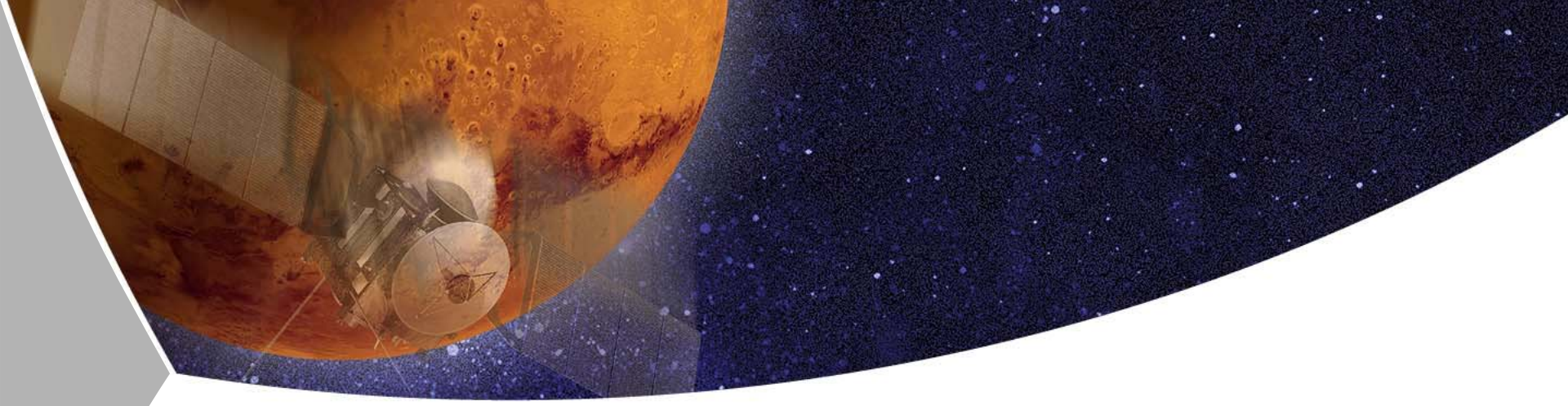

Modeling and Simulation of Satellite Docking Using MBS-Compatible Contact Dynamics Tools

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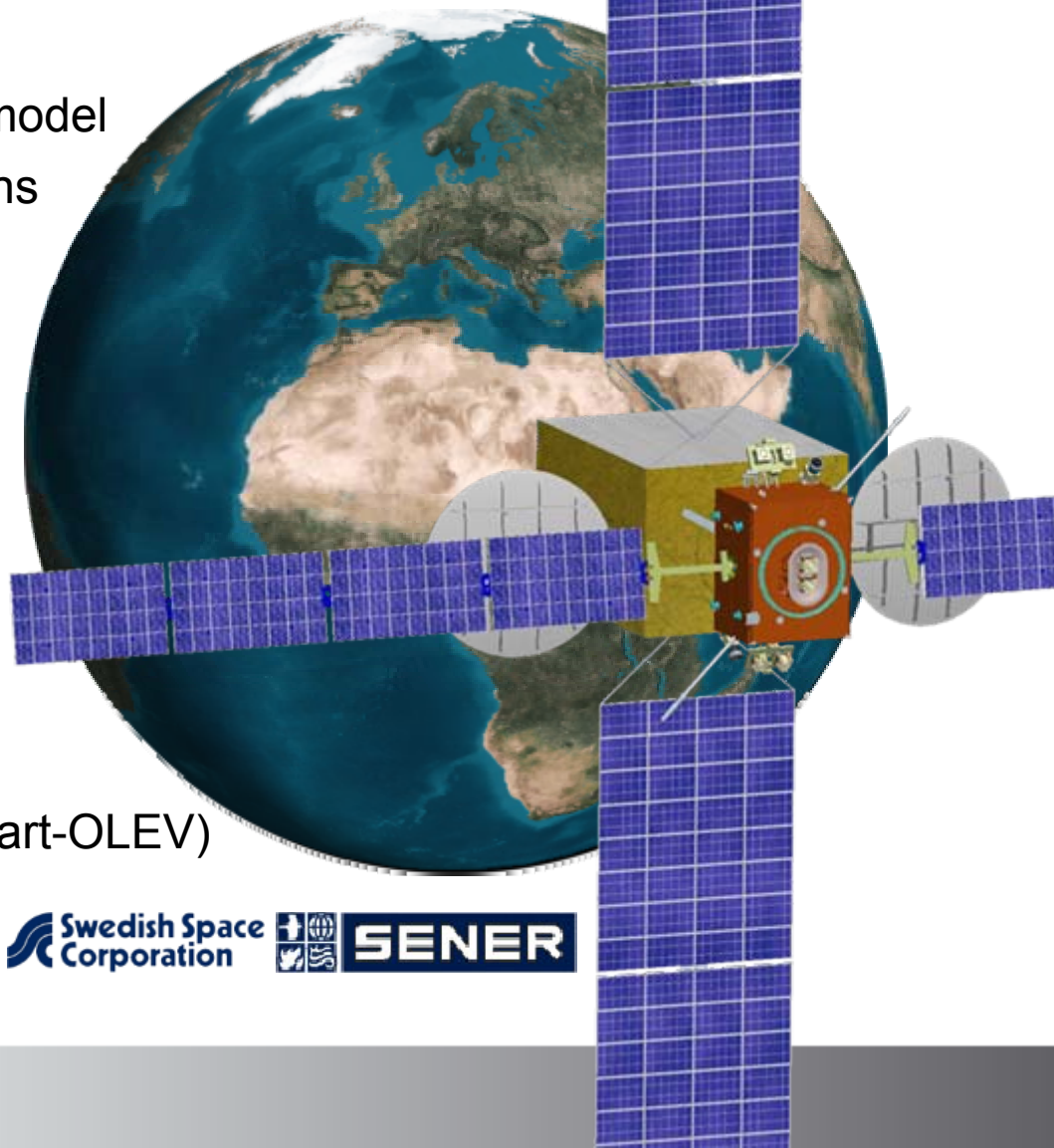
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Contents of Presentation

Modified *Elastic Foundation* contact model applied for satellite docking simulations within MBS based simulators

- Contact dynamics modeling
  - Contact surface generation
  - Contact detection
  - Contact force computation
- Simulation
  - Results (examples from Smart-OLEV)
  - Verification



