The Virtual PaintShop: AI-Boosted Automated Painting – AutoPaint

Cluster Conference 2026

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RESEARCH CENTRE FOR INDUSTRIAL MATHEMATICS

Virtual Paintshop

Novel methods, algorithms and software tools to optimize paint and surface treatment processes to be more environmentally friendly, more energy and cost efficient, and give a better product quality

Spray painting

- Unique algorithms for coupled simulation of air flows, electrostatics and charged paint particles
- Full car spray painting simulations overnight on a standard computer

Hanging optimization

- Optimization of collision free hanging pattern

Sealing

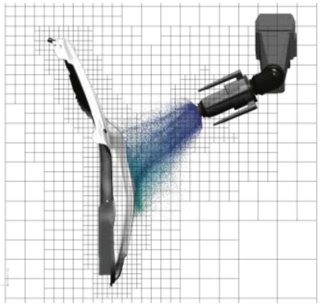
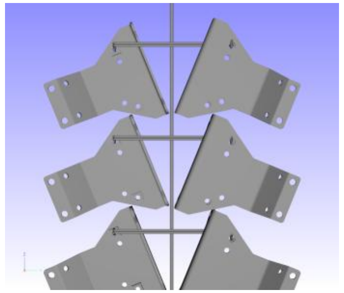
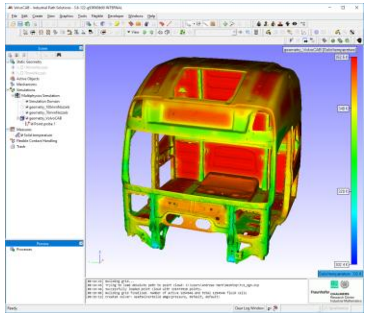
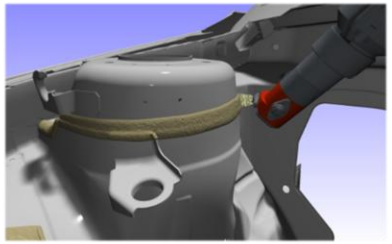
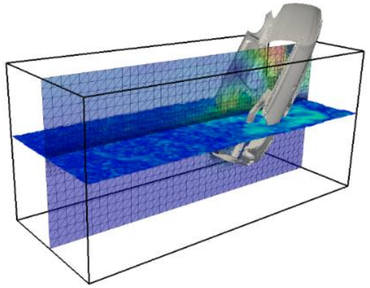
- Fast and accurate process simulation of the material laydown. Extension to adhesives.
- Automatic generation and programming of efficient robot motions

Oven Curing

- Robust and accurate CFD-based approach including conjugated heat transfer of air and solid temperatures

Electrocoating

- Efficient geometric method for access and drainage. Electrostatic simulation of e-coat layer build up

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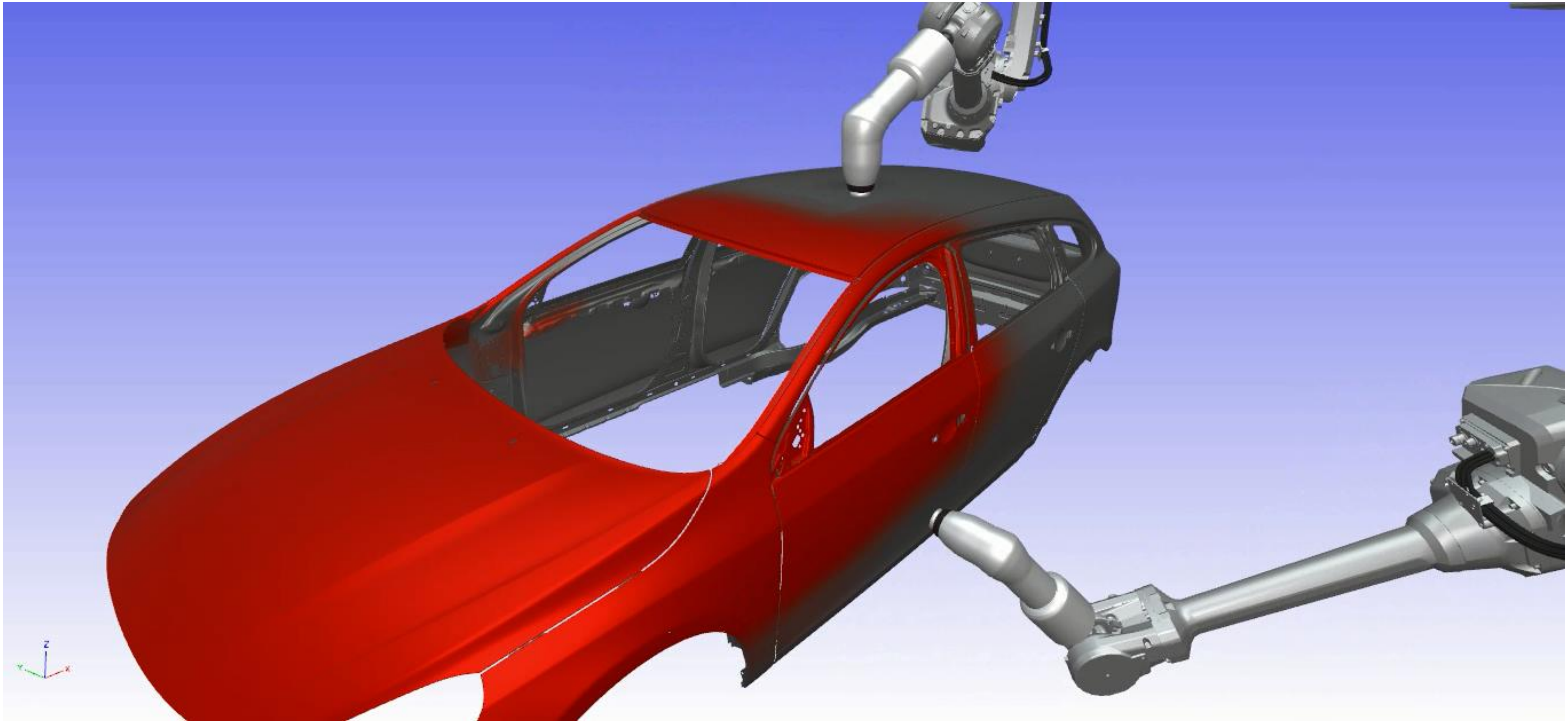
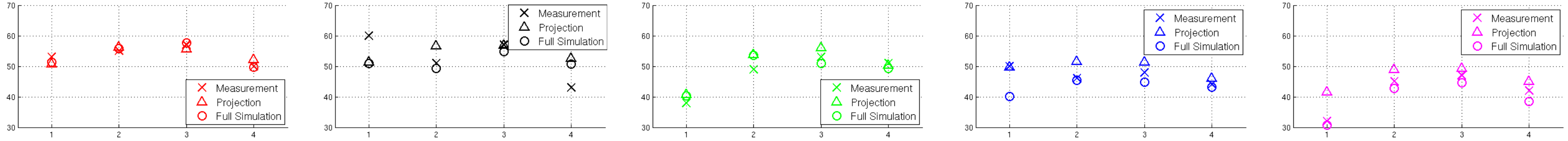
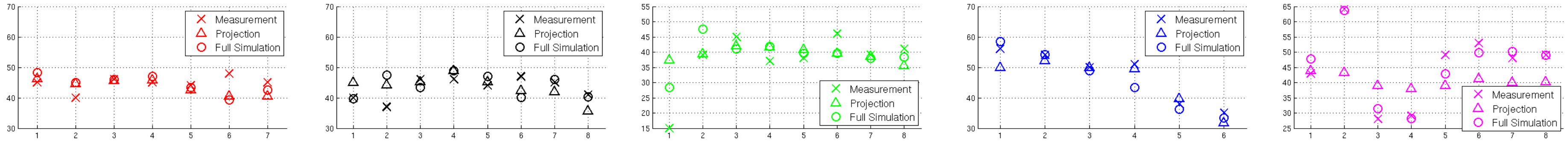


