The Virtual Paint Shop

Fraunhofer

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Research Centre
Industrial Mathematics

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Vice Director

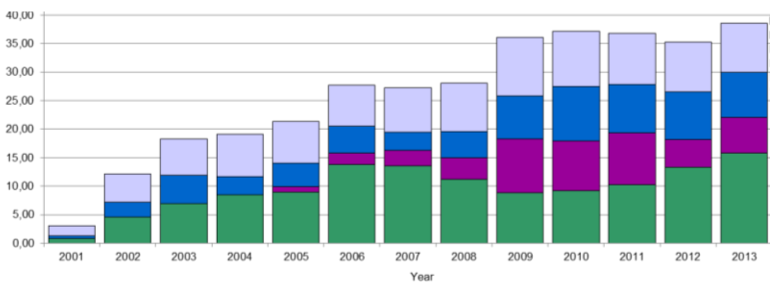
Workshop Math for the Digital Factory
WIAS Berlin, May 18 2014

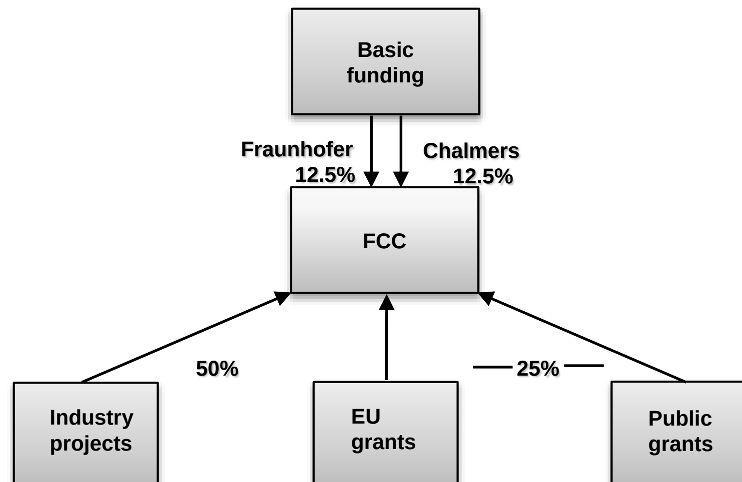
Fraunhofer-Chalmers Centre for Industrial Mathematics

- Founded 2001 by the Fraunhofer Gesellschaft and Chalmers University of Technology
- Offers applied mathematics for a broad range of industrial applications
- Projects defined by companies and public institutes on a commercial basis
- Pre-competitive research and marketing with financing from its founders

2001 **2013**

4 employees **50 full time eq.**





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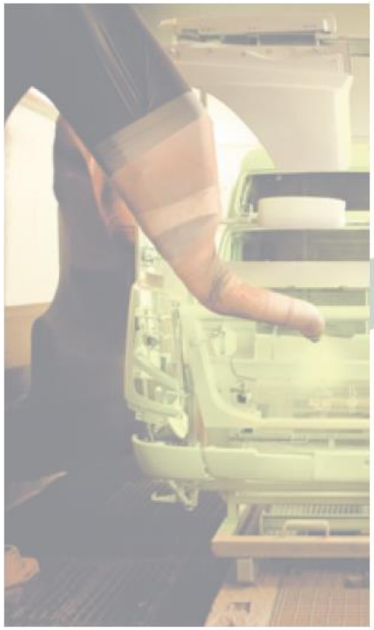
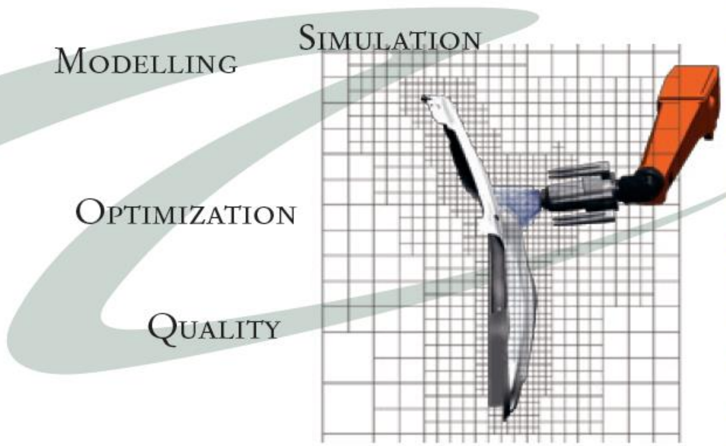
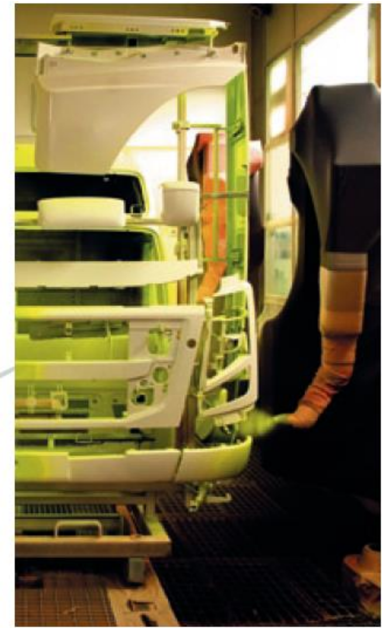
We offer a process for Industrial Innovation







Modelling, Simulation and Optimization of products and processes boost technical development, improve efficiency and cut costs of both large and small businesses.

More than 100 clients and 200 projects

- Short term consultancy projects
- Tailored software development and training
- Long term research collaborations

Mainly towards

- Automotive
- Wood and paper
- Pharmaceuticals

Upcoming

- Electronics
- Energy

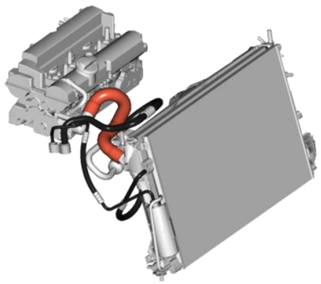
FCC Departments

Geometry
and Motion Planning

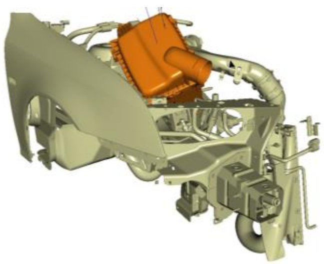
Computational
Engineering and Design

Systems
and Data Analysis

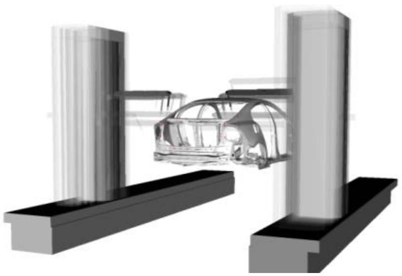
IPS is a math based software tool for automatic verification of assembly feasibility, design of flexible components, motion planning and optimization of multi-robot stations, and simulation of key surface treatment processes. IPS successfully implements the potential of the virtual world.



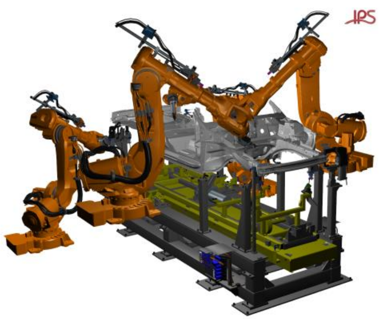
Flexible Structure Simulation



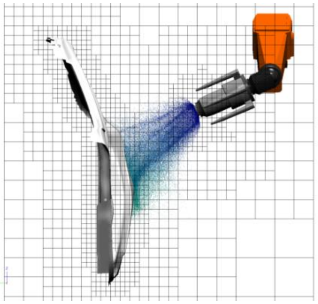
Assembly Path Planner



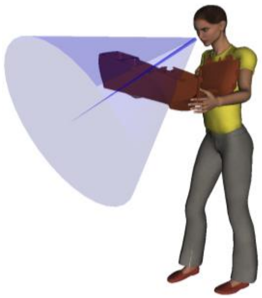
Inspection Path Planner



Robot Path Planner



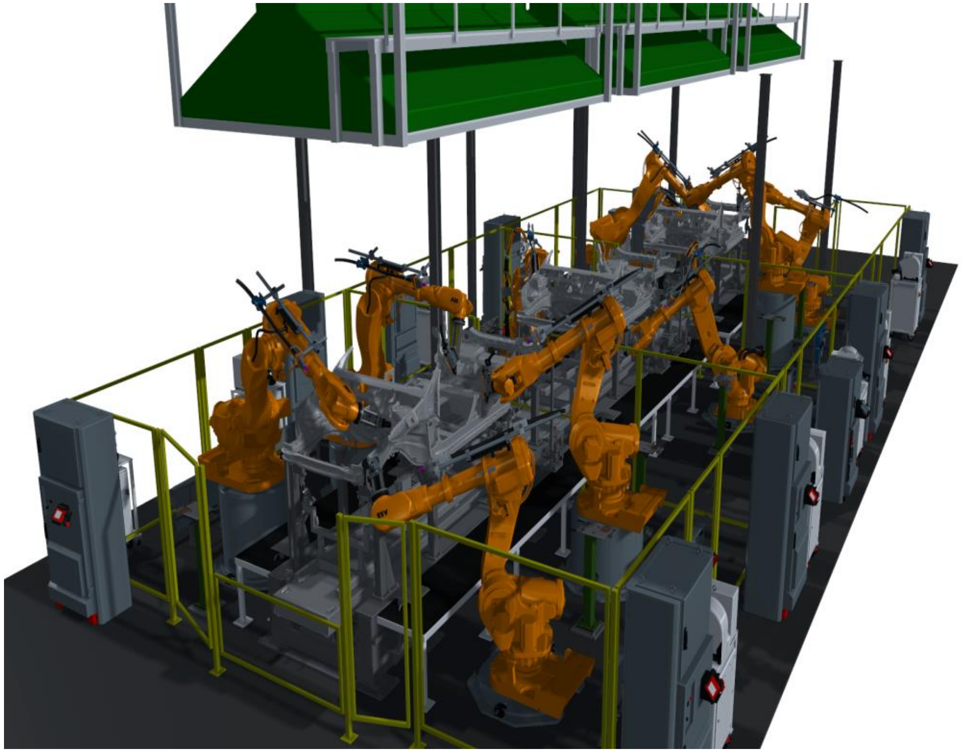
Virtual Paint



IMMA

Optimization of Multi-Robot Station Lines

Algorithms and software for automatic collision free motion planning and cycle time optimization



