Implementation of a High-Fidelity Model of a Racecar into a Path Optimization Problem using Functional Mock-Up Units

Angel Mario Zarate Villazon, Dr. Michael Balchanos, Prof. Dimitri Mavris

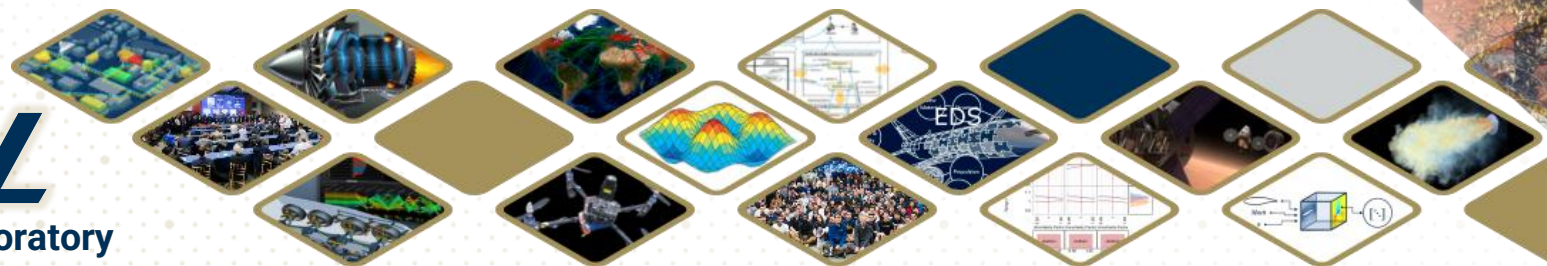
American Modelica Conference 2026, Atlanta, GA.

Paper No. 21

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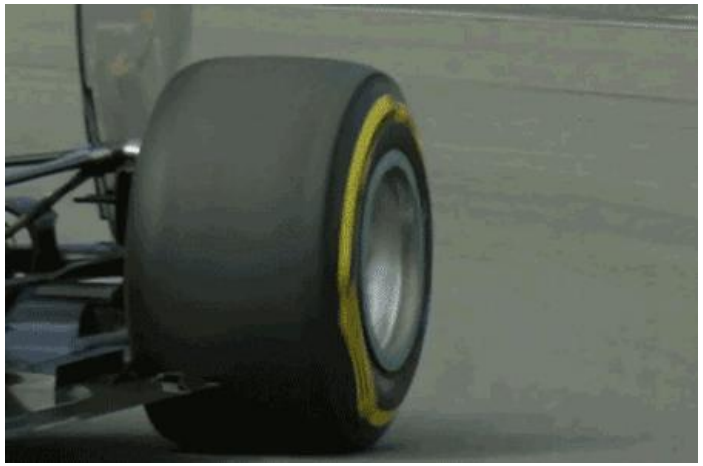




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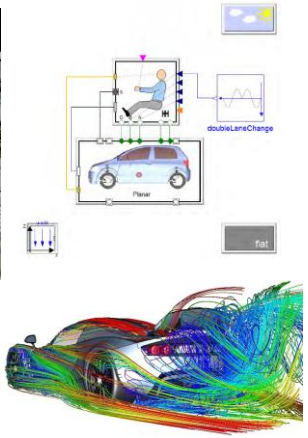
Challenges with High-Fidelity Vehicle Models

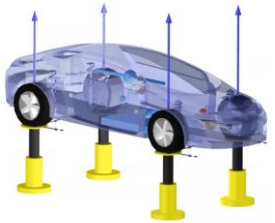
- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks



Capturing **complexity** while maintaining **compatibility** with trajectory optimization







Models are used for **multiple applications**; kinematics & compliance, aerodynamics, thermal management, driver-in-the-loop, energy management, etc.

Typically rely on several assumptions for a given application

→ How to avoid inconsistencies?

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1. Massaro, M., and Limebeer, D. J. N., "Minimum-Lap-Time Optimisation and Simulation," *Vehicle System Dynamics*, Vol. 59, No. 7, 2021, pp. 1069–1113. https://doi.org/10.1080/00423114.2021.1910718

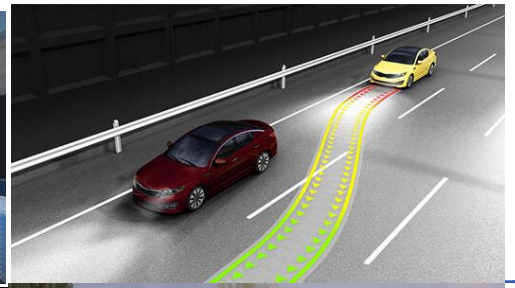


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Capturing Overall Vehicle Behavior

- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks

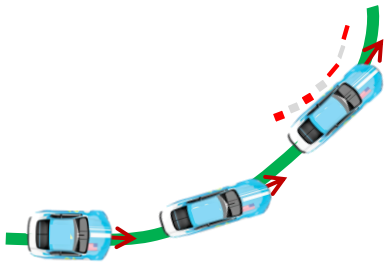








Trajectory Optimization



Useful for:

- Vehicle parameter sensitivities [1,2]
- Setup decisions [3]
- Driver benchmarking [4]

In summary: tool to evaluate the **vehicle as system**

How to find this path?

Optimal Control

Reinforcement Learning

Relies on several assumptions that challenge consistency to make it feasible

- Reduced Compliances
- Joint Simplification
- Tire Model Simplification
- Linearization

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1. Perantoni, Giacomo and David J.N. Limebeer (2014-05). “Optimal control for a Formula One car with variable parameters”. In: Vehicle System Dynamics 52.5, pp. 653–678. ISSN: 17445159. DOI: 10.1080/00423114.2014.889315.
2. Zarate Villazon, Angel M., Ian Brown, Michael Balchanos, and Dimitri Mavris (2026-04). “Lap Time Performance Sensitivity to Tire Model Parameters: An Optimal Control Framework for Model Selection and Calibration”. In: SAE World Congress Experience 2026. SAE International. DOI: 10.4271/ 2026-01-0214.
3. Limebeer, D. J.N., M. Bastin, E. Warren, and H. G. Fensham (2023). “Optimal control of a NASCAR–specification race car”. In: Vehicle System Dynamics 61.5, pp. 1210–1235. ISSN: 17445159. DOI: 10.1080/00423114.2022.2067573.
4. Lockel, Stefan, Andre Kretschi, Peter van Vliet, and Jan Peters (2022). “Identification and modelling of race driving styles”. In: Vehicle System Dynamics 60.8, pp. 2890–2918. ISSN: 17445159. DOI: 10.1080/00423114.2021.1930070.