Truck cab validation

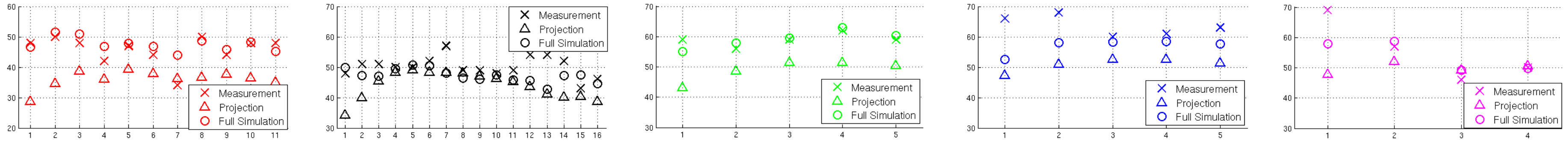
Cab side

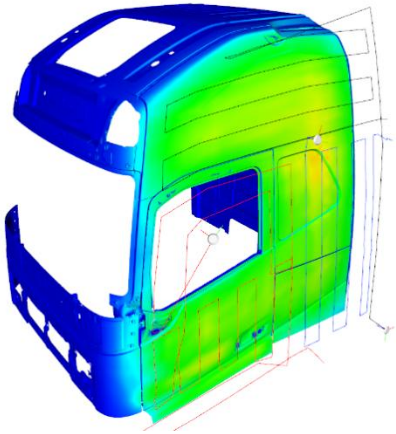


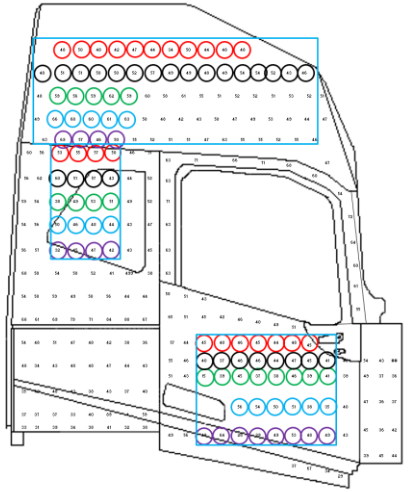
Cab door



Cab roof side







- Physics-based simulation shows excellent agreement
- Projection simulation shows good agreement

Virtual Paint - Spray TM

Virtual Paintshop – Autopaint

Develop methods, techniques and software to automate the product preparation in the paintshop by automatically generating robot paths and process conditions that guarantee a certain wanted paint coverage

Content

- State-of-the-art simulation technology
- Boost performance by AI generated, reduced models based on detailed simulations and measurement input
- Automatic generation of optimized robot programs
- Industrial case studies including wet paint and powder
- Project results packaged in user-friendly software

Expected results

- Improved homogeneity and **quality** of paint layers
- Reduced **commissioning time** for new products with significantly less physical testing
- Optimized **energy** and material consumption and increased **productivity** of the paint processes
- Technology and **knowledge transfer** between project actors

Workflow for Generation of Brush Libraries

Challenge

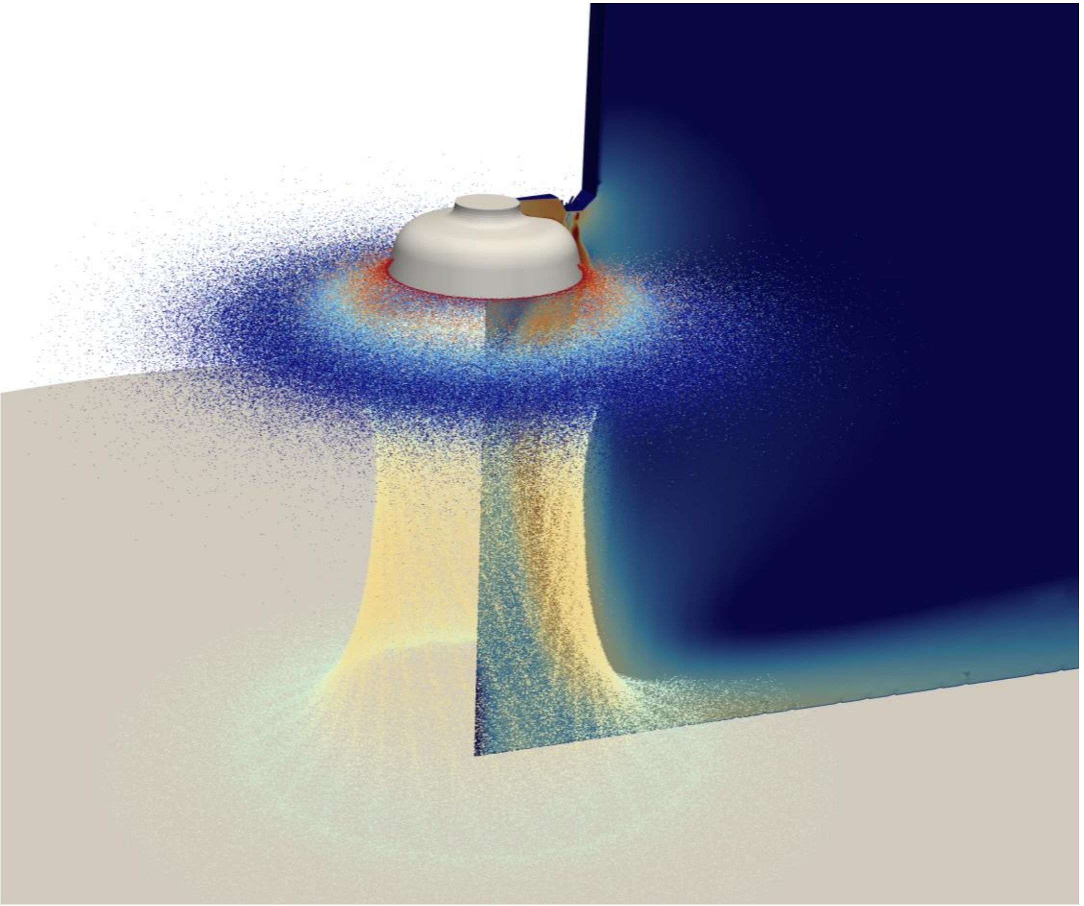
- Characterizing applicators through measurement is costly and requires specialized equipment
- Resolving the physics is very involved — instead, spray behavior is parametrized into a 'brush’
- Turning calibration into a multi-criteria optimization problem currently solved manually

Approach

- Replace manual brush fitting with AI-based surrogate models trained on detailed near-bell CFD simulations
- Mapping process parameters directly to optimal simulation settings

Deliverable

- Optimized single-brush generation, multi-criteria optimization for consistent brush libraries
- An AI surrogate trained on resolved near-bell simulations.