Results

- 75% faster commissioning
- 25% improved cycle time

➡ Work efficiency
  - Cost
  - Speed
  - Quality
  - Flexibility

➡ Energy
  - Lower consumption

➡ Work environment
  - Physical

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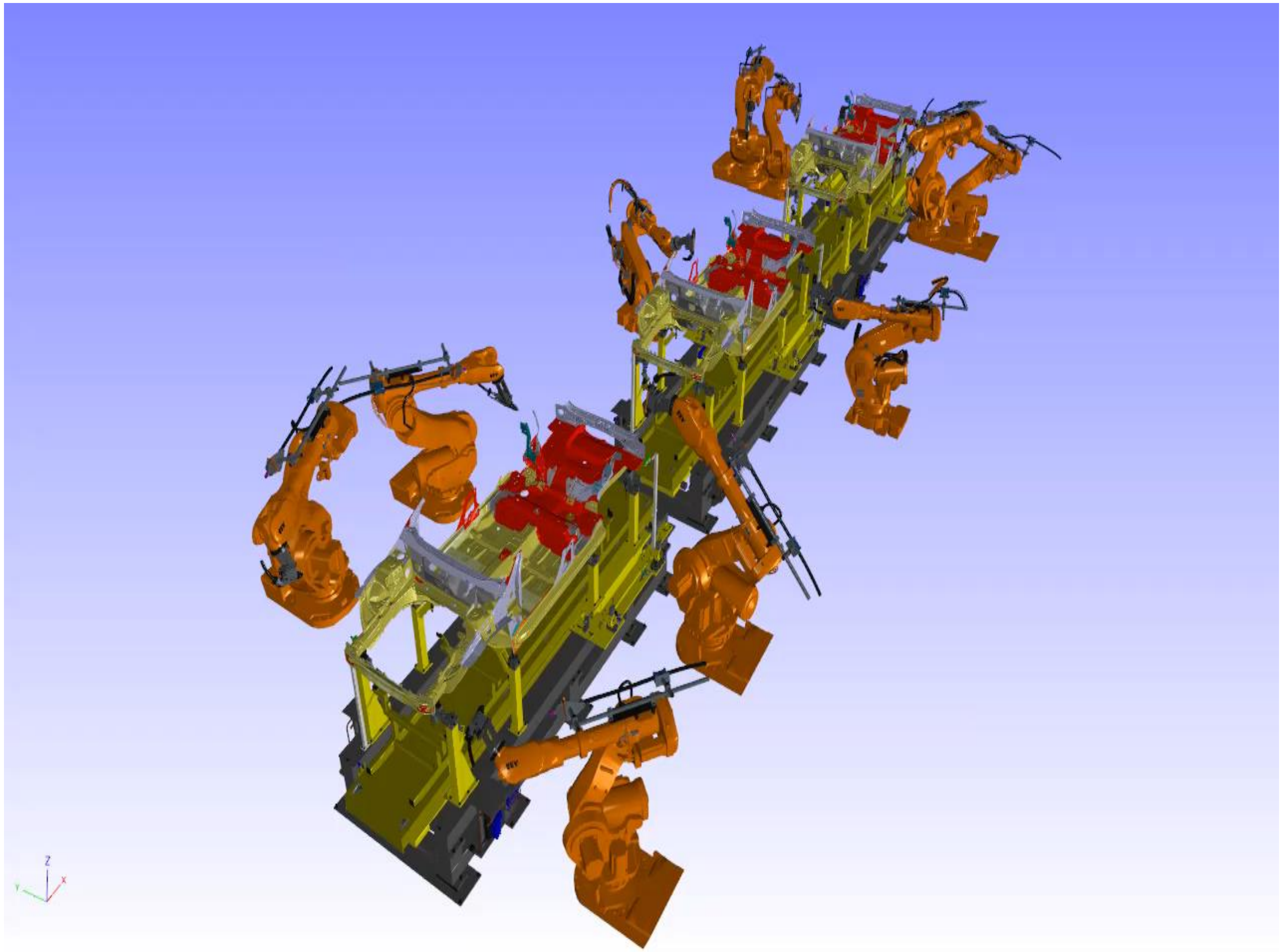
Line Balancing and Automatic Path Planning



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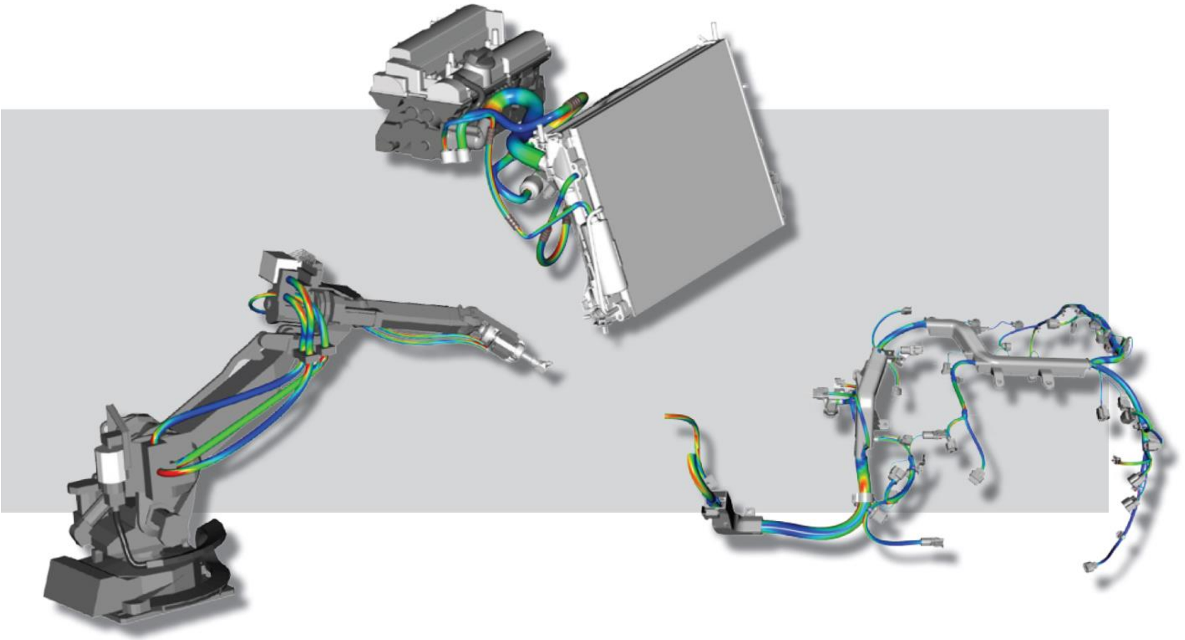
Design and Simulation of Flexibles

Methods and digital tools for efficient geometrical packing, assembly path planning and analysis of flexible parts

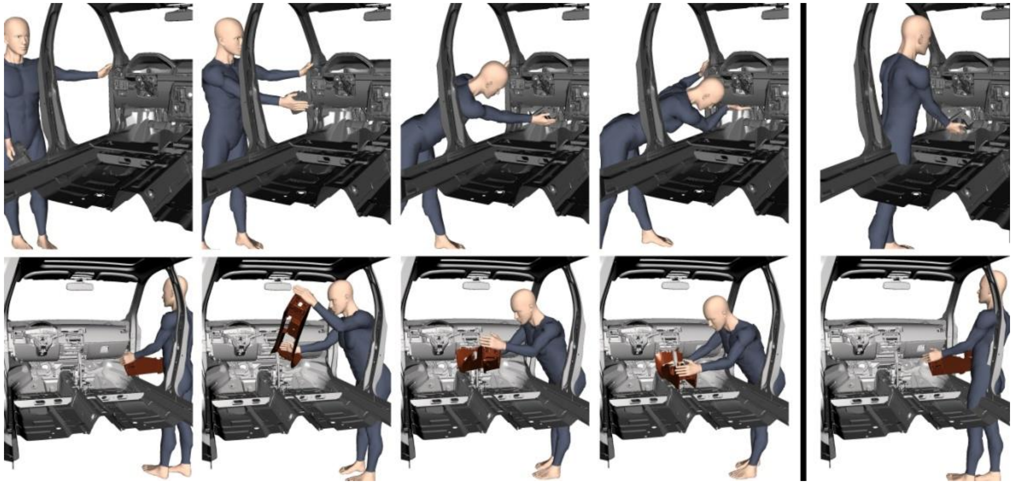
- Work efficiency
  - Quality
  - Speed
  - Flexibility
  - Cost
- Materials
  - Less prototypes
  - Increased life lengths
  - Less raw materials
- Work environment
  - Physical

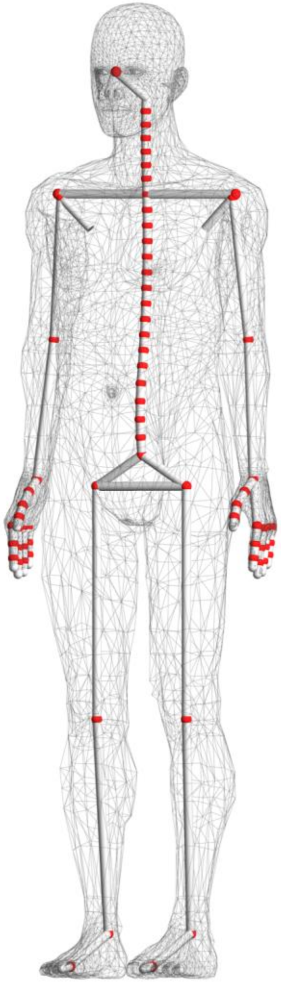


IMMA – Intelligently Moving Manikin

Development of simulation tools and methods for automatic path planning of collision free manual assembly considering ergonomics and human anthropologic diversity

- ➡Work environment
    - Physical
- ➡Work efficiency
    - Quality
    - Speed
    - Flexibility
    - Cost





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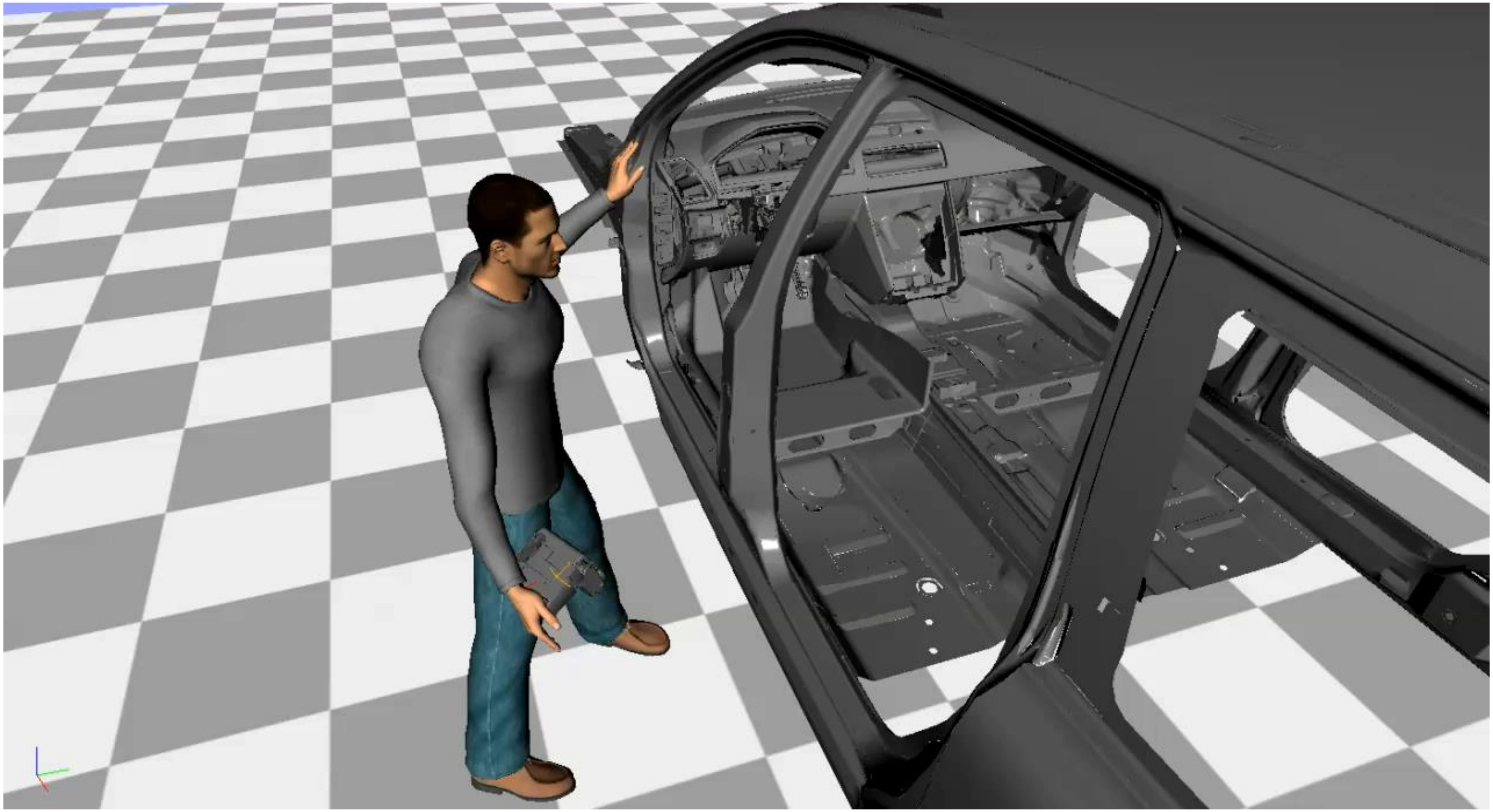
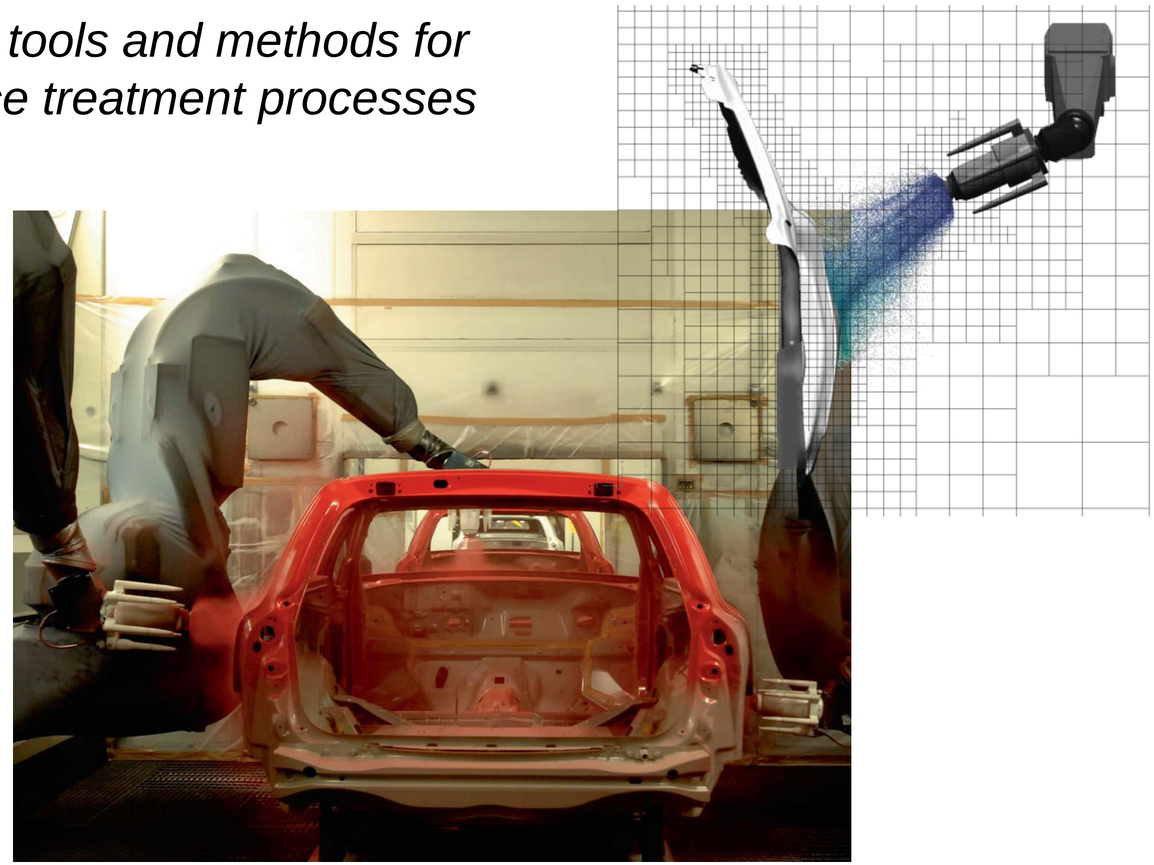


