EMMA4Drive – A dynamic human model for autonomous driving (2021 – 2024)

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35. Forum *„Simulation in der Automobilindustrie“*, Fraunhofer ITWM, 3. Mai 2024

EMMA4Drive – A typical application case and project goals

Automated Driving

- Driver is passively sitting in the car (most of the time)
- Driver suddenly has to take control of the car in certain "dynamic" driving situations

Project Goals

- Simulate realistic human motions of the "virtual driver", e.g. in such "passive to active" transitions, during dynamic driving situations
- Driver-seat interaction: Modeling and efficient computation
- Consider increasing variability of driving situations, postures and body sizes for ergonomic and safety-critical protection in automated vehicle concepts

photo: istock

The EMMA4Drive project consortium

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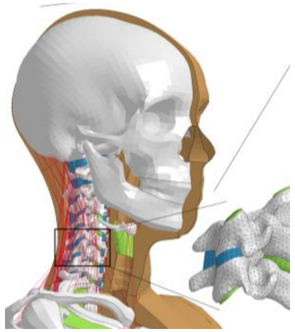

Model order reduction (MOR) of contact interaction between human and seat

Expertise:
- FEM simulation of humans in crash and pre-crash situations
- Model order reduction (MOR) methods

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Include driver seat interaction in motion generation using optimal control methods

Expertise:
- Biomechanical multibody dynamics modeling of humans
- Motion generation by optimal control of muscle actuated multibody DHM

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Link to the automotive industry
Definition of software requirements

Expertise:
- maintenance and distribution of the IPS software, including *IPS IMMA* (a DHM for digital factory applications)
- New module: *IPS Virtual Driver*

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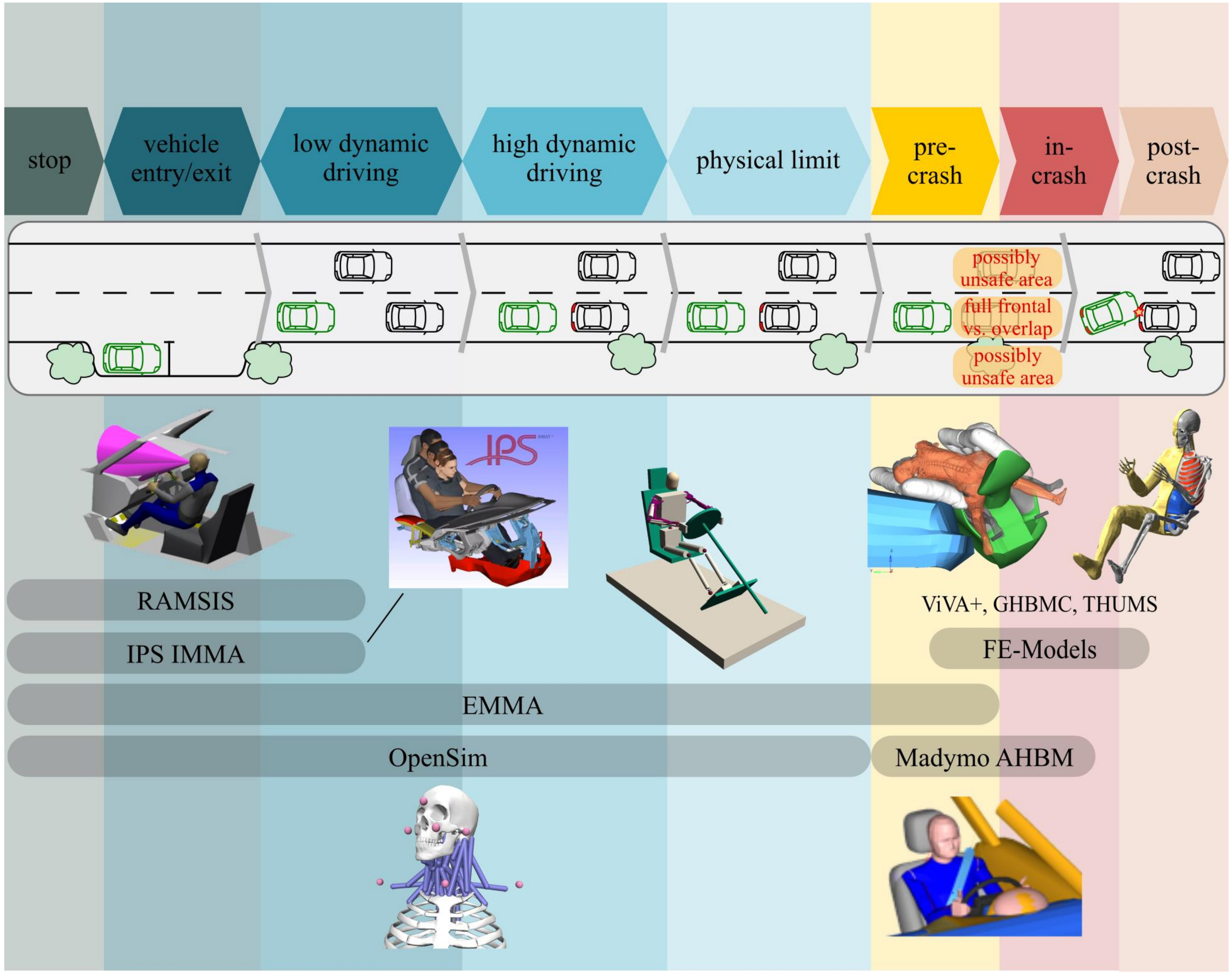
EMMA4Drive: Positioning within the automotive DHM landscape

- **Active behavior** of passenger is relevant in many driving scenarios and is crucial for the initial position of crash phase
- With the rise of automated driving capabilities, the **vehicle** and its **occupants** need to be considered as a whole
- Comfort and safety in automated vehicles needs to be evaluated for **new seating positions**

N. Fahse et al.: *Dynamic Human Body Models in Vehicle Safety - An Overview*, GAMM Mitteilungen, Vol. **46** (2), Juni 2023



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The Digital Human Model EMMA

A biomechanical multibody system

- EMMA is a biomechanical multibody dynamics model with a kinematic tree structure and a system of joints and actuation elements modeling the musculoskeletal system of the human body

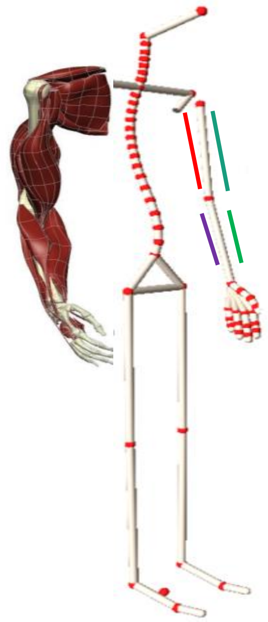
- Different actuation mechanisms are possible:
  - Torque Generators (Motors)
  - Muscle Torque Generators (MTG)
  - Hill-type muscles

- EMMA provides motion generation / prediction using an optimal control approach

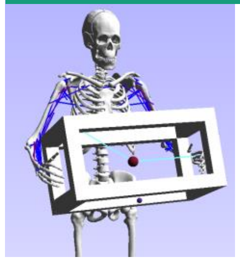
- EMMA can handle rigid contacts

- Aim of EMMA4Drive: Soft Contact Modeling

EMMA



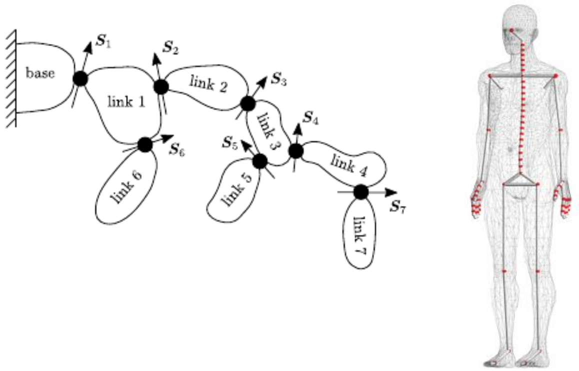
Optimal Control for Motion Generation



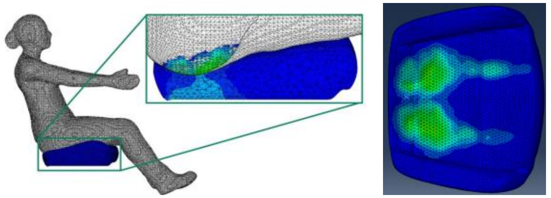
$$\min J(\boldsymbol{q}(t), \boldsymbol{u}(t))$$

$$0 = \ddot{\boldsymbol{q}}(t) - \boldsymbol{f}(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t), \boldsymbol{u}(t), \boldsymbol{\lambda}(t))$$
$$0 = g(\boldsymbol{q}(t))$$
$$0 = e(\boldsymbol{q}(t), \boldsymbol{u}(t))$$
$$0 \leq c(\boldsymbol{q}(t))$$
$$\boldsymbol{q}_- \leq \boldsymbol{q}(t) \leq \boldsymbol{q}_+$$
$$\boldsymbol{u}_- \leq \boldsymbol{u}(t) \leq \boldsymbol{u}_+$$

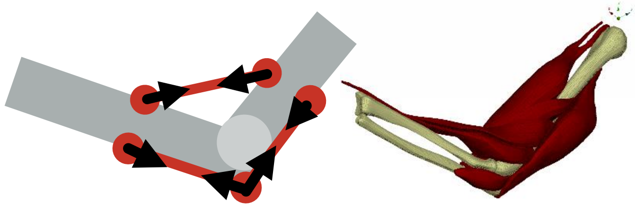
Rigid Multibody System



Rigid (& Soft) Contact Modeling



Muscle (Torque Generator) Modelling



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The Digital Human Model EMMA

