Multiphysics simulation and model-based system testing of automotive e-powertrains

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Doctoral thesis

Ferrol, December 17th, 2021

UNIVERSIDADE DA CORUÑA

Outline

1. Introduction
2. Development and assessment of real-time simulation software
3. State, parameter, and input estimation for digital twins in thermal systems
4. Co-simulation methods for real-time model-based system testing
5. Model-based test bench for electric motors
6. Conclusions and future work

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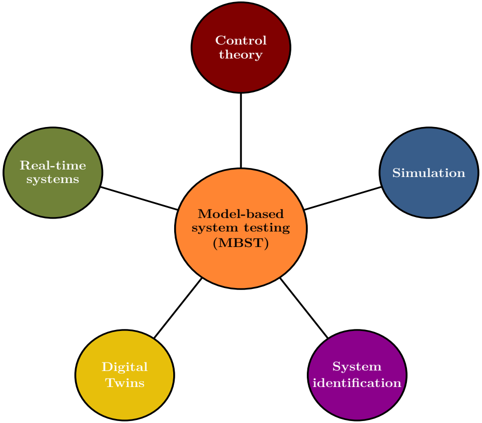
What does Model-Based System Testing stand for?

Model-Based System Testing (MBST)

MBST is a new validation paradigm that combines experimental testing and computer simulation

Model-Based System Testing - Required technologies



Addressed in this thesis

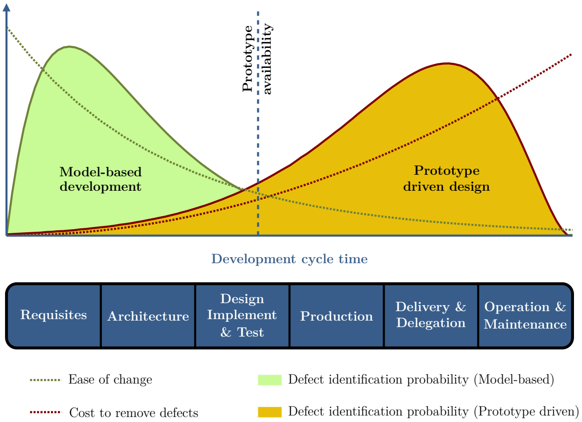
Ensure real-time performance in virtual systems

Advanced RT co-simulation methods and exchange protocols

Accurate parameter identification and virtual model validation

Obtain system information beyond experimental sensor readings

Model-Based System Testing - Advantages



Model-based system testing

- Combining testing and simulation to understand complex systems
- Early experimental validation and flaw detection
- Ease of change to remove development flaws from early stages
- Reduction of the cost to remove defects

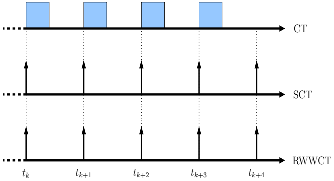
Objectives

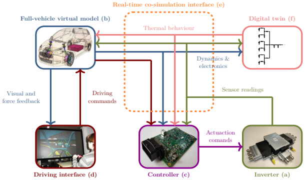
Contribute to the theoretical foundations of Model-Based System Testing

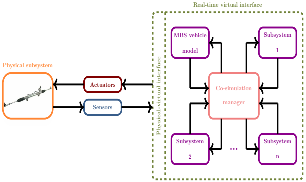
Benchmarking framework to test RT performance

RT-capable PISE algorithms based on the Kalman Filter

Co-simulation focused on stability and accuracy







Motivation

Motivation of this research

Temperature estimation for automotive electric motors (collaboration LIM - GKN)

Extend the knowledge about RT implementations, state observers, and co-simulation

Adapt team expertise to hybrid and electric vehicles

Outline

Numerical methods

System to solve: electric, electronic, and thermal circuits

$$\text{DAE}\left\{\boxed{\begin{aligned}\mathbf{\Phi}\left(\mathbf{x},t\right)=\mathbf{0} \qquad (1)\\ \mathbf{\Gamma}=\mathbf{A}\dot{\mathbf{x}}+\mathbf{b}=\mathbf{0} \qquad (2)\end{aligned}}\right. \begin{aligned}&\rightarrow \quad \text{algebraic}\\ &\rightarrow \quad \text{differential}\end{aligned}$$

Possible approaches

- Differentiating Eq. (1) → System of ODEs. *Issues:* constraint drift, singular system matrix ✗
- Integration of the system of DAEs described in Eqs. (1) and (2) ✓

Selected approach: DAE Solver

Dynamic equilibrium at t_{n+1}

$$\boxed{\mathbf{r}\left(\mathbf{x}_{n+1}\right)=\left[\begin{array}{c}\boldsymbol{\Phi}\\ \boldsymbol{\Gamma}\end{array}\right]_{n+1}=\mathbf{0} \qquad (3)}$$

Solving by means of Newton-Raphson iteration

$$\boxed{\left[\frac{\mathrm{d}\mathbf{r}\left(\mathbf{x}\right)}{\mathrm{d}\mathbf{x}}\right]^{i}\Delta\mathbf{x}^{i+1}=-\left[\mathbf{r}\left(\mathbf{x}\right)\right]^{i}\;; \qquad \textit{where} \qquad \mathbf{x}^{i+1}=\mathbf{x}^{i}+\Delta\mathbf{x}^{i+1} \qquad (4)}$$

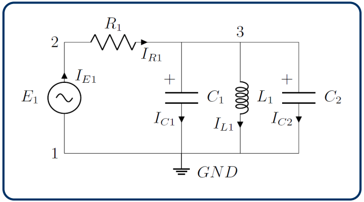
Integration formulas - Trapezoidal rule

- Dynamics equations formulated as DAEs, i.e., $\mathbf{r}\left(\mathbf{x}_{n+1}\right) = \mathbf{0}$
- Derivatives calculated as $\dot{\mathbf{x}}_{n+1} = \frac{2}{h}\left(\mathbf{x}_{n+1} - \mathbf{x}_n\right) - \dot{\mathbf{x}}_n$ ← Necessary $\dot{\mathbf{x}}_n$
- Issues:
  - Eq. (3) imposes $\boldsymbol{\Phi} = \mathbf{0}$, but not $\dot{\boldsymbol{\Phi}} = \boldsymbol{\Phi}_{\boldsymbol{x}}\dot{\mathbf{x}} + \boldsymbol{\Phi}_{\boldsymbol{t}} = \mathbf{0}$
  - Error accumulation due to a non-unique set of derivatives
  - Projection step advisable to fulfill $\dot{\boldsymbol{\Phi}} = \mathbf{0}$

