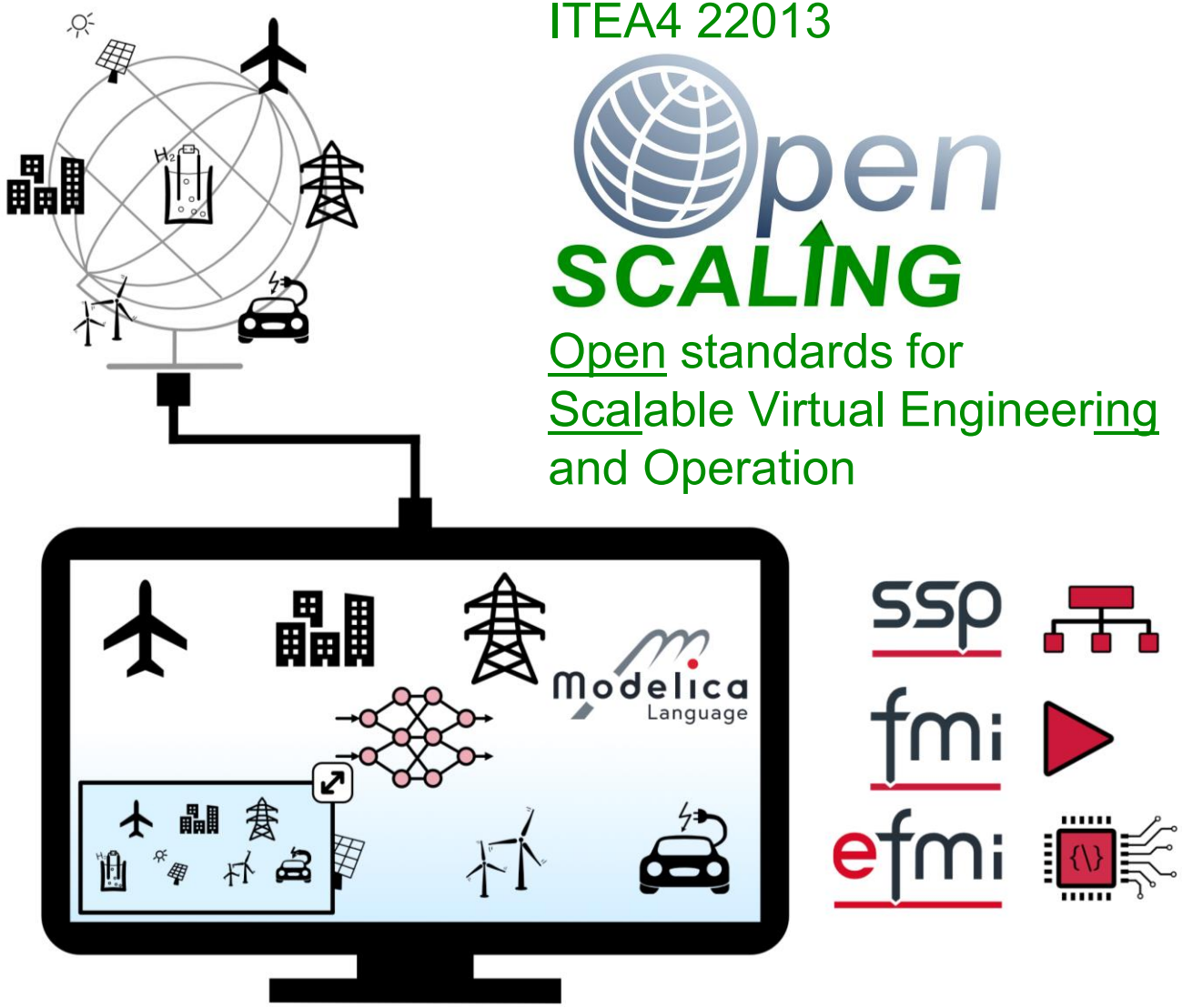
Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System

Tobias Thummerer, Fabian Jarmolowitz,
Daniel Sommer, Lars Mikelsons

The 16th International
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Agenda

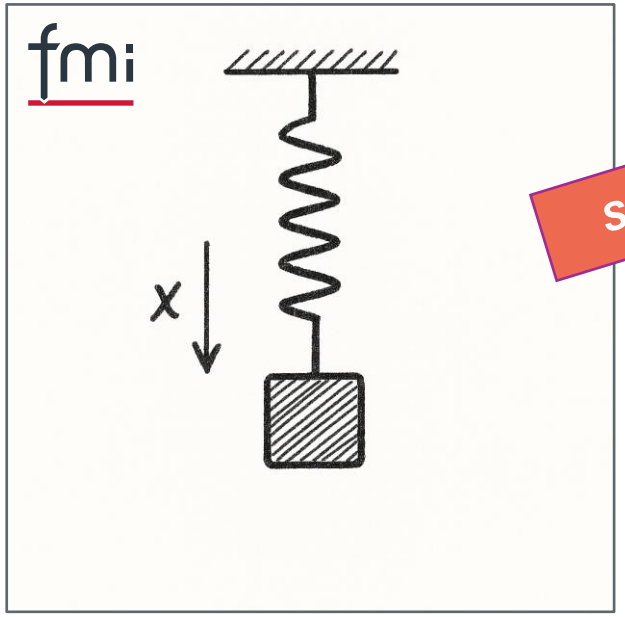
1. Motivation & Introduction
2. Building the Hybrid Model
3. Results
4. Conclusion & Future Work