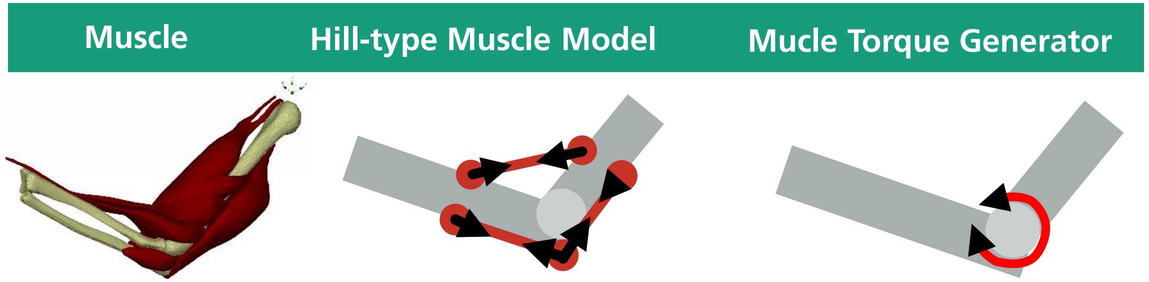
Muscle Torque Generators – New form of actuation

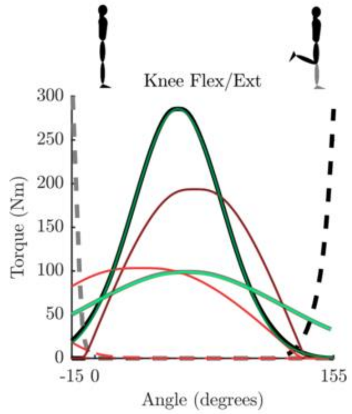
Muscle Torque Generators (MTG):

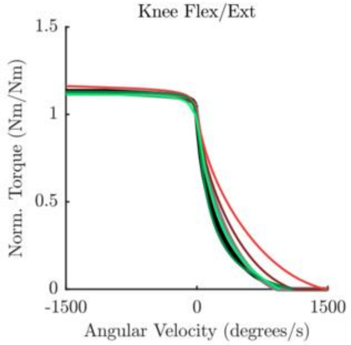
- One MTG represents the muscular properties for the deflection of a limb in one direction.
- Position- and velocity-torque relationship similar to muscle models, but at joint angle level, with rigid tendon.
- $\tau^{MTG} = a f^{A}(\Theta) f^{V}(\omega) + f^{PE}(\Theta)\left(1 - \beta^{PE} \frac{\omega}{\omega_{max}}\right)$

  a: MTG activation, β^{PE}: damping term

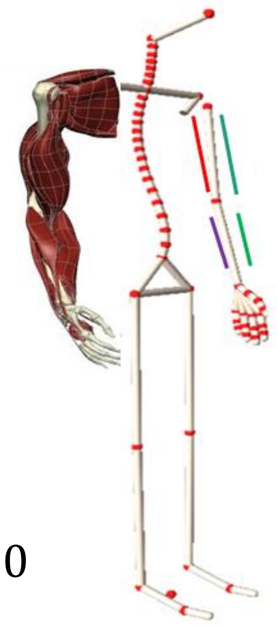
- MTGs are available in EMMA for multiple joints.
- The available set of MTGs is currently extended by performing and evaluating experimental data (2 ongoing master theses at the RPTU Kaiserslautern).







EMMA



EMMA: Motion generation by discrete Lagrangian mechanics and optimal control with constraints

The motion for the EMMA model is obtained by solving a (multiphase) optimal control problem:

- Minimizing a cost function and fulfilling the equation of motion and constraints
- Includes actuation models
- Includes contacts with the environment
- Constraints describe the outline of the motion:
  - Start/End position and velocity
  - Start and contact loss
  - Collision avoidance

$$\min_{q,\dot{q},\lambda,u} J(q,\dot{q},\lambda,u) := \sum_{i=0}^{N} \int_{t_i}^{t_{i+1}} \phi(q,\dot{q},\lambda,u)\, dt$$

$$\frac{\partial}{\partial q} L(q,\dot{q}) - \frac{\partial}{\partial t}\frac{\partial}{\partial \dot{q}} L(q,\dot{q}) - G_i(q)^T\lambda + f(q,\dot{q},u) = 0$$

$$g(q) = 0$$

$$h_i(q,\dot{q},\lambda,u) \geq 0$$

$$e_i(q,\dot{q},\lambda,u) = 0, \qquad i = 0,\ldots,N$$

$$q_- \leq q \leq q_+, \quad \dot{q} \leq \dot{q} \leq \dot{q}_+,$$

$$u_- \leq u \leq u_+\,, \quad \lambda_- \leq \lambda \leq \lambda_+$$

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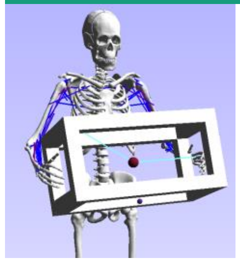
Optimal Control

DMOCC (*discrete mechanics and optimal control for constrained systems*)

- Direct method
- Variational integrator to solve the constrained equation of motions in time
- Discretization is already applied to the Lagrange-d'Alembert principle, and the variation is applied to the discrete equations
- Structure preserving
- Advantages: big step sizes are possible, no numerical drift
- The resulting NLP is solved with the Interior Point Method provided by IPOPT

Optimal Control for Motion Generation



$$\min J(\boldsymbol{q}(t),\boldsymbol{u}(t))$$

$$\begin{aligned}
0 &= \ddot{\boldsymbol{q}}(t) - \boldsymbol{f}(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t),\boldsymbol{u}(t),\boldsymbol{\lambda}(t))\\
0 &= g(\boldsymbol{q}(t))\\
0 &= e(\boldsymbol{q}(t),\boldsymbol{u}(t))\\
0 &\le c(\boldsymbol{q}(t))\\
\boldsymbol{q}_- &\le \boldsymbol{q}(t) \le \boldsymbol{q}_+\\
\boldsymbol{u}_- &\le \boldsymbol{u}(t) \le \boldsymbol{u}_+
\end{aligned}$$

Lagrange –d'Alembert principle:

$$\delta \int L(q,\dot{q}) + g(q)\cdot\lambda dt + \int F(q,\dot{q},u)\cdot\delta q dt = 0$$

Discretizing $[t_o, t_f]$ in intervals with fixed step size $h = \frac{t_f - t_0}{N}$

$$\int_{t_l}^{t_{l+1}} L(q,\dot{q})dt \approx L_d(q^l, q^{l+1})$$

$$\int_{t_l}^{t_{l+1}} g(q)\cdot\lambda dt \approx \frac{h}{2}\left(g(q^l)\cdot\lambda^l + g(q^{l+1})\cdot\lambda^{l+1}\right)$$

$$\int_{t_l}^{t_{l+1}} F(q,\dot{q},u)\cdot\delta q dt \approx F_d^-(q^l,q^{l+1},u^l,u^{l+1})\cdot\delta q^l + F_d^+(q^l,q^{l+1},u^l,u^{l+1})\cdot\delta q^{l+1}$$

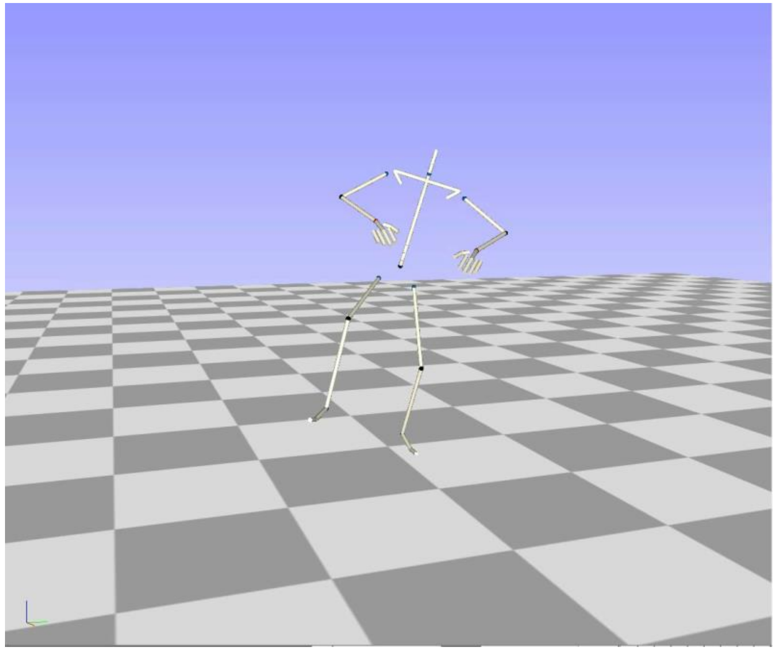
Discretizing objective ϕ and constraints c

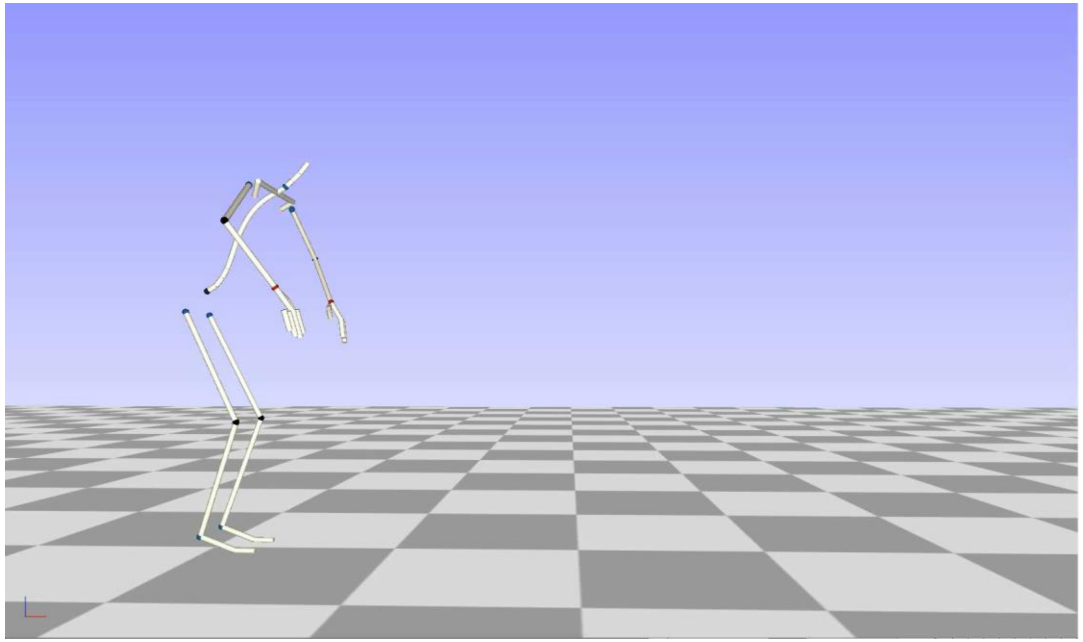
$$\min \sum_{l=0}^{N-1} \phi_d(q^l, q^{l+1}, u^l, u^{l+1})$$