Integration formulas - Backward differentiation formulas

- Dynamics equations formulated as DAEs as well
- Derivatives calculated as $\dot{\mathbf{x}}_{n+1} = -\frac{1}{h} \sum_{\tilde{\alpha}=0}^{\xi} \beta_{\tilde{\alpha}} \, \mathbf{x}_{n-\tilde{\alpha}+1}$ ← Not necessary $\dot{\mathbf{x}}_n$
- No error accumulation in derivatives
- Requirements:
  - Access to ξ already computed states

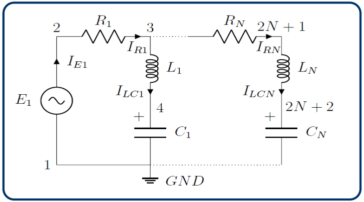
Proposed benchmarks

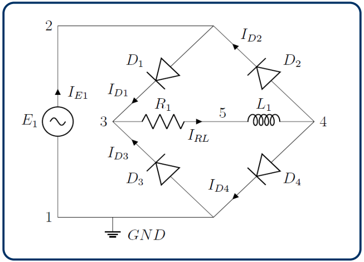


RLC

← Linear →

Scalable RLC

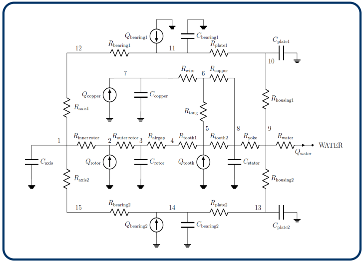




Rectifier

← Nonlinear →

PMSM



Simulation environments

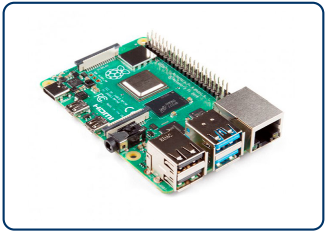
64-bit Intel x86 CPU

Desktop PC

OS: Windows 10 2019 H2

64-bit ARM CPU

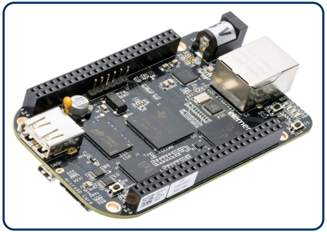
Raspberry Pi 4



OS: Raspbian 4.19.57

32-bit ARM CPU

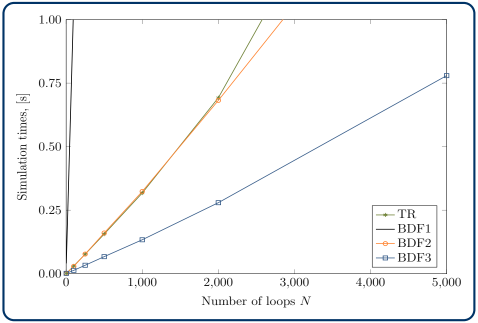
BeagleBone Black



OS: Debian 9.9 IoT

Scalable RLC circuit: Real-time boundaries

Low precision scenario

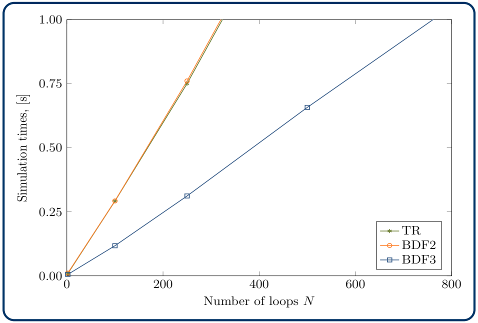


Errors: $V_{2N+2} < 1\ mV$ and $I_{LCN} < 1\ mA$

Simulation length: 1s

$h_{TR} = h_{BDF3} = 2.5\text{ms},\ h_{BDF2} = 1\text{ms}$

High precision scenario



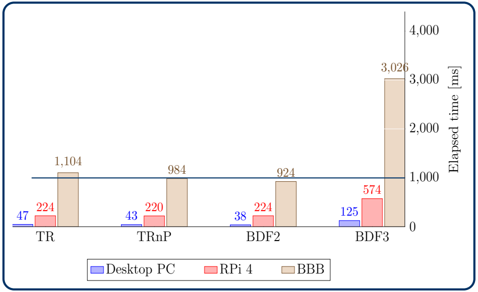
Errors: $V_{2N+2} < 10\ \mu V$ and $I_{LCN} < 10\ \mu A$

Simulation length: 1s

$h_{TR} = h_{BDF3} = 0.25\text{ms},\ h_{BDF2} = 0.1\text{ms}$

Rectifier: Efficiency assessment

Low precision scenario

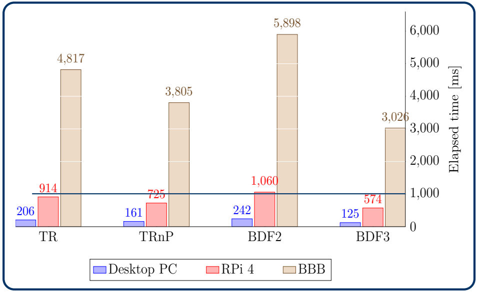


Errors: $\Delta V_{2-3} < 1\ mV$ and $I_{RL} < 1\ mA$

Simulation length: 1s

$h_{TR} = 0.5$ms, $h_{BDF2} = 0.25$ms, $h_{BDF3} = 0.1$ms

High precision scenario



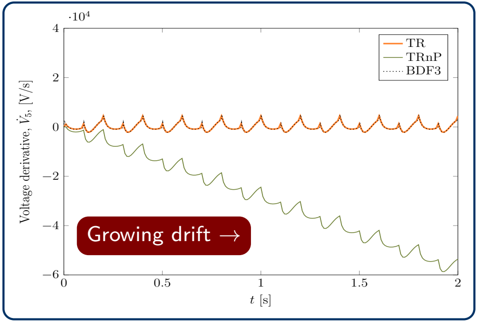
Errors: $\Delta V_{2-3} < 10\ \mu V$ and $I_{RL} < 10\ \mu A$