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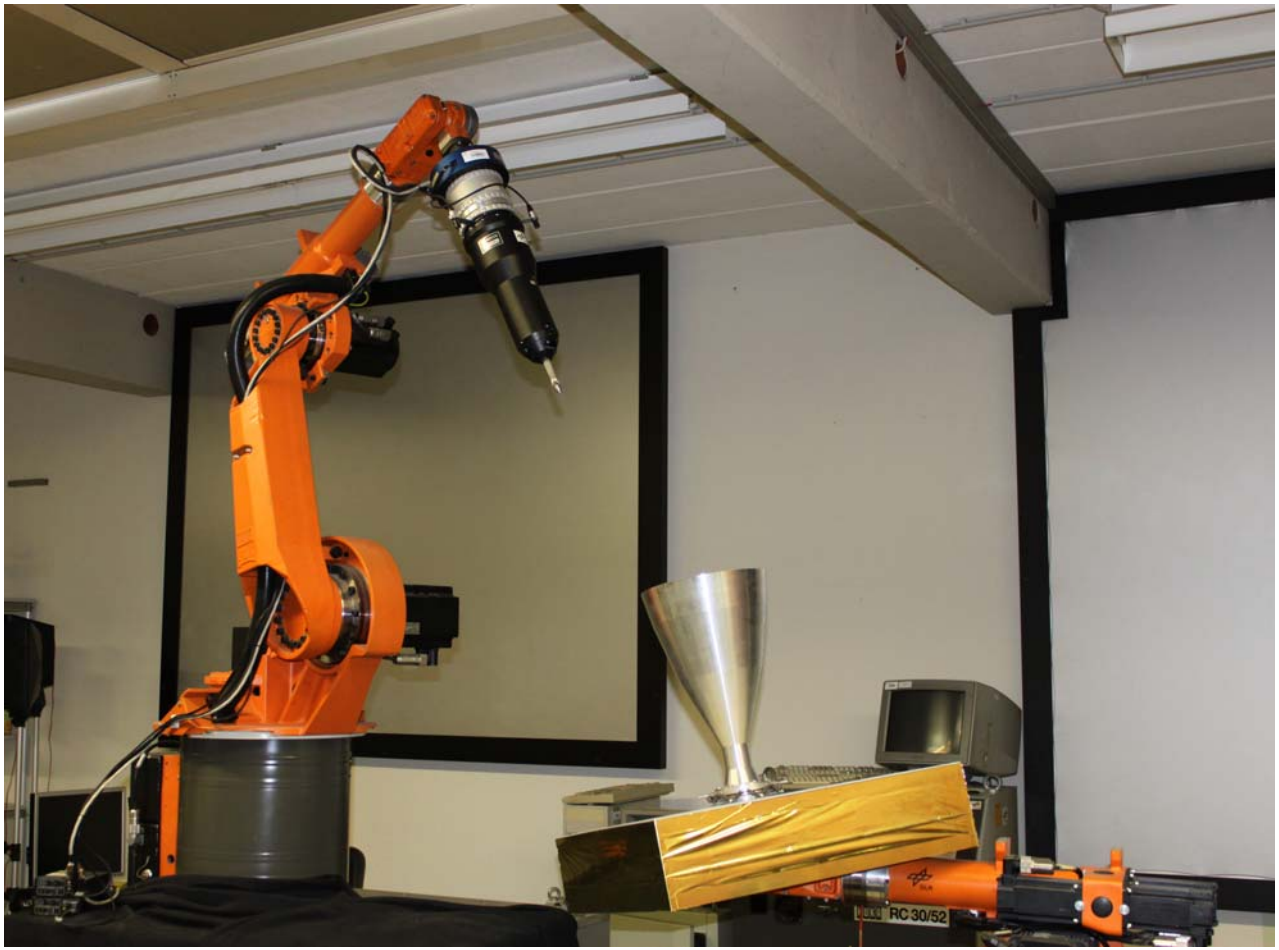
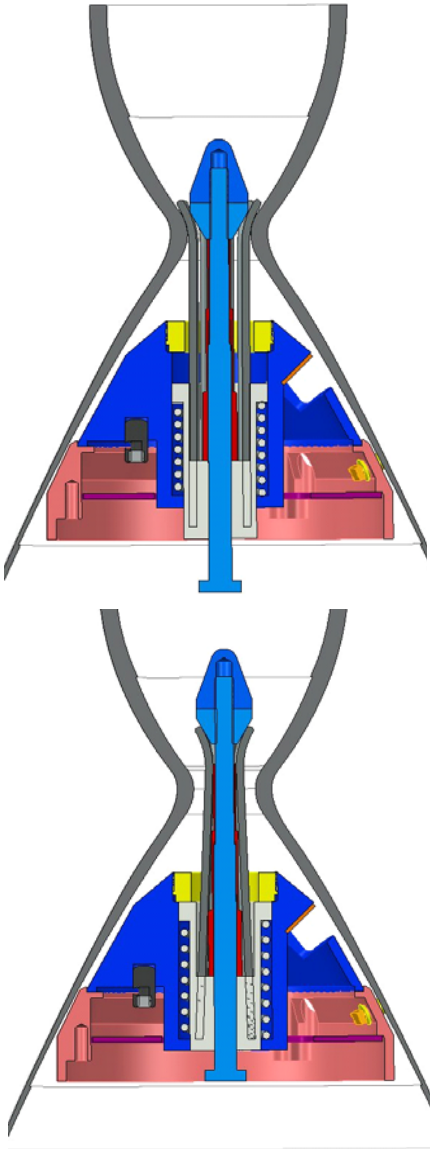
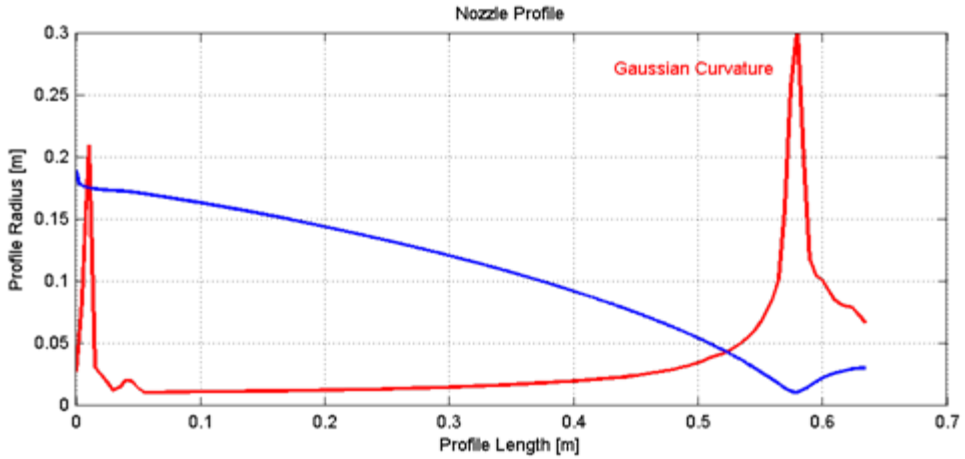
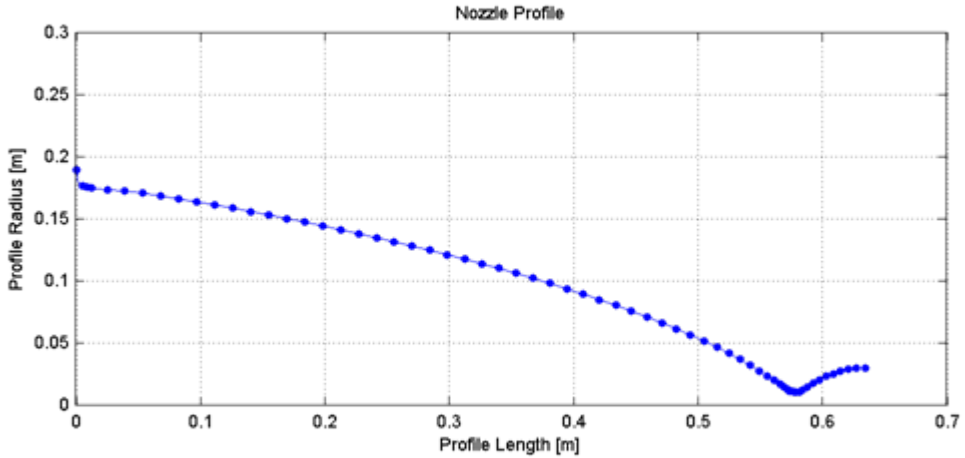
Satellite Capturing Method for OLEV