1

MOTIVATION & INTRODUCTION

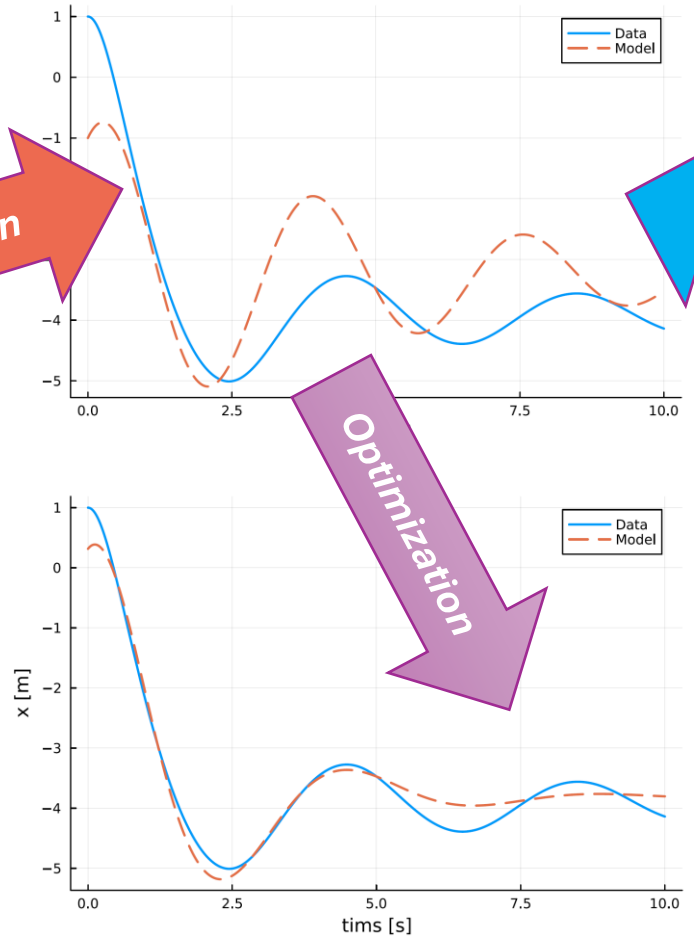
1. Motivation & Introduction

Model calibration with FMI



Translational Pendulum
(Model)

Simulation



Optimization

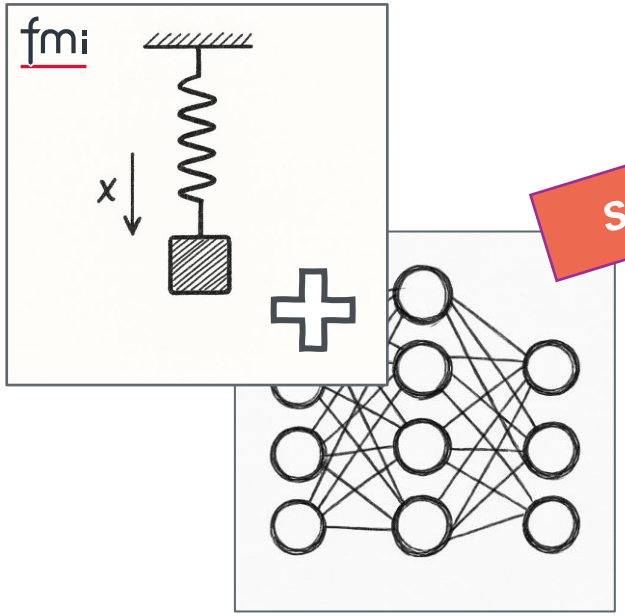
Measurement



Translational Pendulum
(Real-World System)

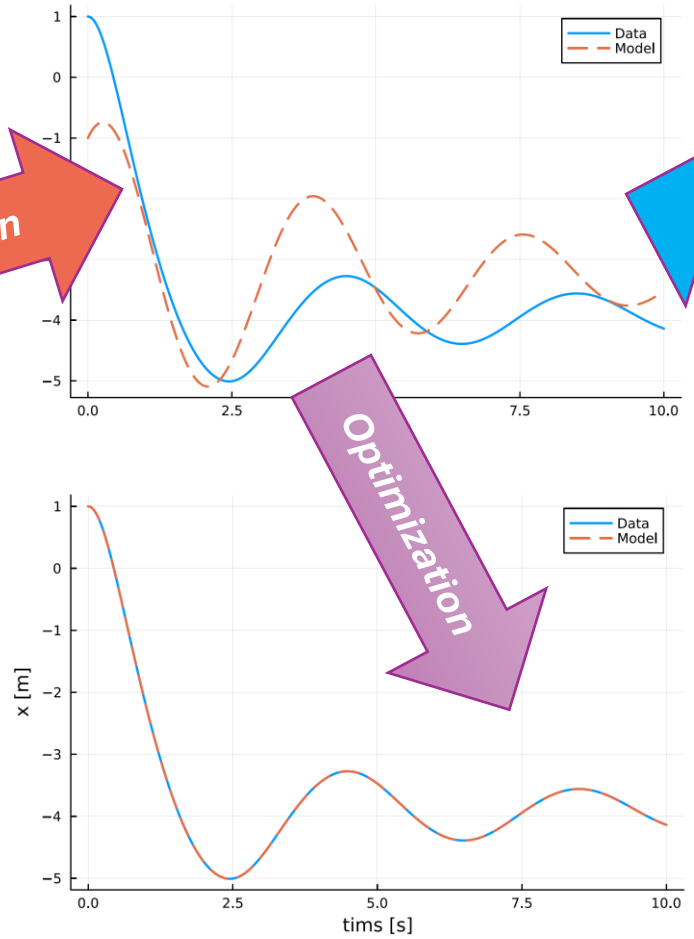
1. Motivation & Introduction

Hybrid Modeling with FMI



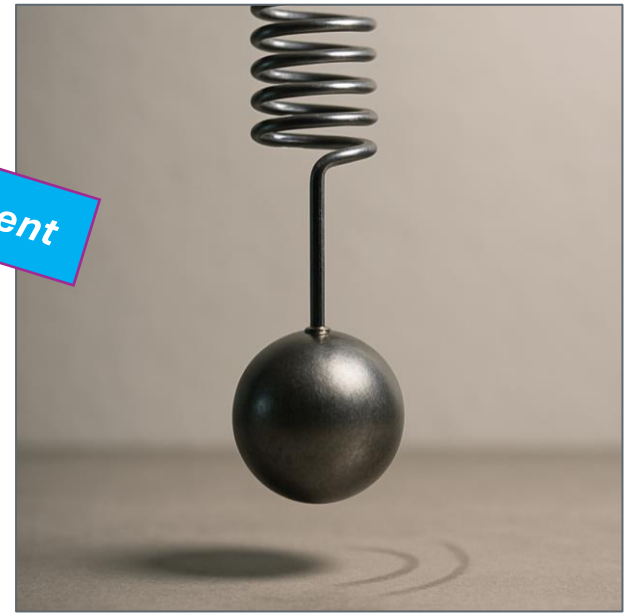
Translational Pendulum
(Neural FMU)

Simulation



Optimization

Measurement



Translational Pendulum
(Real-World System)

Neural FMUs:
2021: Tobias Thummerer Josef Kircher Lars Mikelsons. "NeuralFMU: Towards Structural Integration of FMUs into Neural Networks.„ *Modelica Conferences*. 2021.