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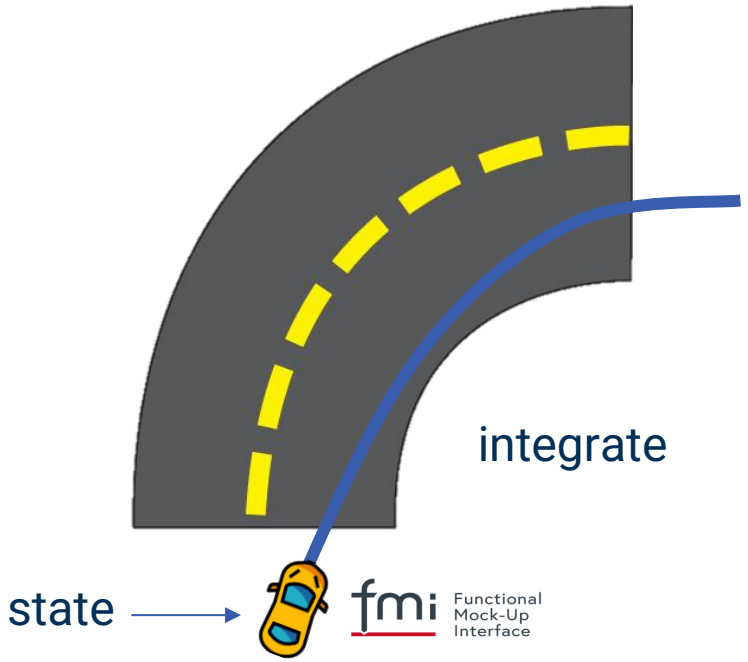
Implementing FMUs for Trajectory Optimization

FMI Standard can support the deployment of more complex models in optimization frameworks

fmi Functional Mock-Up Interface

Applicability of FMUs to maintain consistency in trajectory optimization depends on the technique being followed [1]

- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks



Multiple Shooting depends on the **continuous integration** of all the vehicle states

Naturally **compatible** with how **FMUs** work

Can become very **computationally expensive** when dealing with complex models

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1. Massaro, M., and Limebeer, D. J. N., "Minimum-Lap-Time Optimisation and Simulation," *Vehicle System Dynamics*, Vol. 59, No. 7, 2021, pp. 1069–1113. https://doi.org/10.1080/00423114.2021.1910718



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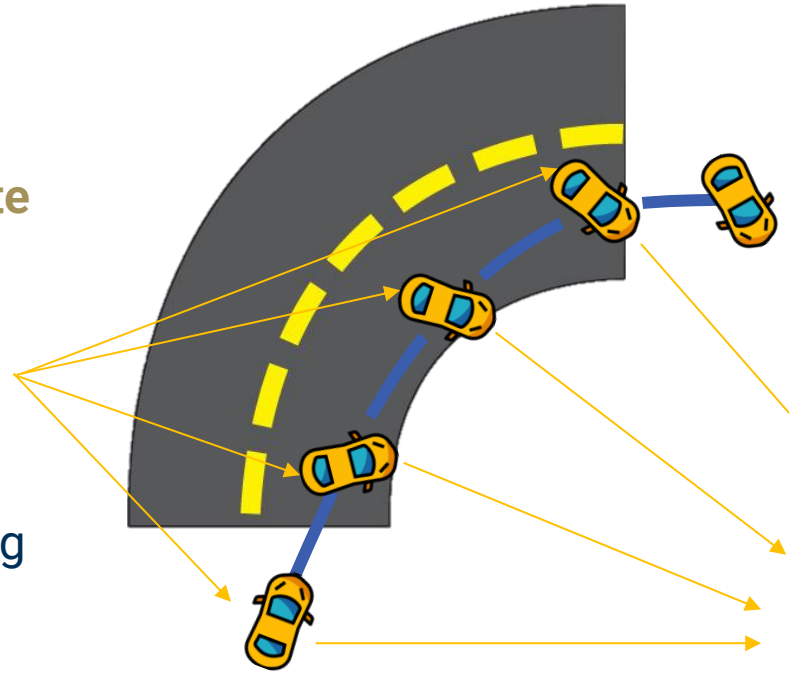
Implementing FMUs for Direct Collocation

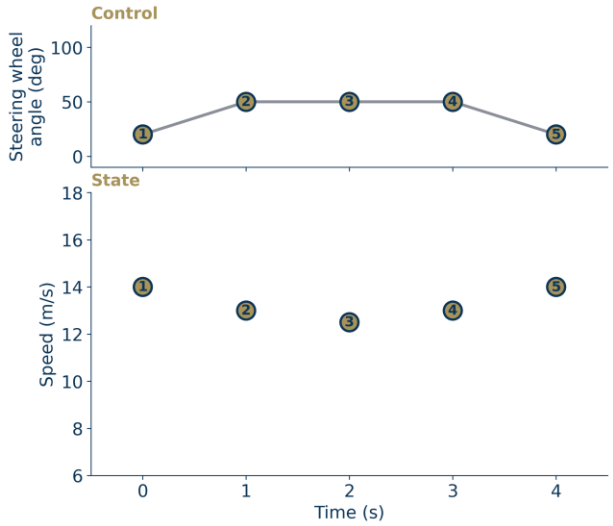
- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks

Direct collocation has emerged as a solution to handle more complex vehicle models [1]

How does direct collocation work? [2]

Start with an **initial guess** of the car's **state** *(positions and velocities at several degrees of freedom)* and **controls** *(throttle, steering and braking)* at specific **nodes** along the trajectory





Evaluate the resulting dynamics, including the **derivatives** *(rates of change for the vehicle state),* based on the control input

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1. Massaro, M., and Limebeer, D. J. N., "Minimum-Lap-Time Optimisation and Simulation," *Vehicle System Dynamics*, Vol. 59, No. 7, 2021, pp. 1069–1113. https://doi.org/10.1080/00423114.2021.1910718
2. Kelly, M. (2017). An introduction to trajectory optimization: How to do your own direct collocation∗. *SIAM Review*, *59*(4), 849–904. https://doi.org/10.1137/16M1062569