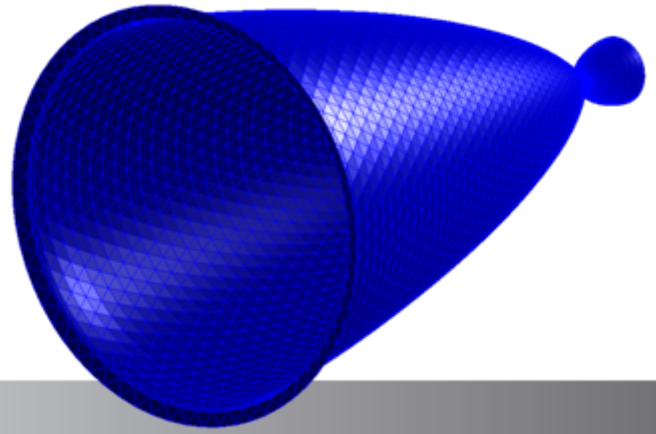


Contact Surface Generation - Meshing



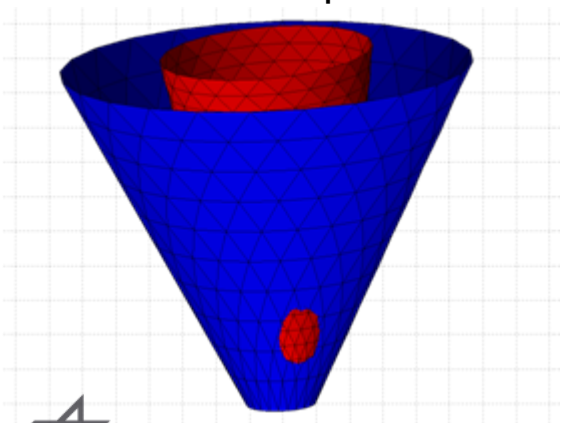


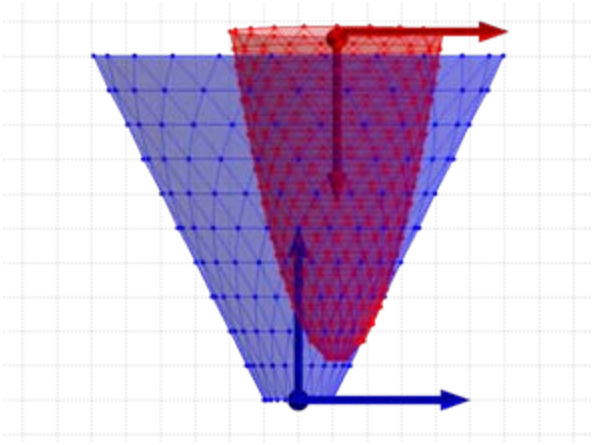
- Contact bodies = rotational bodies
- Surface shape defined by longitudinal profile: r = f(z)
- Sampling point distribution is function of Gaussian curvature
- Meshing by rotation of profile
  - Vertices, triangular faces
  - Surface normals, area size
  - ...

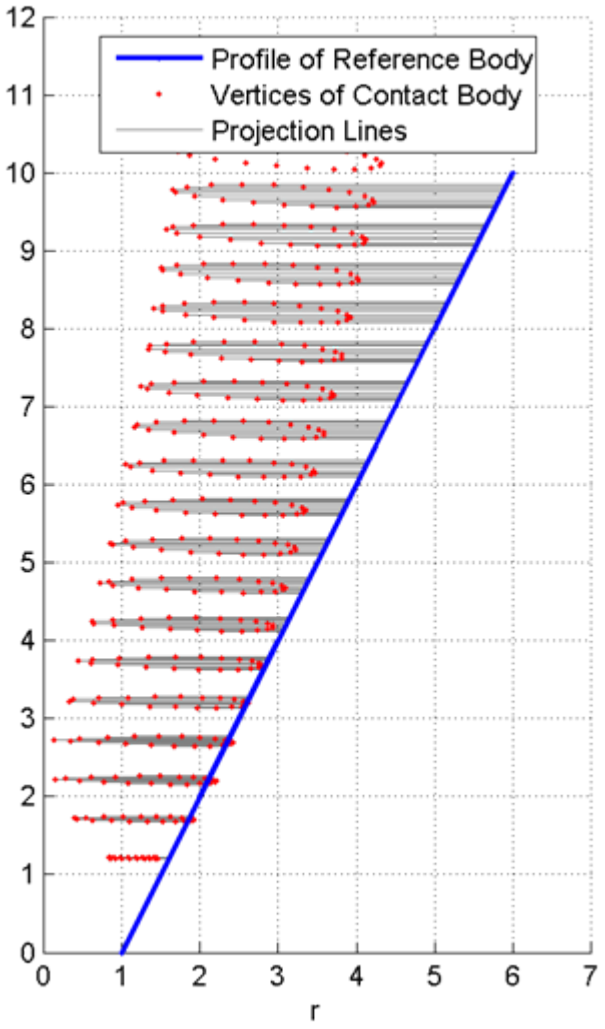


Contact Detection Algorithm

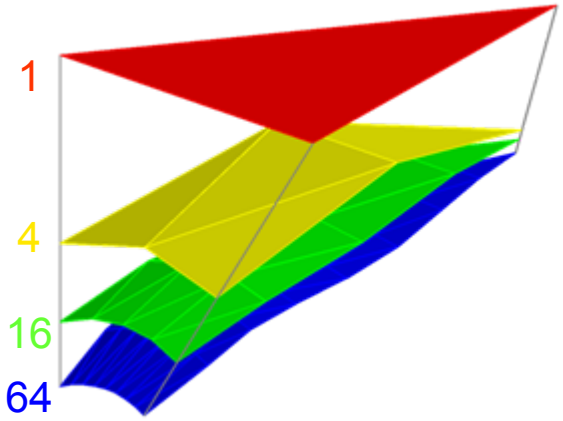
- Mapping of surface vertices
  - Transformation of vertices into body reference frame of reference body
  - 3D Cartesian (x,y,z) → 2D cylindrical (r,z)
    - Reference body: Profile
    - Contact body: Point cloud
- Contact detection based on comparison of radial co-ordinates
  - Convex/convex and concave/convex contact problems
  - Multi-point contact
  - Variable profile



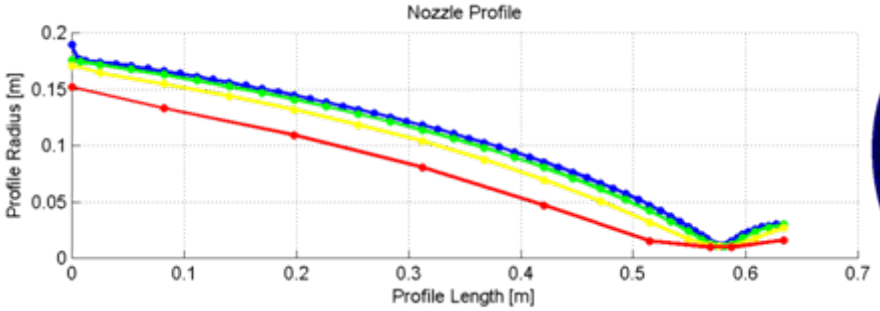


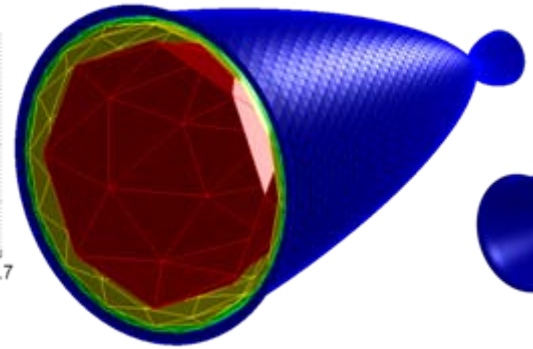


Hierarchical Boundary Surfaces

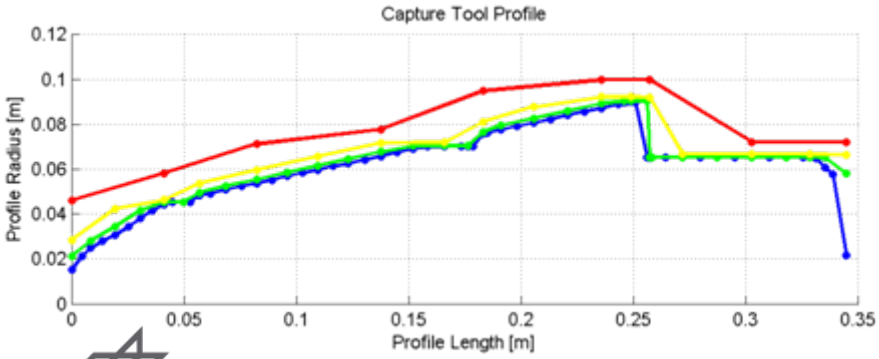


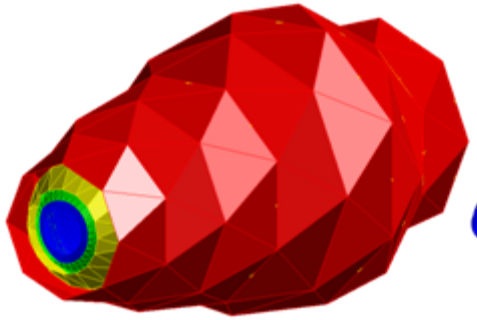
- Face simplification ratio 4:1 (number of faces = 4^n)
- Speed-up of contact detection
- Reduction of computational load