Virtual Paint Shop

Development of simulation tools and methods for prediction of the key surface treatment processes

- *Work efficiency*
  - *Quality*
  - *Speed*
  - *Flexibility*
  - *Cost*
- *Materials*
  - *Less prototypes and paint*
- *Energy*
  - *Lower consumption*
- *Work environment*
  - *Physical*



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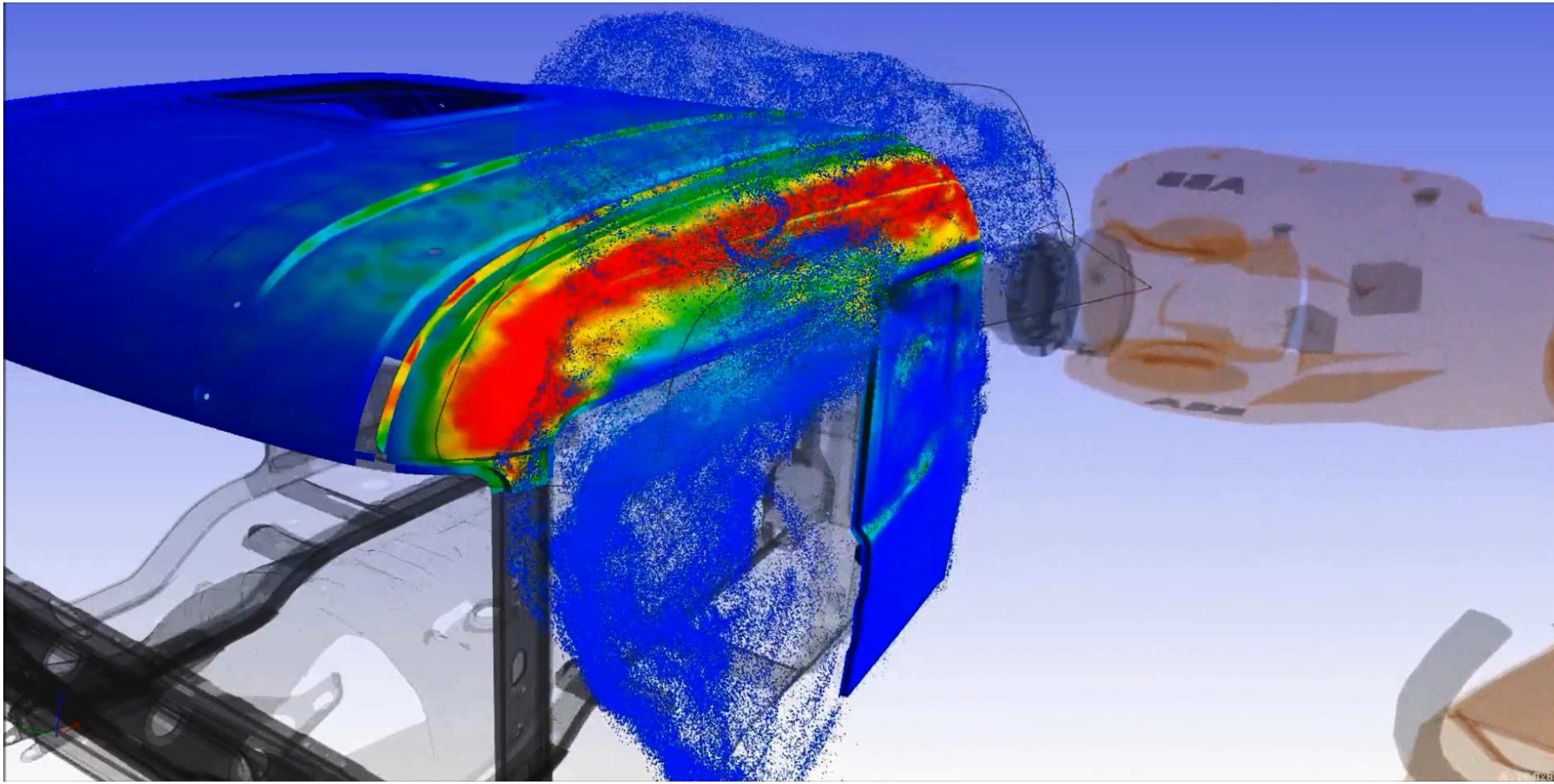

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VOLVO

SCANIA

VOLVO

FORDONS
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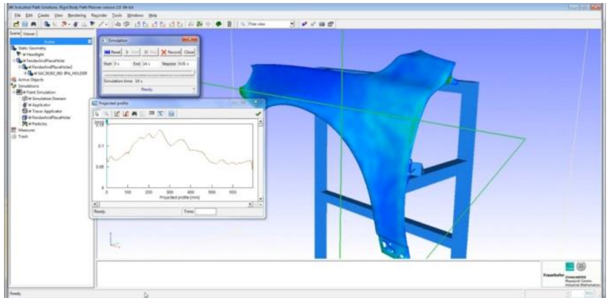
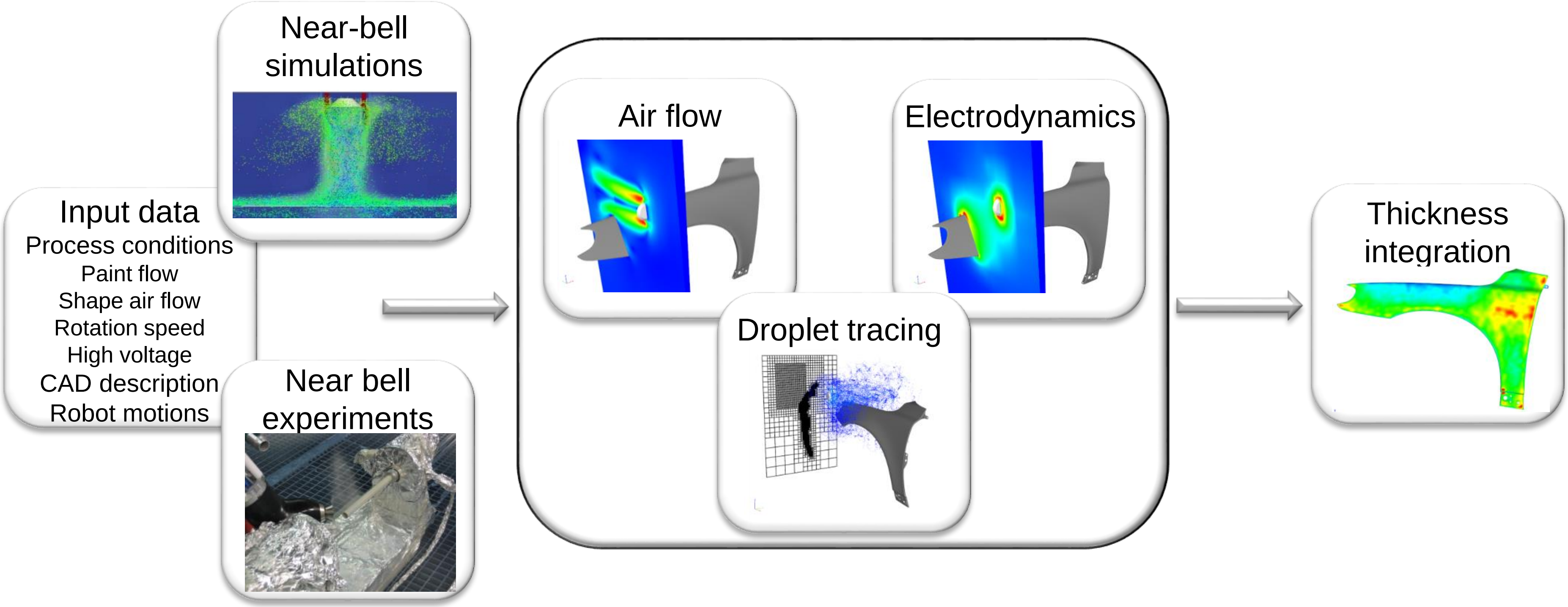
Virtual Spray Painting





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The model: Governing equations - internally charged paint

Incompressible Navier-Stokes equations:

$$\rho_f \frac{\partial \bar{u}}{\partial t} + \rho_f \bar{u} \cdot \nabla \bar{u} = -\nabla \mathrm{p} + \mu \nabla^2 \bar{u} + \bar{s}$$

$$\nabla \cdot \bar{u} = 0$$

Particle equation of motion:

$$\rho_p \frac{d\bar{u}_p}{dt} = (\rho_p - \rho_f)\bar{g} - \bar{u}_r |\bar{u}_r| C_d \frac{\rho_f}{\rho_p} \frac{m_p}{2r_p} + q_p \bar{\mathrm{E}}$$

Poisson's equation:

$$\nabla^2 \phi = -\frac{\rho}{\epsilon}$$

$$\bar{\mathrm{E}} = -\nabla \phi$$

Thickness integration of particle impacts:

$$T_d(x) = \frac{1}{h^2 S_K \sqrt{|\boldsymbol{D}|}} \sum_{i=1}^{n} V_i K \left(\frac{\sqrt{(\bar{x} - \bar{x_i})^T \boldsymbol{D}^{-1} (\bar{x} - \bar{x_i})}}{h} \right)$$

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A. Mark, R. Rundqvist, F. Edelvik, “Comparison Between Different Immersed Boundary Conditions for Simulation of Complex Fluid Flows”, FDMP, 7(3), 2011.