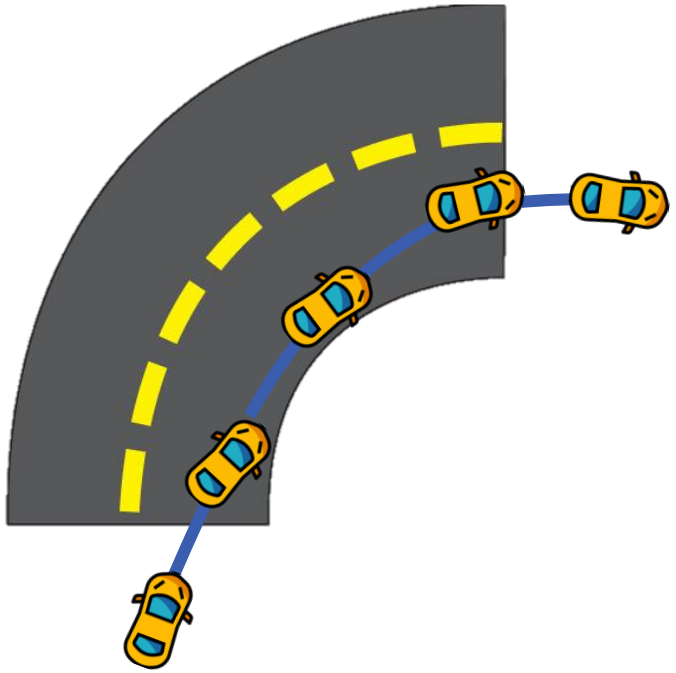
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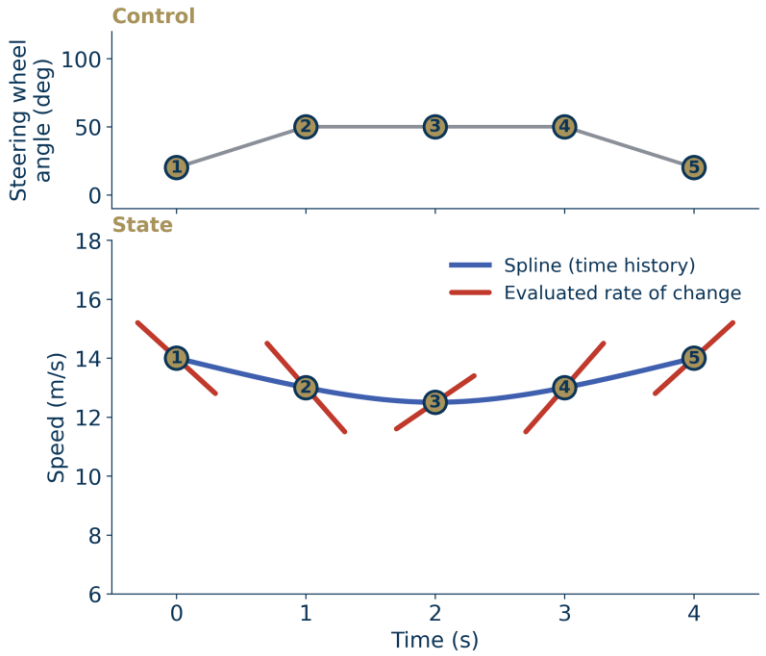
Implementing FMUs for Direct Collocation

- Background + Motivation
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- Results
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How does direct collocation work? [2]

A **polynomial spline** fitted between each node describes the **state's evolution** between each of the **nodes**





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1. Kelly, M. (2017). An introduction to trajectory optimization: How to do your own direct collocation∗. *SIAM Review*, *59*(4), 849–904. https://doi.org/10.1137/16M1062569



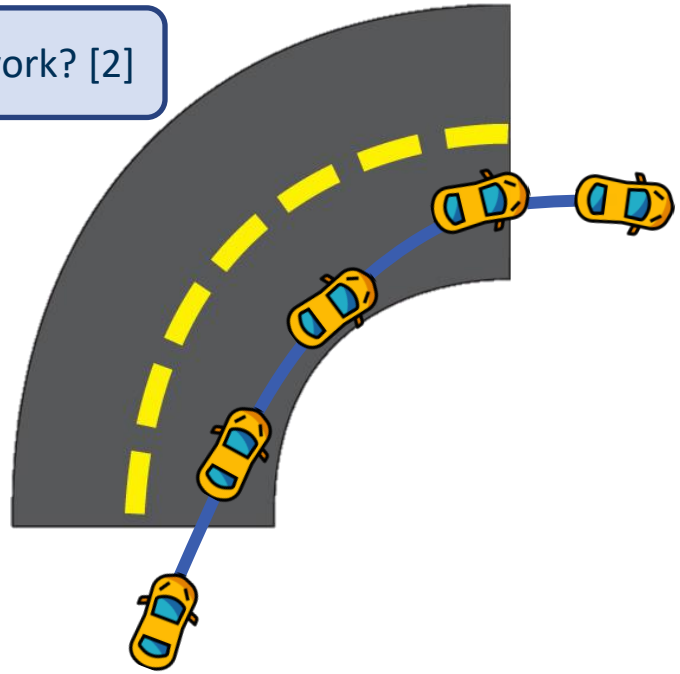
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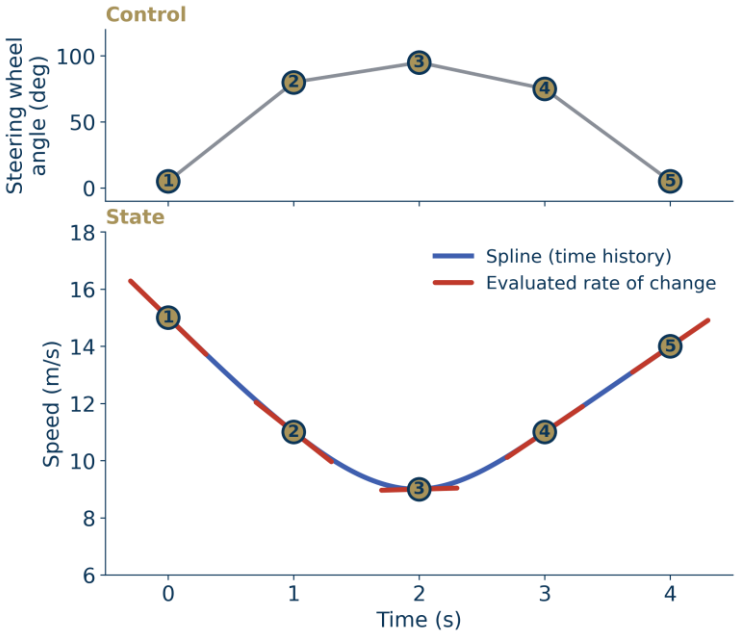
Implementing FMUs for Direct Collocation

- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks

How does direct collocation work? [2]

The optimizer adjusts **states and controls** at every node at once, minimizing an **objective function** *(for example, lap time)*, until the spline's slope **matches the derivatives** at each node





The dynamics are evaluated **independently at each node**, and every evaluation must **start from that node's state**, at every iteration.