Simulation length: 1s

$h_{TR} = h_{BDF2} = 50\mu s$, $h_{BDF3} = 100\mu s$

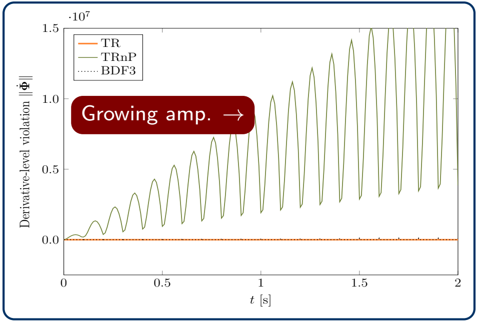
Rectifier: Trapezoidal rule issues in derivatives

Evaluation of $\dot{V}_5$



Growing drift →

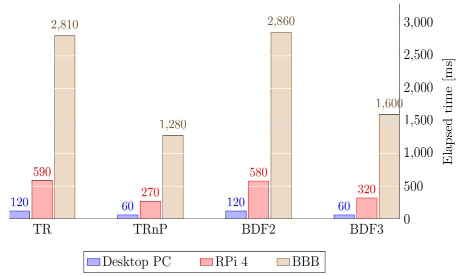
Overall error in $\dot{\mathbf{\Phi}}$



Growing amp. →

PMSM: Efficiency assessment

Low precision scenario

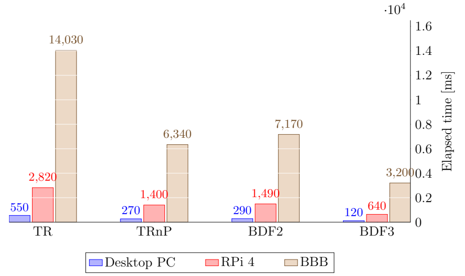


Errors: $T < 0.1\ K$ and $Q_{RL} < 1\ W$

Simulation length: 5000s

$h_{TR} = h_{BDF3} =$ 500ms, $h_{BDF2} =$ 250ms

High precision scenario



Errors: $T < 10\ mK$ and $Q_{RL} < 100\ mW$

Simulation length: 5000s

$h_{TR} = h_{BDF2} =$ 100ms, $h_{BDF3} =$ 250ms

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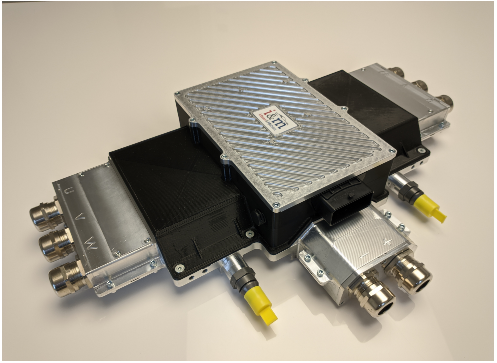
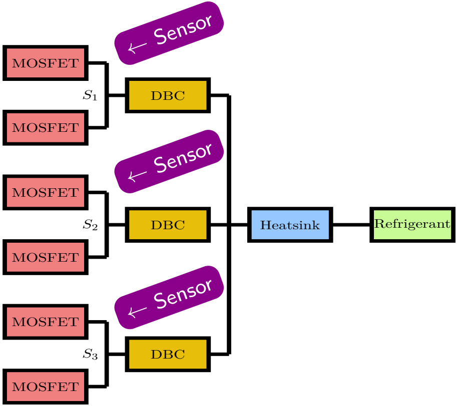
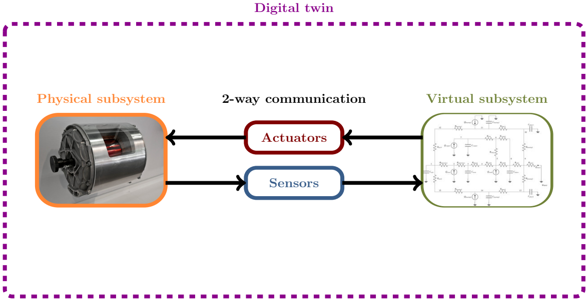
Why is a state estimator necessary?





Goal: monitoring temperature in the MOSFET junctions

Concept of digital twin



Digital twin

Physical subsystem

2-way communication

Virtual subsystem

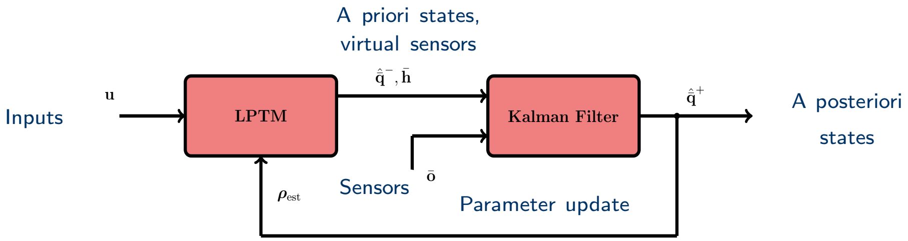
Actuators

Sensors

Basics of a digital twin

- A real component instrumented with sensors and actuators
- A virtual model of the real system as realistic and updatable as possible
- Two-way communication between real and virtual subsystems
- Guarantee real-time performance and communication within the DT

Basics of an Extended Kalman Filter



A priori states,
virtual sensors

$\hat{\bar{\mathbf{q}}}^-, \bar{\mathbf{h}}$

Inputs

$\mathbf{u}$

LPTM

Kalman Filter

$\hat{\bar{\mathbf{q}}}^+$

A posteriori states

Sensors

$\bar{\mathbf{o}}$

$\boldsymbol{\rho}_{\text{est}}$

Parameter update

Step 1

System definition

$$\boldsymbol{\Phi}(\mathbf{x}, \mathbf{v}, t) = \mathbf{0}$$
$$\boldsymbol{\Gamma}(\mathbf{x}, \dot{\mathbf{x}}) = \mathbf{0}$$

Step 2

Reduction to minimal variables

$$\mathbf{z} = \mathbf{B}_0\mathbf{x}$$
$$\mathbf{x} = \mathbf{T}\mathbf{z} + \mathbf{B}\mathbf{v}$$

