the torque derived from the cylinder pressure (blue). The estimated load torque is proportional to their difference. (c) Distance between pivot A and load application point at the quick fit. (d) Resulting estimated external load in tons.

$A_a$ and $A_b$ via

$$\vec{F}_{\text{Cyl}} = [(p_a A_a - p_b A_b) + F_{\text{friction}}] \cdot \frac{\vec{d}_{\text{B,C}}}{\|\vec{d}_{\text{B,C}}\|}. \tag{6}$$

The orientation of the cylinder force has been included via the distance vector $\vec{d}_{\text{B,C}}$ between the two cylinder attachments at superstructure (point B) and boom (point C). A friction force $F_{\text{friction}}$ has been introduced, modeling internal cylinder friction.

The load estimation has been validated using dedicated excavation cycles, i.e. a successive movement of all degrees of freedom of the attachment, see Fig. 6. As described in the previous paragraph, the load estimation algorithm predicts the correct dynamic mass in all conditions for known and unknown distance of the mass' COG to the pivot point. In general, the calculated mass will include time- and distance-dependent contributions, resulting in a time- and distance-dependent mass equivalent $\widetilde{m}(\vec{d}_{\text{A,COG(bk)}}, t)$. As shown in Fig. 6, the mass $m = 1500\,\text{kg}$ of the load bucket is estimated decently well over the whole sequence, staying within 10 % of the correct static mass, with only short larger deviations for highly dynamic maneuvers. Note that the deviation of the estimated mass within the sequence results from the dynamic contributions, with a static correction offset, taking into account the distance between the COG of the external load and its point of application to the model. In this way, the introduced entity works as predicted and overcomes the challenge of load estimation in the context of a tip over warning assistant on a wheeled excavator.

After this first reasonability check, the complete setup has to be evaluated by test engineers and dedicated excavator specialists, rating the ability of the warning assistant to assist an inexperienced operator while not disturbing or confusing experienced operators. Receiving a high acceptance for the assistance system for both experienced and inexperienced operator target groups can only be achieved by matching with the operator's intuitions, thus keeping the algorithm as simple and predictable as possible.

On the prototype machine, only minor tuning of a predefined tuning parameter for the tires' tipping edge was required. This parameter considers the unspecific actual machine's tipping edge caused by a variation of the tire slack size under load. Apart from that, no additional changes were made to the parametrization of the MBS model for the implementation on the prototype machine. For the expert tests, a freely suspended load exceeding the machine's tipping load over the side was attached to the machine's load hook. All the specialists experienced the assistance system behavior on the machine very similar compared to their study runs on the simulator. Subjects who had not been part of the simulator study learned to utilize the system intuitively by experimenting with the load attached to the machine. Even very experienced operators judged the system as a useful support when approaching the tipping position of the machine. Some of them experimented with different settings for hysteresis of the warning message or progression of the warning severity level (see Section 3.1). Thanks to the model-based design approach, the transfer occurred in a plug and play manner from simulator to the prototype machine. The development time on the prototype machine could be significantly reduced due to a high maturity of algorithm and parameterization.

### 3.4 Industrialization

Following the prototype integration, the industrialization process is initiated, aiming to ensure the desired performance of the assistance system not only on a specific prototype, but for the full range of the excavator portfolio. Among other tasks, this process comprises the definition of required parameters, adaption of the algorithm to different machine configurations and potentially the introduction for calibrations, e.g. of the tires' effective tipping edge.

## 4 Results and Conclusions

Within this article, we present the simulator-based development of a stability assistant for wheeled excavators, following the example of a tip over warning assistant. The possibilities and benefits of driving simulation for the development of assistance systems are discussed, with focus on the flexibility of driving simulators to extract various quantities during run time, the ability to tune the warning algorithm and to experience its subsequent communication with the operator, saving precious time and money for hardware-based prototyping. In the discussed context of a tip over warning assistant, the driving simulator particularly enables to study dangerous scenarios in a safe environment even with inexperienced operators.

The important steps in the development process are reported, starting with the validation of fundamental quantities between the underlying MBS model and the current development stage of the real prototype. For the present case of a tip over warning assistant, a special focus is set to the successful validation of the wheel contact forces within the MBS model. Thereafter, the implementation of the tip over assistance algorithm at RODOS® based on these entitites is described, followed by the online tuning session with experts. Here, RODOS® enables test engineers to operate the machine close to the tipping point with a high amount of realism, being able to experience, tune and evaluate the intuitivity and responsiveness of the algorithm and different HMI implementations with visual and auditive feedback. Finally, the implementation process of the assistance system on the real prototype machine is described, with special focus on the availability of sensors and the strategies used to provide the required inputs to feed the algorithm. In this stage, expert test drivers ensured a high agreement in behavior of the tip over warning assistant between simulator and prototype machine.