Can an FMU, built to simulate forward in time, be evaluated **at discrete nodes where** the optimizer needs the system's dynamics?

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1. Kelly, M. (2017). An introduction to trajectory optimization: How to do your own direct collocation∗. SIAM Review, 59(4), 849–904. https://doi.org/10.1137/16M1062569



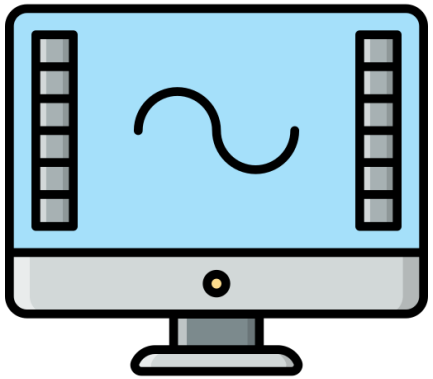
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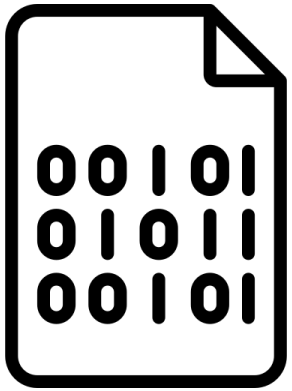
Serialization: possible enabler for collocation with FMUs

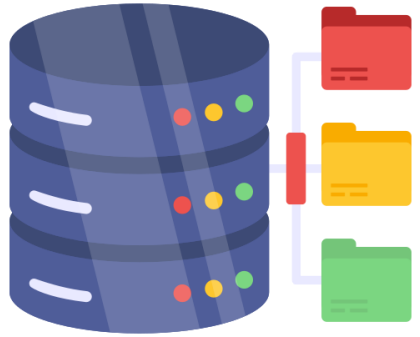
- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks

Serialization [1]

Simulation stopped at a given timestep → Encode the simulation state into binary → Store the state in memory







Restart simulation from saved state ← Decode the binary simulation state ← Retrieve from memory

Deserialization [1]

Serialization can become the solution to obtain and modify the vehicle's dynamics at each collocation node

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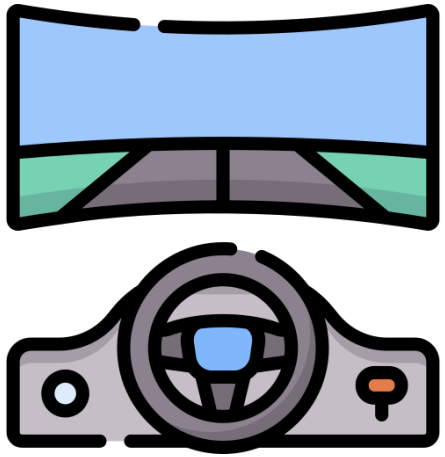
1. Modelica Association (2023-07). Functional Mock-up Interface Specification version 2.0.4. Tech. rep. Modelica Association.URL: https://github. com/modelica/fmi-standard/releases/download/v2.0.4/FMI-Specification-2.0.4.pdf



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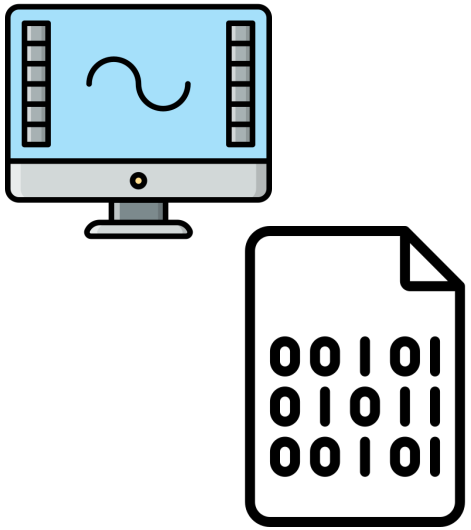
Proposed technical approach

- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks



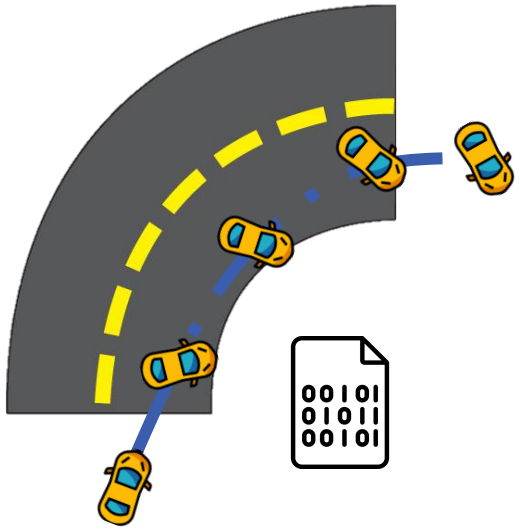
Record data in a Driver in the Loop Simulator

1



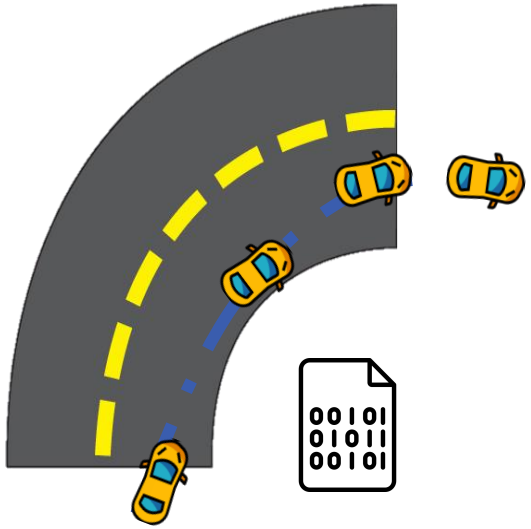
Initialize FMU with the recorded data and generate serialization files