Step 3

State-space representation

$$\mathbf{z}_{k+1} = \mathbf{F}_k\mathbf{z}_k + \mathbf{G}_k\mathbf{v}_k$$

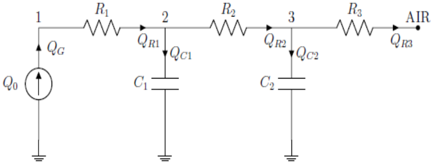
Step 4

Application of state-estimator equations

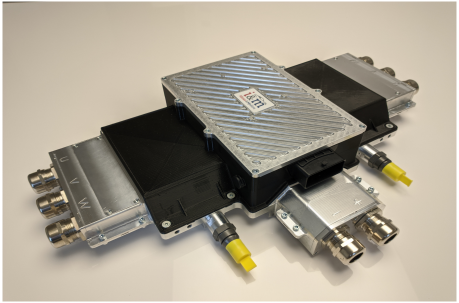
Proposed problems

Generic RC LPTM

Not intended to describe a real system



3-phase inverter



Simulation environments

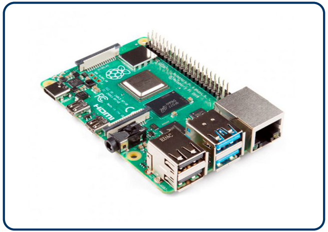
64-bit Intel x86 CPU

Laptop PC

OS: Kubuntu 20.10

64-bit ARM CPU

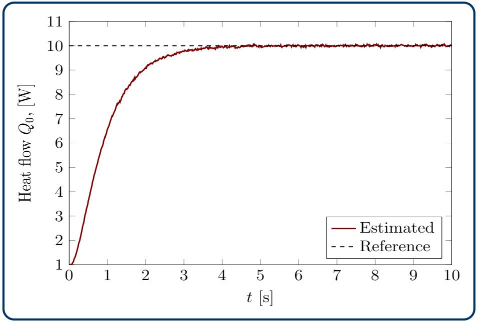
Raspberry Pi 4



OS: Raspbian 5.4.83

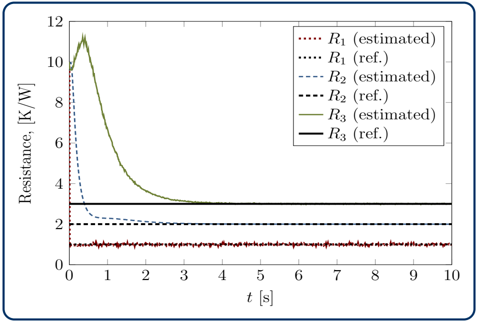
Generic RC LPTM: Input and resistor estimation

Input source estimation



Sensors: Node 3

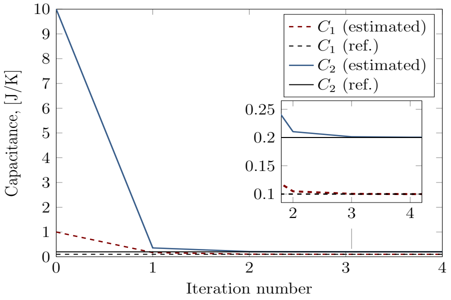
Resistor estimation



Sensors: Nodes 1, 2, and 3

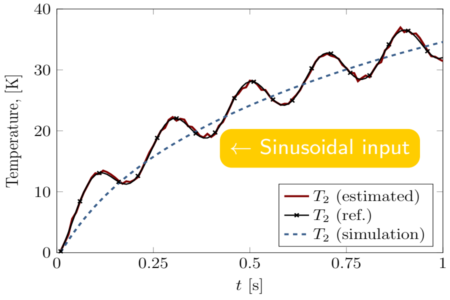
Generic RC LPTM: Capacitor and state estimation

Capacitor estimation



Sensors: Nodes 2 and 3

State estimation

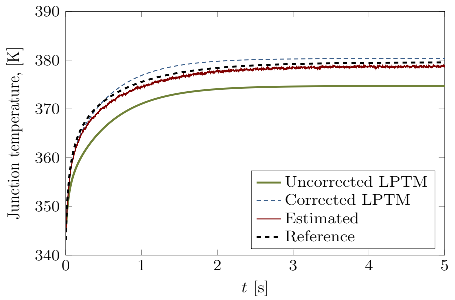


← Sinusoidal input

Sensors: Nodes 2 and 3

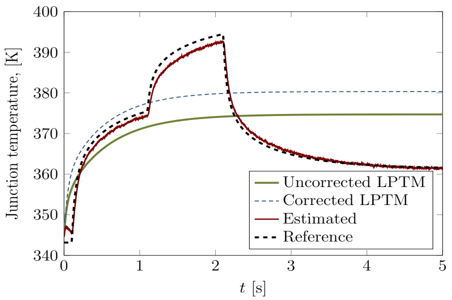
3-phase inverter: Junction temperature estimation

Constant input



Sensors: 3 units at DBC

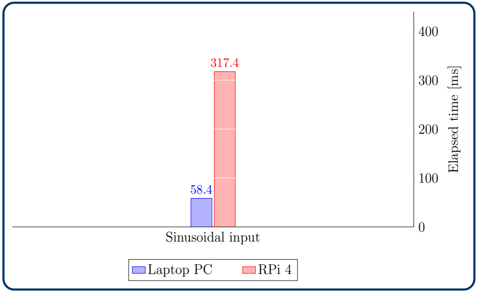
Step input



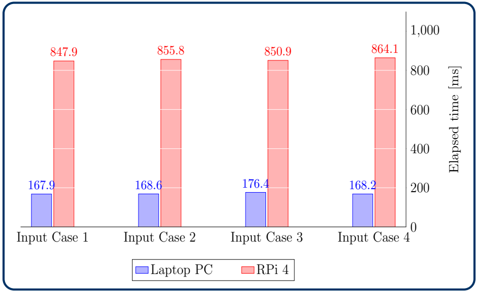
Sensors: 3 units at DBC

State estimation: Efficiency assessment

Generic RC LPTM



3-phase inverter



Simulation length: 5s, stepsize h: 1ms

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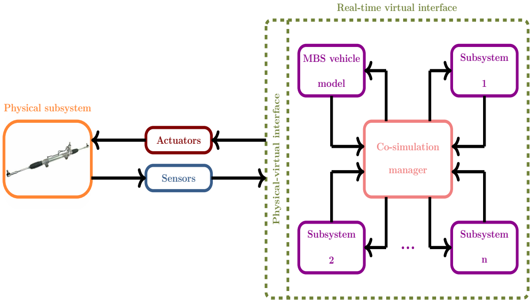
Connecting components in MBST environments