Two-way coupled and fully resolved near bell simulation

Capturing the multi-physics of rotary bell atomization

High-speed rotating bell cup

- Paint is fed onto a cup spinning at up to 60 000 RPM.
- Centrifugal force drives a thin liquid film to the bell edge, where it breaks up into ligaments and droplets.

Transonic shaping air

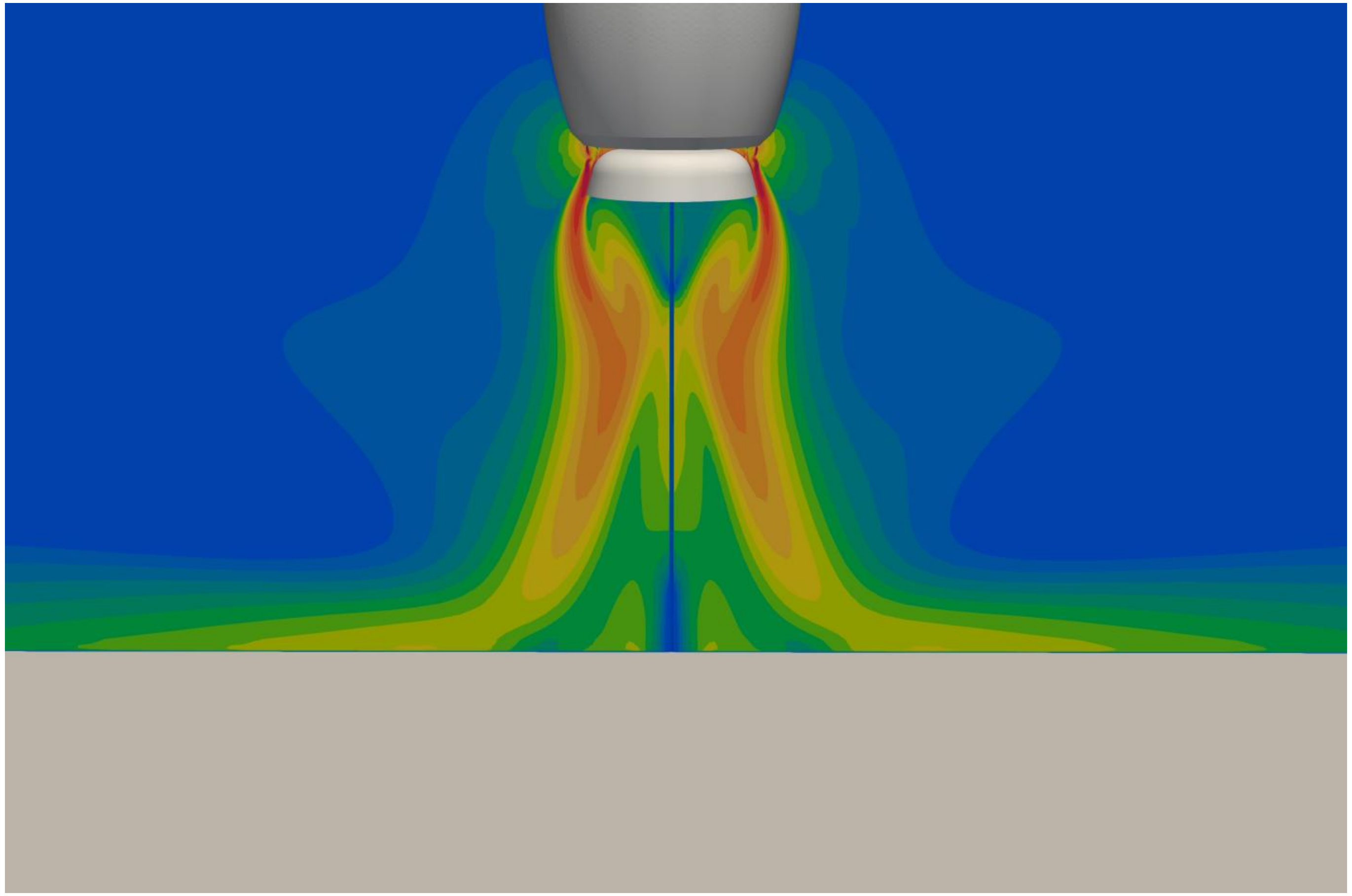
- Annular air jets surrounding the bell reach near-sonic velocities
- Directing and focusing the resulting spray cloud toward the target surface

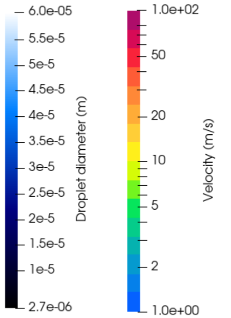
Compressible turbulent flow field

- The interaction between the high-swirl rotation and the shaping-air jets creates a complex three-dimensional flow that must be solved as compressible and turbulent

Lagrangian droplet transport

- Millions of individual paint droplets are tracked through the flow field, exchanging momentum and heat with the surrounding air





1. Movie of rotary bell atomization with spray cloud
2. Movie of rotary bell atomization (hidden spray cloud) to show two-way coupling effect of velocity field

Simulation shown is 35 ms physical time

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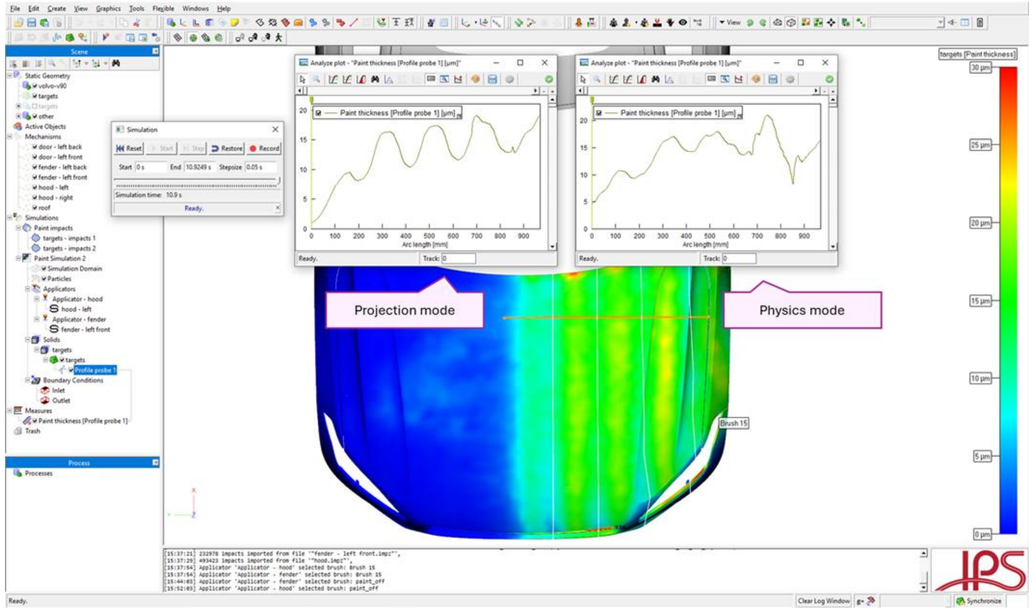
AI-boosted fast simulation methods