Summing up, the presented development workflow successfully reveals the potential of driving simulators as a versatile tool, assisting engineers through the entire development cycle of stability assistance systems, such as a tip over warning assistant.

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# Compact 6-DoF Driving Simulator for Flexible Research Activities

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**Abstract.** In industrial and academic research, a variety of different concepts for driving simulators can be found. The spectrum ranges from static "low-end simulators" to very complex "high-end simulators" with high dynamics and sometimes more than six degrees of freedom. In this paper, a driving simulator with 6 degrees of freedom is presented which, with a compact design and high cost-efficiency, opens up the most flexible application possibilities for the simulation of passenger and commercial vehicles as well as mobile working machines. The concept of the simulator includes the realization of open interfaces for as many simulation tools as possible as well as the adaptability of the simulator structure. Furthermore, a virtual reality setup (VR setup) is presented, which is integrated into the simulator environment and allows an all-round projection of the simulated scenario with limited hardware effort. In addition to the characterization of the transmission behavior of the motion platform, two application fields of the simulator are presented in this paper. The topics include on the one hand the consideration of driving comfort aspects and on the other hand the development of energy efficiency oriented driving assistance systems (EFAS).

**Keywords:** Simulation, Driving Simulator, HMI, EFAS, MPC, VR, Driving Comfort.

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# Kompakter 6-DoF-Fahrsimulator für flexible Forschungsanwendungen

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**Kurzfassung.** In der industriellen und akademischen Forschung ist eine Vielzahl verschiedener Konzepte für Fahrsimulatoren zu finden. Das Spektrum reicht dabei von statischen „Low-End-Simulatoren" bis zu sehr komplexen „High-End-Simulatoren" mit hoher Dynamik und z.T. mehr als sechs Freiheitsgraden. Im vorliegenden Beitrag wird ein Fahrsimulator mit 6 Freiheitsgraden vorgestellt, der bei kompakter Bauform und hoher Kosteneffizienz, flexibelste Einsatzmöglichkeiten zur Simulation von Personen- und Nutzfahrzeugen sowie von mobilen Arbeitsmaschinen eröffnet. Das Konzept des Simulators beinhaltet dabei die Realisierung offener Schnittstellen für möglichst viele Simulationswerkzeuge sowie die Anpassbarkeit des Simulatoraufbaus. Des Weiteren wird ein Virtual-Reality-Setup (VR-Setup) vorgestellt, das in die Simulatorumgebung integriert ist und eine Rundumprojektion des simulierten Szenarios mit begrenztem Hardware-Aufwand ermöglicht. Neben der Charakterisierung des Übertragungsverhaltens der Bewegungsplattform werden im vorliegenden Beitrag zwei Anwendungsfelder des Simulators vorgestellt. Die Themenfelder umfassen dabei einerseits die Betrachtung von Fahrkomfortaspekten und andererseits die Entwicklung energieeffizienzorientierter Fahrassistenzsysteme (EFAS).

**Keywords:** Simulation, Fahrsimulator, HMI, EFAS, MPC, Fahrkomfort, VR.

## 1 Einleitung

Simulationen sind in nahezu allen Facetten der (Fahrzeug-)Entwicklung ein wichtiges Werkzeug. Gesamtfahrzeugsimulationen greifen meist auf Fahrzeugmodelle mit einem hohen Detaillierungsgrad zurück und sind in der Lage, das reale Fahrzeugverhalten gut darzustellen. Um den Realbetrieb von Fahrzeugen in der Simulation abbilden zu können, ist es notwendig, die Interaktion des Fahrzeugs mit der Umwelt und der Fahrerin / dem Fahrer zu berücksichtigen. Aufgrund der Möglichkeit der Interaktion mit dem

Fahrzeugmodell erlauben Fahrsimulatoren somit, die Brücke zum realen Fahrzeugtest in der Systementwicklung zu schlagen (Driver-in-the-Loop).

Fahrsimulatoren kommen nicht nur bei der fahrzeugseitigen Entwicklung und Erprobung von Systemen zum Einsatz. Die Möglichkeiten reichen vom Einsatz für Schulungszwecke [1] bis hin zur Untersuchung medizinischer, physiologischer und psychologischer Aspekte, wie z. B. kognitive Belastungen von Fahrer*innen[2]. Auch Untersuchungen des Fahrerverhaltens [3; 4], des Fahrverhaltens [5], der Fahrdynamik [6] und des Fahrkomforts [7] sind je nach Simulationsmodell und Hardware möglich.