concave contact surface

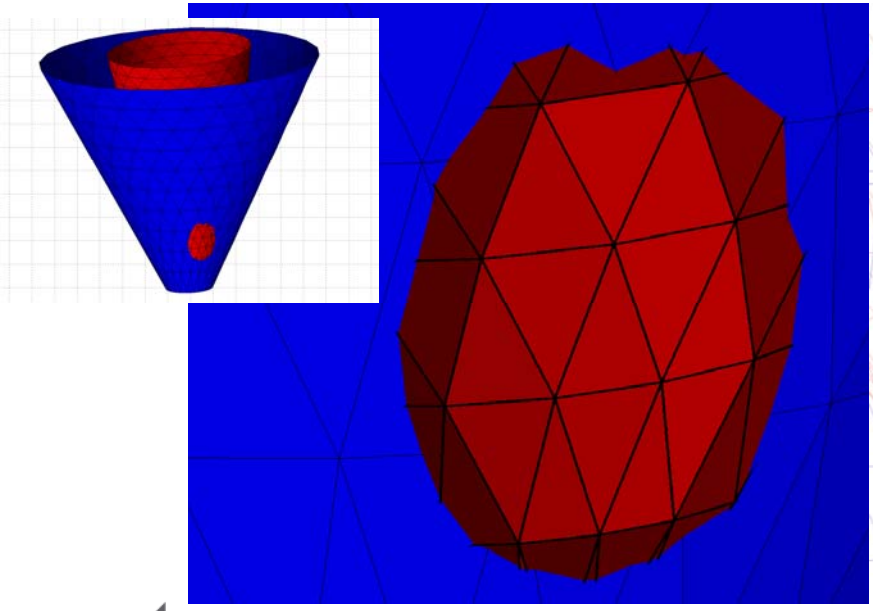


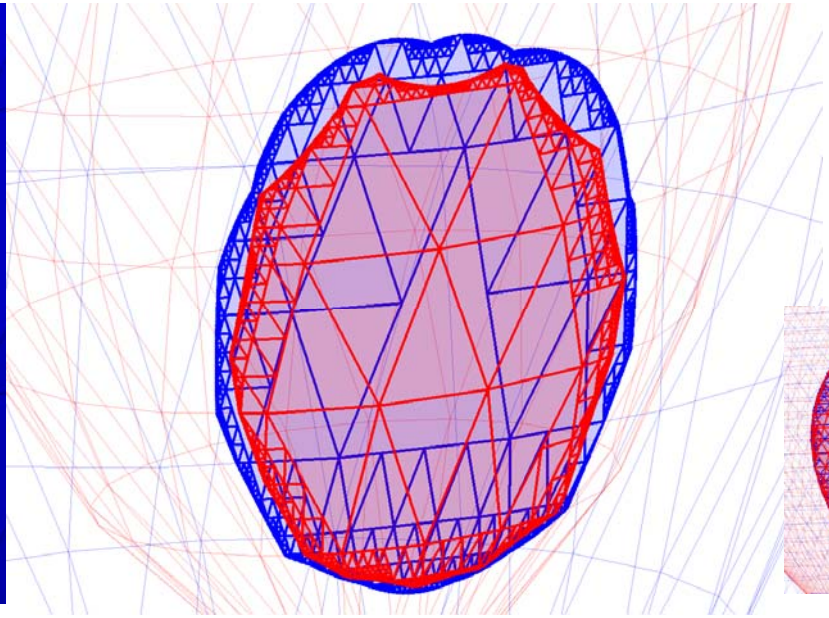


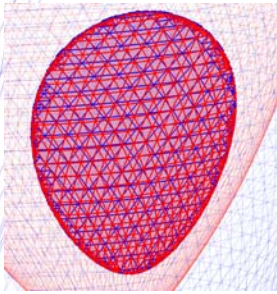
convex contact surface

Contact Patch Generation with Refinement

- Contact faces: 3 of 3 vertices per face in contact
- Ambiguous contact faces: 1 or 2 of 3 vertices per face in contact
  - Refinement of patch border (sub-faces)
  - Re-call of contact detection for sub-face vertices
- Smooth force signals important for fast MBS solver progress

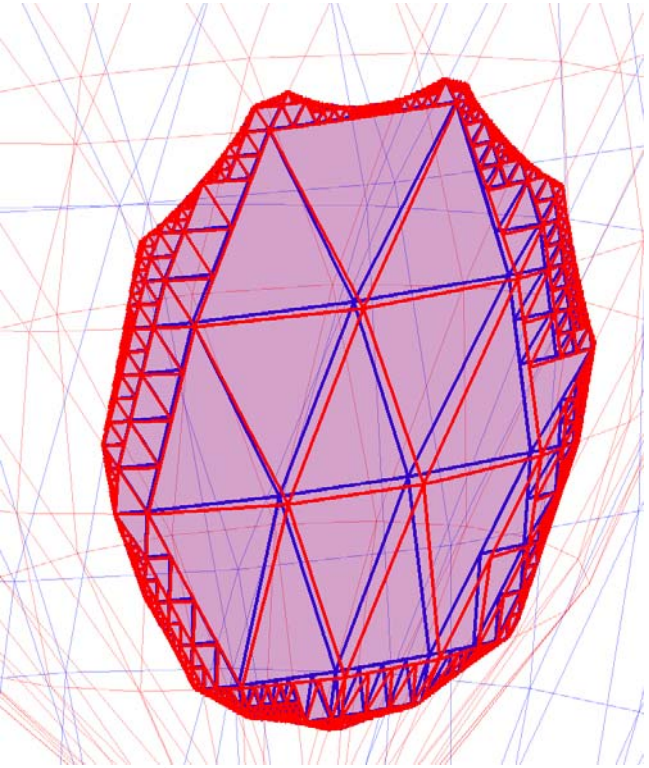






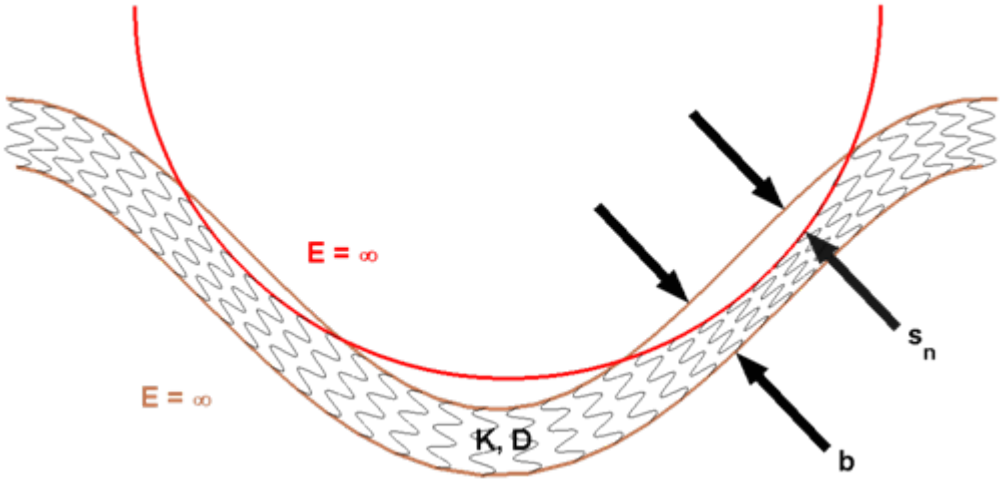
Contact Kinematics of Contact Patch

- Mapping of contact shape faces onto reference body
- Relative motion states between well-defined polygon pairs