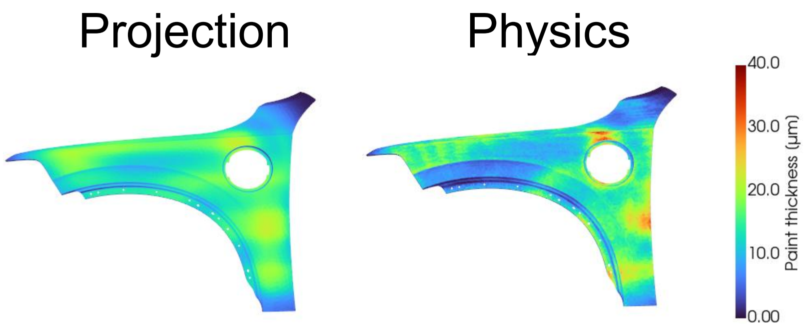
Methodology

- Train an AI model on the difference between detailed physical and projection simulations
- Crucial input to generate optimal robot programs

Deliverable

- An AI framework for fast paint simulations that combines projection simulations, and physics-based simulations





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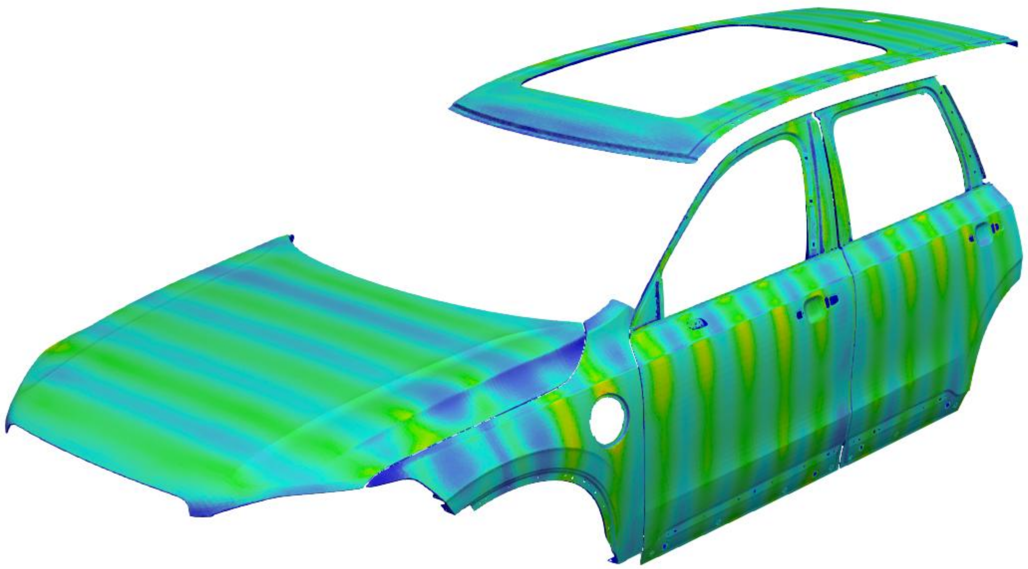
AI-boosted fast simulation training

Training

- Extract simulation data
  - Perform projection and CFD on same geometry and path
  - Extract current paint profile: paint thickness added during each timestep
  - Image generation using ray tracing
- Train AI network on difference between physics and projection simulation

AI-boosted Simulation:



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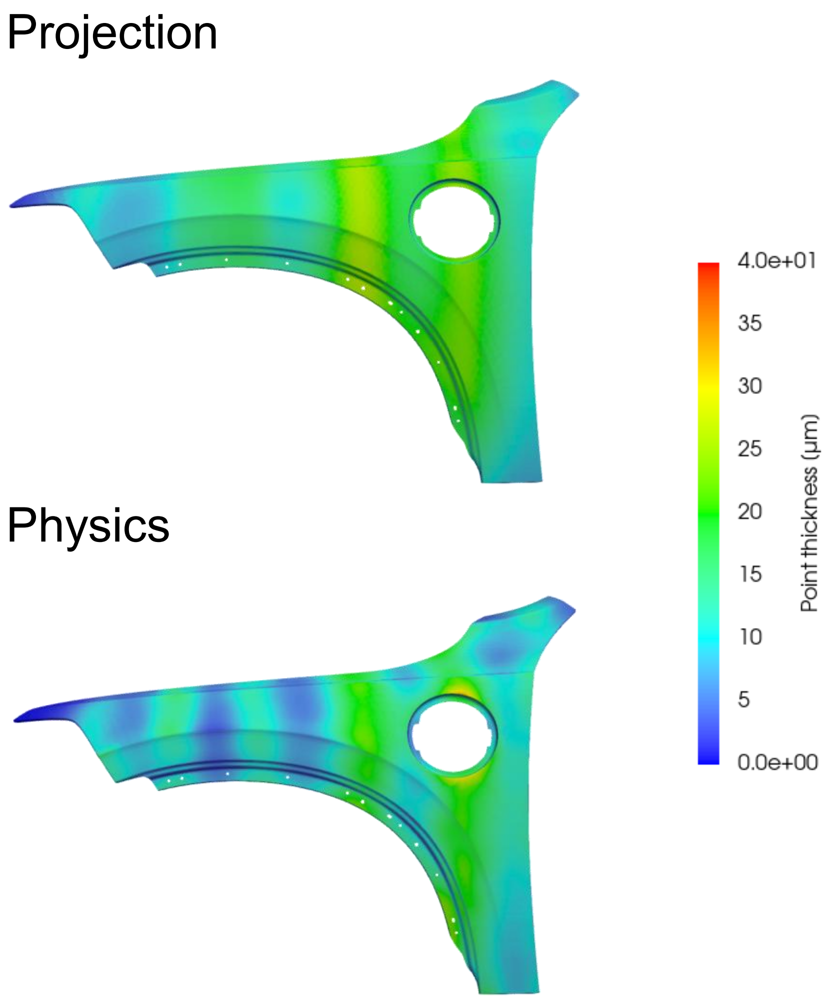

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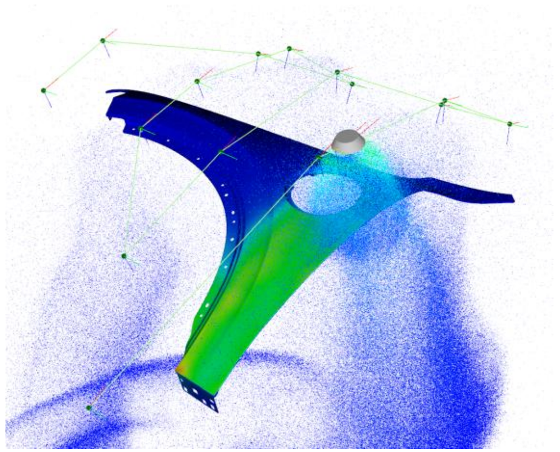