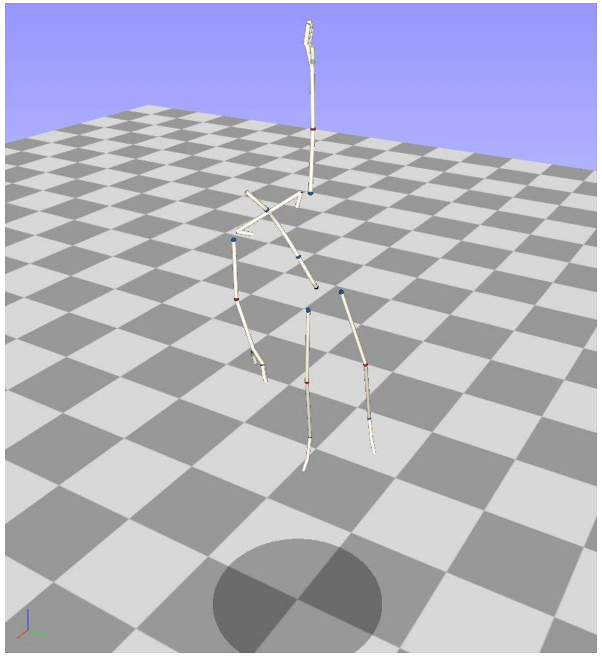
$$\begin{aligned}
\partial_2 L_d(q^{l-1},q^l) + \partial_1 L_d(q^l,q^{l+1}) + F_d^-(q^l,q^{l+1},u^l,u^{l+1}) + \mathrm{F}_\mathrm{d}^+(\mathrm{q}^\mathrm{l},\mathrm{q}^{\mathrm{l}+1},\mathrm{u}^\mathrm{l},\mathrm{u}^{\mathrm{l}+1}) - h\mathrm{G}^\mathrm{T}(\mathrm{q}^\mathrm{l})\lambda^l &= 0, \qquad l = 0,\dots,N-1\\
\mathrm{g}(q^l) &= 0, \qquad l = 0,\dots,N\\
c_- \le c(q^l, u^J, \lambda^K) &\le c_+
\end{aligned}$$

[S. Leyendecker et al. Optim. control Appl. Methods, 31(6), 505–528, 2010]

Motion generation without MoCap by Discrete Mechanics & Optimal Control







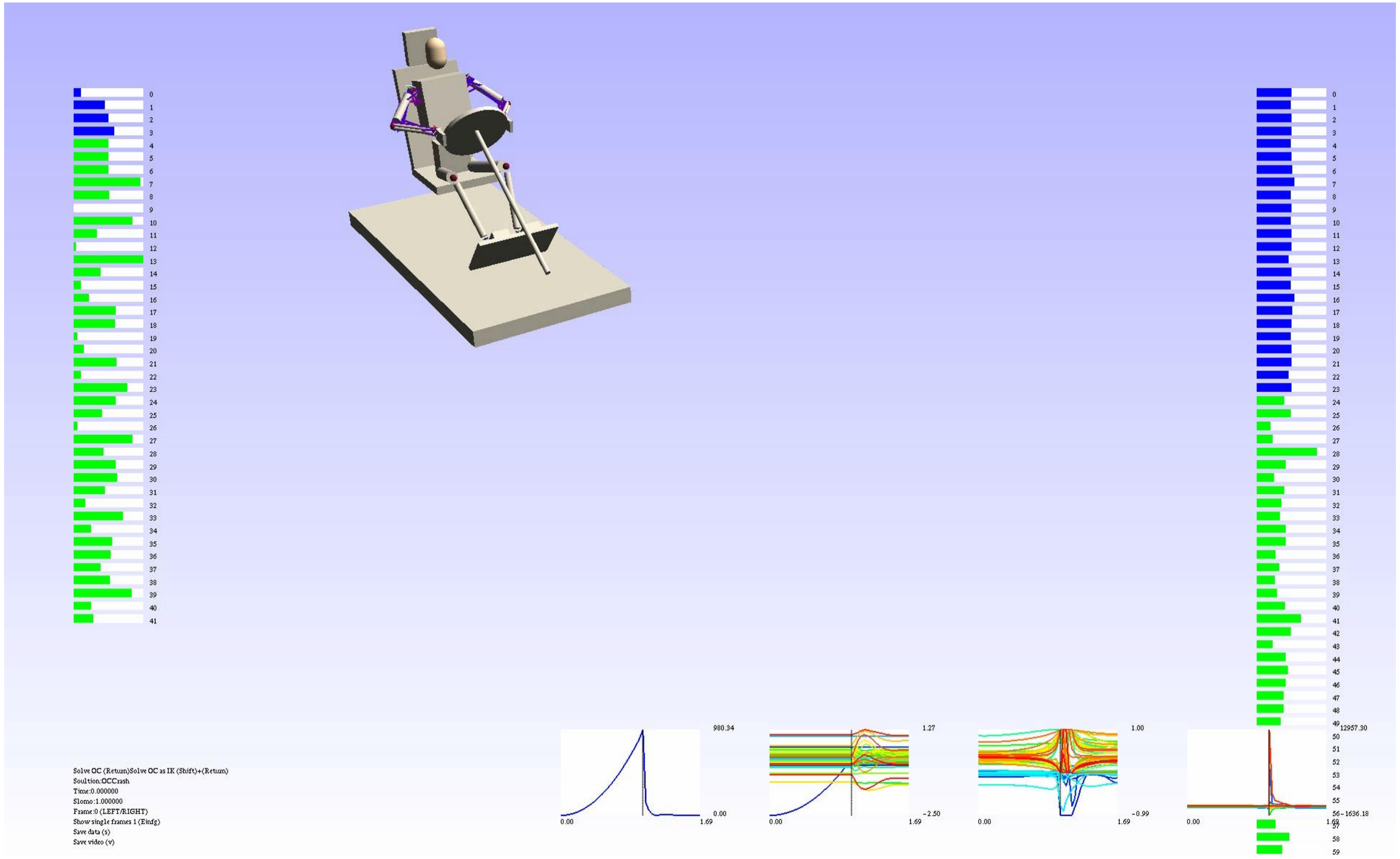
Simulation of a breaking manoeuvre with the EMMA model

Model:

- Each arm:
  - 29 Hill-type muscles
  - 7 degrees of freedom
- Hip, knees, knuckles, lower back, neck controlled by joint torques
- Buttocks fixed to seat
- Hands fixed to steering wheel
- Feet fixed to pedals

Optimal Control Setup:

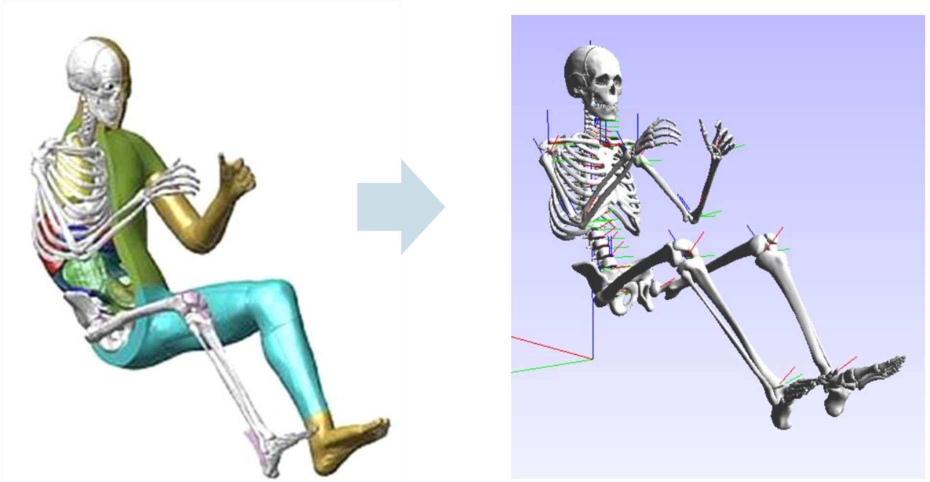
- Constantly accelerated to 5m/s
- Sudden break to 0 m/s
- Rest to rest
- Minimize Control

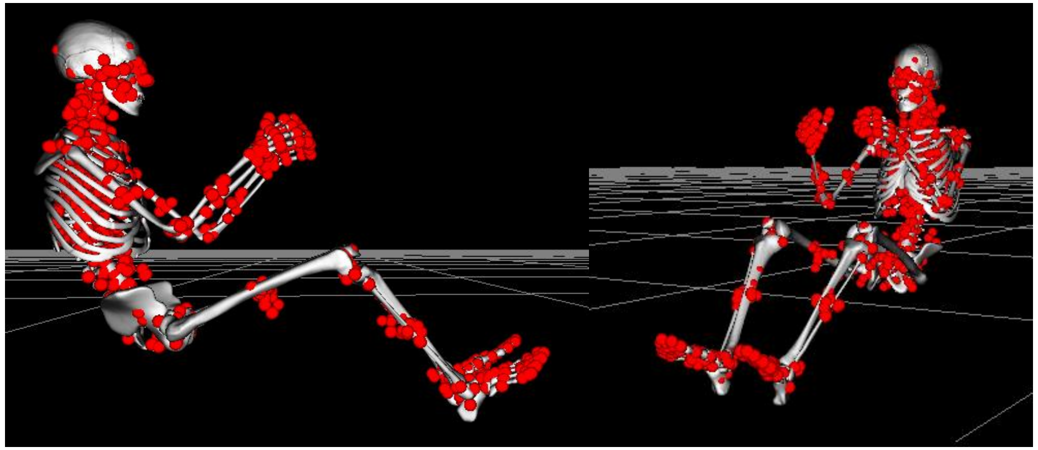


THUMS Model Transfer

THUMS-based RMBS Model

- Export of the skeleton segments
- Setup of the model using the coordinate systems proposed by the EU-project „Piper“
- Definition of the joints based on the old model
- Implementation of new joints in EMMA
- Read-in of the LSDyna-output of the THUMS occupant model in the „neutral“ state: mass, CoM, inertia tensors
- Manual assignment of each FE object to the segments of the RMBS model EMMA
- Automatic Transfer of the dynamic parameters to the EMMA model including merging of all FE objects that belong to one segment