2



Use the serialization files to leverage the initial guess

3



Solve the optimal control problem by using serialized FMU and an intermediate model

4

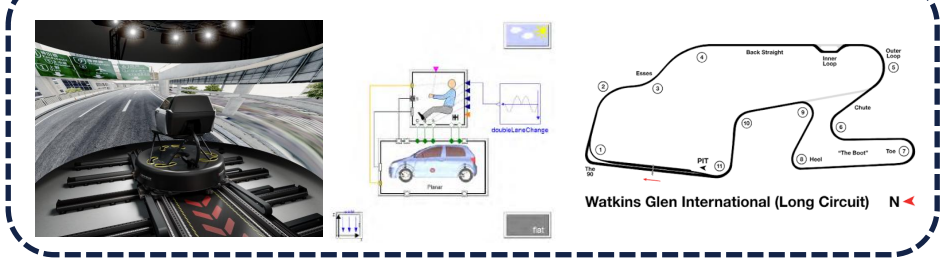
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Testing the technical approach

- Background + Motivation
- Technical Approach
- Results
- Concluding Remarks



Use Case:
- FMU Open-Loop Driver for DIL
- Watkins Glen Track/Oval qualifying lap
- Direct Collocation in Dymos

Series of tests to establish the technical feasibility of the approach

Model-Related Tests: These test **serialization behavior** for the use case model:

M1: Recreation through serialization
M2: Control sensitivity
M3: Model integration tests

Optimizer-Related Tests: These test **optimizer stability and compatibility** for the selected approach:

O1: External code convergence verification
O2: Precise node location definition
O3: Integration tests of model derivatives

Establish a feasibility path towards finding a convergent solution to the optimization problem

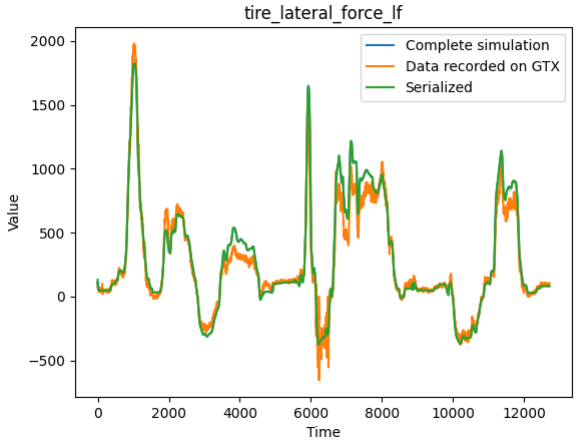


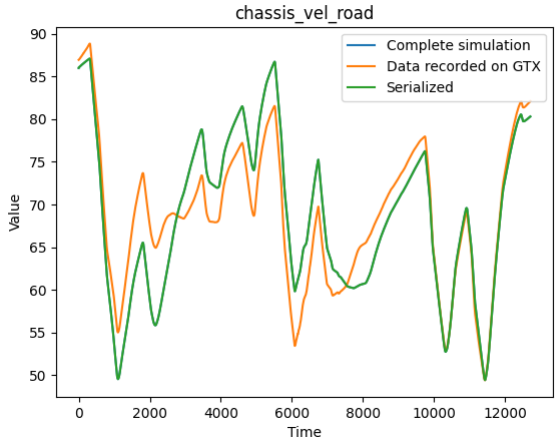
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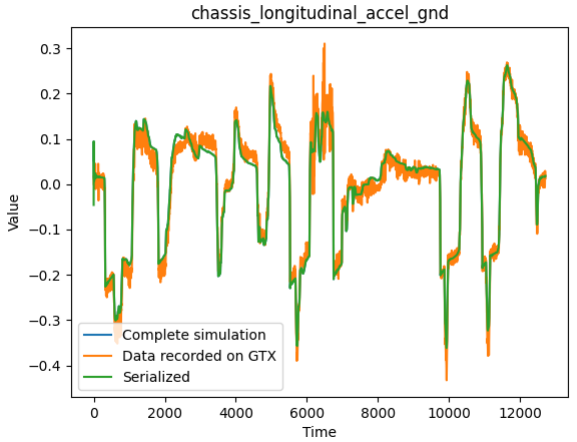
M1: Recreation through serialization

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks

- *Objective*: Verify the serialization implementation by comparing a reconstructed simulation with DIL simulator data and a single-shot simulation
- *Method:* Several tests were conducted with **different driving behaviors** and an **increasing number of discretization** points.
- *Results:* Agreement across all channels between the **full simulation** and the **serialized one** for the open-loop driver experiment from the OEM







These results demonstrate that a **robust approach** to run simulations **using serialization** has been established, and consequently, serialization can be tried as an **enabler** for the problem