Die Bandbreite von Fahrsimulatoren erstreckt sich von statischen Simulatoren („Low-End“) bis hin zu sehr komplexen dynamischen Simulatoren mit mehr als sechs Freiheitsgraden und aufwändiger 360°-Visualisierung („High-End“). In der Regel sind dynamische Fahrsimulatoren große, mehr oder weniger geschlossen aufeinander abgestimmte Soft- und Hardwaresysteme. Gerade beim Einsatz in der akademischen und industriellen Forschung und Entwicklung sind Modularität, Flexibilität und Erweiterbarkeit jedoch von großer Bedeutung, da Fragestellungen aus unterschiedlichsten Disziplinen untersucht werden sollen [8; 9].

Aus diesem Grund wird im vorliegenden Beitrag der Aufbau eines möglichst kompakten und modularen Konzepts für einen Fahrsimulator vorgestellt, der dennoch eine gute Immersion der Simulation ermöglicht. Modular ist dabei sowohl die Wahl und das Design des Hardwareaufbaus als auch die Softwarestruktur bzgl. des Fahrzeugmodells und der Umgebungsdarstellung. Vorgestellt wird im vorliegenden Beitrag eine Hardwarearchitektur bestehend aus einer 6-DoF-Bewegungsplattform, einem Aufbau zur Simulation von Nutzfahrzeugen und verschiedene Visualisierungsmöglichkeiten (Abb.1). Das Konzept hinter dem Hardware- und Softwareaufbau wird in Kapitel 2 vorgestellt.

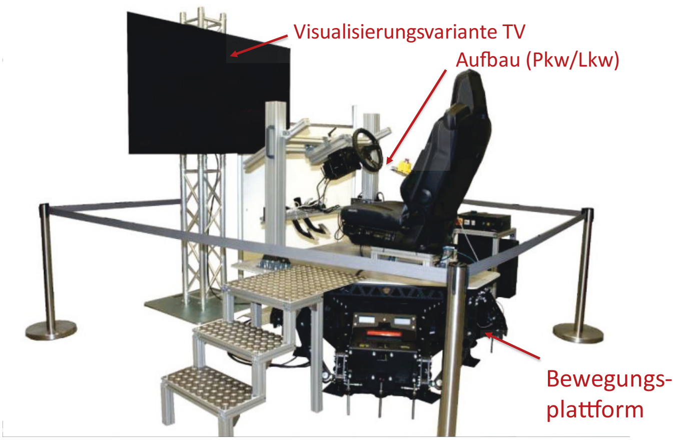


**Abb. 1.** Hardware-Setup des Fahrsimulators

Zur Visualisierung kann ein Virtual-Reality-Setup (VR-Setup) eingesetzt werden (Kapitel 3), welches vergleichsweise einfach eine natürliche, dreidimensionale Darstellung der kompletten Szene erlaubt und es ermöglicht, verschiedene Fahrzeugtypen ohne größere Umbaumaßnahmen auf dem Fahrsimulator zu untersuchen. Durch den Einsatz von VR wird zum einen die Immersion, verglichen mit einem stationären Bildschirm, gesteigert, zum anderen ergeben sich Vorteile in Bezug auf die Untersuchung der Wahrnehmung und Reaktion der Probandinnen und Probanden auf dem Simulator. Zu nennen sind an dieser Stelle Optionen zur Speicherung der Blickführung und Möglichkeiten zur Hervorhebung von Objekten für Betrachterinnen / Betrachter außerhalb der Szenerie, unabhängig von der Visualisierung für die Probandin / den Probanden. So kann z. B. untersucht werden, ab wann ein Objekt durch Probanden wahrgenommen wird.

Des Weiteren wird im vorliegenden Beitrag das dynamische Verhalten der Bewegungsplattform anhand einer Parametervariation für Amplitude und Frequenz am Beispiel der Hubbewegung charakterisiert und Latenzen zwischen Simulation und Plattformbewegung untersucht (Kapitel 4).

Im fünften Kapitel des vorliegenden Beitrags werden zwei Anwendungsgebiete des Fahrsimulators aufgezeigt:

In Kapitel 5.1 wird die Eignung des Fahrsimulators für Fahrkomfortuntersuchungen (autonomer) Nutzfahrzeuge anhand von Vergleichsmessungen untersucht. Dabei werden Messdaten aus realen Fahrten eines schweren Lkw mit auf dem Fahrsimulator gemessenen Daten verglichen. Als Eingang für die Simulation dienen dabei die gemessenen Daten aus den realen Fahrten.