1. Motivation & Introduction

Modeling the Bosch Integrated Power Brake (IPB)

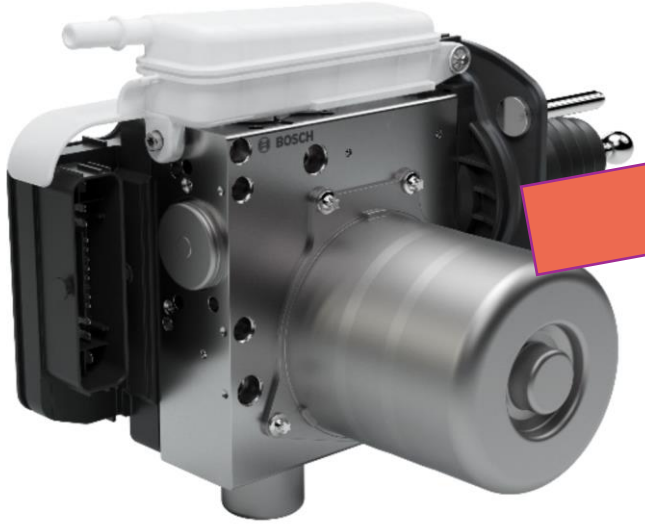
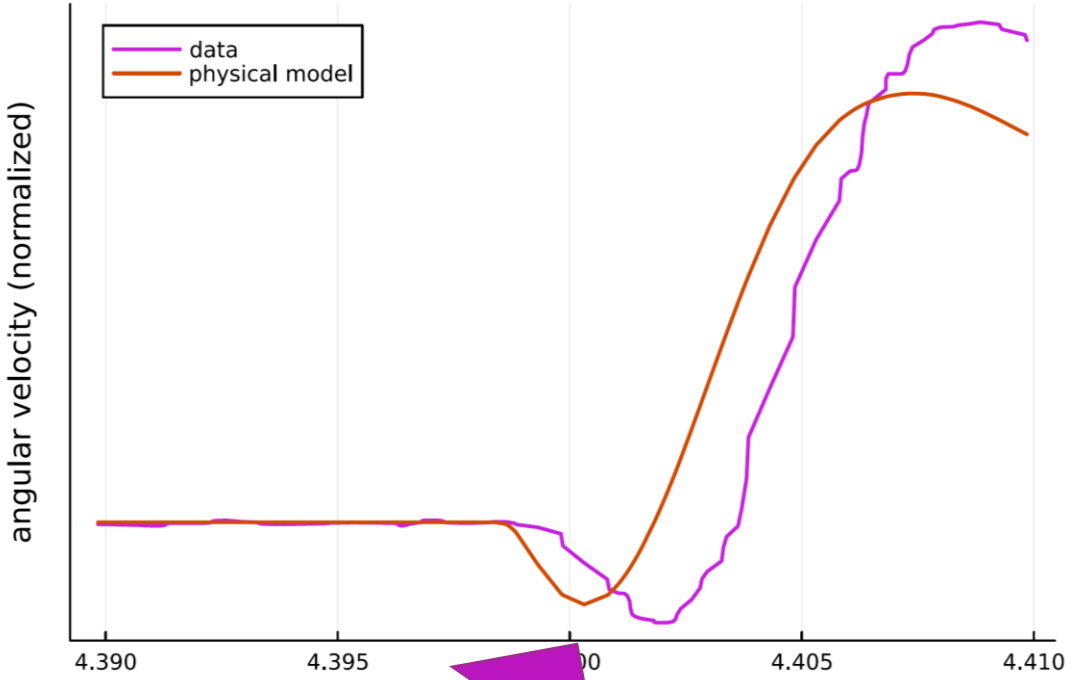
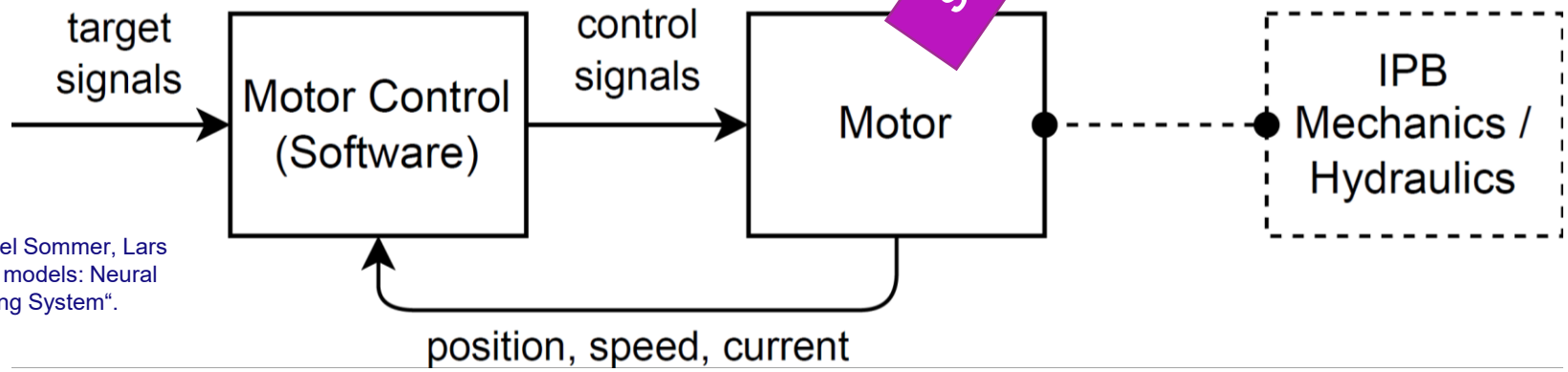


Image of IPB
Source: https://www.bosch-mobility.com/de/loesungen/fahrsicherheit/integrated-power-brake/