The occupant version as EMMA model. The position of the red spheres represents the position of the FE objects‘ center of masses.

http://piper-eu.piper-project.org/

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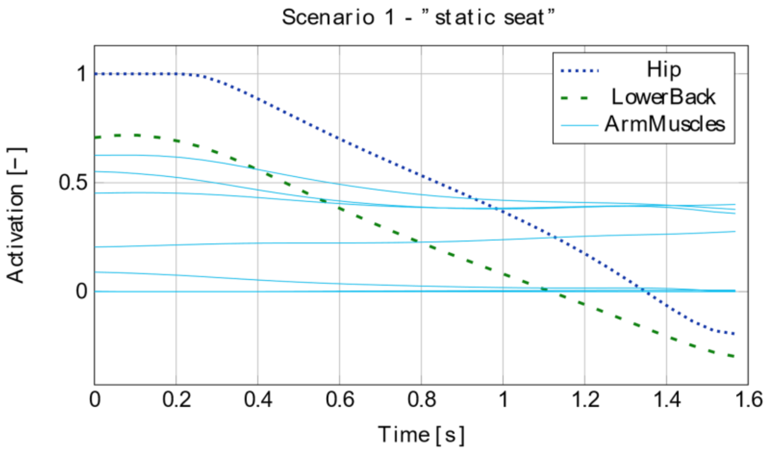
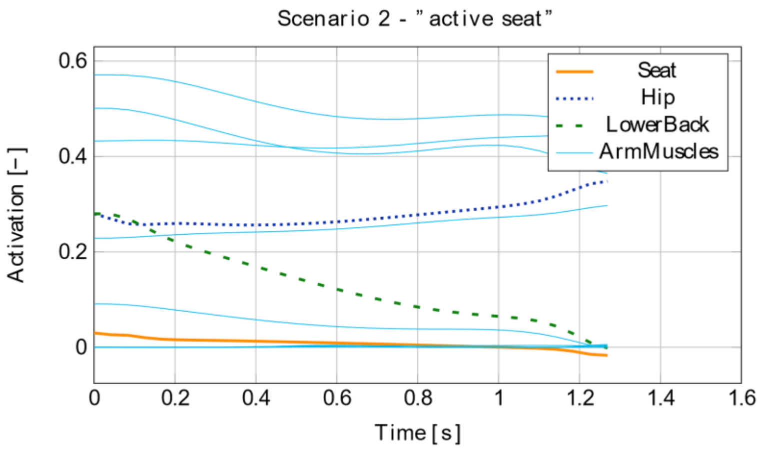
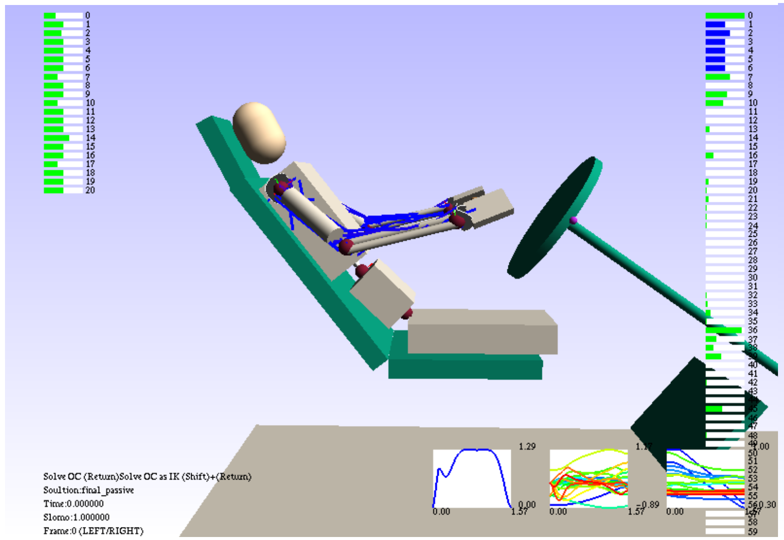
EMMA4Drive: Simulation of a steering wheel takeover

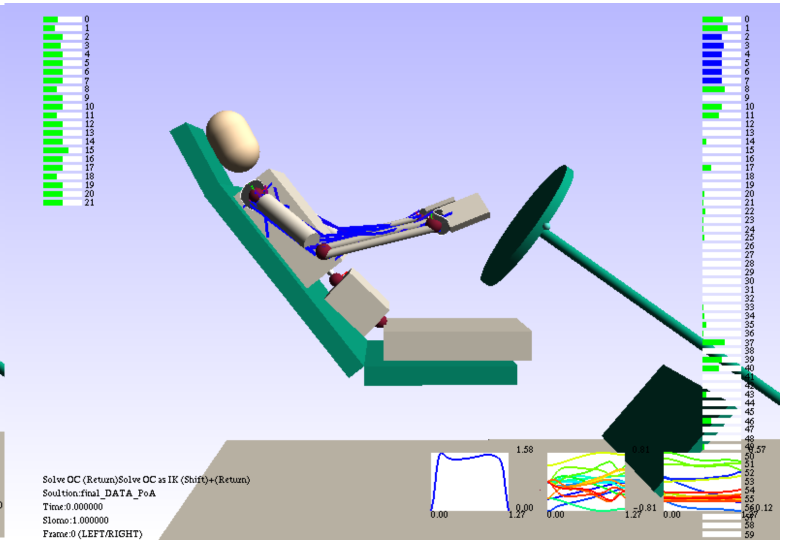
Simulation of a steering wheel takeover

- Initial Position: “Zero Gravity”
- Final Position: Hands on the steering wheel
- Two simulation scenarios: with and without a powered seat
- Back and seat are coupled by 2 linear springs
- The driver is rigidly connected at the lower limb
- The motion is predicted by minimizing a combination of
  - Control & control change effort
  - Duration
  - Kinetic Energy









Simulation of safe optimal braking in a shuttle bus

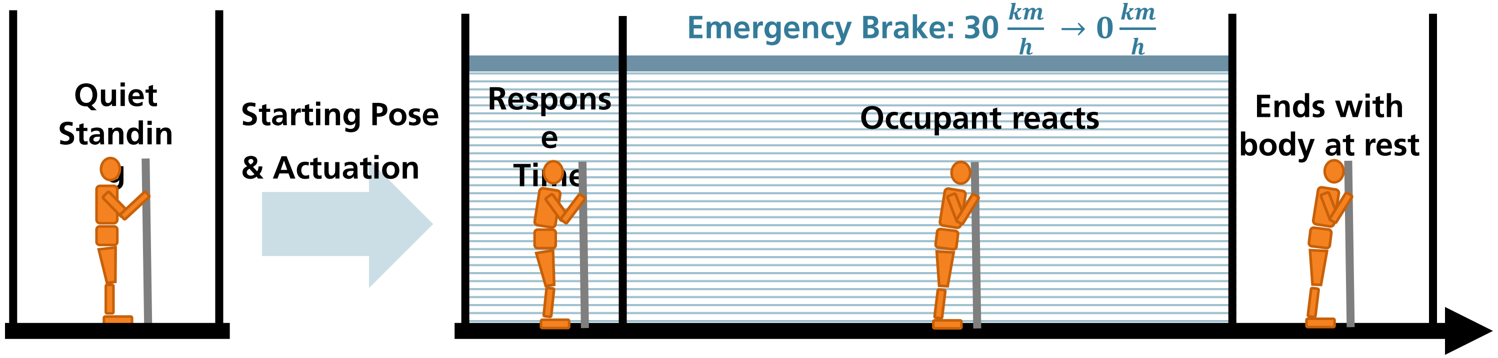
THUMS-based RMBS Model (Industry project with ZF Friedrichshafen)