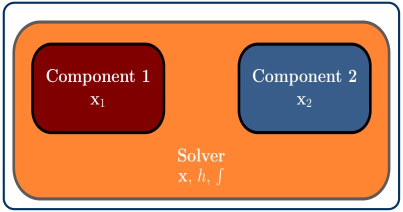


Main issues

- Need to synchronize execution
- Use of tailored algorithms for each subsystem
- Guarantee communication between continuous and discrete subsystems

Monolithic vs co-simulation

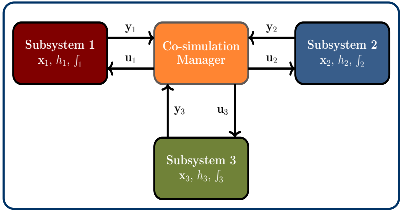
Monolithic



Single solver for all components

All-encompassing set of equations

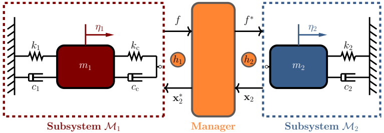
Co-simulation



Tailored solvers

Need to synchronize integrations

Co-simulation configuration options



Time-grids

- **Matching**
- Nonmatching

Coupling variables

- Force-displacement
- Displacement - displ. ...

Co-simulation schemes

- Jacobi
- Gauss-Seidel ...

Input extrapolation

- Zero-order hold
- First-order hold ...

Step-sizes

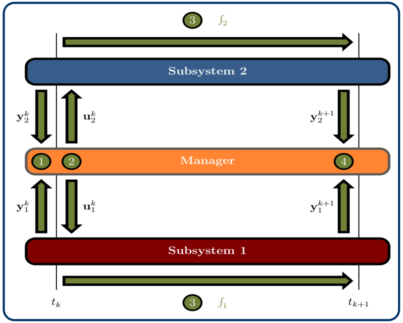
- Single-rate
- Multi-rate

Integrators

- Implicit
- **Explicit**

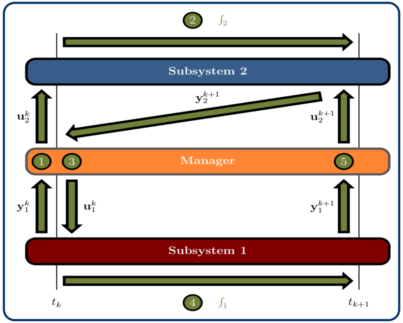
Explicit coupling schemes for real-time applications

Jacobi



Parallelizable integration

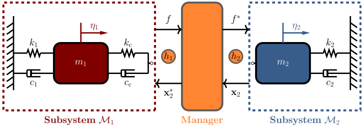
Gauss-Seidel



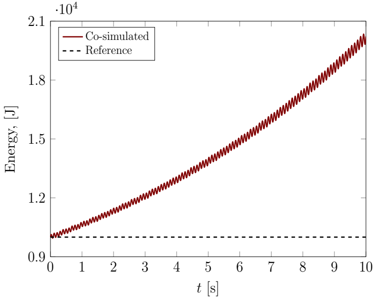
Sequential integration

Real-time explicit co-simulation with constant timesteps

Example to co-simulate



Mechanical energy

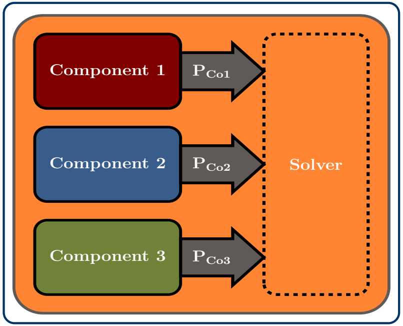


Selected setup: Matching grids, single-rate, explicit Jacobi, force-displacement

Time-discrete interface introduces discontinuities into the system, affecting its energy

Co-simulation quality assessment

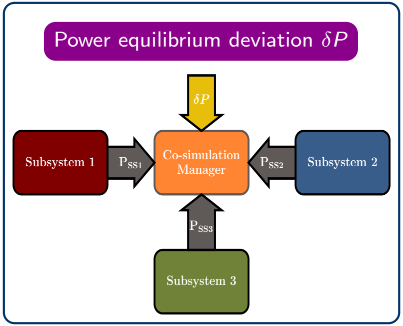
Monolithic



Power error caused by the solver

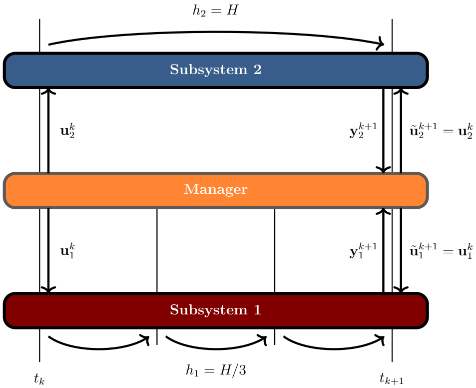
No interface error

Co-simulation



Power error caused by the interface, but also by the solvers

Power residual



Stands for the error in the power balance of a system as

$$\begin{aligned}\delta P^{k+1} &= -\left(\mathbf{u}^{k+1}\right)^T \mathbf{y}^{k+1} \\ &\approx -\left(\tilde{\mathbf{u}}^{k+1}\right)^T \mathbf{y}^{k+1} \neq 0 \qquad (5)\end{aligned}$$

- Theoretically, δP should be zero
- In co-simulation, outputs evaluated before receiving inputs: δP no longer zero

Energy residual

Energy residual

Integral of the residual power

$$\delta E = \int_{t_0}^{t} \delta P\left(t\right)\, \mathrm{d}t \qquad (6)$$

Errors in energy

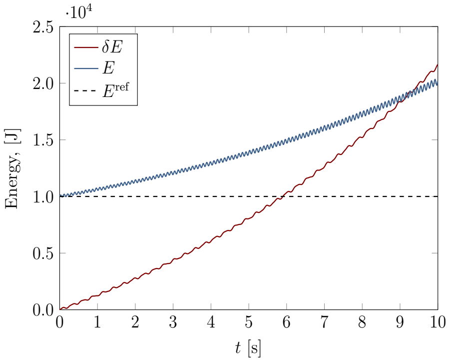
Actual energy deviation

$$E\left(t\right) - E_0 - W_{nc}\left(t\right) = \varsigma\left(t\right) \qquad (7)$$