- For each contact polygon:
  - Contact surface penetration depth s_n
    → normal contact force (linear spring)
  - Normal penetration velocity v_n
    (compression, decompression)
    → normal damping force (linear damper)
  - Tangential contact velocity v_t
    → Coulomb friction force (slip)
  - Track of contact location P
    → Coulomb friction force (stick)

Contact Force Computation
Elastic Foundation Model



- Two rigid bodies
- One surface covered with thin elastic layer
- Definition of contact dynamics properties

$$f_n = \left(Ks_n + Dv_n\right);$$

$$K = \frac{1-\nu}{(1+\nu)(1-2\nu)} \cdot \frac{E}{b}$$

$$D = D_0 \cdot T\left(b, s_n\right) \cdot H\left(v_n\right)$$

f_n: Specific normal contact force

s_n: Normal contact penetration depth

v_n: Normal contact penetration velocity

E: Young's modulus of elastic layer

ν: Poisson ratio of elastic layer

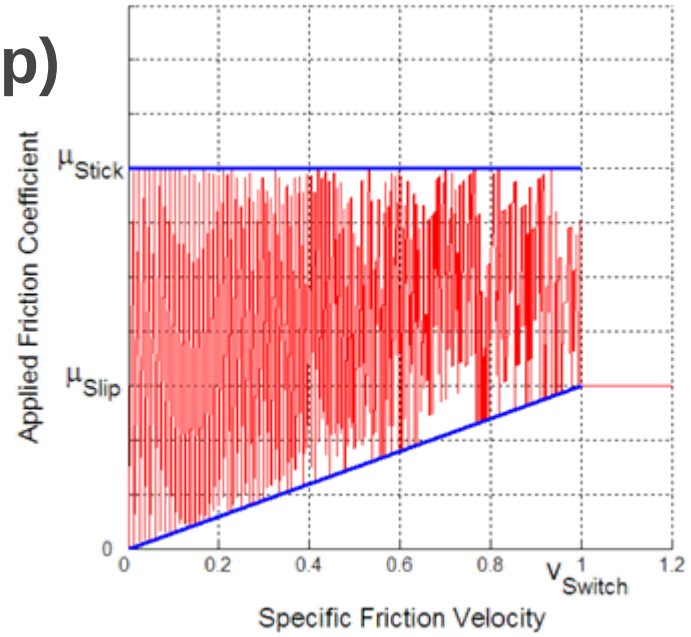
D_0: Areal damping coefficient of elastic layer

b: Elastic surface layer thickness

Friction Force Computation (Stick-Slip)

$$state = \begin{cases} stick \Rightarrow & \left(\mu_{stick} \dfrac{s_t}{s_{switch}} + \mu_{slip} \dfrac{v_t}{v_{switch}} \right) & \begin{cases} \leq \mu_{stick} \Rightarrow stick \\ > \mu_{stick} \Rightarrow slip \end{cases} \\ slip \Rightarrow & v_t & \begin{cases} < v_{switch} \Rightarrow stick \\ \geq v_{switch} \Rightarrow slip \end{cases} \end{cases}$$

$$f_t = \begin{cases} stick \Rightarrow & \left(\mu_{stick} \dfrac{s_t}{s_{switch}} + \mu_{slip} \dfrac{v_t}{v_{switch}} \right) f_n \\ slip \Rightarrow & \mu_{slip} f_n \end{cases}$$



f_t: Specific friction force

f_n: Specific normal contact force

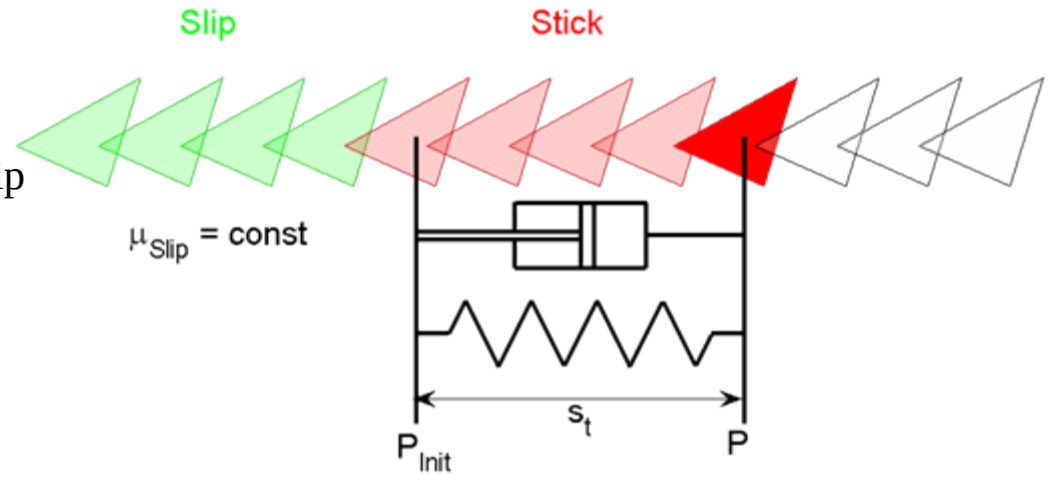
$\mu_{stick/slip}$: Coulomb friction coefficient for stick/slip

s_t: Friction strain (stick)