Simulation Scenario

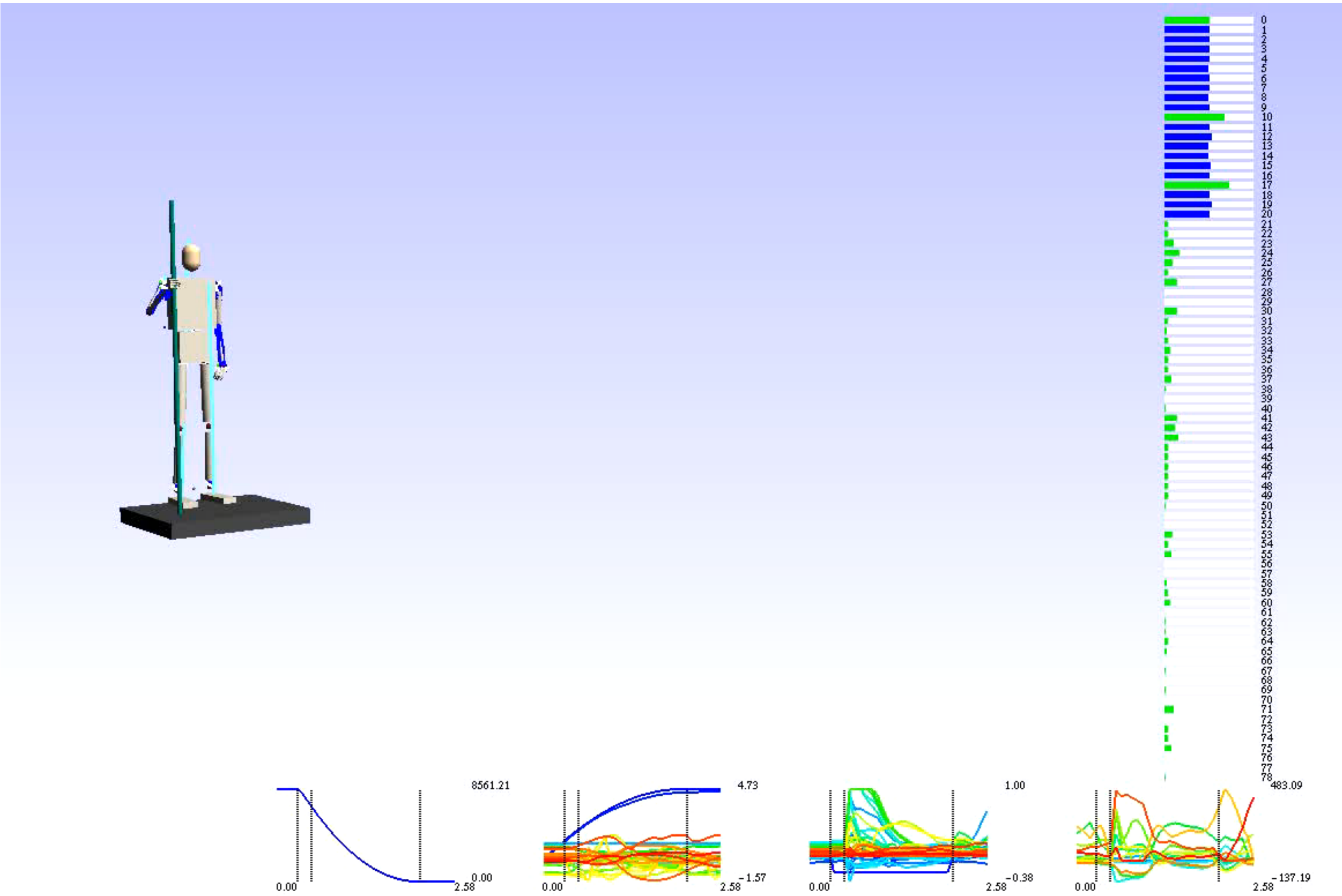
- A passenger is standing in an autonomous-driven bus,
- may hold or not hold onto a vertical handrail,
- has to balance a sudden braking maneuver:
  - Piecewise linear acceleration profile
  - Acceleration profile is prescribed or optimized

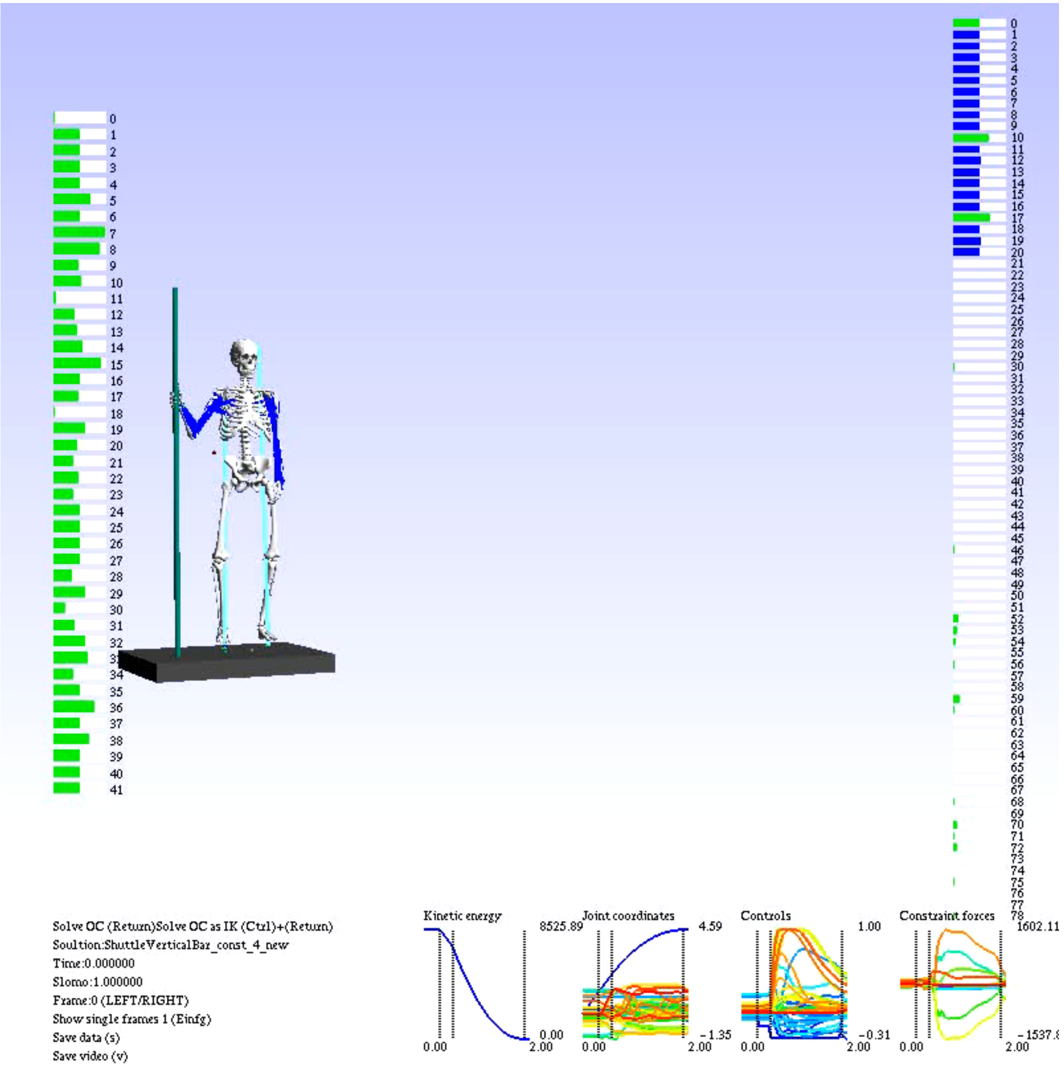
Project Goal

- Comfort and safety studies: What is an optimal brake profile for the bus so that
  - The bus comes to a stop quickly
  - The Passenger‘s risk of injury is low



EMMA4Drive: Simulation of safe optimal braking in a shuttle bus





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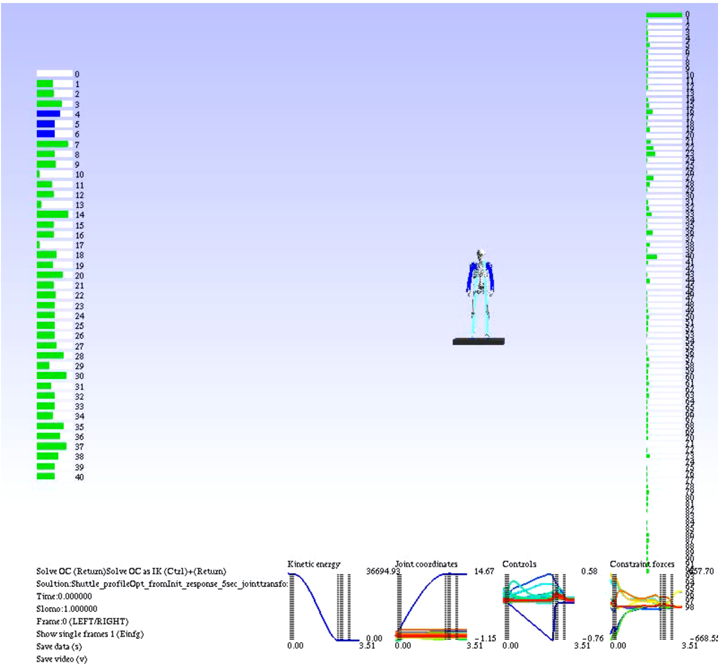
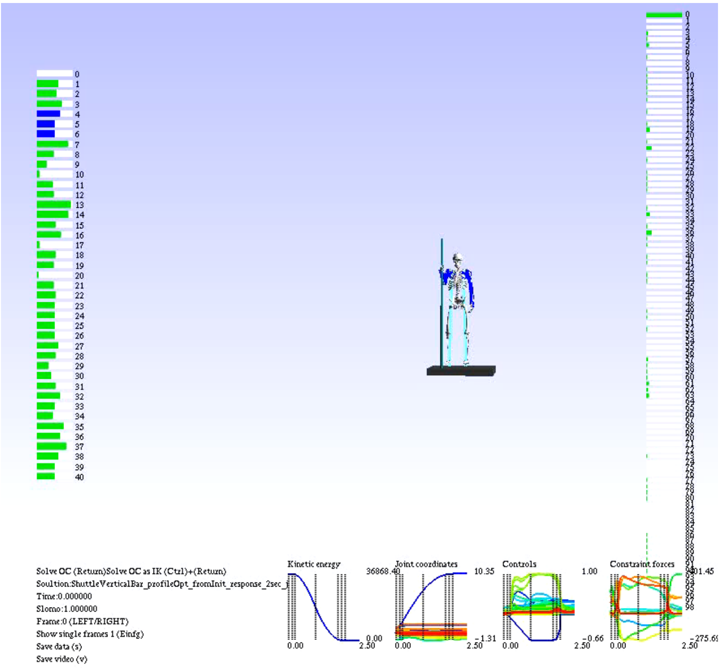
Simulation of safe optimal braking in a shuttle bus

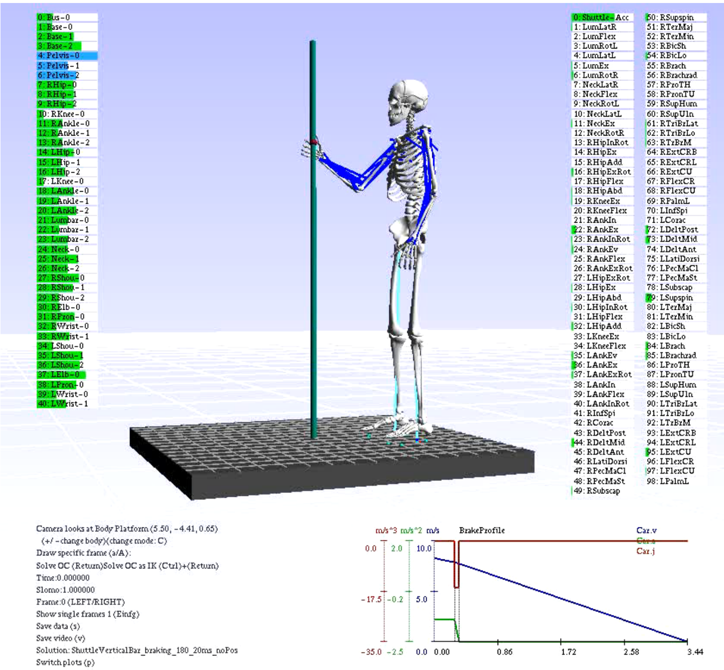
Shuttle Passenger Simulation



Brake profile optimization of a passenger standing in driving direction without handrail support.