Measurement



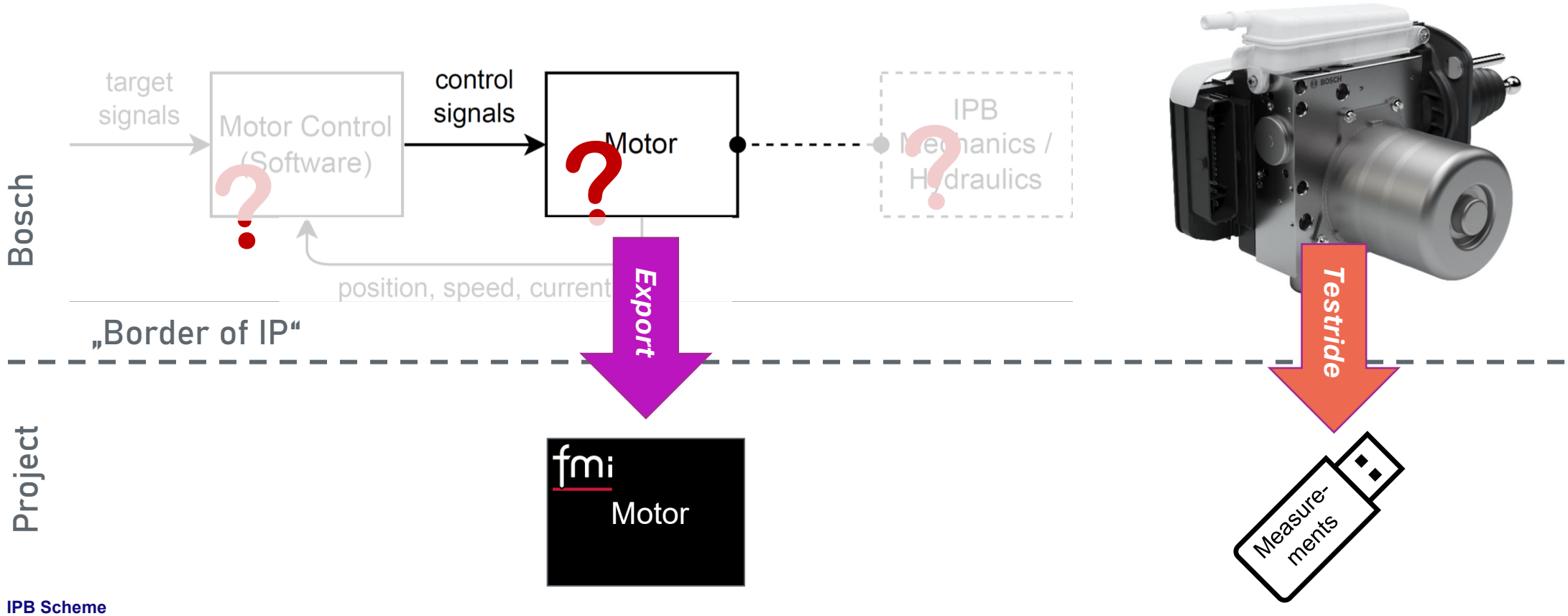
Simulation



IPB Scheme & Plot
Source: 2025: Tobias Thummerer, Fabian Jarmolowitz, Daniel Sommer, Lars Mikelsons. „Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System“. Modelica Conference. 2025.

1. Motivation & Introduction

Modeling the Bosch Integrated Power Brake (IPB)



IPB Scheme
Source: 2025: Tobias Thummerer, Fabian Jarmolowitz, Daniel Sommer, Lars Mikelsons. „Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System“. Modelica Conference. 2025.

Image of IPB
Source: https://www.bosch-mobility.com/de/loesungen/fahrsicherheit/integrated-power-brake/

2

BUILDING THE HYBRID MODEL

2. Building the Hybrid Model

Modeling the Bosch Integrated Power Brake (IPB)