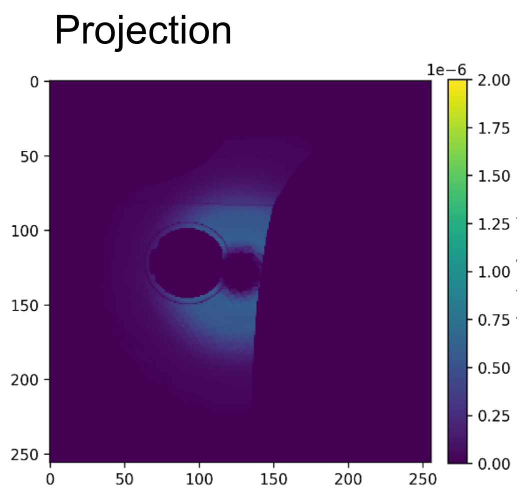

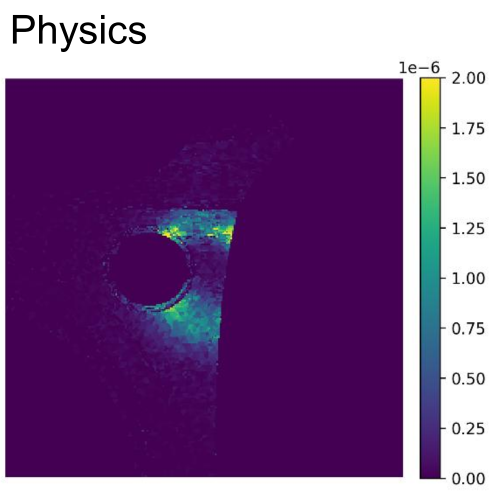

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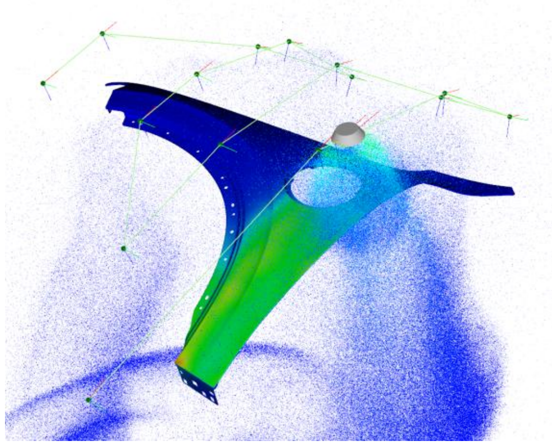
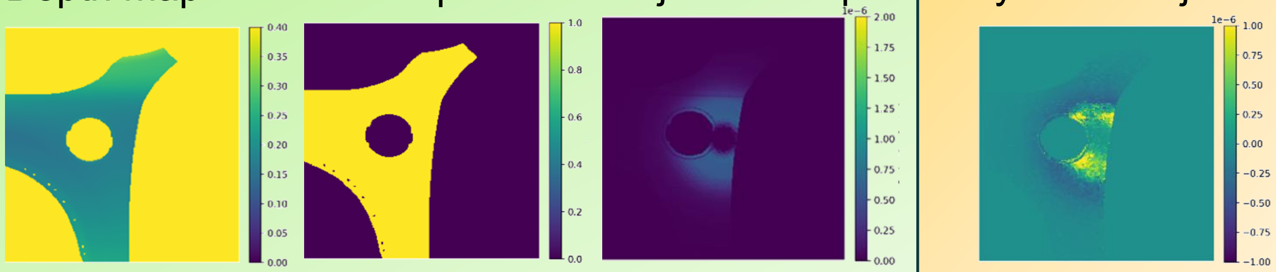


Network input:

Depth map | Hit map | Projection map

Training target:

Physics - Projection



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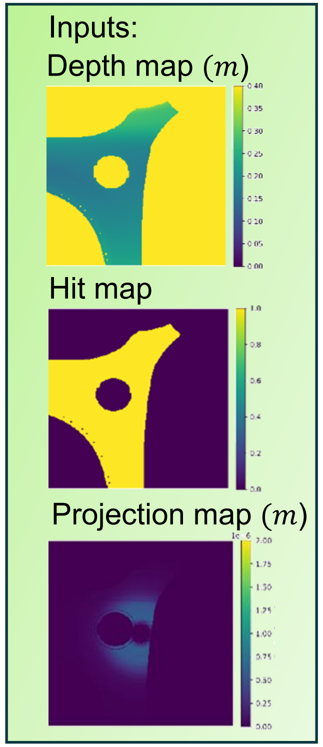
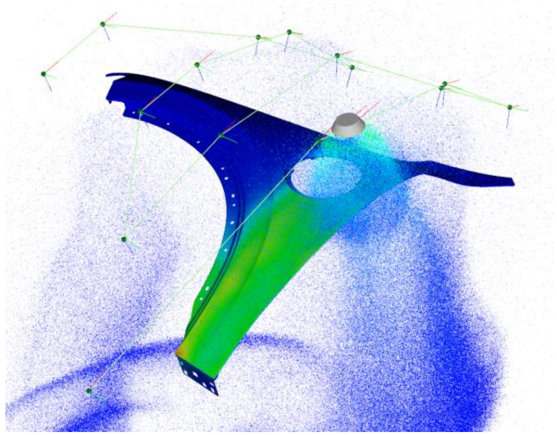
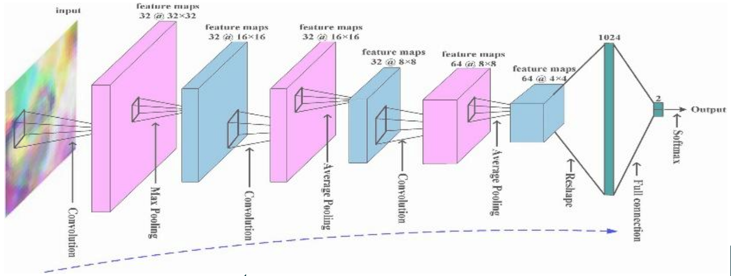
x