Brake profile optimization of a passenger standing in driving direction with handrail support.



A passenger standing opposite to the driving direction with handrail support balancing a prescribed braking maneuver.

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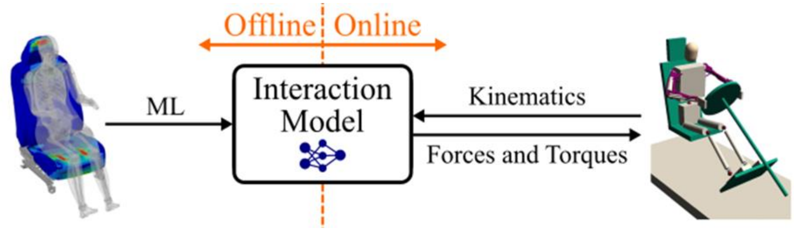
MOR: Efficient simulation of driver-seat interaction by surrogate models



Goals:

- Capable of adequately representing the (complex) contact situation
- Runtime-efficient
- Able to represent closing and opening of contact
- Applicable in the optimal control setup: sufficiently smooth and automatically differentiable

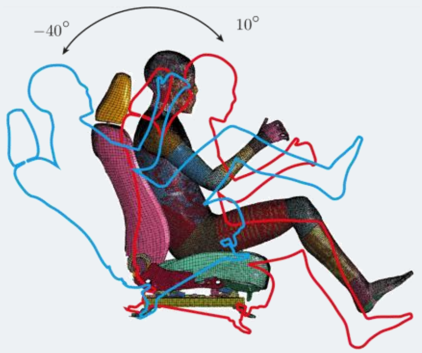
Method:

- FE simulations provide realistic contact forces that are used to train NNs which can be included in EMMA

Focus on head and headrest to develop a robust and general method to obtain such contact models

Generation of Interaction Force Dataset

- High fidelity & long running FEM simulations
- Parameter variations



Surrogate Model

Optimal Control with Driver-Seat Interaction

- MBS simulations
- Evaluate ergonomics
- Simulate long scenarios
- Simulate active controlled movements

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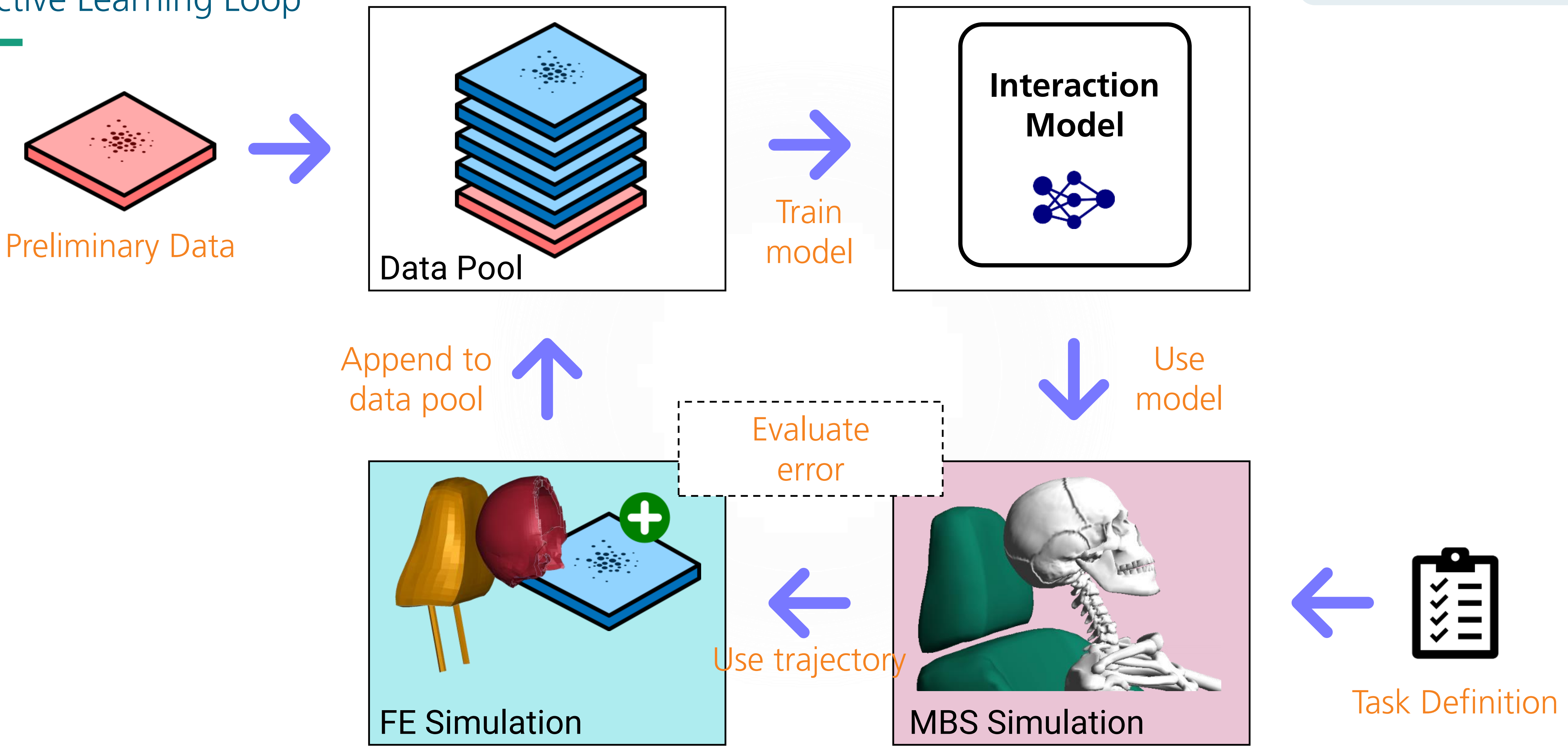
Contact Simulation (between head and headrest)

Active Learning Loop



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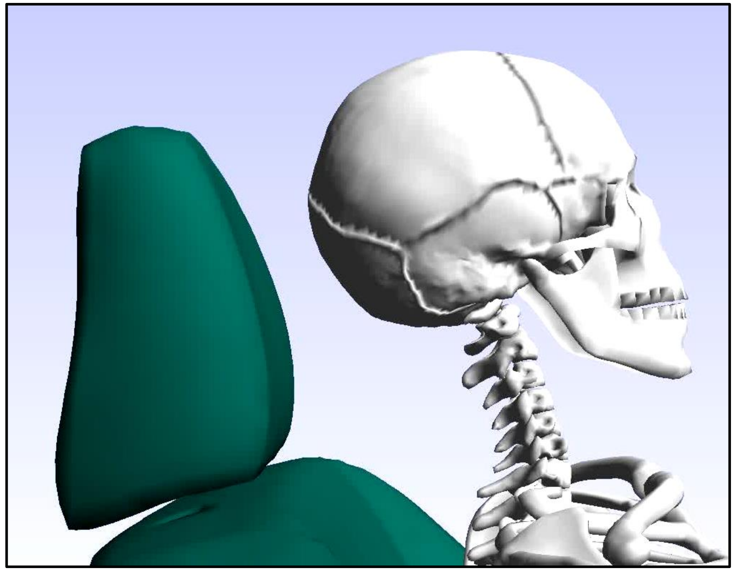
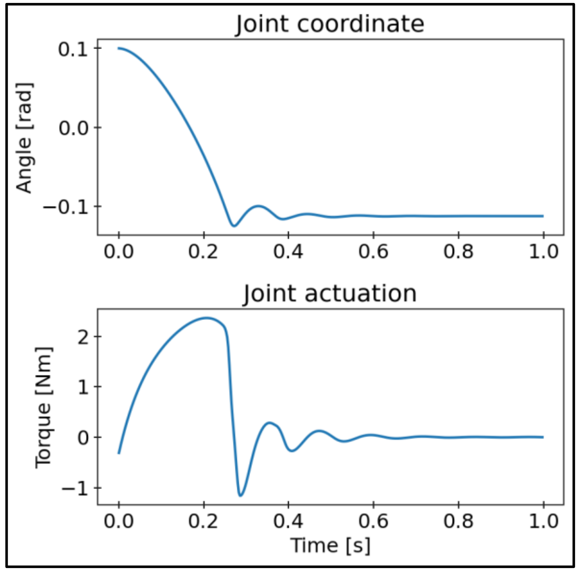
Contact Simulation (between head and headrest)