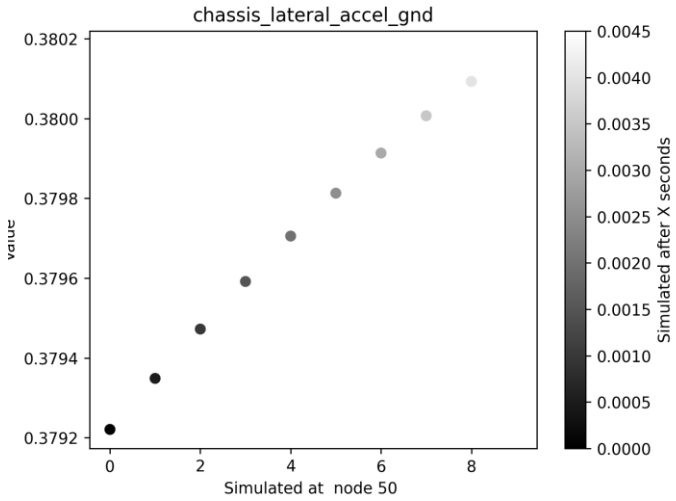


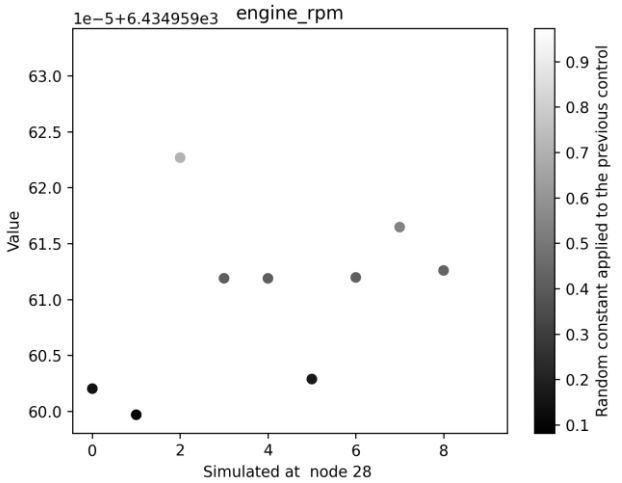
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M2: Control Sensitivity

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks

- *Objective*: **determine a timestep** to use in the optimization problem and identify sensitivity of serialized simulation to control inputs
- *Method*: Run **different timesteps** at random nodes with **constant controls** and select the timestep before nonlinearities cause dramatic differences. Once the timestep is determined, try **different magnitudes in the controls**
- *Results:* Increasing **impact of effects as timestep grows** across all nodes. Non-linear effects in the control magnitude for several nodes.





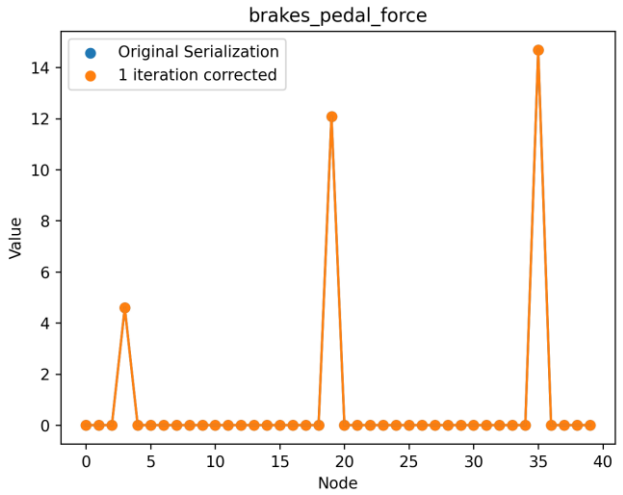
The model sensitivity to changes in controls has been established and test procedures to update it depending on optimization needs have been

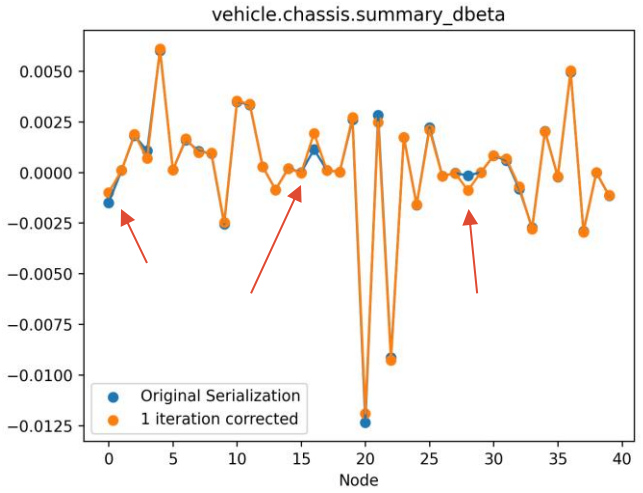


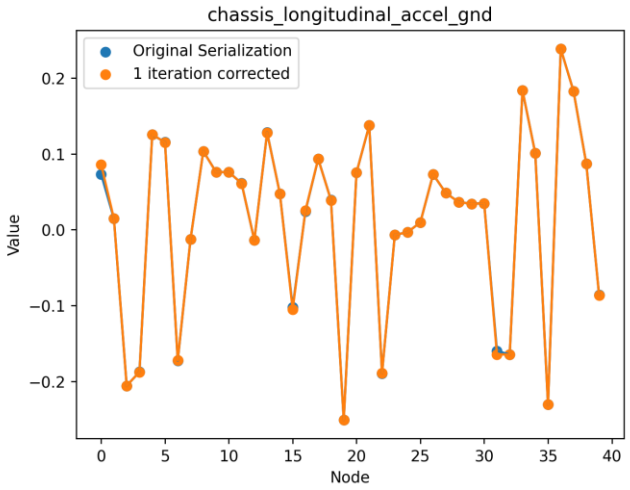
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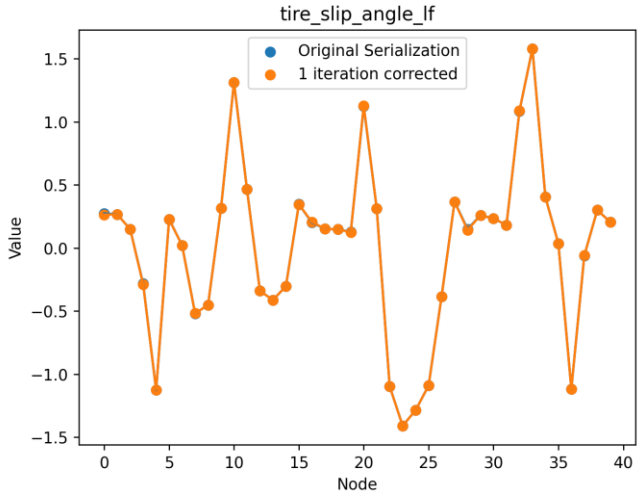
M3: Connection of the Model

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks









- *Objective*: determine if the **FMU connection** with the rest of the optimization problem is correct
- *Method:* **Execute** the problem over **one iteration** and review the state modification
- *Results:* The state obtained from **serialization was transferred** after one iteration, with slight influences from the optimizer

These tests show that the FMU is properly integrated into Dymos and ready to start interfacing with the optimizer