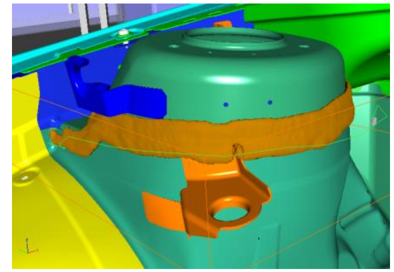
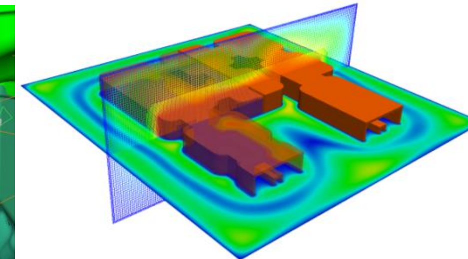
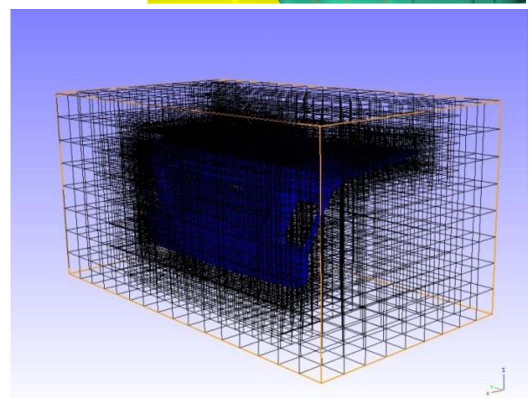
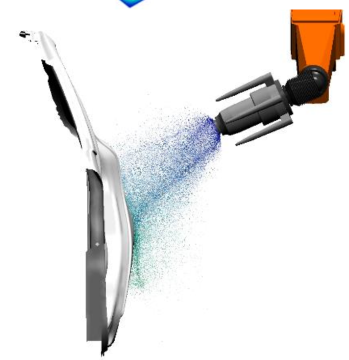
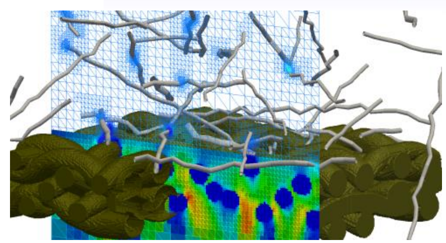
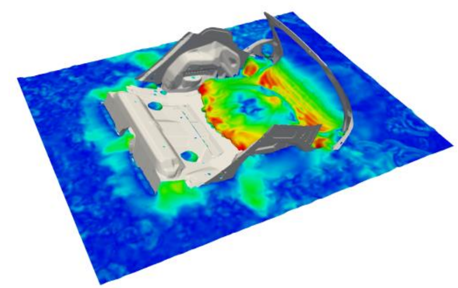
S. Tafuri, F. Ekstedt, J. S. Carlson, A. Mark, F. Edelvik, “Improved Spray Paint Thickness Calculation From Simulated Droplets Using Density Estimation”, ASME 2012.

A. Mark, B. Andersson, S. Tafuri, K. Engström, H. Söröd, F. Edelvik, J. S. Carlson, “Simulation of Electrostatic Rotary Bell Spray Painting in Automotive Paint Shops”, Automization & Sprays, 23(1), 2013.

– Immersed Boundary Octree Flow Solver

IBOFlow

- Incompressible Navier-Stokes solver
- Co-located finite volume discretization
- SIMPLEC pressure velocity coupling
- Fully dynamic and automatic refinement and coarsening of Cartesian octree grid
- Novel immersed boundary methods
- GPU solver
- Modules
  - Particle and spray models
  - Turbulence models
  - Volume of fluids
  - Structural dynamics
  - Heat transfer
  - Electrostatics

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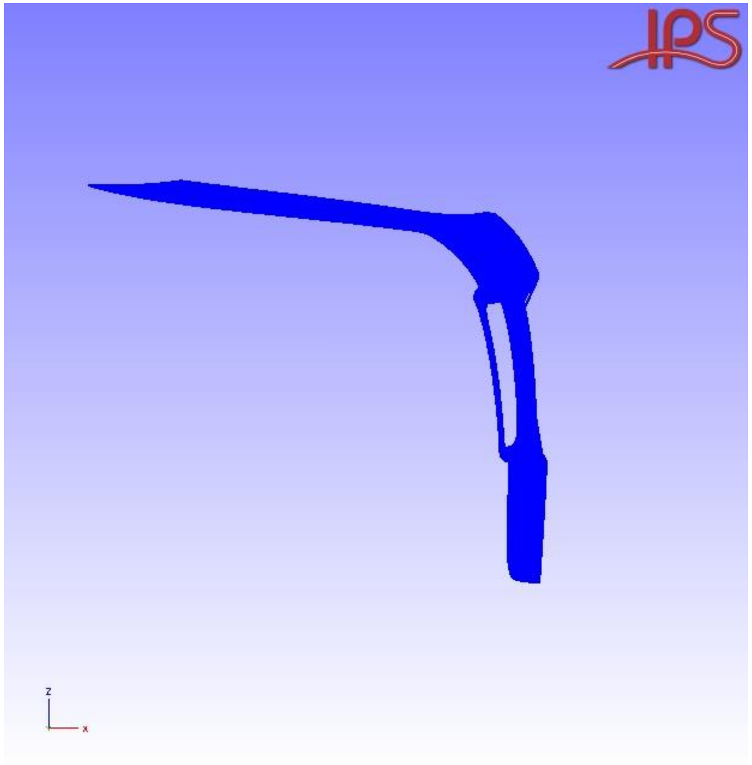
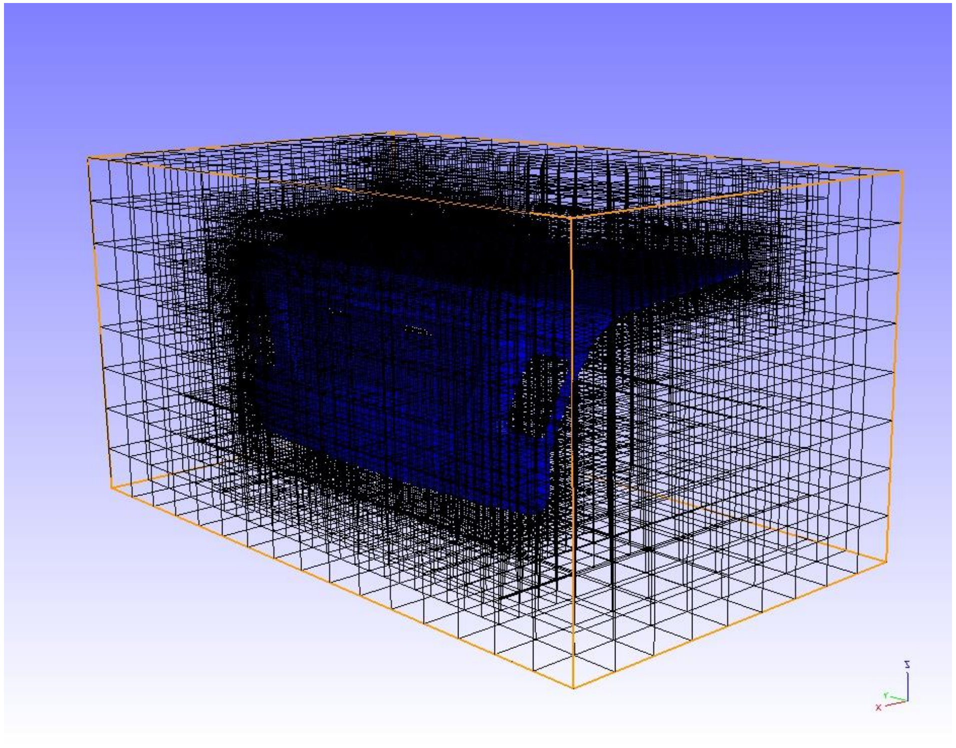
Automatic generation and refinement of background grid





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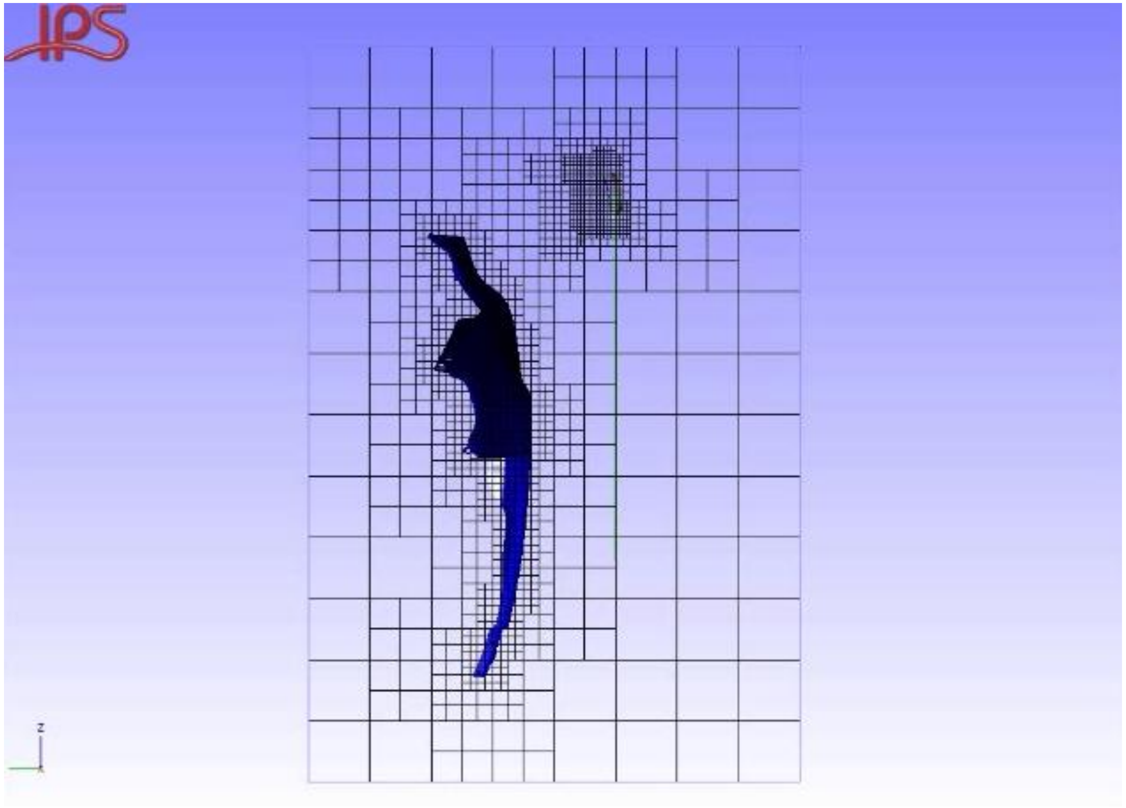
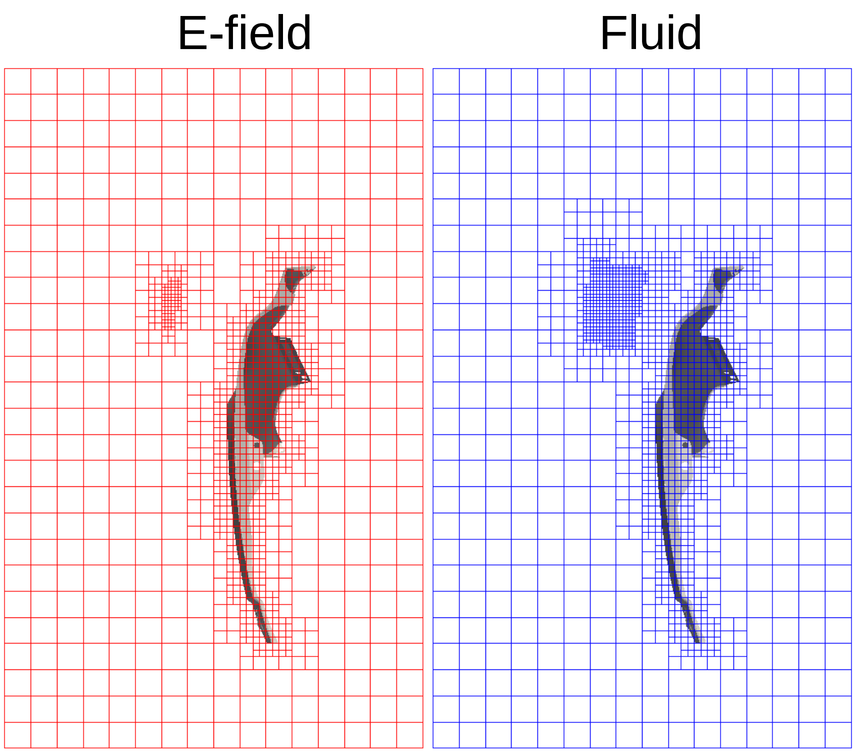
Dynamic grid refinements around moving objects