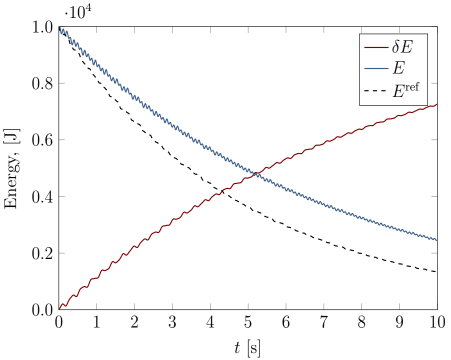
- $\varsigma\left(t\right) = \mu\, \delta E\left(t\right)$
- Increase of mechanical energy for conservative systems
- Deviation from energy balance in nonconservative ones

Residual power as indicator of co-simulation quality

Undamped linear oscillator



Damped linear oscillator



Co-simulation energy correction

$$\mathcal{B}_{corr}^{k+1} = \mu \frac{-\delta E^{k+1}}{\mathcal{A}^{k+1}\ H} - k_{\mathrm{i}} \frac{\mathcal{E}^{k+1}}{\mathcal{A}^{k+1}\ H} \tag{8}$$

$$\mathcal{E}^{k+1} = \mathcal{E}^{k} + \mu\delta E^{k+1} + \mathcal{B}_{corr}^{k+1}\mathcal{A}^{k+2}H \tag{9}$$

Limitations:

Nonzero speed $\mathcal{A} \neq \mathbf{0}$

Applied in opposite direction of $\mathcal{A}$

Energy correction method

$\mathcal{A}$ usually position or speed, whereas $\mathcal{B}$ often force, μ and k_{i}, corrective coefficients

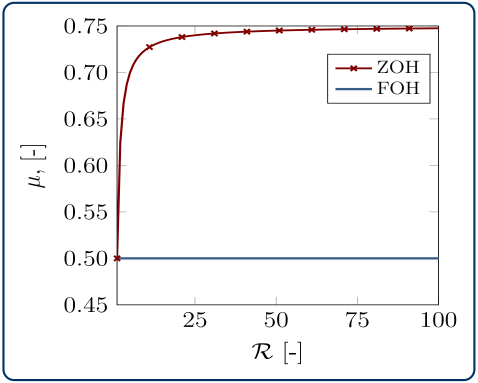
$\mu\delta E^{k+1}$ energy intended to correct, however, $\mathcal{B}_{corr}^{k+1}\mathcal{A}^{k+2}H$ is finally corrected

$\mathcal{B}_{corr}$ is assumed constant, but $\mathcal{A}$ usually varies between two macrosteps

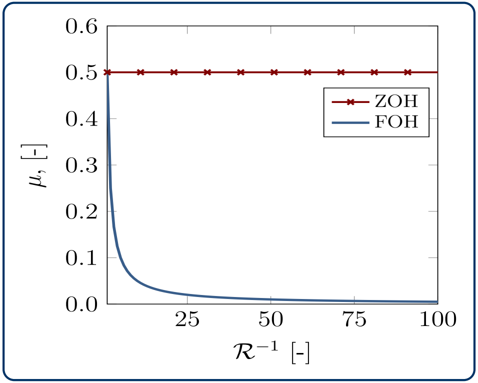
Correction depends on $\mathcal{R}$, extrapolation order, and direct feedthrough

Selection of the correction coefficient μ

Largest step → direct feedthrough

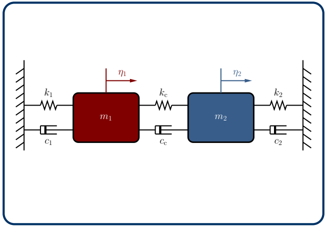


Smallest step → direct feedthrough



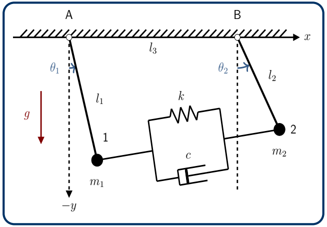
Proposed benchmarks

Double oscillator



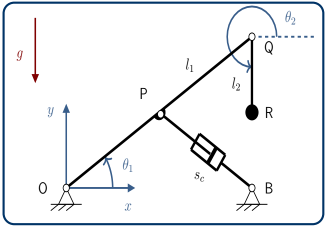
Linear and nonlinear

Coupled pendula



Nonlinear

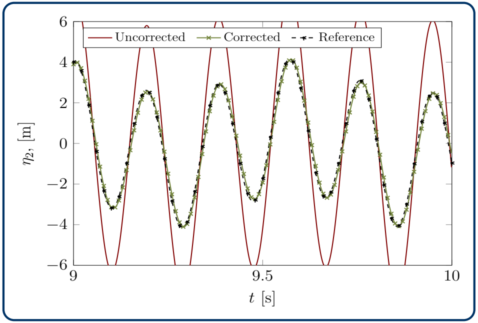
Hydraulic crane



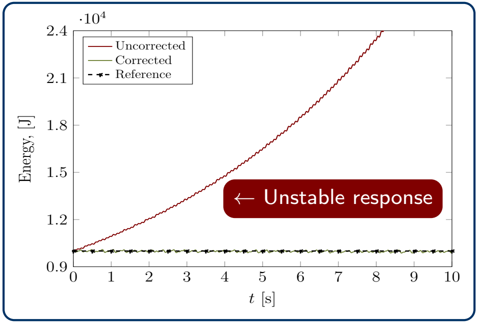
Multiphysics and nonlinear

Linear oscillator: errors and correction

Mass 2 displacement



Mechanical energy

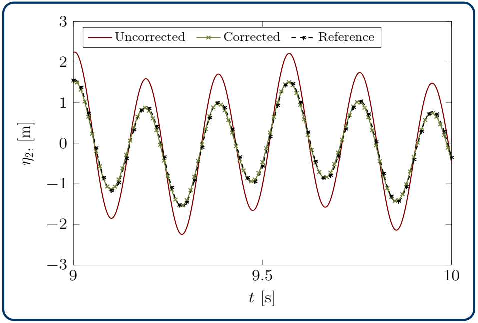


← Unstable response

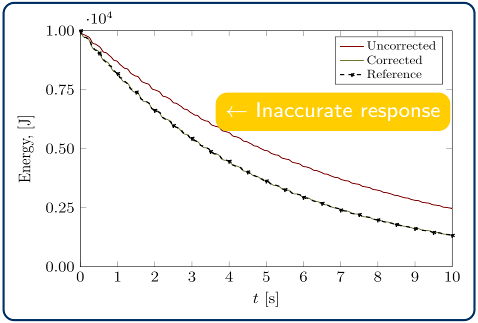
Undamped, Multi-rate: $H = h_{\mathcal{M}_1} = 1\text{ms}$, $h_{\mathcal{M}_2} = 0.1\text{ms}$, ZOH, $\mu = 0.725$, $k_i = 0$