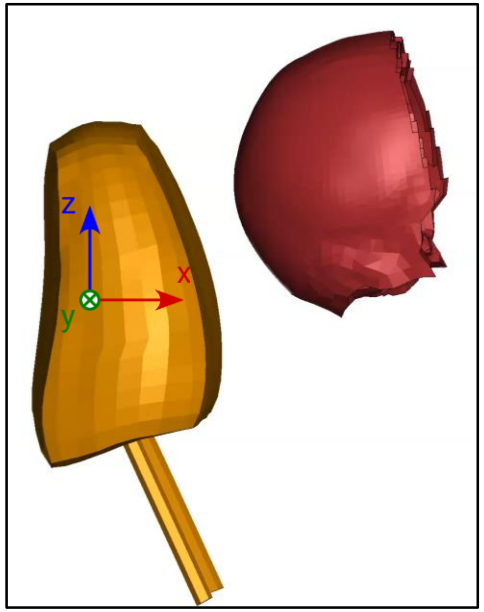
EMMA Simulation vs. FE Simulation

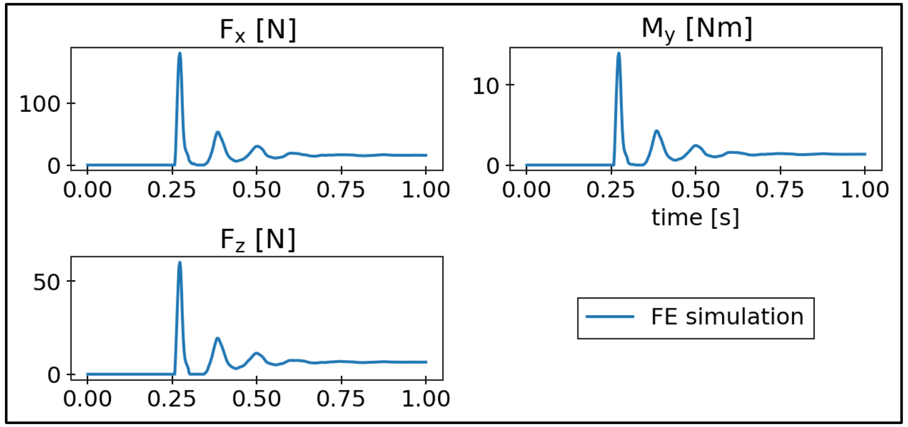
Niklas Fahse
University of Stuttgart

- Current contact model is applied in EMMA
- EMMA simulation is performed
- The model’s kinematics of the EMMA simulation is transferred to FE
- The contact forces of the FE simulation is evaluated and included in the training data









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Contact Simulation (between head and headrest)

EMMA Simulation vs. FE Simulation

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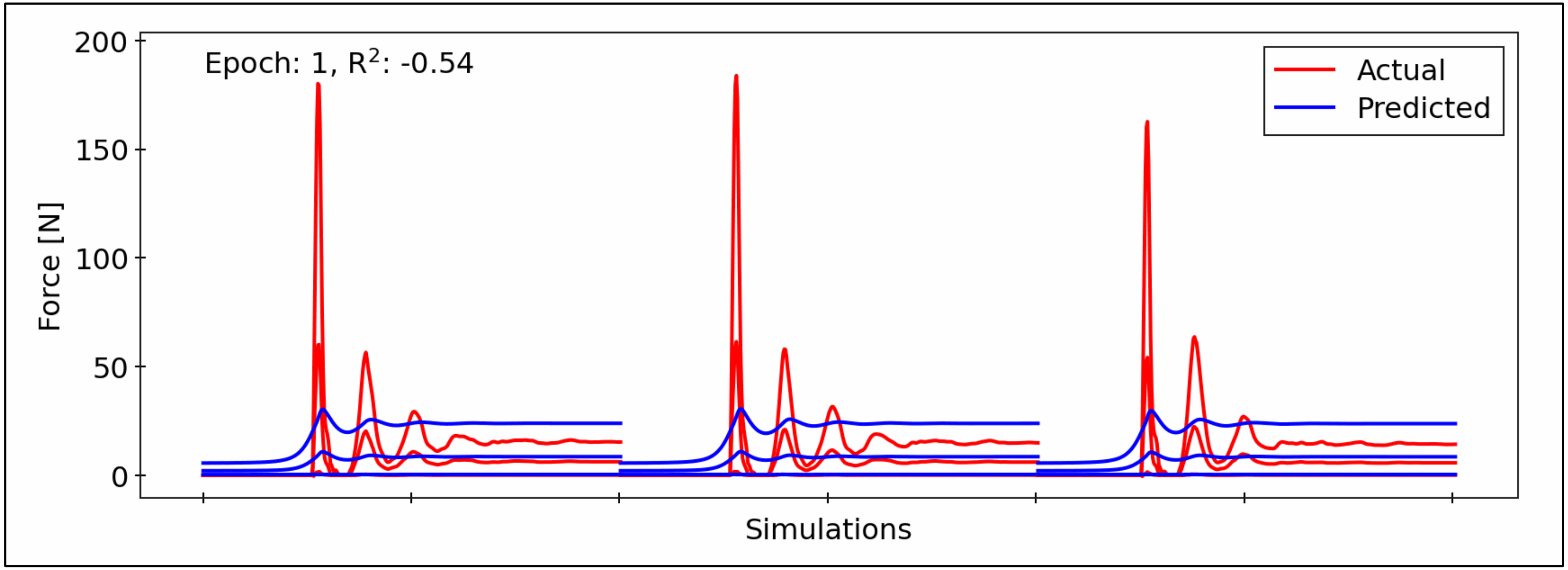
University of Stuttgart

- Train **MLP Regressor** to learn interaction forces/torques from relative kinematics
- Split data pool into 70% training and 30% test data
- Evaluate training on test data:



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Contact Simulation (between head and headrest)

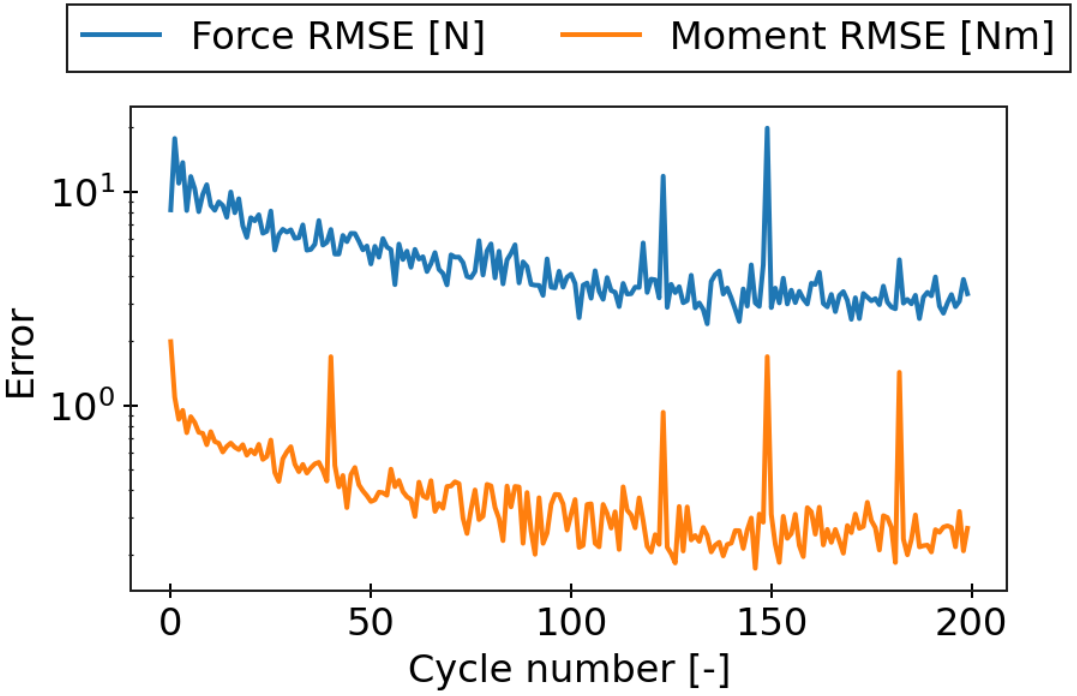
Convergence Evaluation and next steps

Niklas Fahse
University of Stuttgart

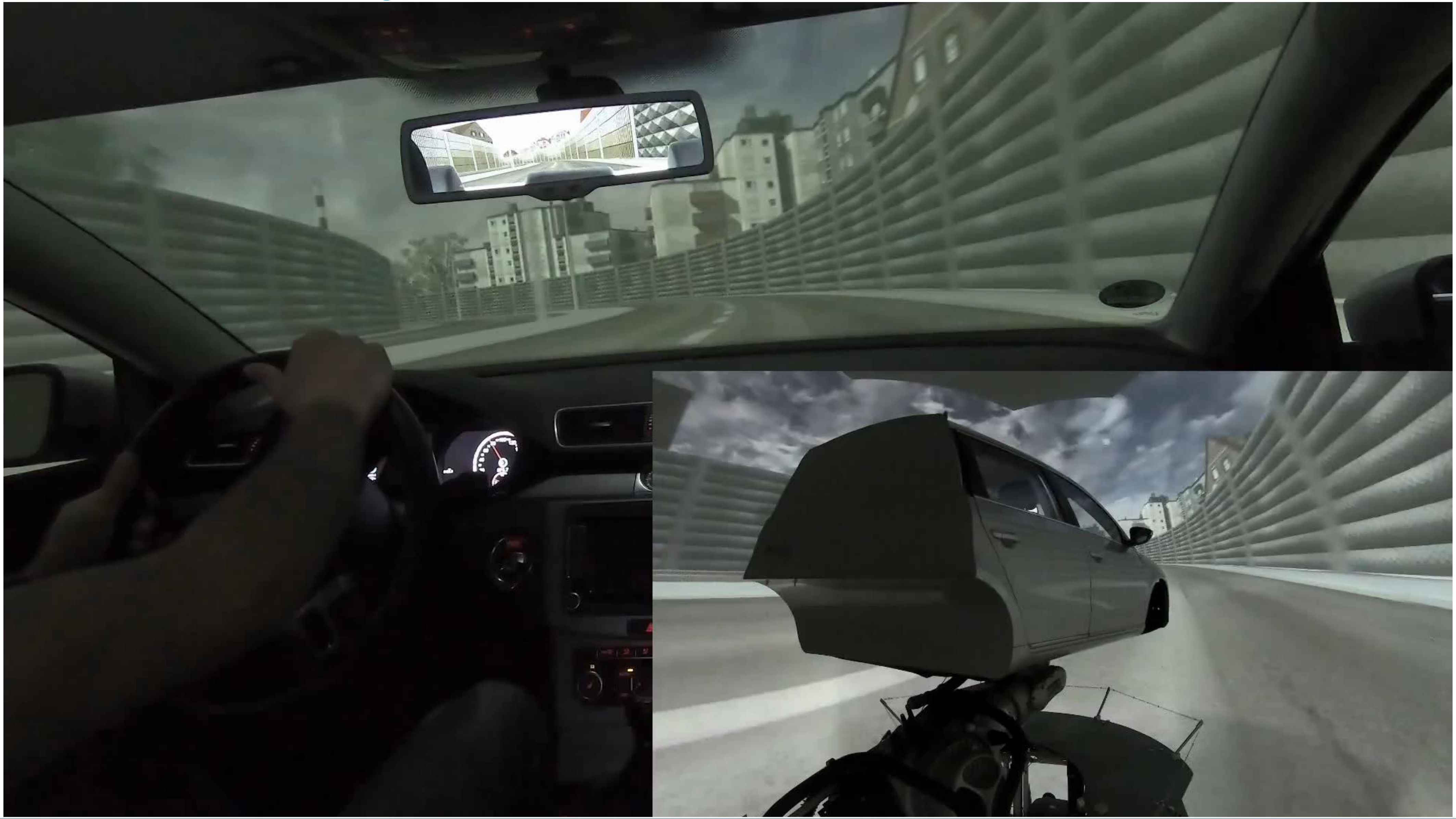
Compare contact forces/torques between the current contact model and FE simulations:

