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

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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
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
  - ...

Nozzle Profile

Gaussian Curvature

Profile Radius [m]

Profile Length [m]
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
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

\[ f_n = (Ks_n + Dv_n); \]
\[ K = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} \cdot \frac{E}{b} \]
\[ D = D_0 \cdot T(b, s_n) \cdot H(v_n) \]

\( f_n \): Specific normal contact force
\( s_n \): Normal contact penetration depth
\( v_n \): Normal contact penetration velocity
\( E \): Young's modulus of elastic layer
\( \nu \): Poisson ratio of elastic layer
\( D_0 \): Areal damping coefficient of elastic layer
\( b \): Elastic surface layer thickness
Friction Force Computation (Stick-Slip)

\[
\text{state} = \begin{cases} 
\text{stick} & \Rightarrow \left( \mu_{\text{stick}} \frac{s_t}{s_{\text{switch}}} + \mu_{\text{slip}} \frac{v_t}{v_{\text{switch}}} \right) \\
\text{slip} & \Rightarrow v_t 
\end{cases}
\]

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

- \( f_t \): Specific friction force
- \( f_n \): Specific normal contact force
- \( \mu_{\text{stick/slip}} \): Coulomb friction coefficient for stick/slip
- \( s_t \): Friction strain (stick)
- \( v_t \): Friction velocity
- \( s_{\text{switch}} \): Max. friction strain (stick)
- \( v_{\text{switch}} \): 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
Verification of Simulation Results

- Elastic Foundation Model valid? → Maximum contact penetration depth
- Contact area resolution sufficient? → Number of contact polygons
New EPOS @ DLR GSOC