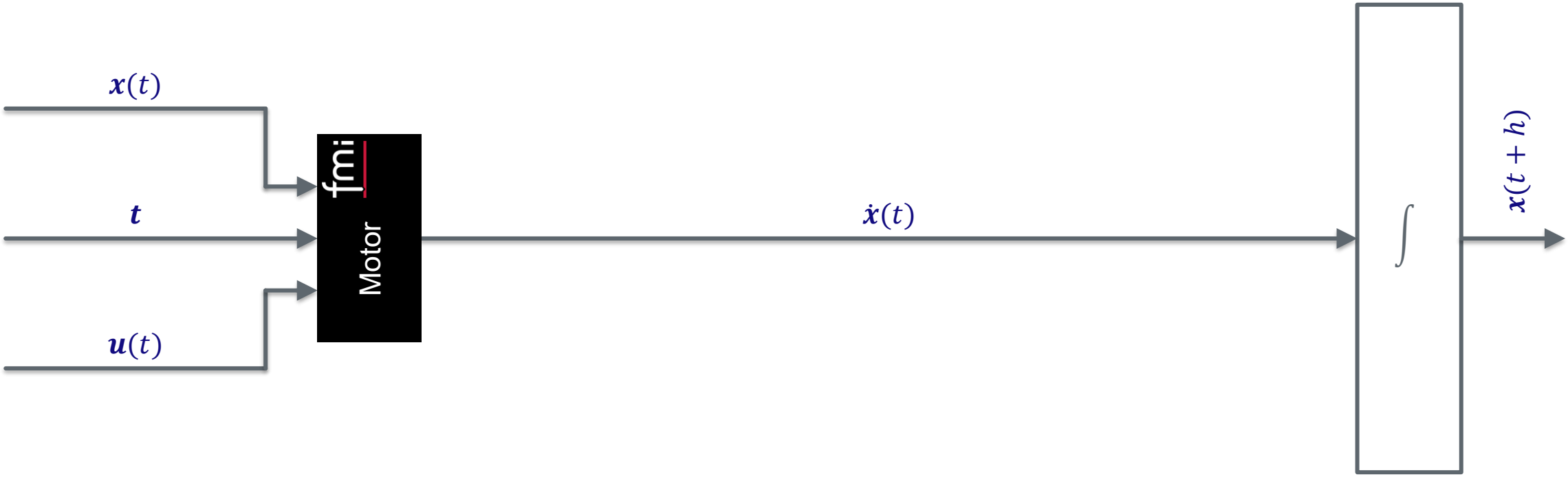


Model Prediction Quality



2. Building the Hybrid Model

Starting with the “classical” simulation loop …

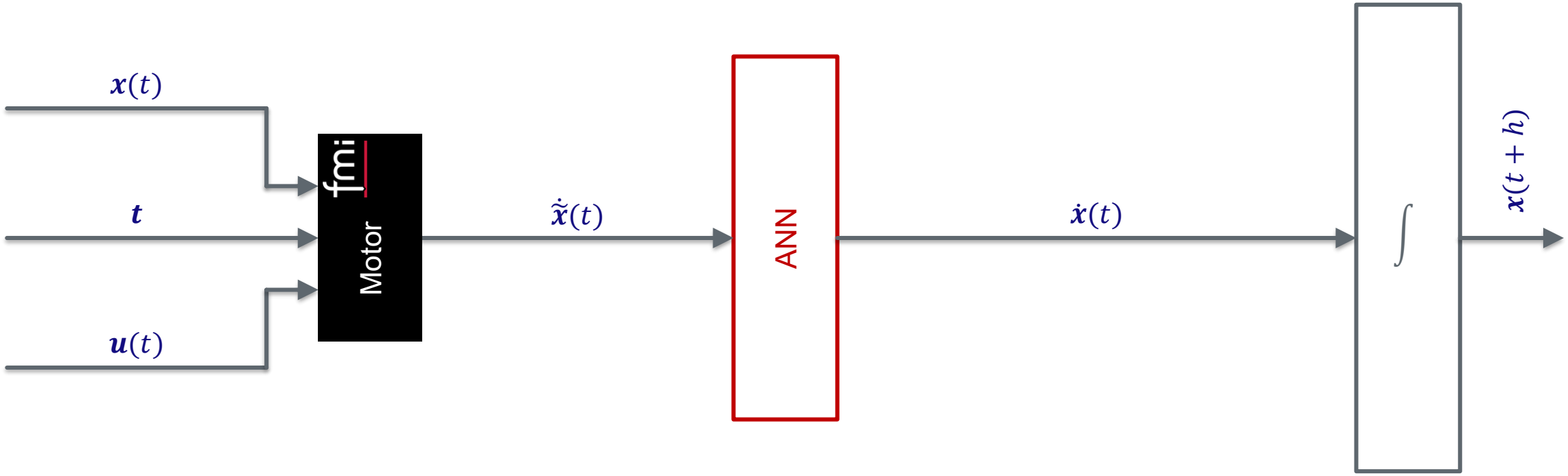


Model Prediction Quality

Knowledge

2. Building the Hybrid Model

Making the simulation model “hybrid” …

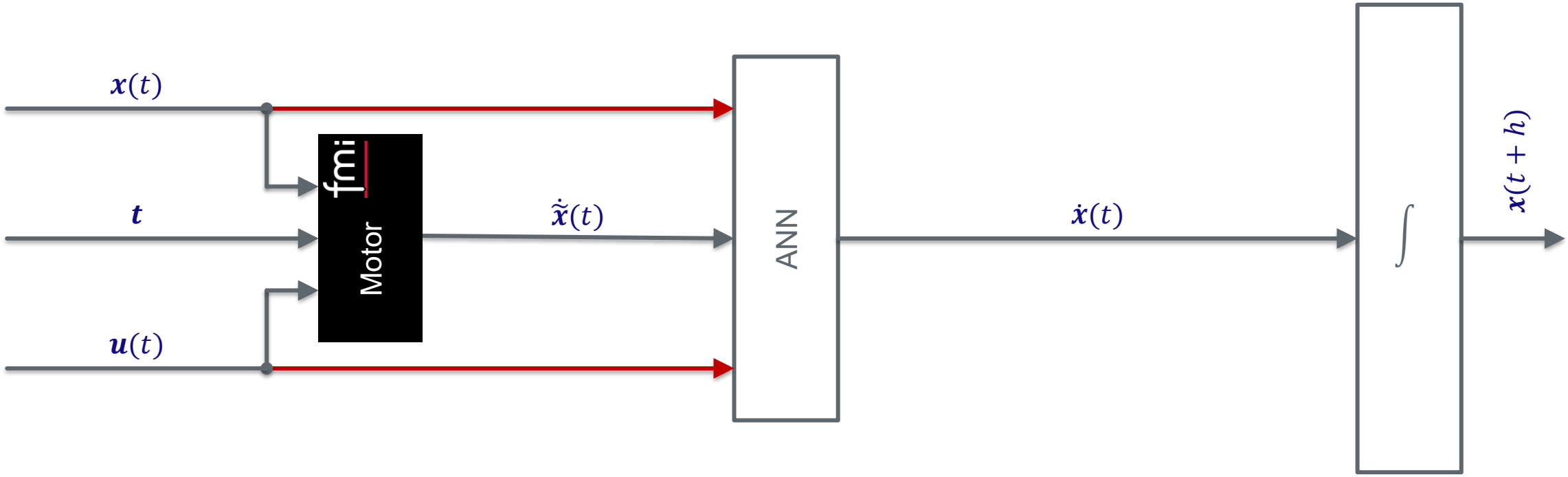


Model Prediction Quality



2. Building the Hybrid Model

Adding the state and input to the ANN …

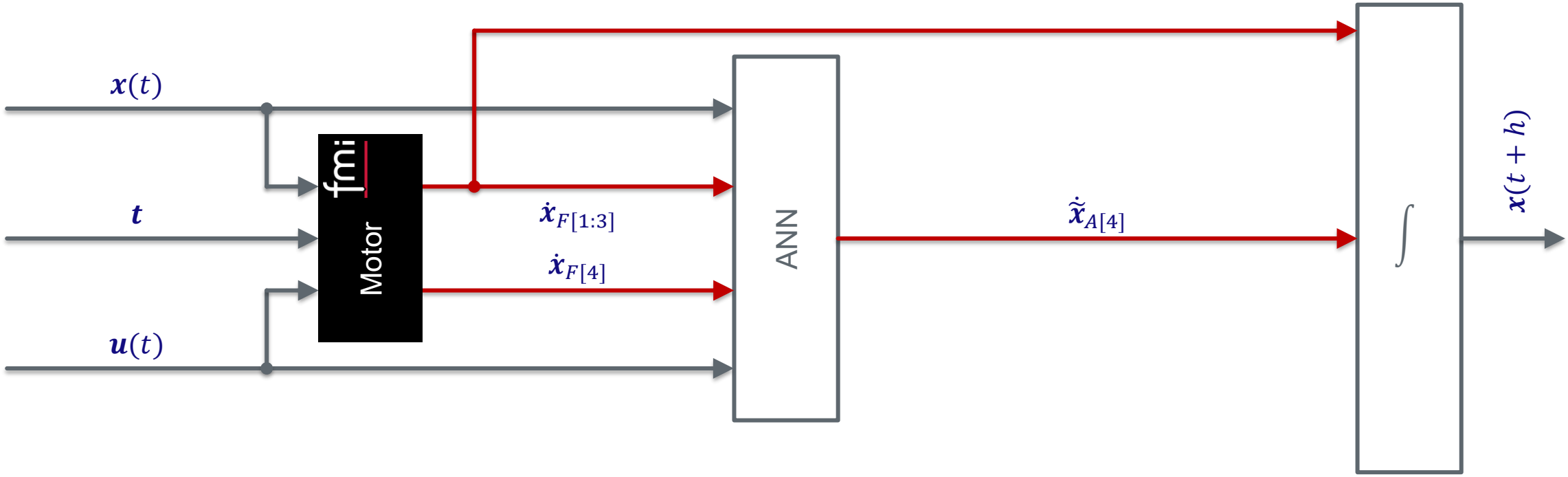


Model Prediction Quality



2. Building the Hybrid Model

Only manipulate the rotor acceleration …

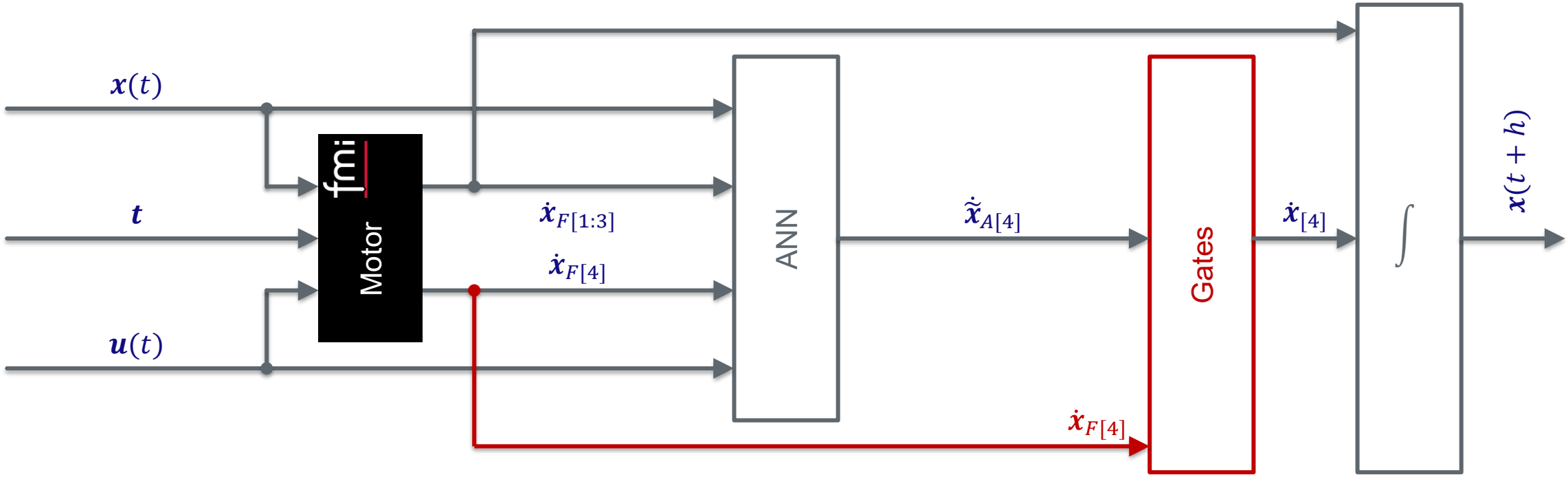


Model Prediction Quality



2. Building the Hybrid Model

Allowing for “reuse” of the rotor acceleration from the ANN …