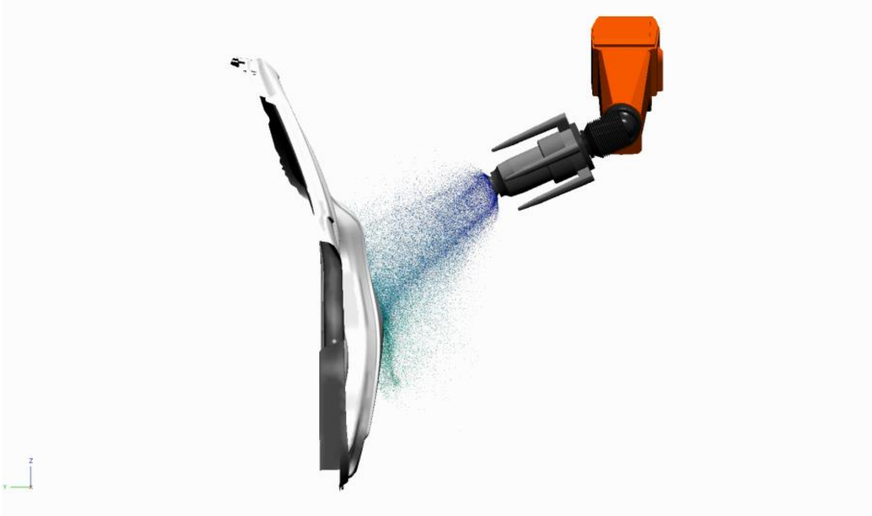


E-field solver

- Paint droplets are charged
- Fluid and E-field solvers handle different physics
- Two computational grids
  - Edge effects
  - Different refinement levels
- Poisson’s equation
- Electric field
- Uses the same discretization stencil as the fluid solver
- Moving objects are also handled by immersed boundary method



Paint droplets

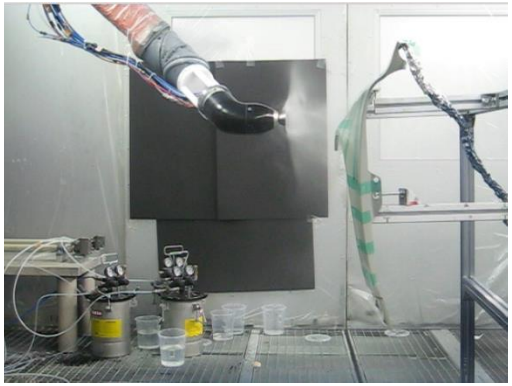


- Simulated as Lagrangian particles
- Basset-Boussineq-Oseen equation
- Sundials ODE solver
- Adaptive time stepping
- Two way fluid and E-field coupling
- Octree search tree

$$\rho_p \frac{du_{pi}}{dt} = (\rho_p - \rho_f)\, g_i - u_{ri}\, |u_r|\, C_d \frac{\rho_f}{\rho_p} \frac{m_p}{2r_p} + E_i q_p$$

Validation campaigns

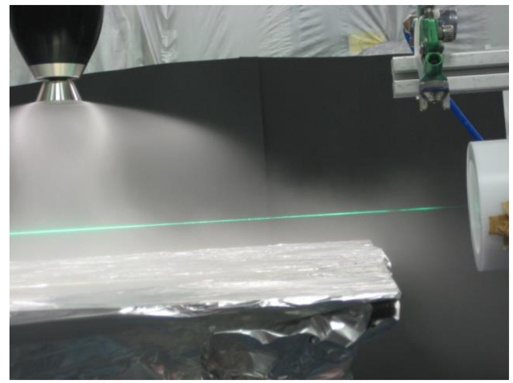
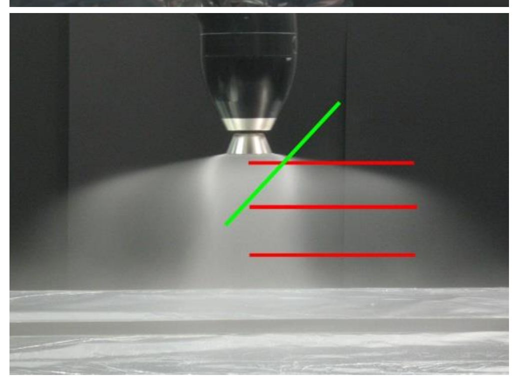
- Volvo Cars 2011
  - V60 car fender, plates
  - Dürr Ecobell 2 atomizer, internally charged
  - Clear coat
  - Measurements performed at Fraunhofer IPA, Stuttgart
- General Motors NA 2012
  - Car hood, car door
  - Dürr Ecobell 2, internally charged
  - Clear coat
- Volvo Cars 2013
  - Full car
  - Atomizers ABB G1, ABB RB1000, internally charged
  - Clear coat, base coat, filler
- General Motors NA 2013
  - Full car
  - Atomizer Fanuc, internally charged
  - Base coat

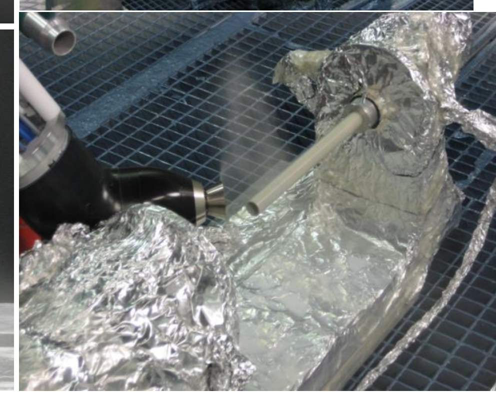


Fender campaign

Input data

- Paint properties (clear coat)
  - Density, dry content, viscosity, surface tension
- Robot path and velocity (300 mm/s)
- Object CAD description
- Process data
  - Paint flow 330 ml/min ± 20%
  - Shape air 260 slpm ± 20%
  - Rotation speed 40000 rpm ± 20%
  - Downdraft speed 0.3 m/s
  - High voltage 70 kV



Experimental input

- Particle size distribution (Malvern)
- Air velocities close to bell cup (LDA)
- Painted horizontal and vertical plates
- Pictures of spray cone

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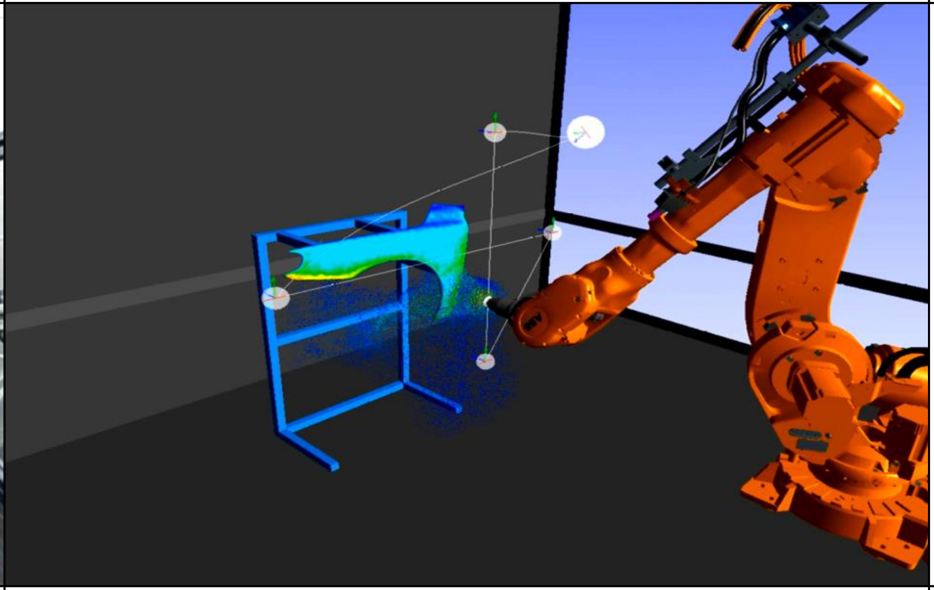
A. Mark, B. Andersson, S. Tafuri, K. Engström, H. Söröd, F. Edelvik, J. S. Carlson, “Simulation of Electrostatic Rotary Bell Spray Painting in Automotive Paint Shops”, Automization & Sprays, 23(1), 2013.