y

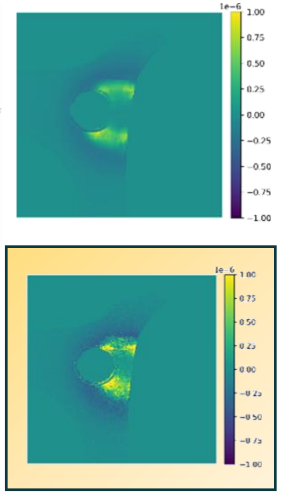
Network input







Backpropagate the loss between the model's prediction and the training target



Network label

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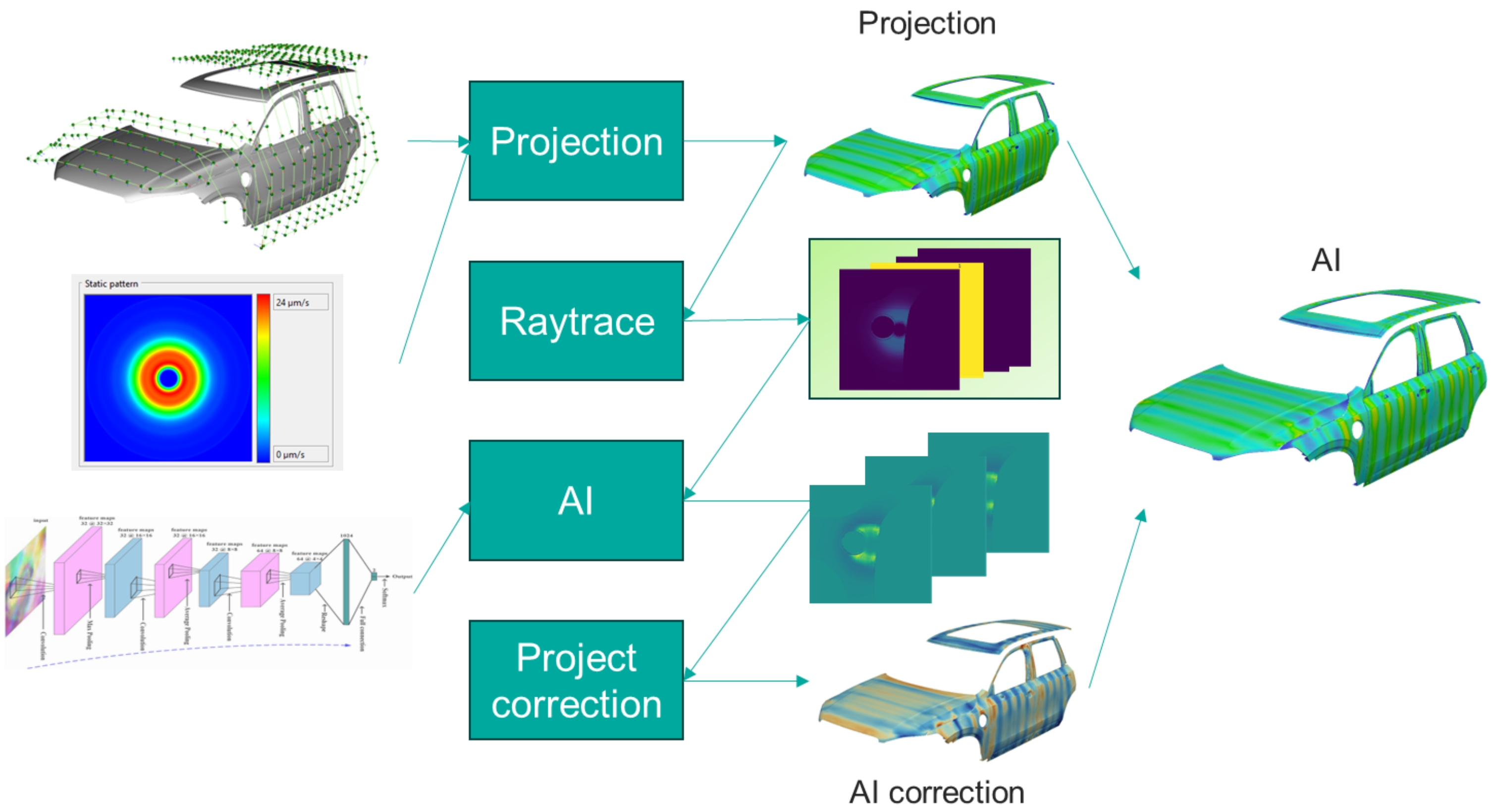
AI-boosted fast simulation – Apply AI model

Apply AI model

- Run projection simulation using the nozzle path, applicator file and object geometry
- Use ray tracing to generate image data from the projection results and pass it to a trained AI model
- Project and apply the AI-predicted correction to improve the projection simulation



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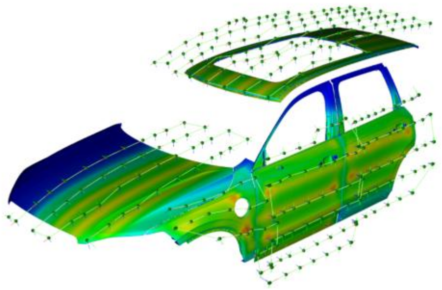
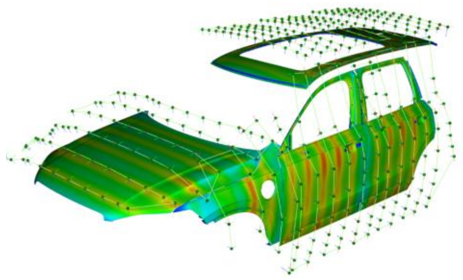
AI-boosted fast simulation results

Results

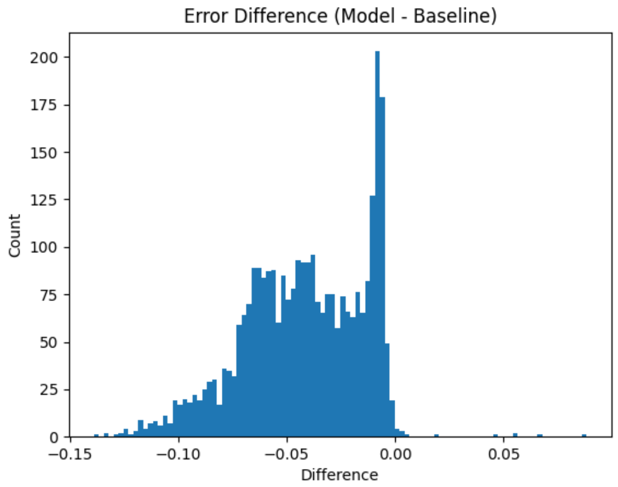
- Train AI model on simulations from one path and evaluate on a different path
- 55% decrease in MSE compared to the projection method on evaluation path
- Even improvement across parts
- The AI model outperforms* the projection method on almost all samples (99.6 % of time points)



Training path



Evaluation path



* error difference: $mean(|(AI_{error})| - |Proj_{error}|)$

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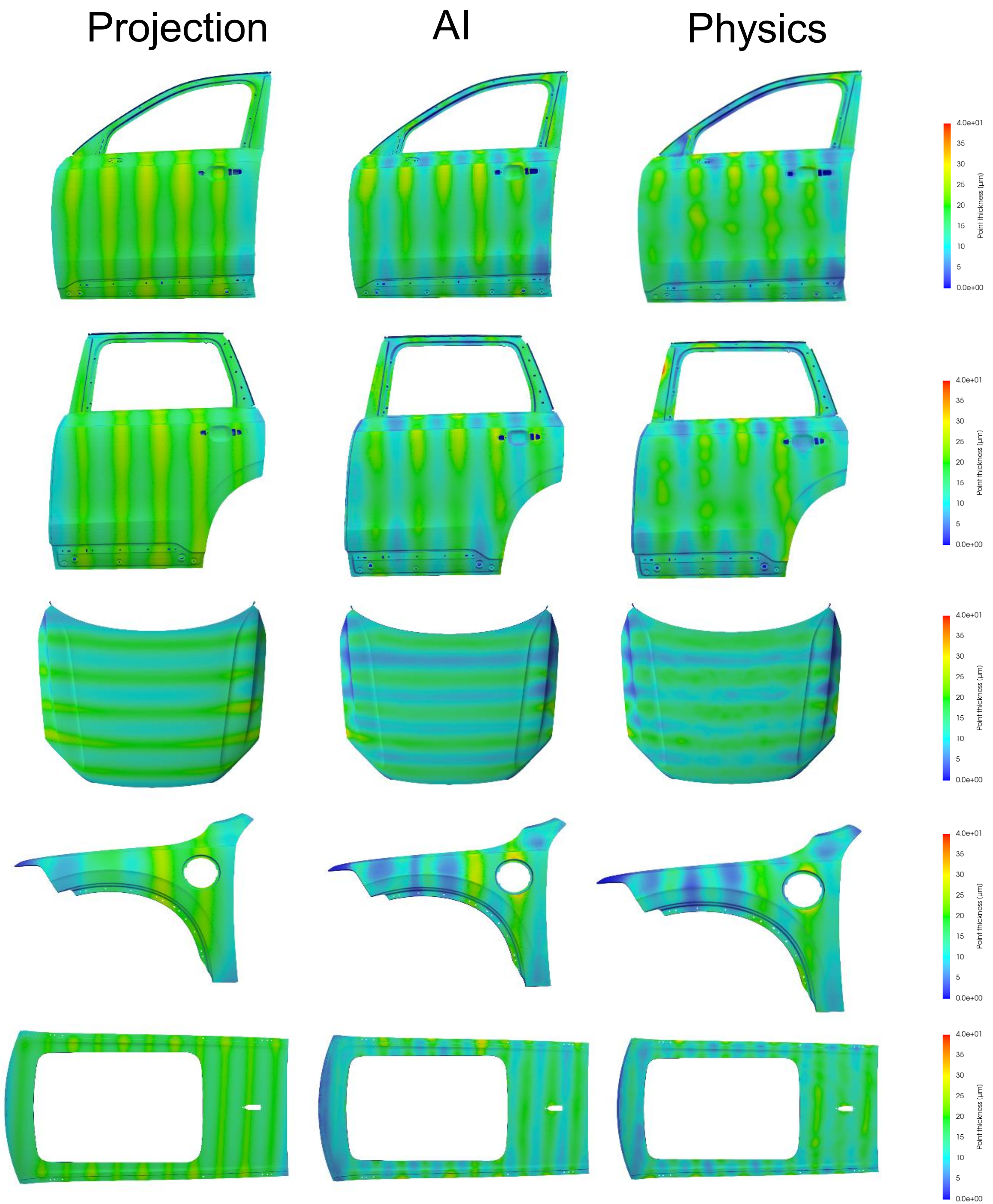
AI-boosted simulation