Linear oscillator: errors and correction

Mass 2 displacement



Mechanical energy

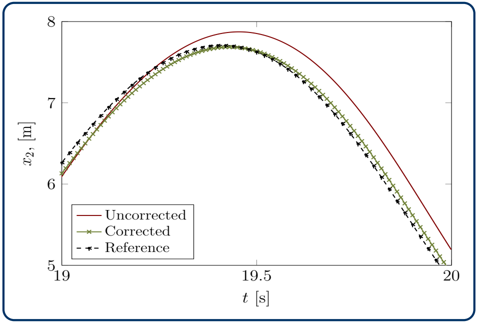


← Inaccurate response

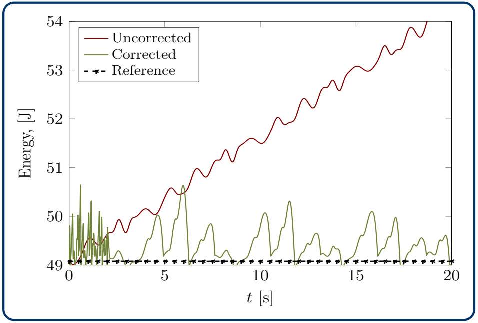
Damped, Multi-rate: $H = h_{\mathcal{M}_1} = 1\text{ms}$, $h_{\mathcal{M}_2} = 0.1\text{ms}$, FOH, $\mu = 0.5$, $k_i = 0$

Coupled pendula: errors and correction

Mass 2 horizontal displacement



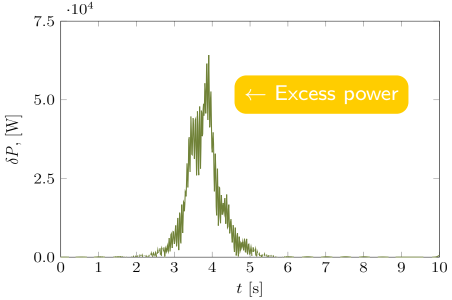
Mechanical energy



Single-rate: $H = h_{\mathcal{M}_1} = h_{\mathcal{M}_2} = 1\text{ms}$, $\mu = 0.5$, $k_i = 1.0$

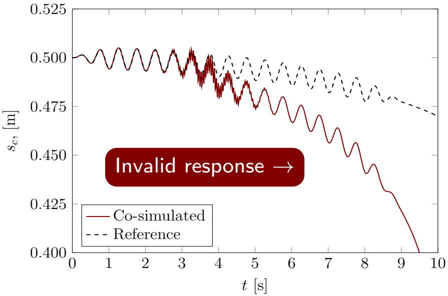
Hydraulic crane: errors

Residual power



← Excess power

Actuator displacement



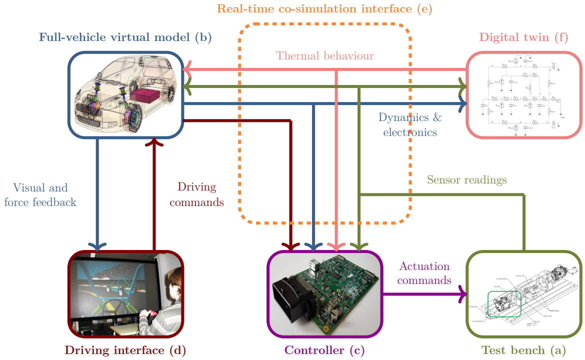
Invalid response →

$H = h_{\mathcal{M}} = 11.5$ms and $h_{\mathcal{H}} = 0.1$ms, FOH, incorrect dynamics

Outline

1. Introduction
2. Development and assessment of real-time simulation software
3. State, parameter, and input estimation for digital twins in thermal systems
4. Co-simulation methods for real-time model-based system testing
5. Model-based test bench for electric motors
6. Conclusions and future work

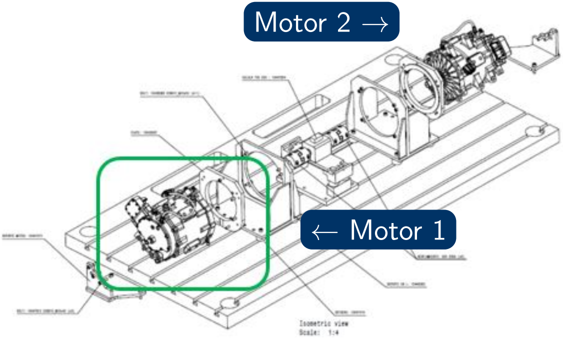
Cyber-physical test benches



Prototype test bench

- Real components are interfaced to simulations
- Systematic and repeatable gathering of experimental data
- Easy and safe to reproduce dangerous manoeuvres
- Prototype-driven testing strategies do not often allow this flexibility

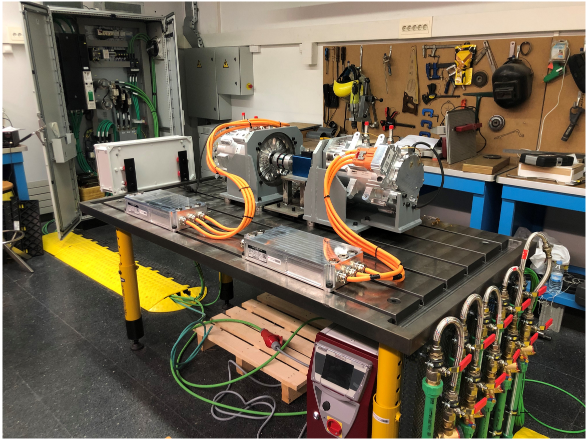
Application: testing e-powertrain components



Why using cyber-physical tests?