Volvo V60 Car Fender



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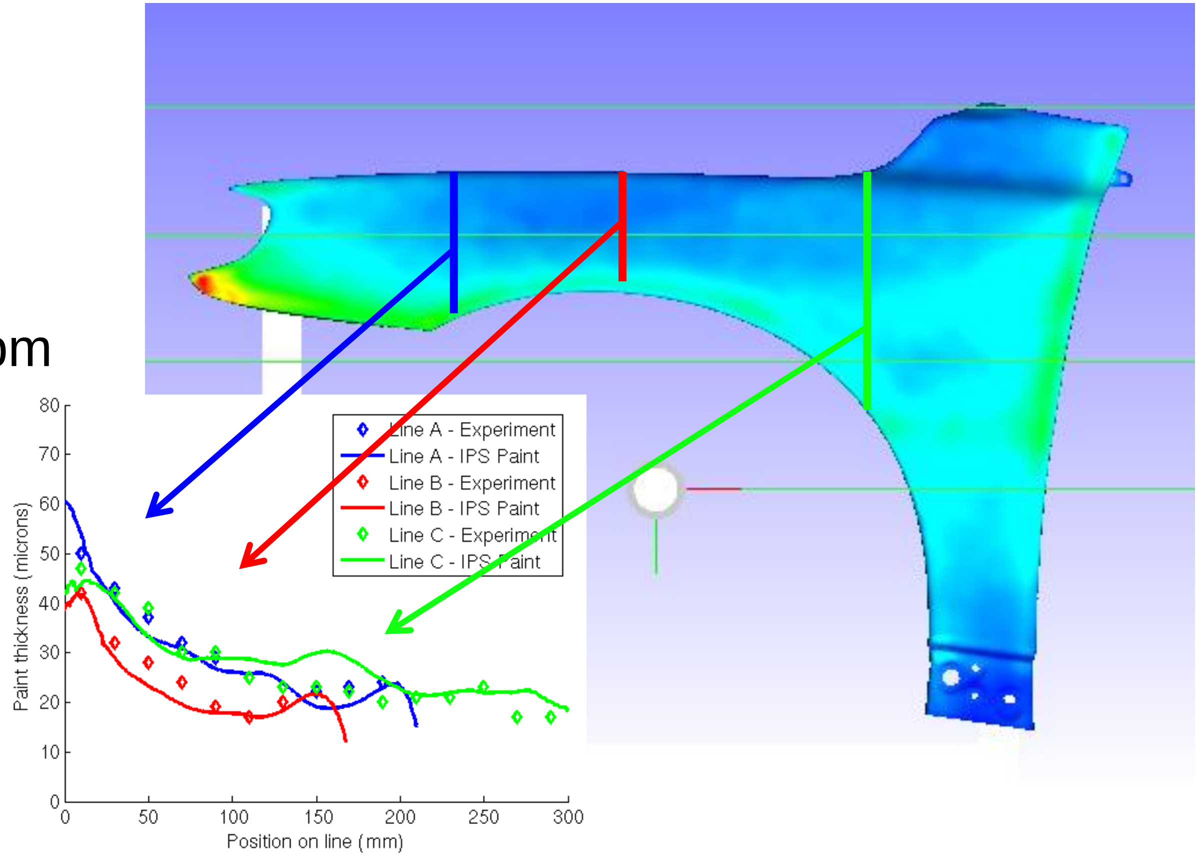
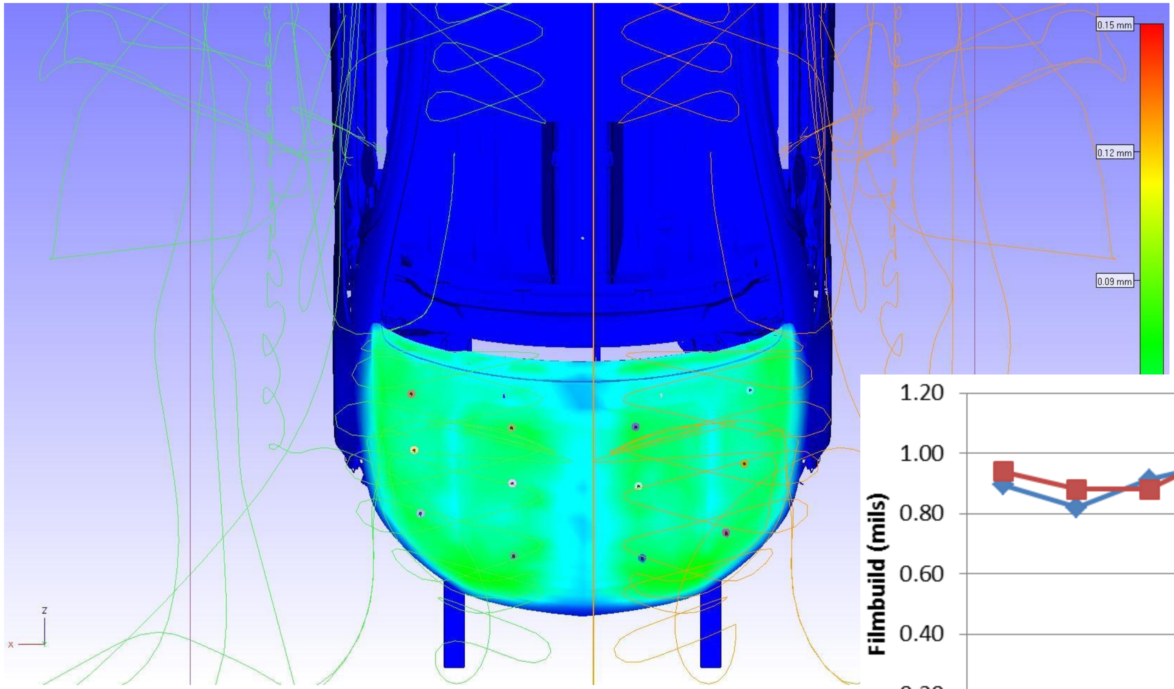
Fender Validation – Oscillating motion

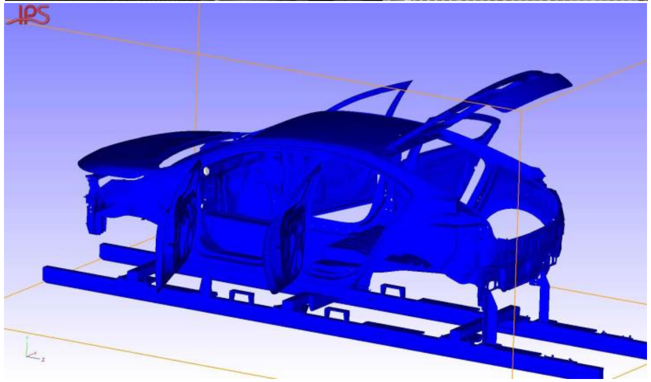
- Volvo V60 fender
- Internally charged Dürr Ecobell 2 atomizer
- Clear coat paint
- Shaping air flow 260 slpm
- Paint flow 330 ml/min
- Rotation speed 40000 turns/min
- Downdraft 0.3 m/s
- Bell voltage 70 kV
- Robot speed 300 mm/s

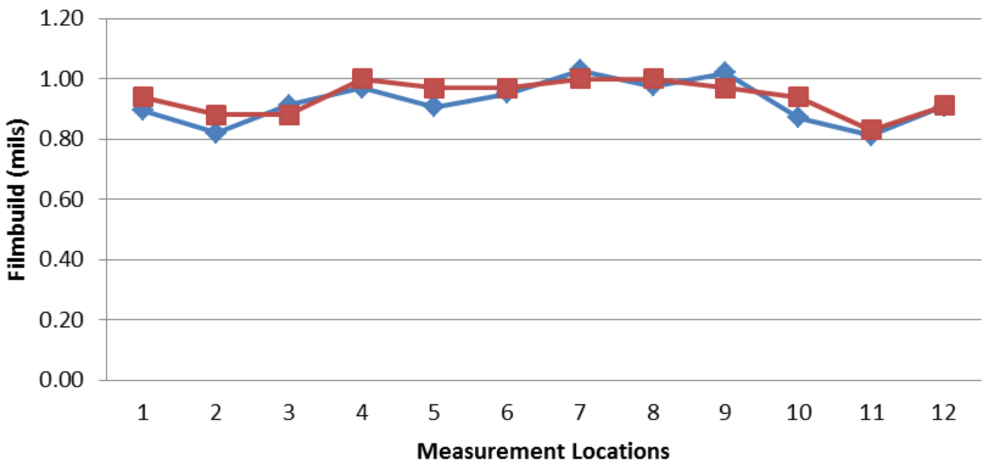


Exterior filmbuild on GM Volt

- Atomizer Fanuc, internally charged
- Four robots spraying
- Code 50 Summit white base coat







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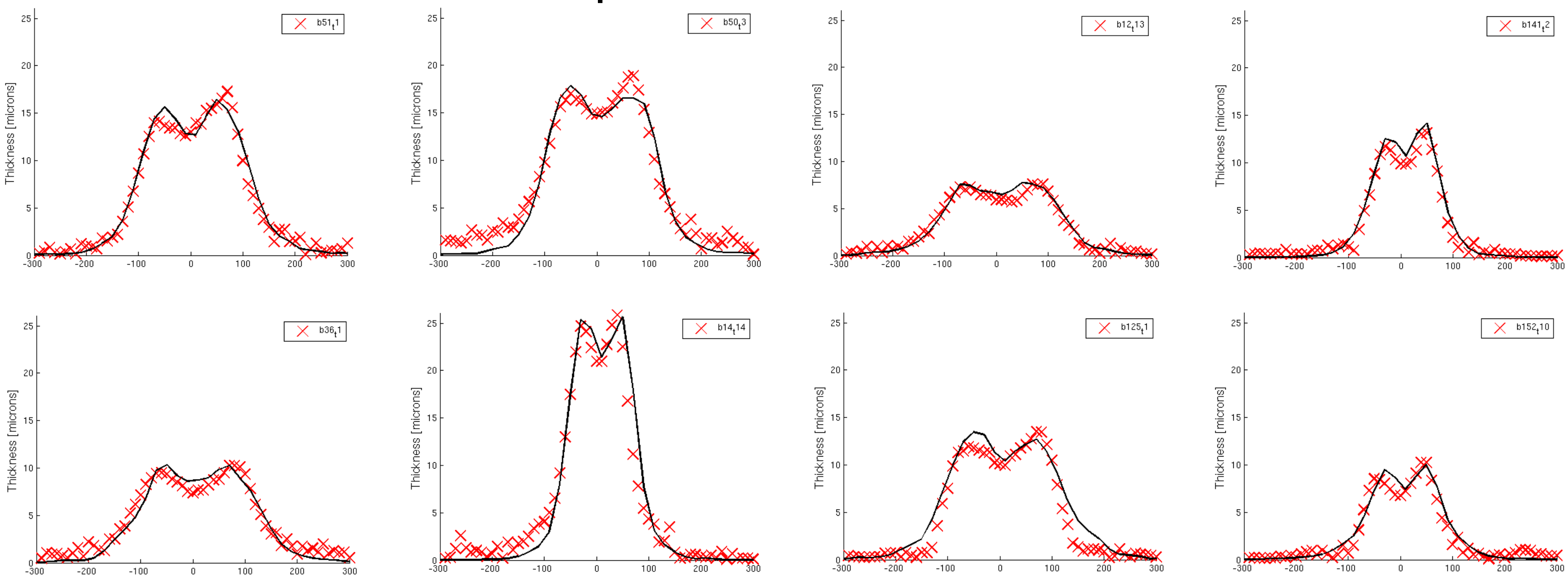
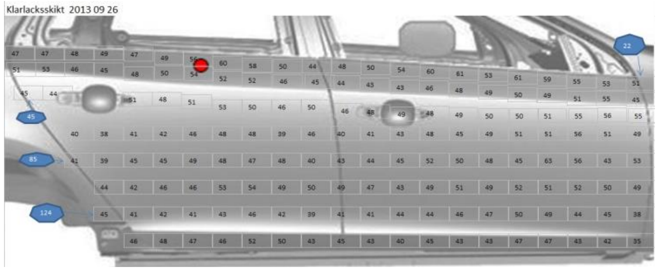
Full Car Simulation at Volvo

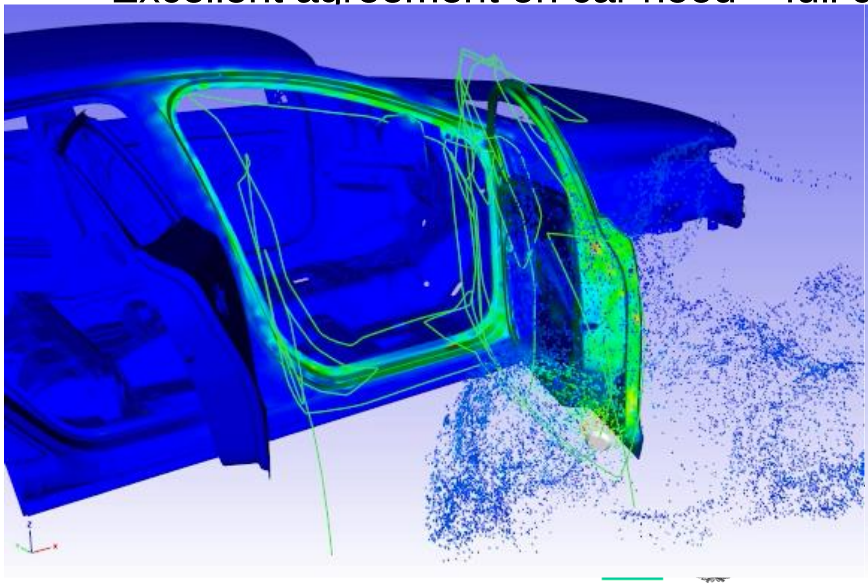
- Generation of exterior paint brushes for clear coat and filler in Torslanda
- Generation of all interior paint brushes used in Gent