Results

- Improved accuracy compared to projection-based method
- Real-time simulation capability

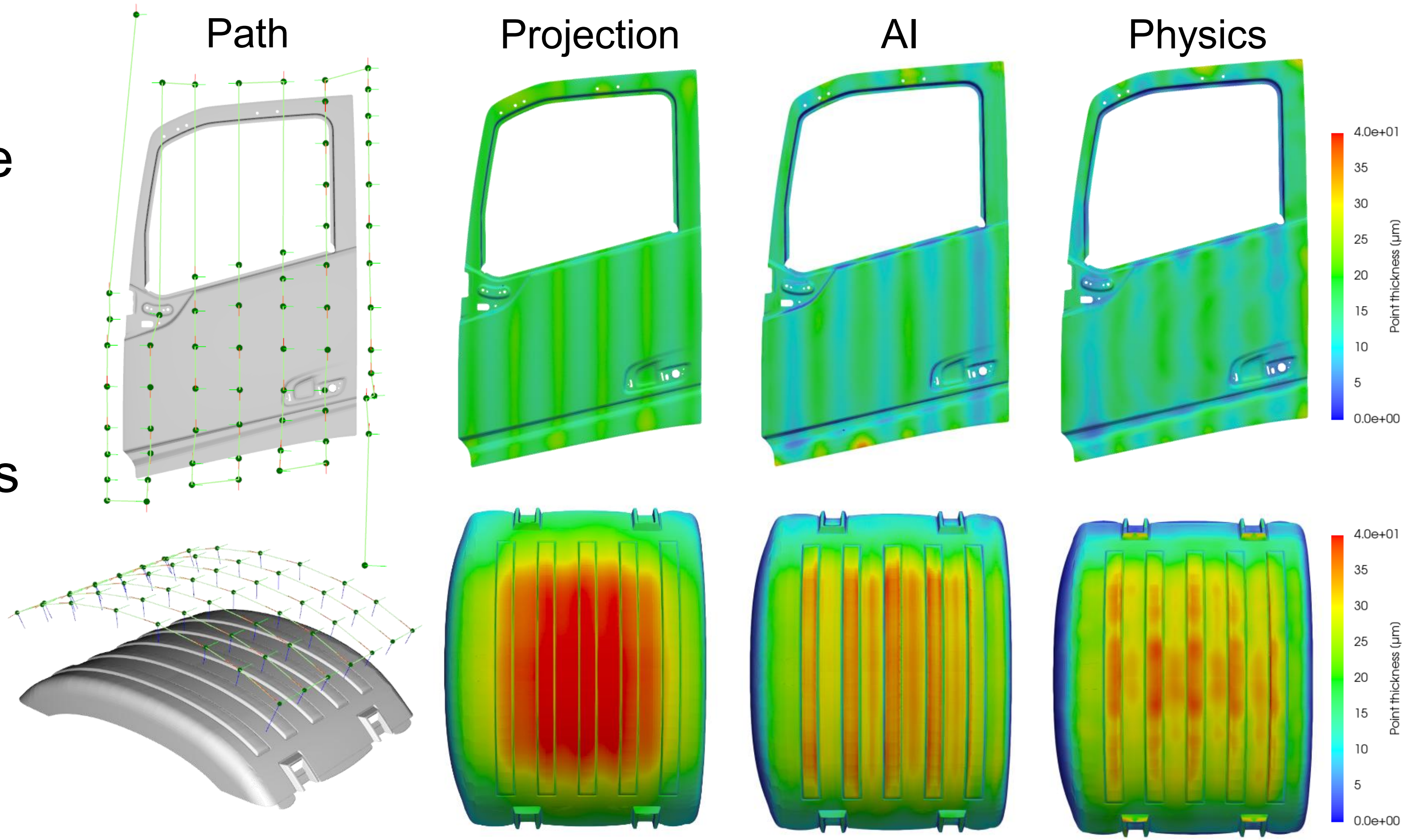
Geometry	Simulation time	Real time	Number of cells
Roof	8.3 s	24.3 s	131 546
Hood	9.6 s	16.7 s	590 357
Fender	3.7 s	6.0 s	48 390
DoorLB	10.1 s	13.9 s	635 180
DoorLF	9.8 s	15.0 s	554 045



AI-boosted fast simulation results

Results

- Generalizes well to geometries similar to the training data.
- Learned corrections transfer across similar shapes and features
- More diverse geometries are needed to achieve broader generalization