- Gain insight into component behaviour and mutual interaction
- Enhance virtual models of the components
- Verify the effect of new materials and designs
- Enable early tests when full-vehicle prototypes are not available yet

Test bench for automotive-grade e-motors



Automotive test bench

MBST evaluation of automotive-grade electric motors

Currently under construction

Back-to-back configuration

Two three-phase PMSMs of up to 200 kW, 15,000 rpm, and 400 Nm

Prototype test bench

Prototype test bench

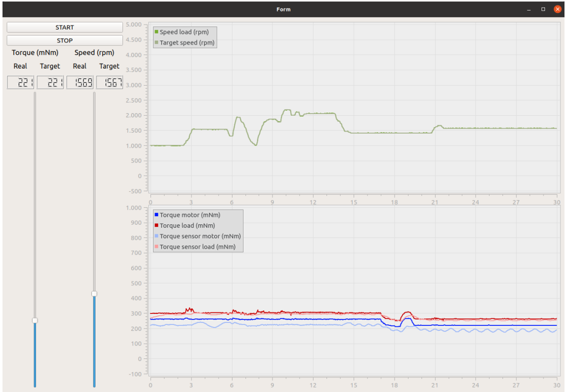
Cyber-physical testing device

Two low-power BLDCs in a back-to-back configuration

First motor is under test

Second motor applies the load calculated in the simulation

Prototype test bench - Results



Prototype test bench

Torque-speed in motors are updated by a simulation or sliders

Currently evaluating errors due to the co-simulation scheme

Intended to be demonstrator of algorithms developed in this research

Outline

Conclusions

Real-time models

Multiphysics models contribute to a better understanding of the interactions between components

Models are required to interact in RT within MBST environments

A multiplatform framework is necessary to evaluate RT performance

PIS estimation

DT is of help in MBST, consisting of physical and virtual systems, and their mutual communication

PISE techniques based on Kalman Filters can be incorporated to the digital twin

Possibility to estimate magnitudes that cannot be measured by sensors

Conclusions

Co-simulation

RT co-simulation allows to integrate separately real and virtual components in MBST

Co-simulation may introduce artificial energy or damping into the system

Important to identify co-simulation errors and eliminate them, before the numerical integration becomes unstable or inaccurate

Cyber-physical test benches

MBST application, in which some real components are interfaced to a computer simulation

The objective is to ensure the reliability in cyber-physical applications

Future work

Real-time models

Model-order reduction for single-board computers

PIS estimation

Sensitivity analysis for the LPTM initial tuning

Co-simulation

Generalization of error monitoring and correction algorithms

Cyber-physical test benches

Gain insight into e-powertrains through test campaigns and validation

Works derived from this thesis

Published journal papers

- B. Rodríguez, F. González, M. Á. Naya, and J. Cuadrado. Assessment of Methods for the Real-Time Simulation of Electronic and Thermal Circuits. *Energies* (2020). DOI: 10.3390/en13061354.
- B. Rodríguez, E. Sanjurjo, M. Tranchero, C. Romano, and F. González. Thermal Parameter and State Estimation for Digital Twins of e-Powertrain Components. *IEEE Access* (2021). DOI: 10.1109/ACCESS.2021.3094312.

Submitted journal papers (under review)

- B. Rodríguez, A. J. Rodríguez, B. Sputh, R. Pastorino, M. Á. Naya, and F. González. Energy-based Monitoring and Correction to Enhance Accuracy and Stability of Explicit Co-simulation Schemes. *Multibody System Dynamics - Special Issue on Co-simulation*.

Journal papers in preparation

- I.Tamellin, B. Rodríguez, D. Richiedei, and F. González. Eigenstructure of Explicit Co-simulation Problems.

Conference communications

- **Conference communications**
  - B. Rodríguez, F. González, M. Á. Naya, and J. Cuadrado. A Test Framework for the Co-simulation of Electric Powertrains and Vehicle Dynamics. In *9th ECCOMAS Thematic Conference on Multibody Dynamics*, Duisburg, Germany, July 2019.
  - B. Rodríguez, A. Zar, F. González, M. Á. Naya and J. Cuadrado. Use of Energy Indicators in the Explicit Co-simulation of Multibody Systems. In *Proceedings of the ASME 2020 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Saint Louis, USA, August 2020.
  - B. Rodríguez, A. Zar, B. Sputh, M. Á. Naya, F. González and R. Pastorino. Evaluation of Indicators for the Accuracy and Stability of Explicit Co-simulation Schemes. In *COSIM 2021 - International Symposium on Co-Simulation and Solver Coupling in Dynamics*, Ferrol, Spain, May 2021.
  - B. Rodríguez, A. J. Rodríguez, D. Maceira, E. Sanjurjo, U. Lugrís, M. Á. Naya, F. González and J. Cuadrado. Cyber-Physical Test Benches for Model-Based System Testing of Electric Motors. In *1st International Conference on Machine Design*, Porto, Portugal, September 2021.

Conference communications

- **Conference communications (cont.)**
  - B. Rodríguez, A. J. Rodríguez, D. Maceira, F. Bottero, E. Sanjurjo, U. Lugrís, M. Á. Naya, F. González and J. Cuadrado. Development of a Cyber-Physical Test Bench for E-Powertrain Components. In *10th ECCOMAS Multibody Conference 2021*, Budapest, Hungary, December 2021.
  - G. Boschetti, F. González, G. Piva, D. Richiedei, B. Rodríguez and A. Trevisani. Synthesis of an Extended Kalman Filter for Cable-Driven Parallel Robots. In *10th ECCOMAS Multibody Conference 2021*, Budapest, Hungary, December 2021.
- **Submitted conference communications**
  - B. Rodríguez, A. Zar, F. González, M. Á. Naya and J. Cuadrado. Monitoring Energy Errors in Explicit Co-Simulation Setups. In *6th Joint International Conference on Multibody System Dynamics and 10th Asian Conference on Multibody System Dynamics*, New Delhi, India, October 2022.

Multiphysics simulation and model-based system testing of automotive e-powertrains

Thank you for your attention!

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