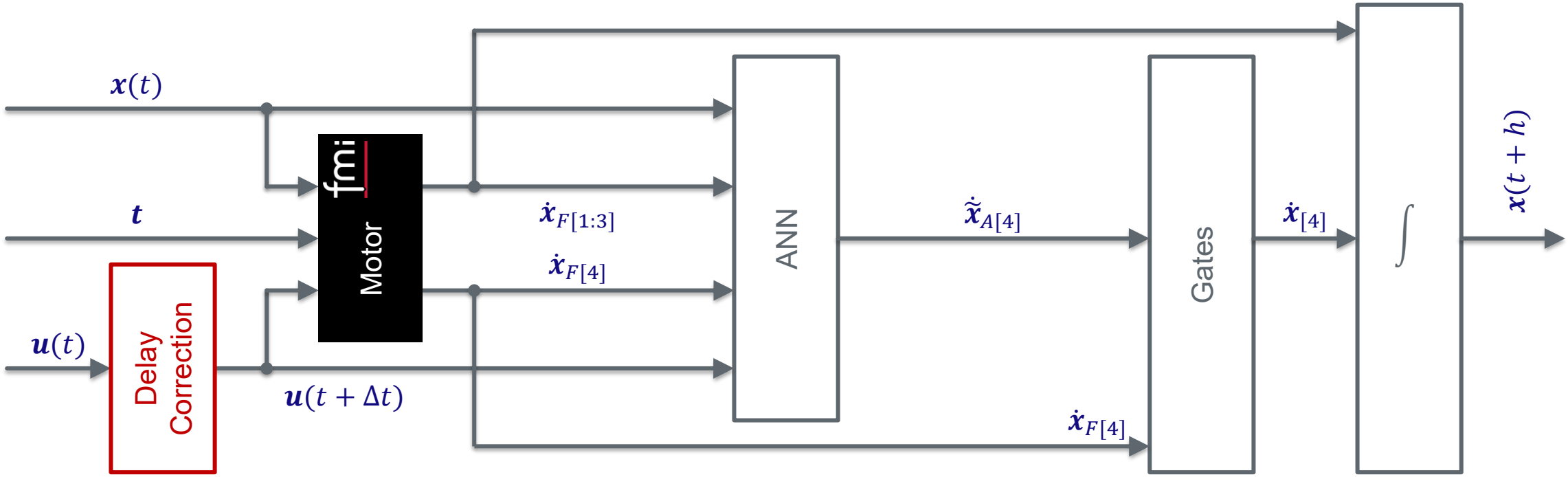


Model Prediction Quality



2. Building the Hybrid Model

Add a temporal correction for inputs …

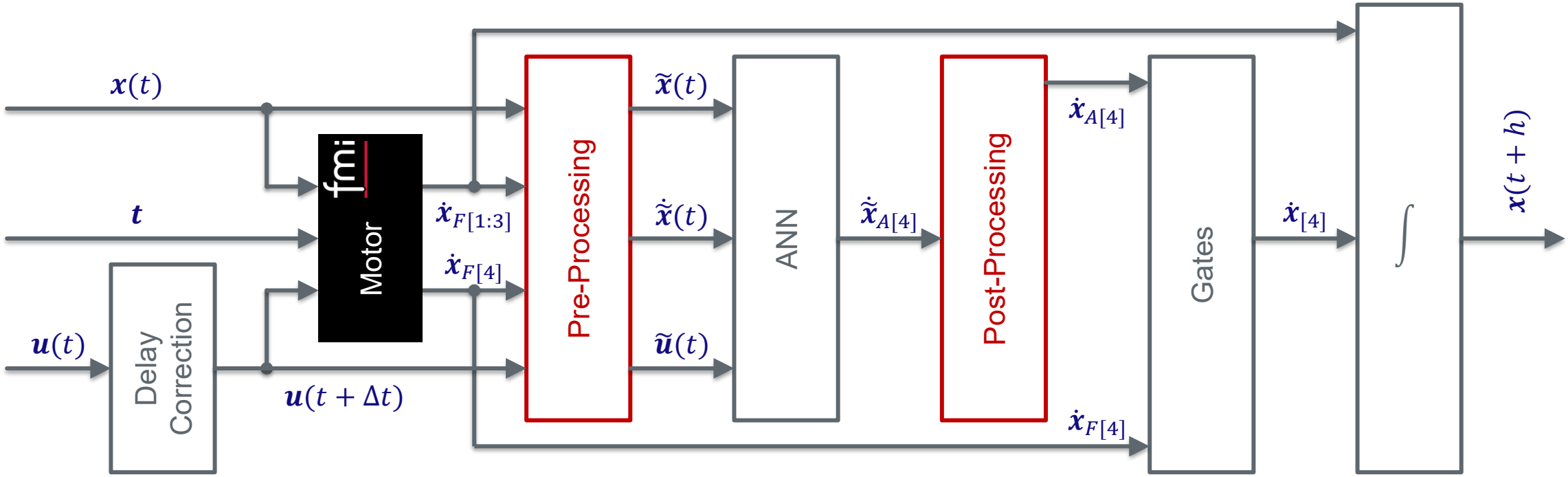


Model Prediction Quality



2. Building the Hybrid Model

Add pre- and postprocessing …

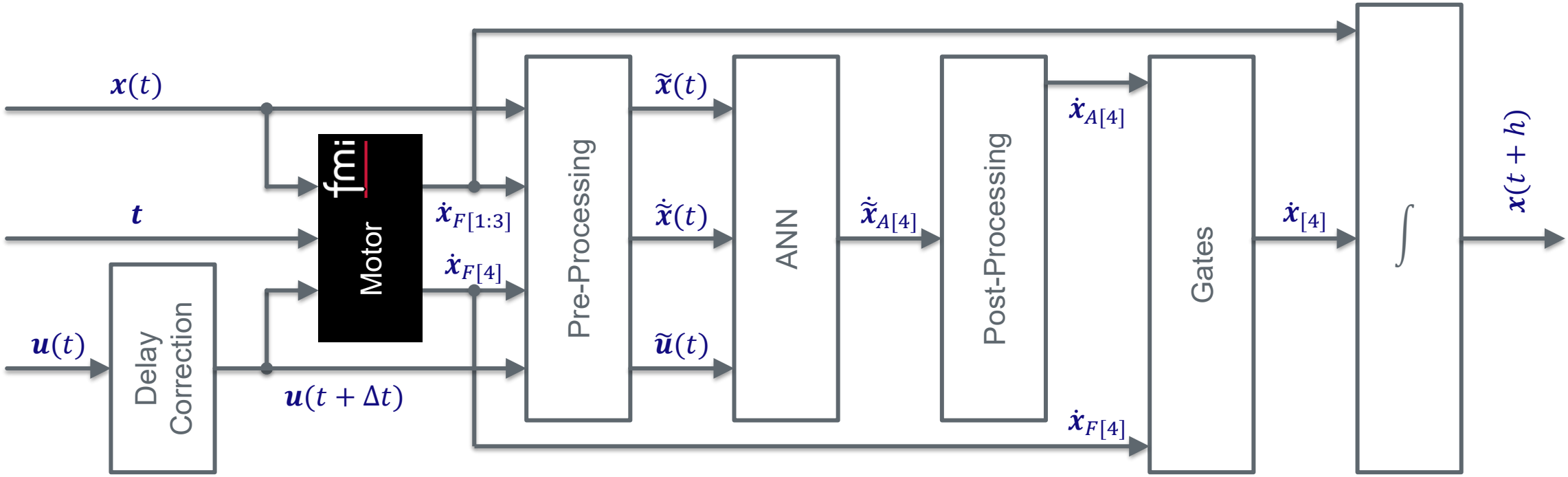


Model Prediction Quality



2. Building the Hybrid Model

The hybrid model … at a glance



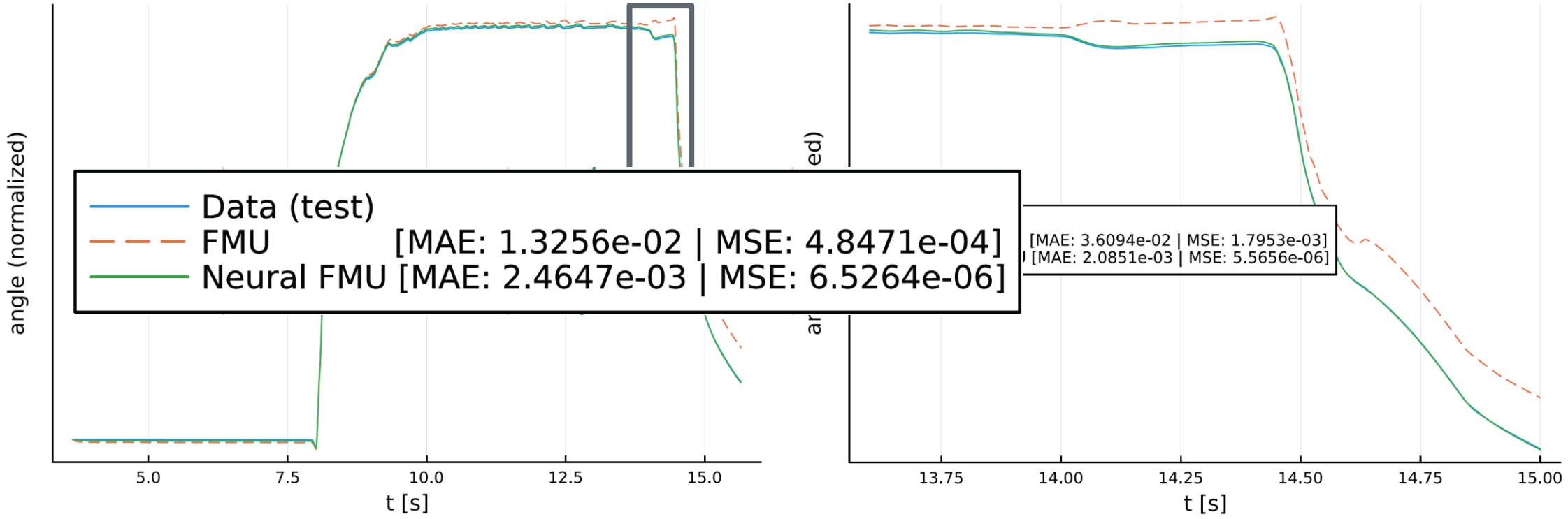
Model Prediction Quality



3 RESULTS

3. Results

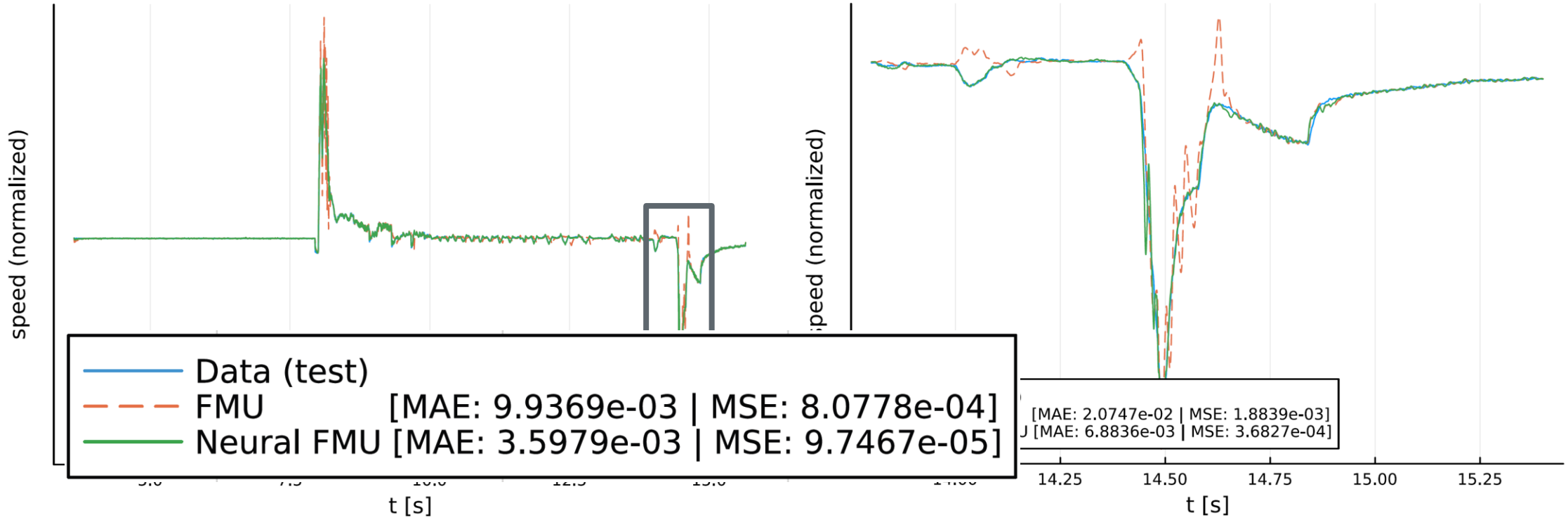
Neural FMU prediction for rotor angle on testing data



Images Source:
2025: Tobias Thummerer, Fabian Jarmolowitz, Daniel Sommer, Lars Mikelsons. „Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System“. Modelica Conference. 2025.