- Deviation of contact forces/torques is reduced
- Lower reduction in the forces than in the moment because of non-ideal preliminary data

- 200 cycles
- Calculation time on a standard laptop: ~6 days



The RODOS driving simulator @ ITWM

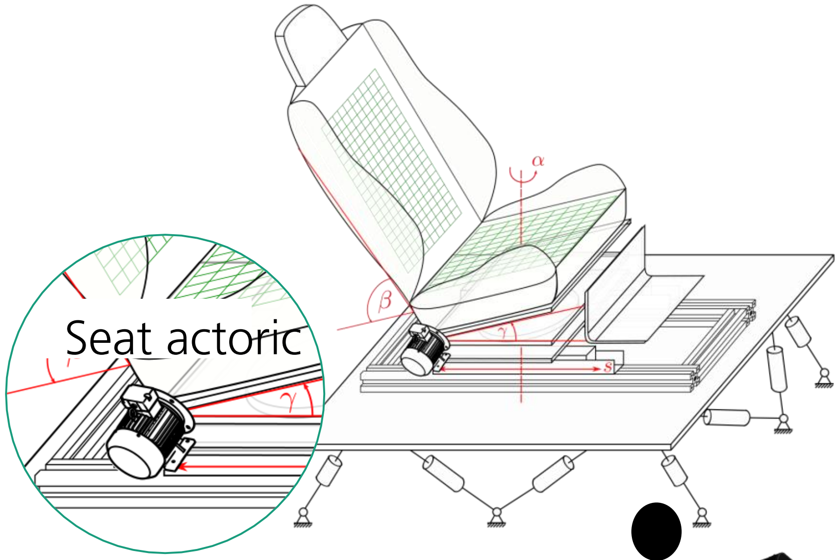


Experiments

for validation / additional data for Emma4Drive simulations

- Movement recordings during different driving maneuvers, positions and level of alertness of the driver
- Level of comfort, savety, and trust in the systems are rated by the subjects

- Robot based driving simulator RODOS (@ ITWM)



- Driver in the loop simulator/seat tilting device (ITM)

Transfer of RODOS maneuvers to EMMA

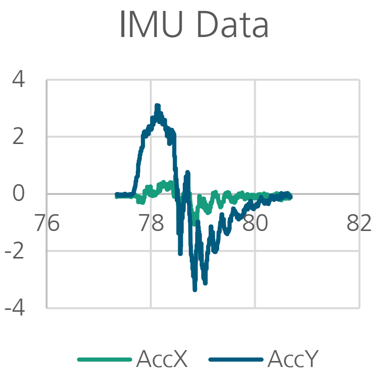
Overview

Goal:

- Transfer the movement of the cabin during Rodos experiments to EMMA
- Predict driver movements with EMMA
- Compare EMMA movements with those of the subjects

Method:

- Actuator was implemented that allows for a direct control of the accerleration of a body
- Read-In and including an LSQ term for the IMU-Data



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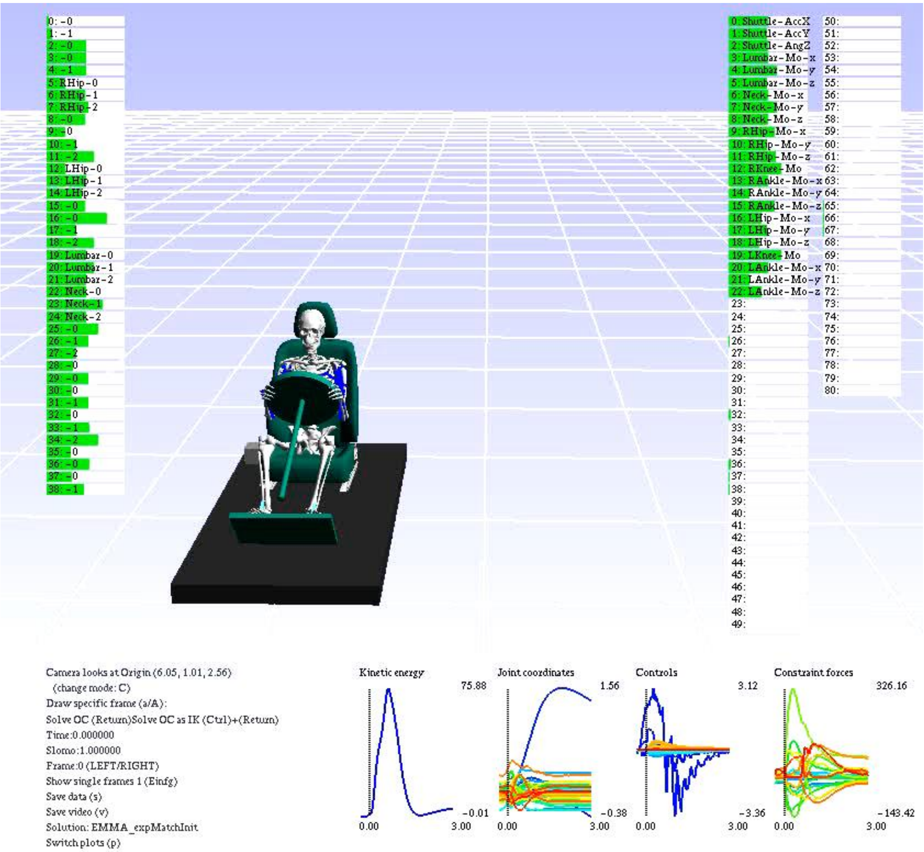
Transfer of RODOS maneuvers to EMMA

First Simulation results

Simulation:

- EMMA Manikin based on THUMS skeleton was placed in the seat
- 2-Phase approach:
  - 1. Phase: no change in manikin actuation was allowed during the response time
  - 2. Phase: Manikin reacts to the maneuver of the car



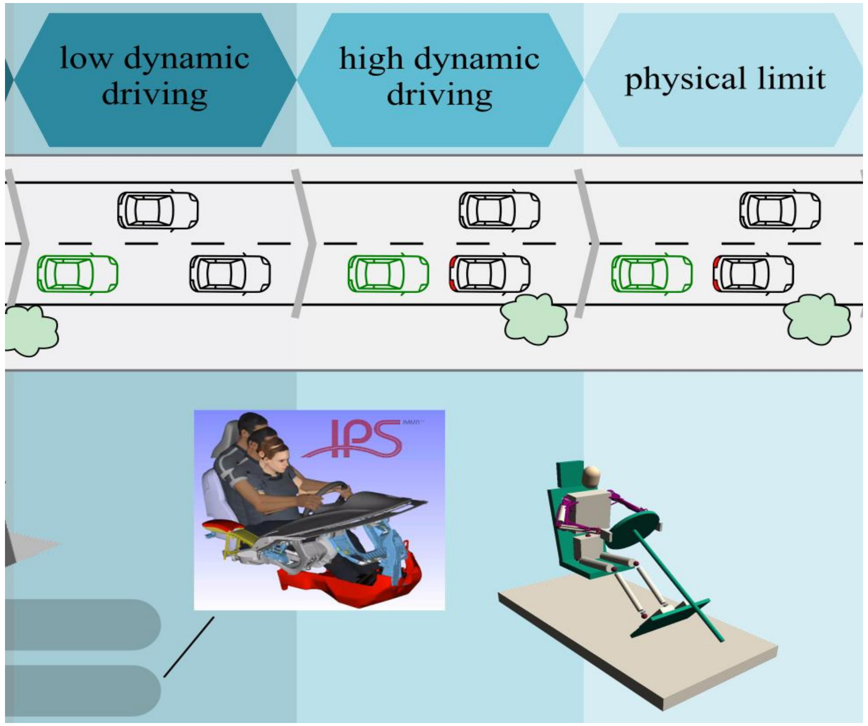
Next steps:

- Compare movement with video data
- Adjust objective function
- Test simulation with NMPC approach

EMMA4Drive – A dynamic human model supporting research and early phases in development for passenger safety concepts in autonomously driving vehicles

Goals of the EMMA4Drive project:

- Simulate realistic human motions of the "virtual driver", e.g. in such "passive to active" transitions, during dynamic driving situations
- Driver-seat interaction: Modeling and efficient computation
- Consider increasing variability of driving situations, postures and body sizes for ergonomic and safety-critical protection in automated vehicle concepts



Outcomes of the EMMA4Drive project:

- A box of software tools that support the development process of passenger safety concepts already in early phases …
- … and fill a gap in the current DHM landscape for applications in automotive engineering
- IPS Virtual Dynamic Driver: A new IPS software module for engineers in automotive industry

DFG Deutsche Forschungsgemeinschaft German Research Foundation
University of Stuttgart Institute of Engineering and Computational Mechanics (ITM)
fleX structures
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Thank you for your attention!

Fraunhofer ITWM