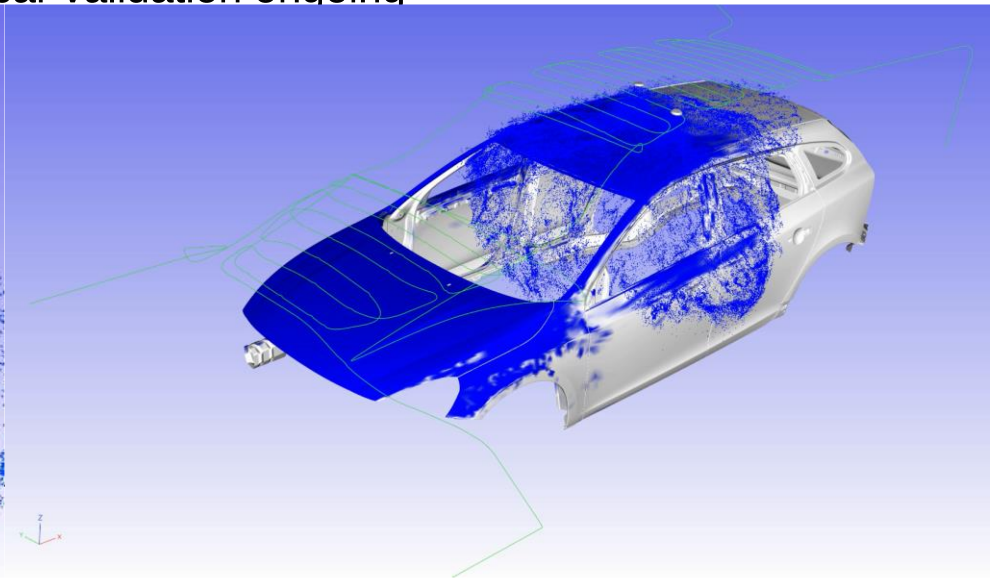


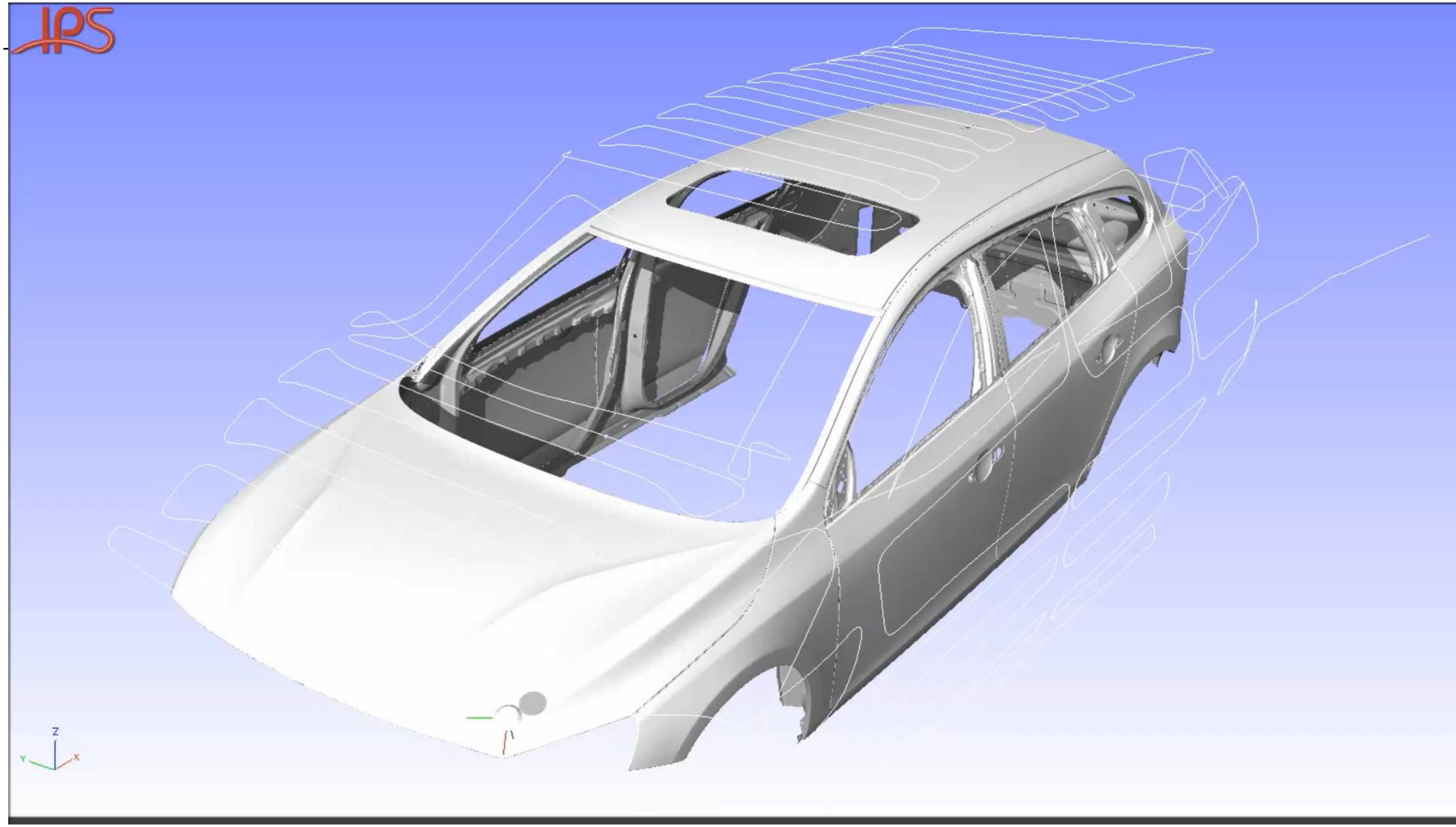
Full Car Simulation at Volvo



- Gent interior simulation of front door
- Torslanda simulation of full car
  - Simulated horizontal and vertical brushes separately for shorter simulation time
  - Simulation with horizontal brushes finished over night!! (Roughly 2s physical time per hour simulation time on standard computer)
- Saving impacts from the simulation and then importing them together yields full simulation result
- Excellent agreement on car hood – full car validation ongoing

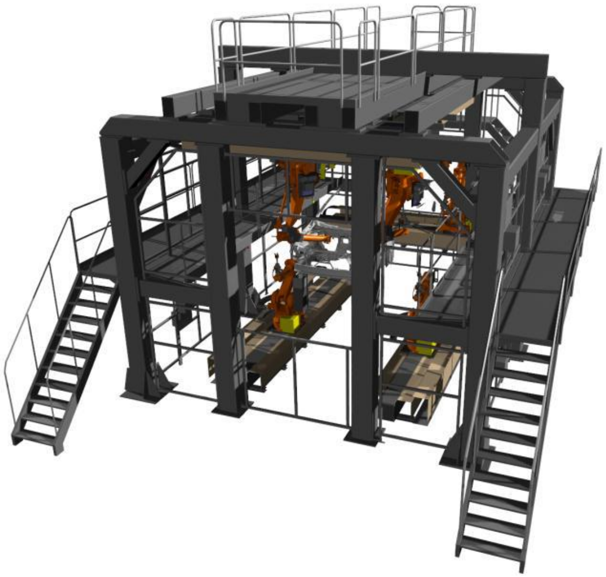


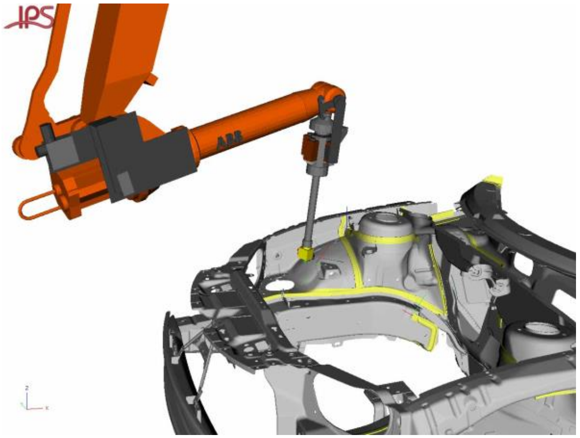



IPS
Z
Y
X

Virtual Sealing

- Dampen noise and cover cavities where moisture otherwise can create a corrosive environment
- Goals
  - For a given a robot motion predict the thickness of applied material to reduce waste and pinpoint critical regions
  - Automatic generation and optimization of robot motions
- Challenges
  - Complex multi-phase flow modeling and simulation
  - Complex automatic path planning, load balancing and sequencing

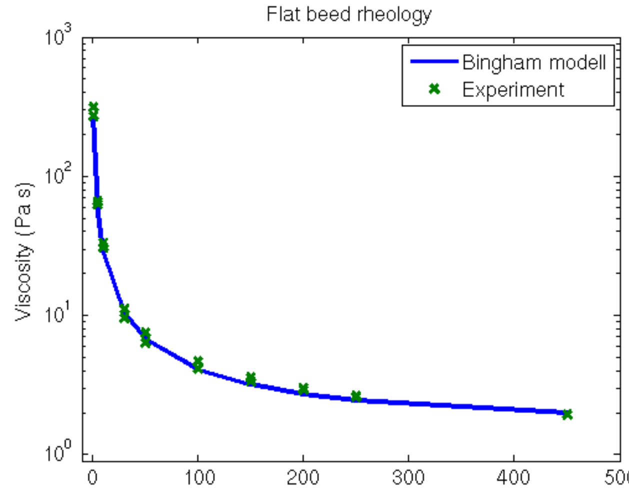


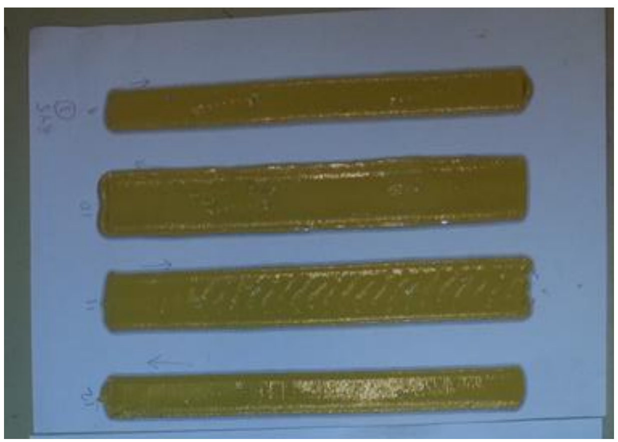


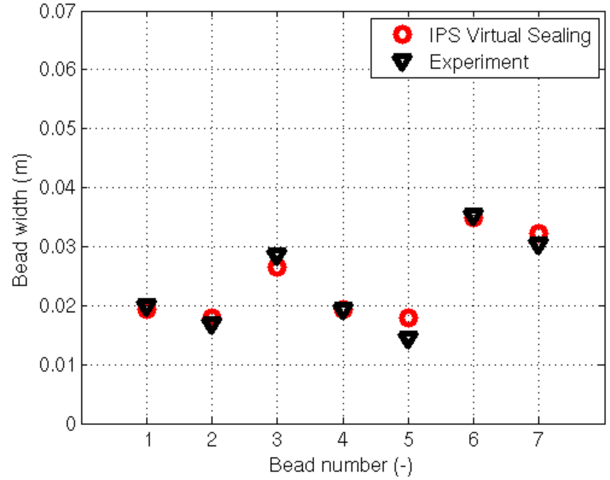
A. Mark, R. Bohlin, D. Segerdahl, F. Edelvik, J. S. Carlson, “Optimisation of Robotised Sealing Stations in Paint Shops by Process Simulation and Automatic Path Planning”, International Journal of Manufacturing Research, 9(1):4-26, 2014.