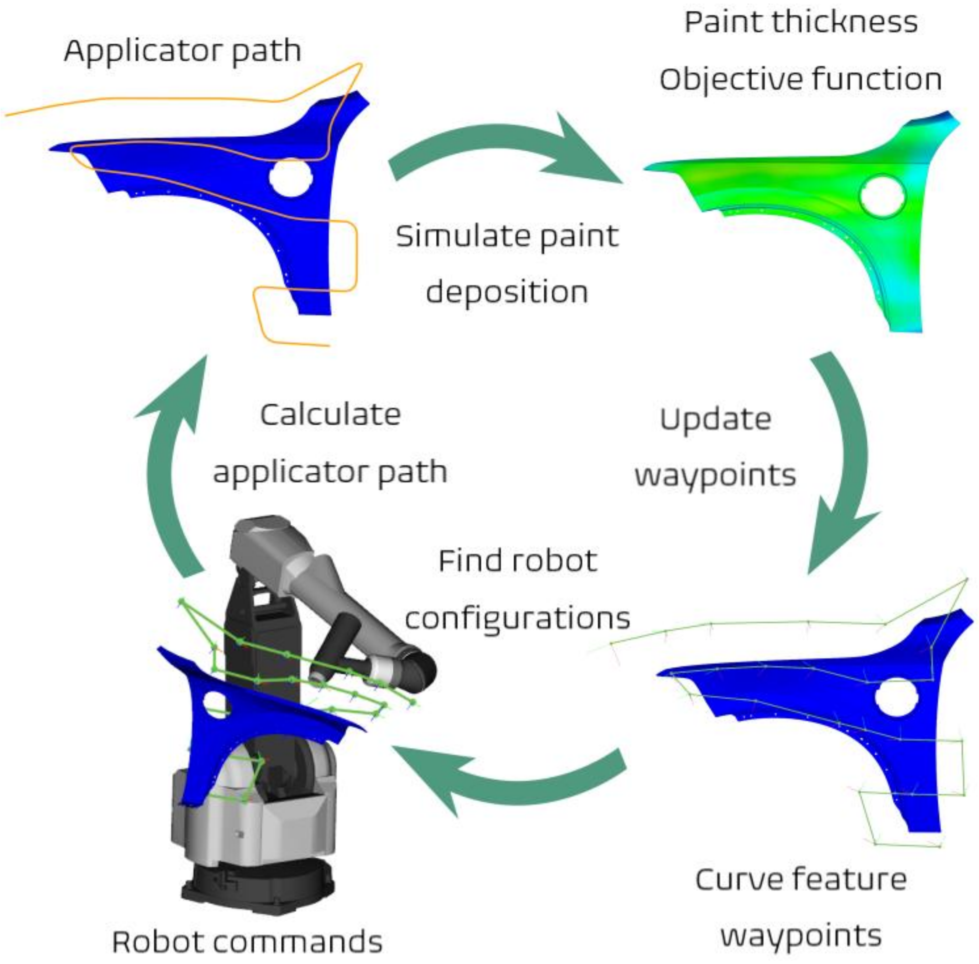


Optimization Methodology

Methodology

- Efficient evaluation of paint deposition enables painting trajectory optimization
- CMA-ES* black box optimization is used to find optimal paint trajectories
- Robot controller simulation is included in the loop for accurate applicator paths
- Robot code parameters are used as optimization variables to enable robot code export of optimal solutions

**Covariance matrix adaptation evolution strategy*



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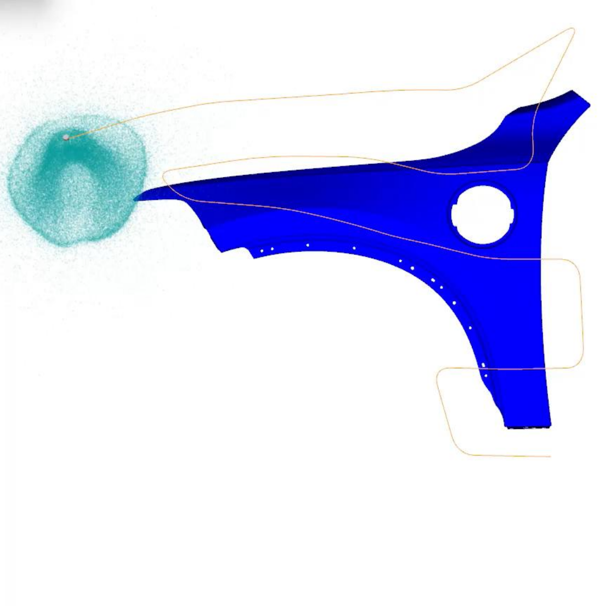
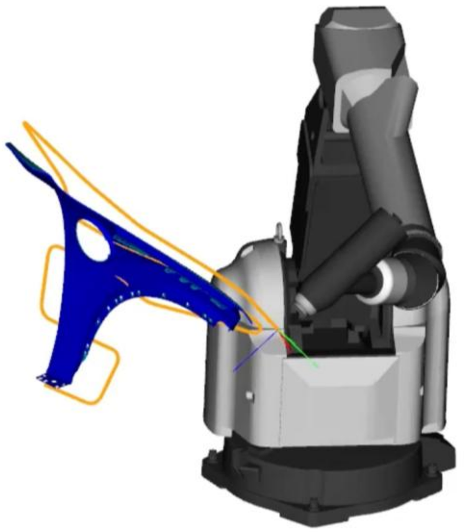
Optimization Results





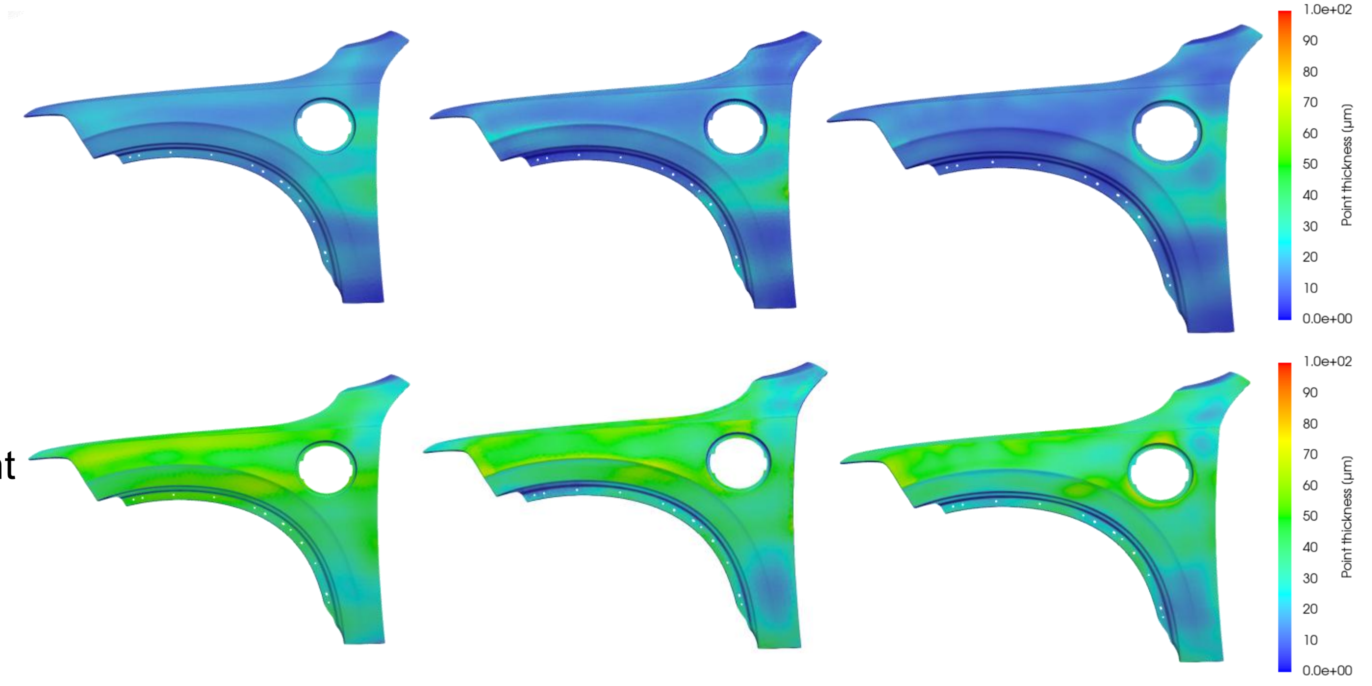
Results

- The target thickness is set to 50 μm
- The projection method is used to evaluate the resulting paint thickness
- Future work will integrate the AI framework into the optimization loop to improve the results

Projection | AI | Physics

Initial paint coverage:

Optimized paint coverage:



Summary

- From days to minutes: AI-enhanced simulation enables accurate, real-time prediction of spray painting processes
- Future work in AutoPaint
  - Robost generation of optimized robot paths
  - Industrial validation through wet paint and powder case studies
  - Expanded database covering more parts, geometries and spray equipment
  - Refined AI algorithms and improved software workflow
  - Integration of methods and algorithms into a software prototype
- Our aim is the virtual paintshop where modeling, simulation and optimization are used to
  - increase quality
  - reduce energy and material consumption
  - shorten product preparation time
  - facilitate efficient automation
- IPS Virtual Paint used by more than 20 companies
  - Global customers are automotive OEMs and suppliers, furniture industry

Thank you!

Get in touch:

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