Abschließend wird in Kapitel 5.2 ein Einsatz des Simulators zur Entwicklung von energieeffizienzorientierten Fahrassistenzsystemen (EFAS) [10; 11] vorgestellt. Dabei kommt ein Gesamtfahrzeugmodell eines Stadtbusses in der Simulationsumgebung zum Einsatz. Untersucht werden insbesondere das Einsparpotential des Systems mit realen Fahrerinnen und Fahrern sowie die Akzeptanz der Visualisierung der Fahrhinweise.

## 2 Konzept

Bei der Konzeption des im vorliegenden Beitrag vorgestellten Fahrsimulators wurden die Modularität und die damit einhergehende Flexibilität in den Vordergrund gestellt. Das System ist so konzipiert, dass es transportabel ist und für Untersuchungen oder Demonstrationen an verschiedenen Orten betrieben werden kann. Das Konzept ist auf einen „Mid-Range-Simulator“ ausgerichtet, der zwischen quasi-statischen „Low-End-Simulatoren“ und komplexen „High-End-Simulatoren“ mit z.T. zusätzlichen Freiheitsgraden eingeordnet werden kann. Das Gesamtsystem ist dabei auf eine hohe Kosteneffizienz ausgerichtet, d.h. mit möglichst geringen Anschaffungs- und Betriebskosten eine möglichst großen Mehrwert in der Simulation zu erreichen.

Kern des Simulators ist eine Bewegungsplattform mit sechs Freiheitsgraden und einer Tragfähigkeit von 550 kg. Darauf befindet sich derzeit ein Aufbau, der sowohl zur

Simulation von Pkw-Fahrten als auch zur Simulation von Nutzfahrzeug-Fahrten genutzt werden kann. Der Aufbau besteht aus einem Sitz mit vielfältigen Einstellmöglichkeiten, bei dem bei Bedarf eine Luftfederung zugeschaltet werden kann, um die Verhältnisse in einem LKW oder einer mobilen Arbeitsmaschine zu simulieren. Die Plattform ist außerdem mit einem Lenksimulator ausgestattet, bei dem das Lenkverhalten softwareseitig angepasst werden kann. Der Lenksimulator besitzt zudem eine Schnellwechseleinrichtung, um den Einsatz verschiedener Lenkräder zu ermöglichen. Das maximale Drehmoment ist ausreichend, um die Lenkkräfte während einer Lkw-Fahrt mit einem Lenkrad im Originaldurchmesser darzustellen. Die hydraulischen Simulationspedale erlauben es, das Pedalgefühl physisch über Elastomerelemente und verschiedene Federn zu verändern, wobei die elektronische Signalkennlinie variabel eingestellt werden kann. Durch die vielfältigen Hardware-Konfigurationsmöglichkeiten ergeben sich verschiedenste Einsatzpotenziale des Aufbaus mit geringen Rüstzeiten.

Die Ansteuerung der Bewegungsplattform über Matlab/Simulink ermöglicht es, auch bezüglich der Simulationssoftware flexibel zu bleiben. Damit können bestehende Modelle der Nutzerinnen / Nutzer, im Gegensatz zu geschlossenen Systemen, oft mit geringem Aufwand angepasst werden. Bisher kommen Gesamtfahrzeugsimulationsmodelle von IPG Automotive und dSPACE zum Einsatz. Zudem können auch einfache Fahrzeugmodelle aus Gaming-Engines, wie der Unreal Engine 4, verwendet werden.

Die Umsetzung der simulierten Bewegungen des Fahrzeugmodells auf die Bewegungsplattform erfolgt über einen Motion-Cueing-Algorithmus. Der Motion-Cueing-Algorithmus kann entweder über ein eigenes Simulinkmodell implementiert oder über die Software der Bewegungsplattform realisiert werden. Durch Anpassung von Parametern des Motion-Cueings können die Bewegungen in den einzelnen Freiheitsgraden skaliert und/oder gefiltert werden und dadurch an das Empfinden von Probandinnen und Probanden angepasst werden.

Das Visualisierungskonzept sieht einerseits einen großen Bildschirm vor, der vor der Bewegungsplattform platziert ist, anderseits wird eine Visualisierung über eine VR-Umgebung eingesetzt (Kapitel 3). Der Bildschirm dient primär der Darstellung des Szenarios für Umstehende. Zudem stellt dieser eine einfache Visualisierungsmöglichkeit in der Aufbau- und Testphase neuer Modelle dar.

Wie aus Abb. 2 hervorgeht, kann eine Vielzahl software- und hardwareseitiger Kombinationsmöglichkeiten umgesetzt und die Komplexität des Simulationsaufbaus der Simulationsaufgabe angepasst werden. Beispielsweise können auch nur Teile des vorgestellten Hardwaresetups genutzt werden oder bei Bedarf auch mit dem in [8] vorgestellten statischen Simulator kombiniert werden.