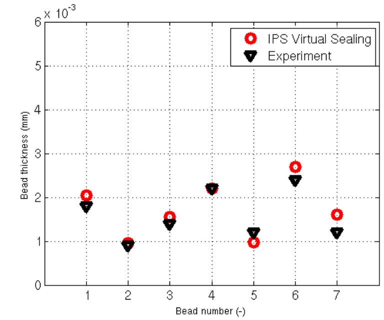
Rheology and process simulation

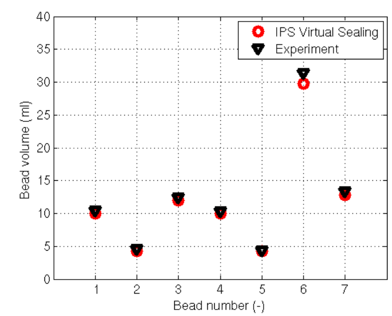
- Bingham fluid is used to model rheology of sealing material
- Two material parameters are fitted; yield stress and plastic viscosity
- Novel VOF method
- Comparison of visual appearance, width, height and volume of bead











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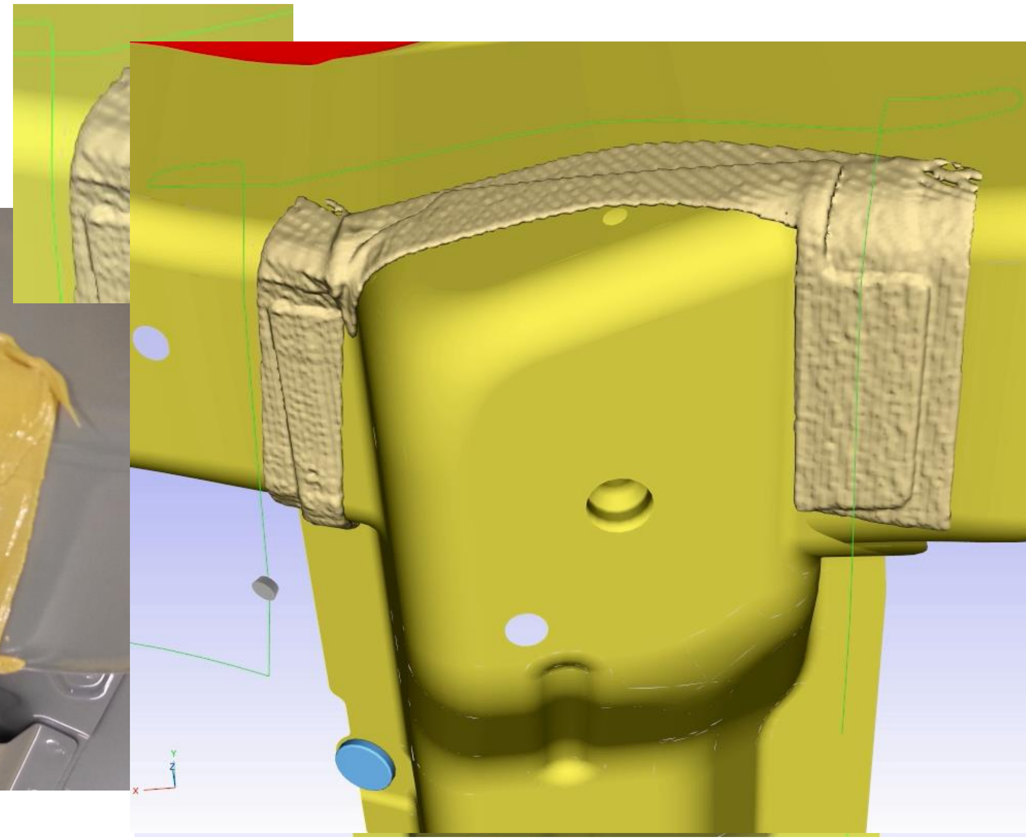
Sealing laydown on a Volvo V60



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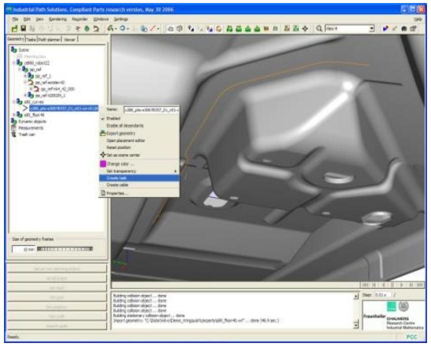
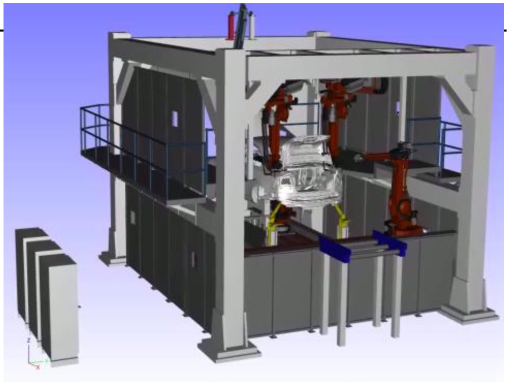
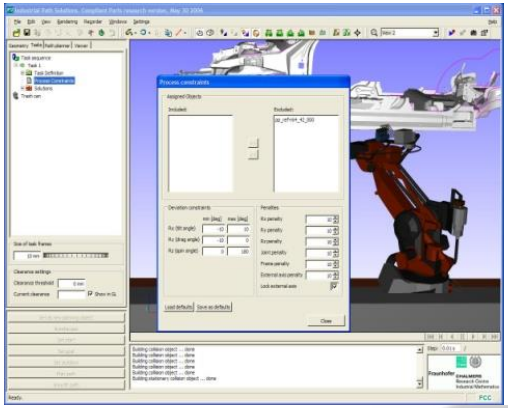
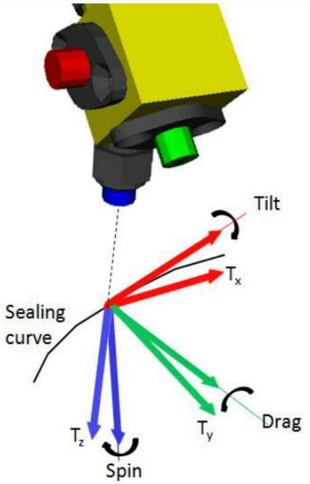
Automatic Path Planning of Sealing in IPS

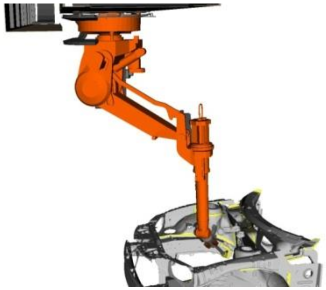
- Task definition
  - Input – sampled target curve on surface
  - Parametrization and orientation
  - Allow small deviation
- Process constraints
  - Multiple nozzle flat spray / hollow cone
  - Deviation in tilt, drag, spin, TCP distance
- Intra path planning
  - Find a number of collision-free low-cost solutions that satisfies process constraints
  - Multiple inverse configurations
- Inter path planning and sequencing
  - Input – A number of collision free motions for each sealing bead
  - Find collision free motions between sealing beads
  - Sequencing – Connect solutions and optimize total cycle time by solving a Traveling Salesman Problem

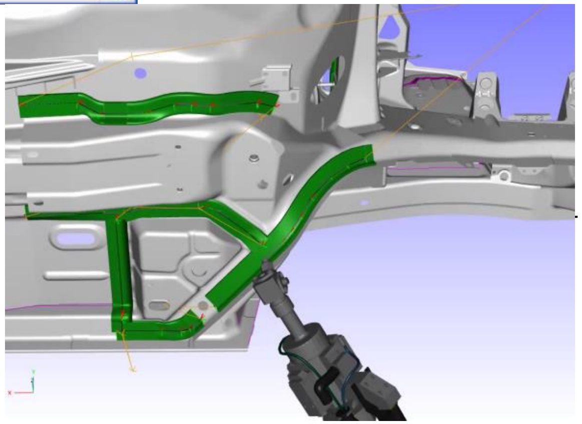












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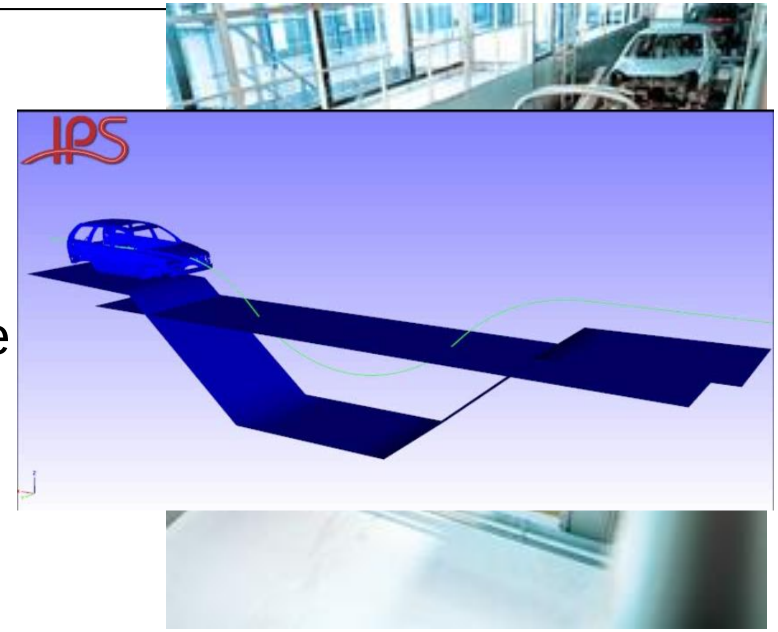
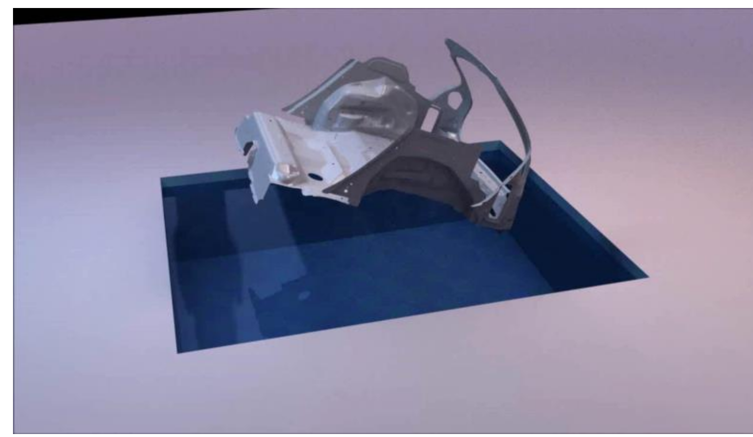
Virtual Electrocoating

- Object dipped in an electrolyte solution
- Air pocket prediction is important to ensure that all relevant parts are covered in electrolyte
- Electrodeposition is predicted from the electrochemically caused current in the bath

IPS Virtual Paint solution

- Novel immersed boundary conditions for efficient motion handling
- Adaptive grids
- Volume of Fluid (VOF) module in IBOFlow





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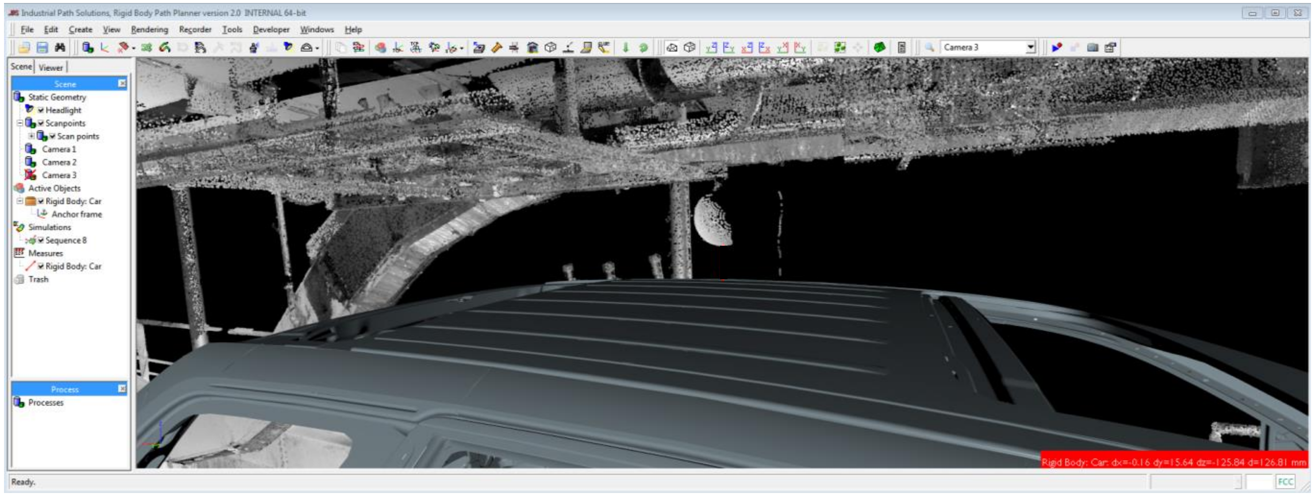
Scanned Paint Shop

Shortest Distance Analysis



Summary

- Simulation technology based on mesh-less methods
  - Pre-processing is greatly simplified
  - Efficient treatment of dynamic problems with moving and interacting objects
- A step towards the Virtual paint factory
  - Realistic simulation times
  - Accurate results
  - Coupling to robot path planning software
- Processes can be optimized to
  - be more environmentally friendly
  - consume less energy
  - be more cost efficient
  - give a higher product quality