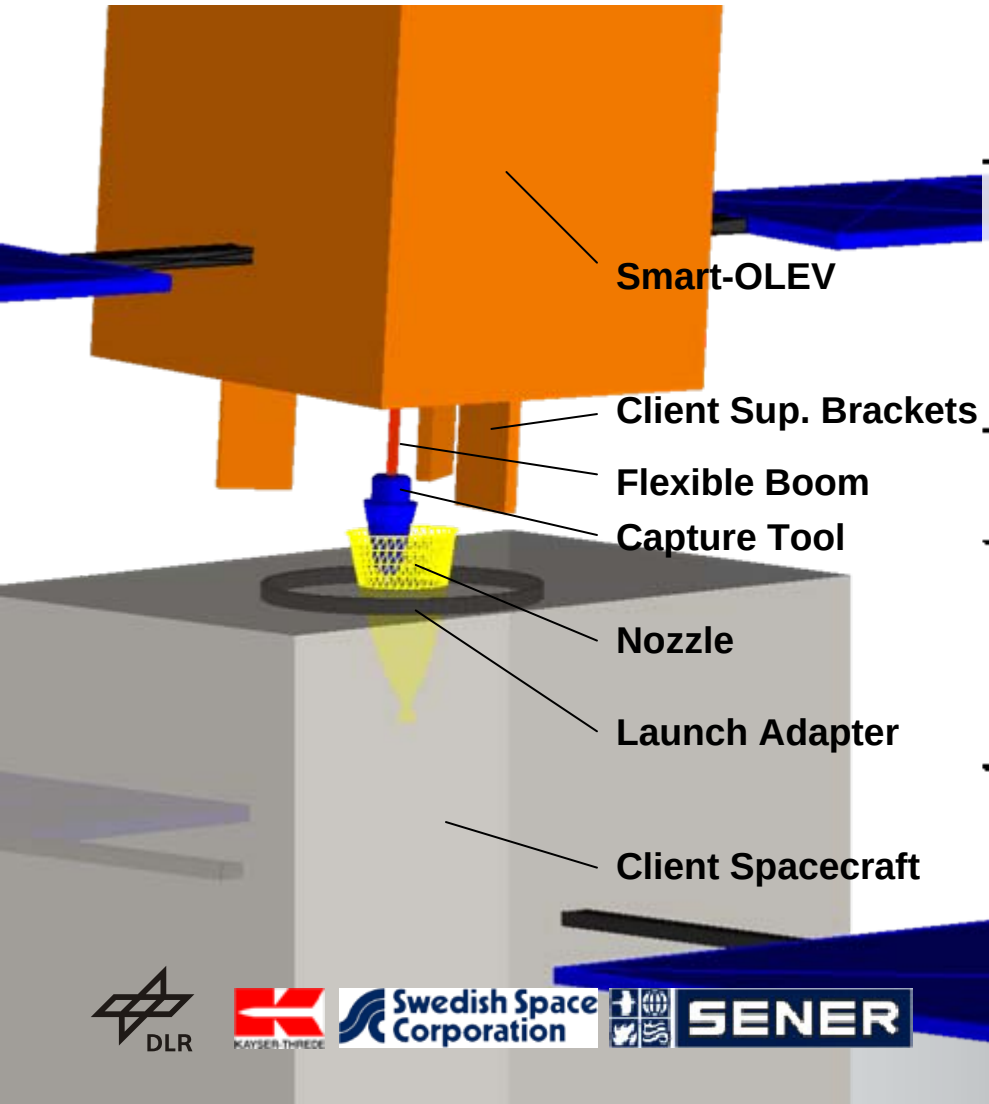
v_t: Friction velocity

s_{switch}: Max. friction strain (stick)

v_{switch}: Min. slip velocity



Multibody System for Satellite Docking



- Client
  - Hot Bird series, with flexible solar wings
  - Orbit: GEO
  - AOCS deactivated, momentum wheels loaded
  - Aerojet/Marquardt R4D nozzle, tilted
  - 1194 mm launch adapter
- Smart-OLEV
  - Orbit: GEO + 2.178 m (R-bar)
  - AOCS active
  - 75 mm lateral misalignment,
    2° orientation error in all axes
- Flexible Capture Tool deployment mechanism
  - 0 ... ± 4 mm/s deployment/retraction velocity
- Capture Tool
  - Radial laser distance sensor
  - Contact switches
  - Operational Locking Crown
- Contact sensitive bodies:
  - Nozzle vs. Capture Tool + Locking Crown
  - Launch adapter vs. Client Support Brackets

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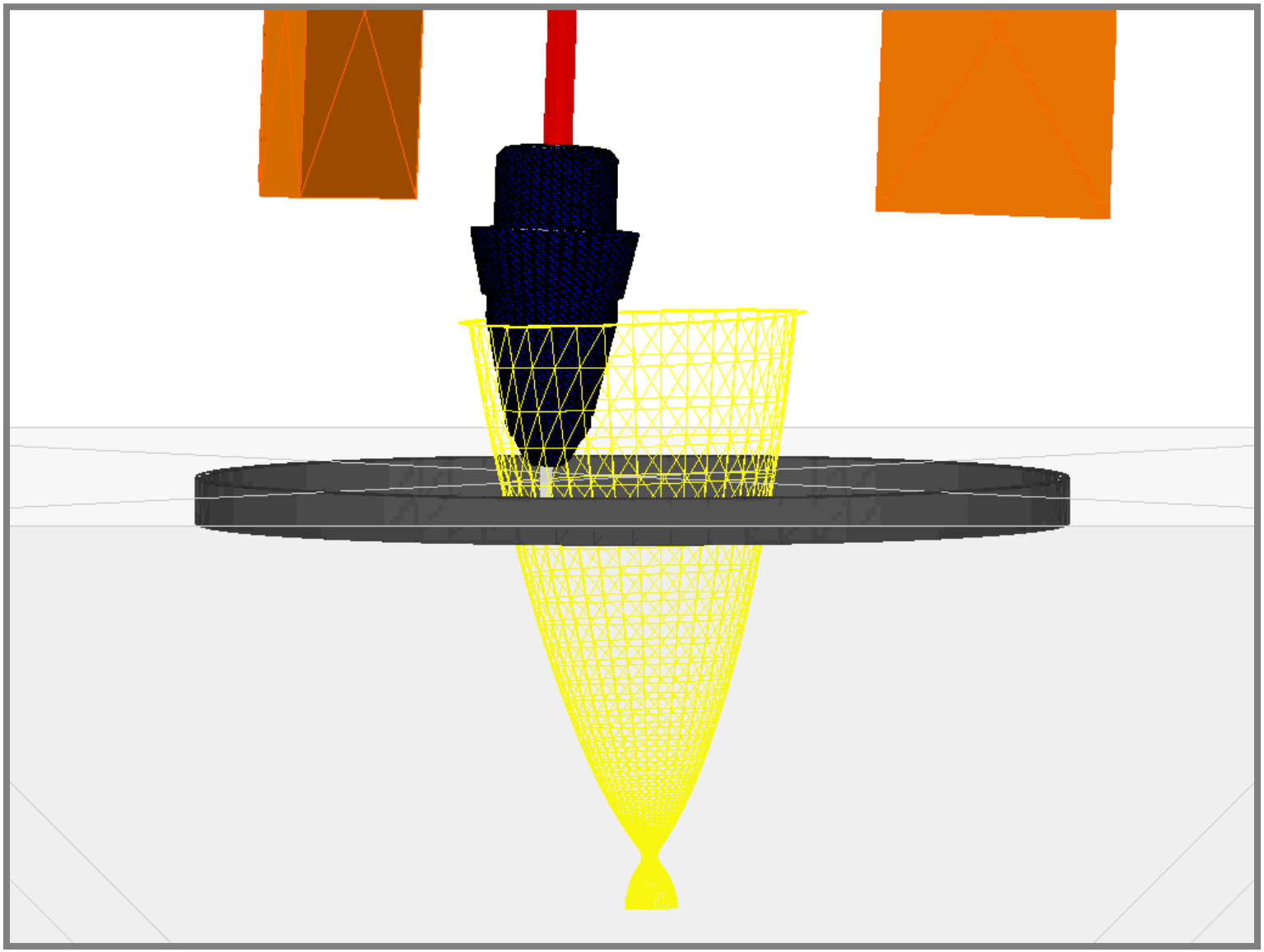
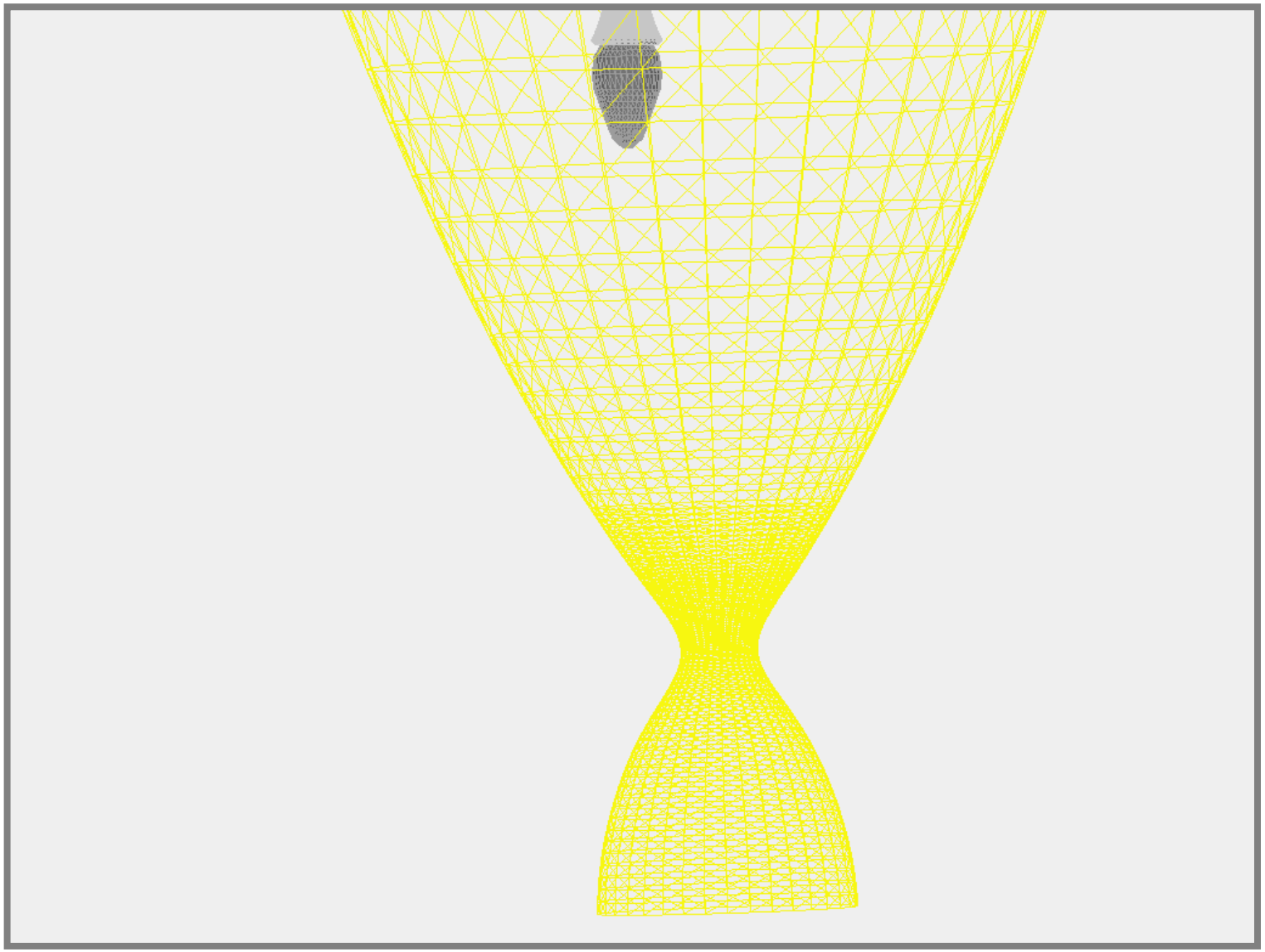
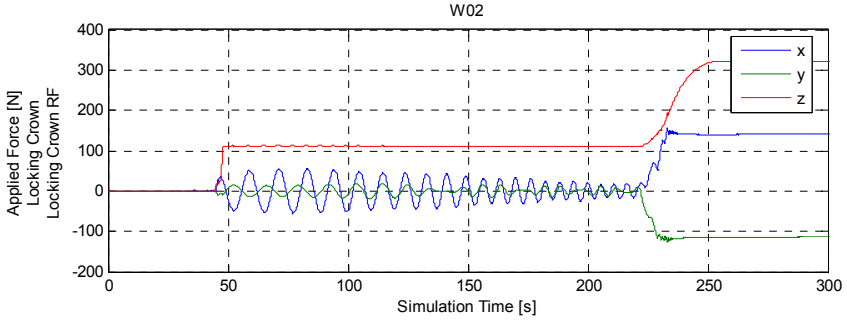
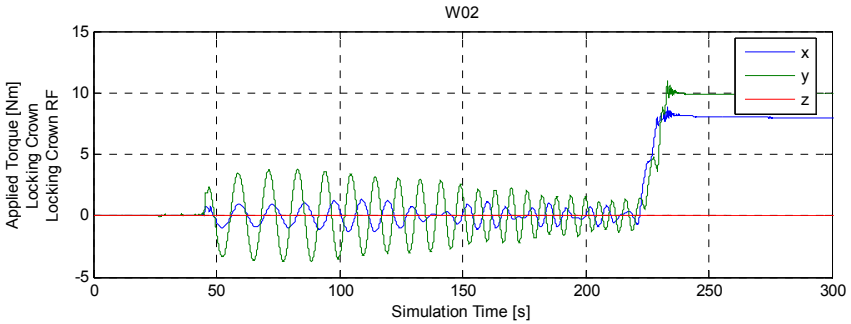
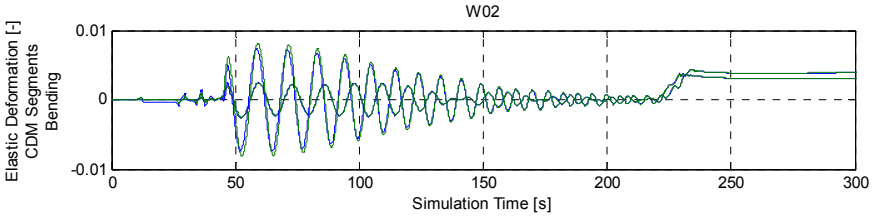
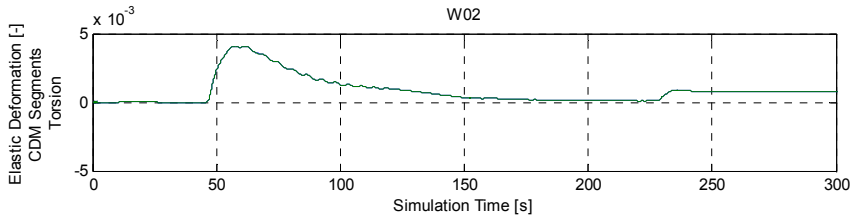