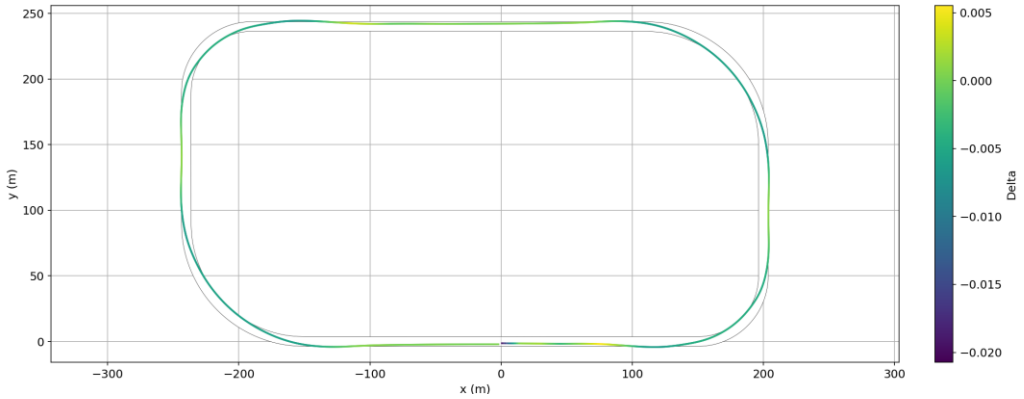


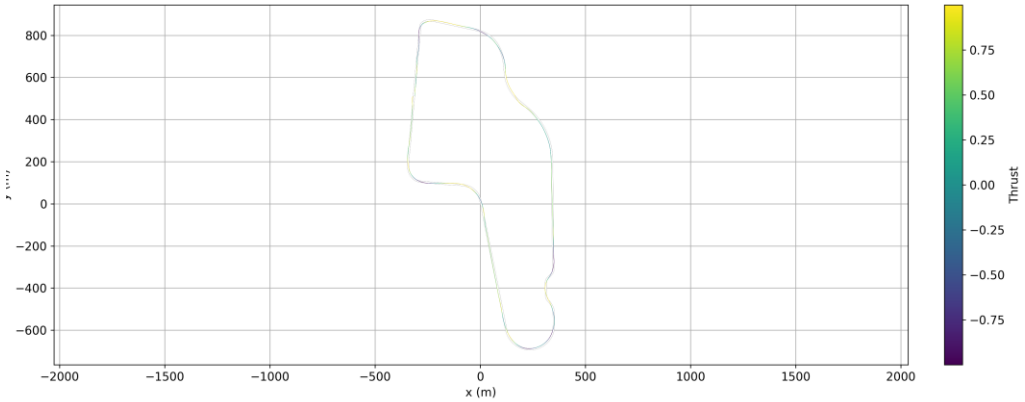
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O1: External Code in Dymos Feasibility Experiment

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks

- *Objective*: Obtain a **convergent solution** optimization problem using a piece of **external code** to calculate some state and its derivatives
- *Method:* Implemented the **proprietary tire model** to calculate the **tire forces**
- *Results*: **Convergence was achieved** in the simulation of the oval and Watkins Glen track





This demonstrates that Dymos is capable of **converging** on an optimal solution using calculations computed on an **external code**

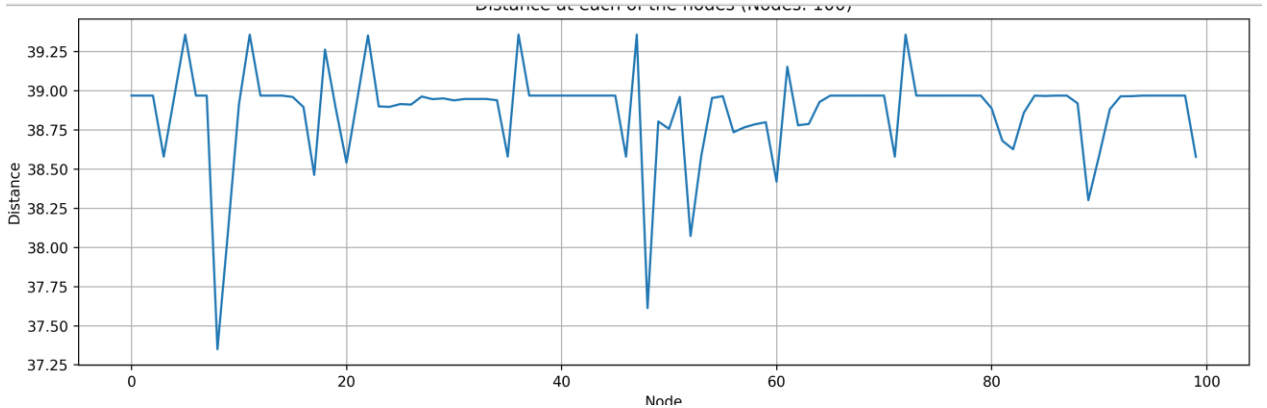


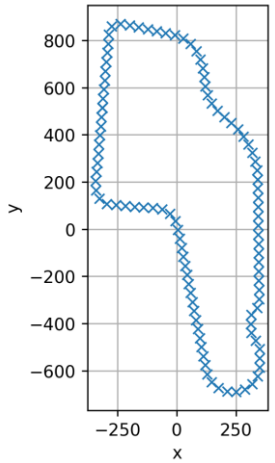
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O2: Node Location Definition

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks

- *Objective*: Determine **how Gauss-Lobato discretization is applied to** the problem to define how **the serialized states** need to be determined
- *Method:* Obtain the node location and **determine the distance between the nodes** to understand how the node definition algorithm works
- *Results*: The results show the algorithm uses **some sort of equidistance** but **not** quite there if **Euclidean** distances are used





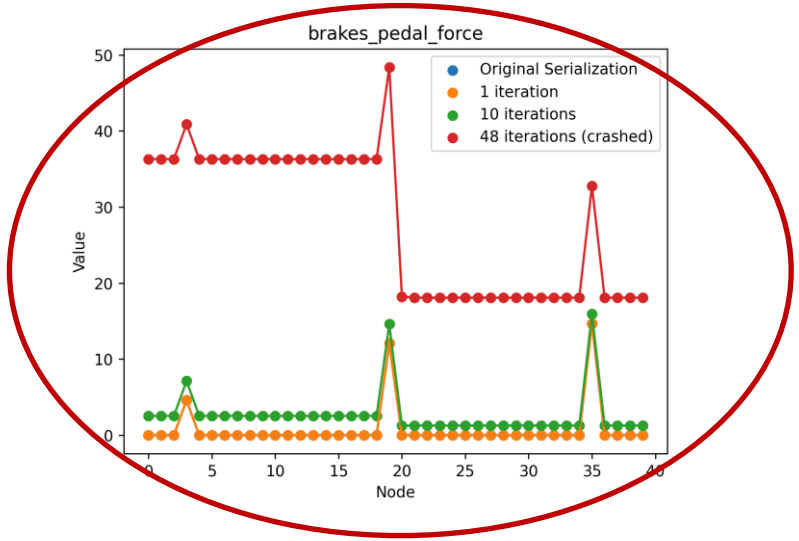
These results show that an approach where the nodes are serialized based on the specific location of the nodes may be needed