3. Results

Neural FMU prediction for rotor speed on testing data



Images Source:
2025: Tobias Thummerer, Fabian Jarmolowitz, Daniel Sommer, Lars Mikelsons. „Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System“. Modelica Conference. 2025.

4

CONCLUSION & FUTURE WORK

Conclusion and Outlook

Summary

- Hybrid modeling is a valuable approach …
- … even if you can't open the black box (FMU).
- Very efficient hybrid modeling requires knowledge of the system …
- … even if the knowledge is quite abstract (e.g. second order ODE).
- Architecture design can be seen as the "engineer's role" in data-efficient hybrid modeling
  → further reading: *Learnable & Interpretable Model Combination in Dynamical Systems Modeling*

Future Work

- Validate the hybrid model within the entire simulation (was not possible during project runtime).
- Re-build the motor model & imitate the real measurements, in order to publish an open-source version of this use case (student work).

Universität Augsburg
Fakultät für Angewandte Informatik



Tobias Thummerer
Chair of Mechatronics
University of Augsburg
tobias.thummerer@uni-a.de

Fabian Jarmolowitz
Daniel Sommer
Lars Mikelsons

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UNLEASH POTENTIALS IN SIMULATION
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Federal Ministry of Education and Research

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Thank you for your attention.

Questions? Feedback? Comments?

Yes, please!