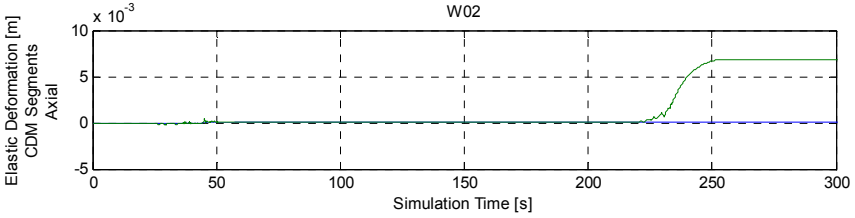


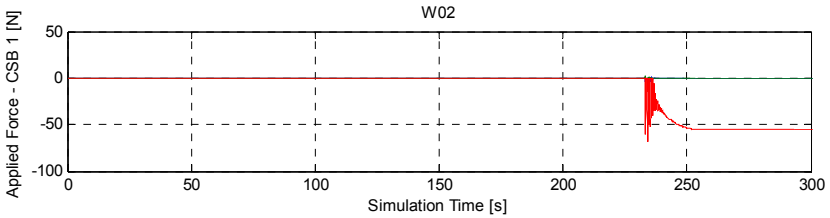

W02
Applied Force [N]
Locking Crown
Locking Crown RF
x
y
z
Simulation Time [s]

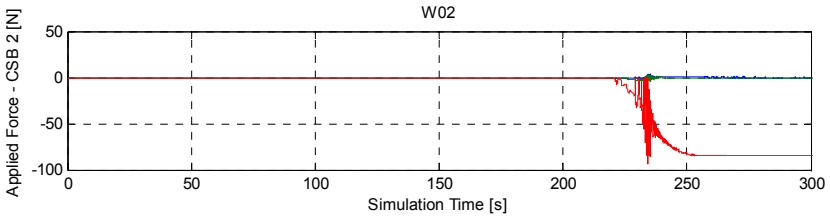

W02
Applied Torque [Nm]
Locking Crown
Locking Crown RF
x
y
z
Simulation Time [s]

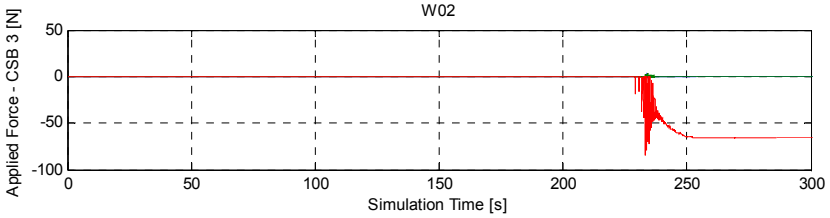

W02
Elastic Deformation [-]
CDM Segments
Bending
Simulation Time [s]