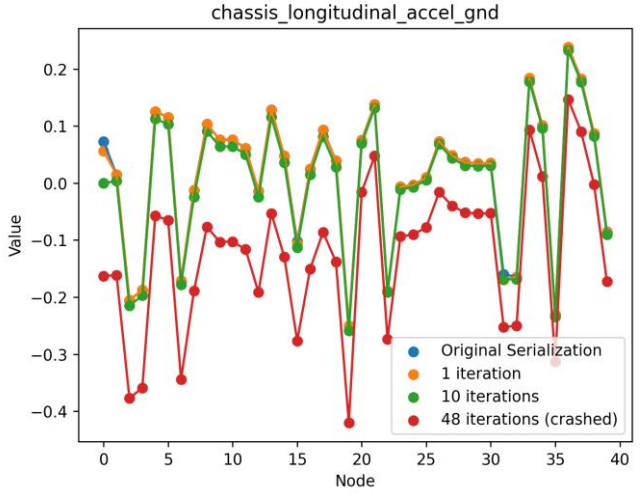


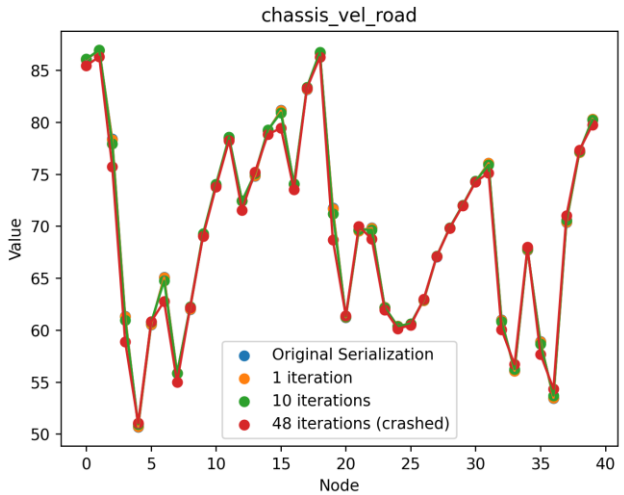
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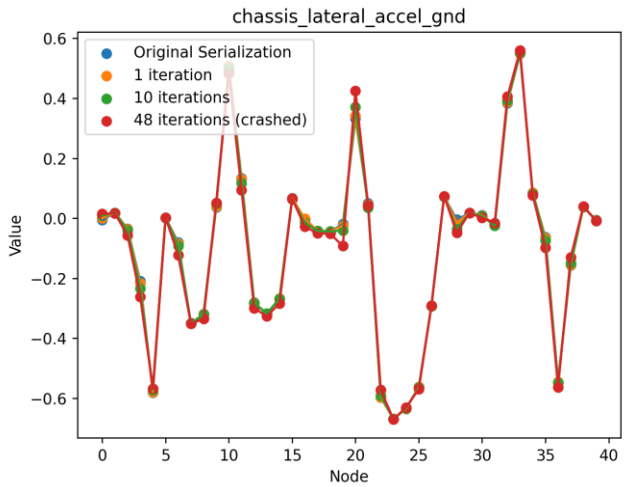
O3: Test of different derivative approaches

Background + Motivation
Technical Approach
Results
Model Compatibility
Optimizer Compatibility
Concluding Remarks









- *Objective*: diagnose possible **issues with numerical derivatives**
- *Method:* only allow for **small control inputs** and review cases of **divergence**
- *Results:* identified issues with possible divergence with the **brake pedal force** before optimization crashes

These results suggest that **a derivative divergences** might be causing **issues.**
Investigation of other approaches like **automatic differentiation** can be necessary

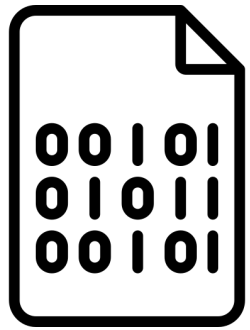


Mario Zarate

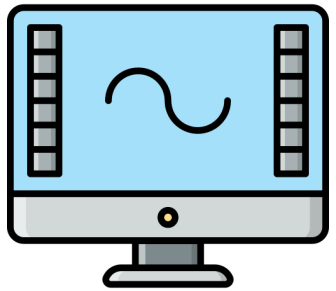
Background + Motivation
Technical Approach
Results
Concluding Remarks

Lessons from Serialization of FMUs for Optimal Path

- **Serialization** supports workflows where restarting the simulation might be needed
  - For collocation, **serialization** and evaluating the dynamic states at the collocation nodes with a FMU has been demonstrated
  - This can be expanded for other applications where **discrete evaluation** of a model is useful (i.e design sensitivity anlyses in unsteady states)



- Challenges remain in the integration of the models:
  - **Improving derivative calculation** with serialization has the **potential to allow convergence**
  - Important to investigate derivative calculation strategies supported by FMI standard, such as automatic differentiation





Future Work: Estimating the lap time given setup changes

Background + Motivation
Technical Approach
Results
Concluding Remarks

- Known challenges remaining:
  - Formulate an **adequate combination of derivatives** that is able to produce convergent results
  - **Robustness and sensitivity** of serialization to changes in the setups
  - Modify the experiment to be able to **use faster laps recorded in the Driver in the Loop Simulator**
- Once this has been established, a **tool to estimate the lap time given setup changes** by proposing a change in the controls recorded from a lap will be ready
- This development spiral **focuses on small changes in the controls to increase the possibilities of the solver converging**. A future spiral considers increasing the set of allowable controls to obtain an overall solution

Thank you!

Questions?

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