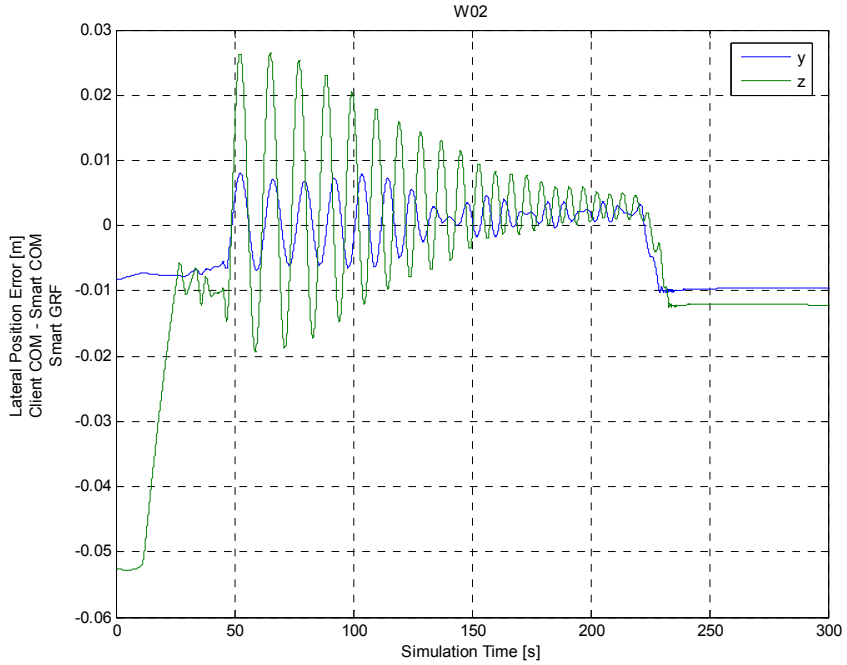

W02
x 10^-3
Elastic Deformation [-]
CDM Segments
Torsion
Simulation Time [s]


W02
x 10^-3
Elastic Deformation [m]
CDM Segments
Axial
Simulation Time [s]


W02
Applied Force - CSB 1 [N]
Simulation Time [s]

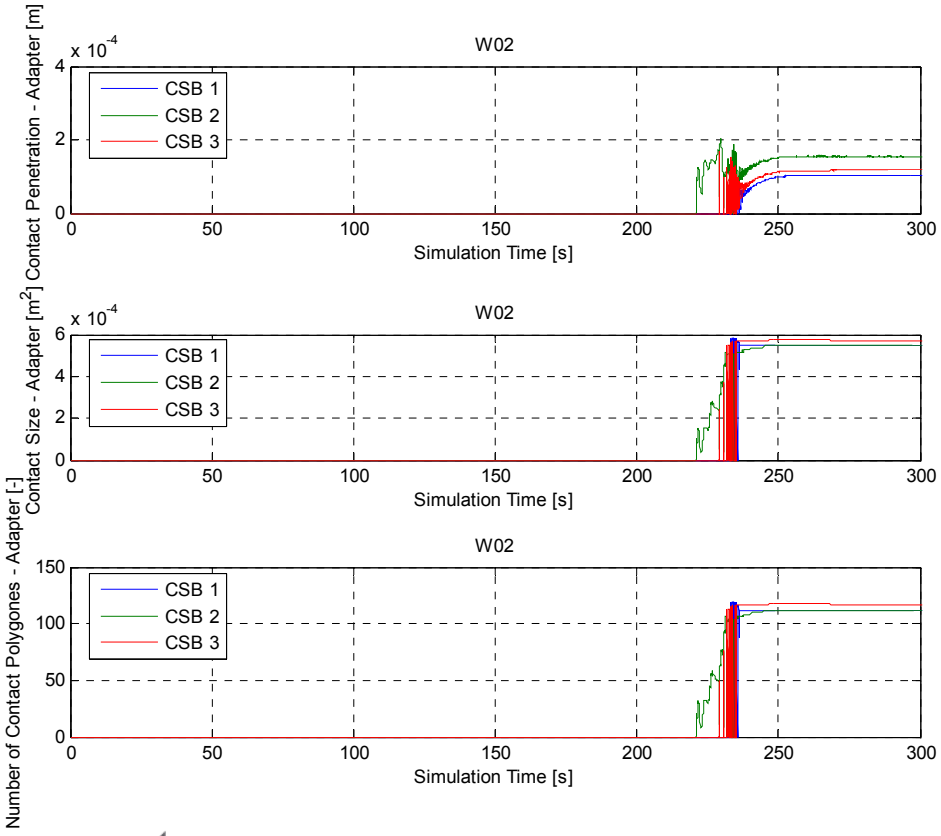

W02
Applied Force - CSB 2 [N]
Simulation Time [s]

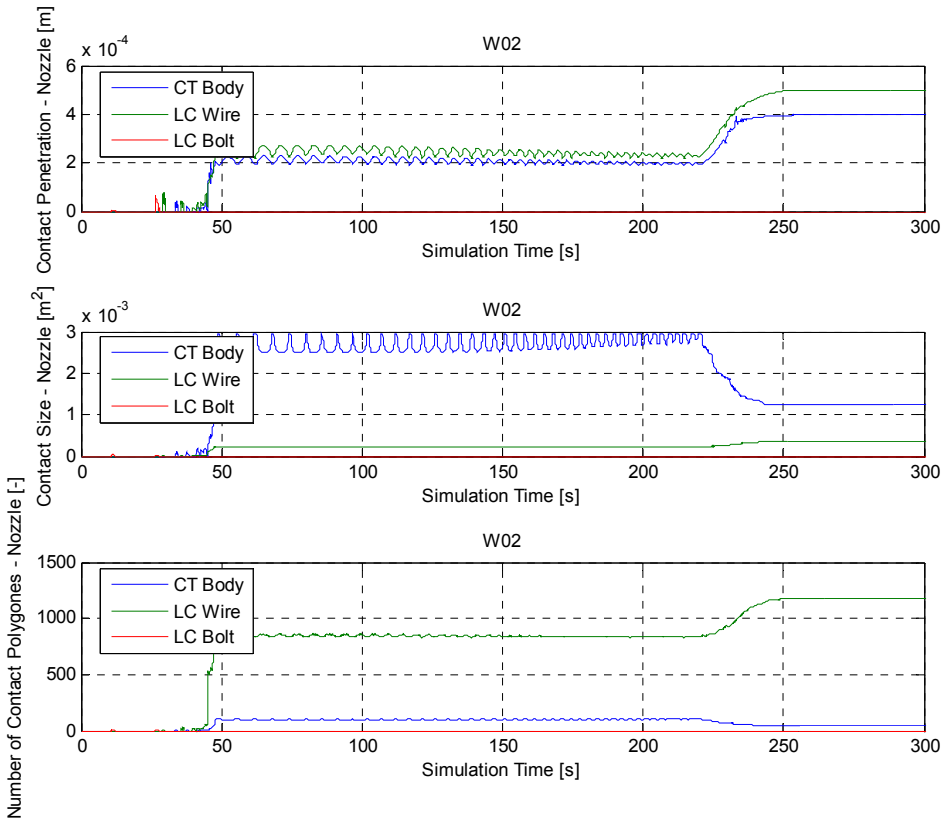

W02
Applied Force - CSB 3 [N]
Simulation Time [s]


W02
Lateral Position Error [m]
Client COM - Smart COM
Smart GRF
y
z
Simulation Time [s]

Verification of Simulation Results

- Elastic Foundation Model valid? → Maximum contact penetration depth
- Contact area resolution sufficient? → Number of contact polygons





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