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An Algorithm for Compliant Contact between Complexly Shaped Surfaces in Multibody Dynamics

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Motivation

Weak points of contact point approach:

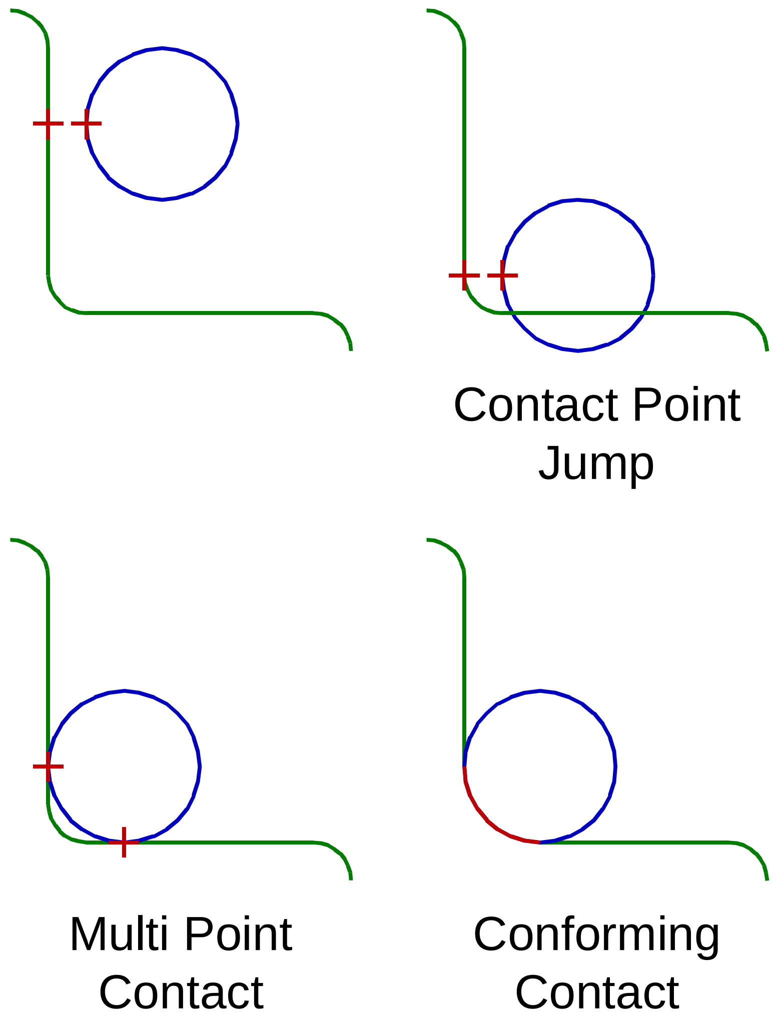
- Extreme simplification of complex physical phenomena
- Geometric determination of contact points requires smooth surfaces
- Contact kinematics fails in several arrangements of non strictly convex surfaces

Weak points of FEA contact analysis:

- Efficiency not compatible with MBS simulation
- Extremely complex in theory and implementation

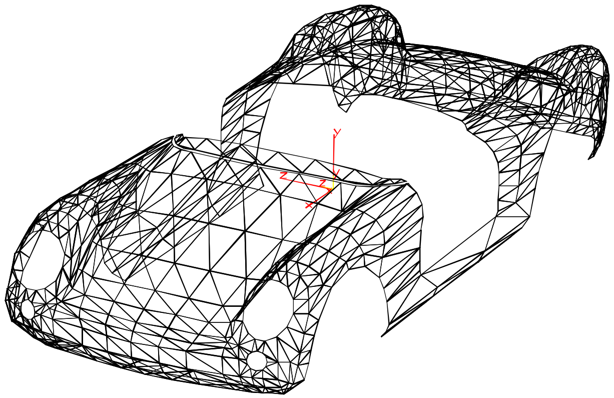
Polygonal Contact Model (PCM):

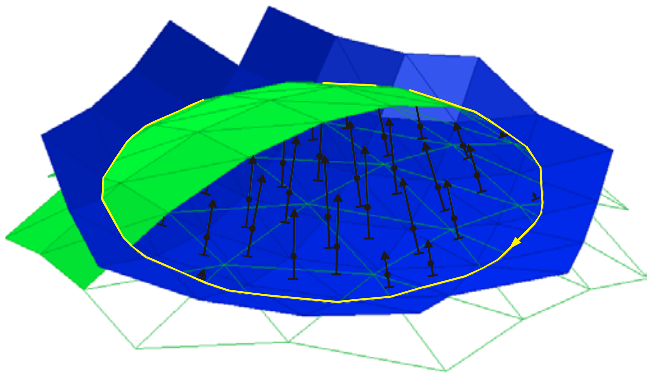
- Contact model for complexly shaped bodies
- Robust, efficient algorithm for MBS simulation

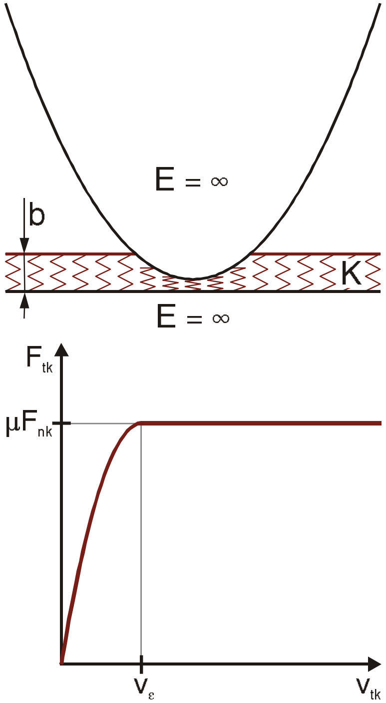


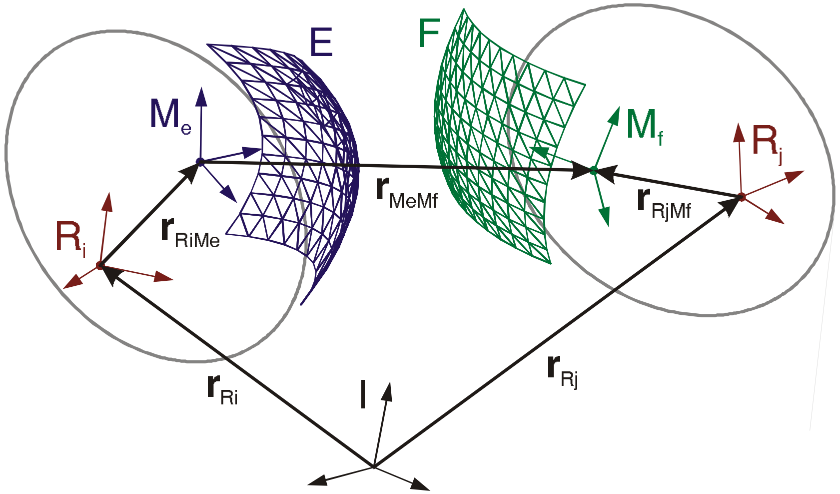
Basic Ideas

- Body surfaces represented by polygon meshes
- “Aereal” discretisation of contact patches
- Contact elements represent elastic foundation model and regularised Coulomb’s friction
- Resulting force vector acts as applied force of the MBS (force element)

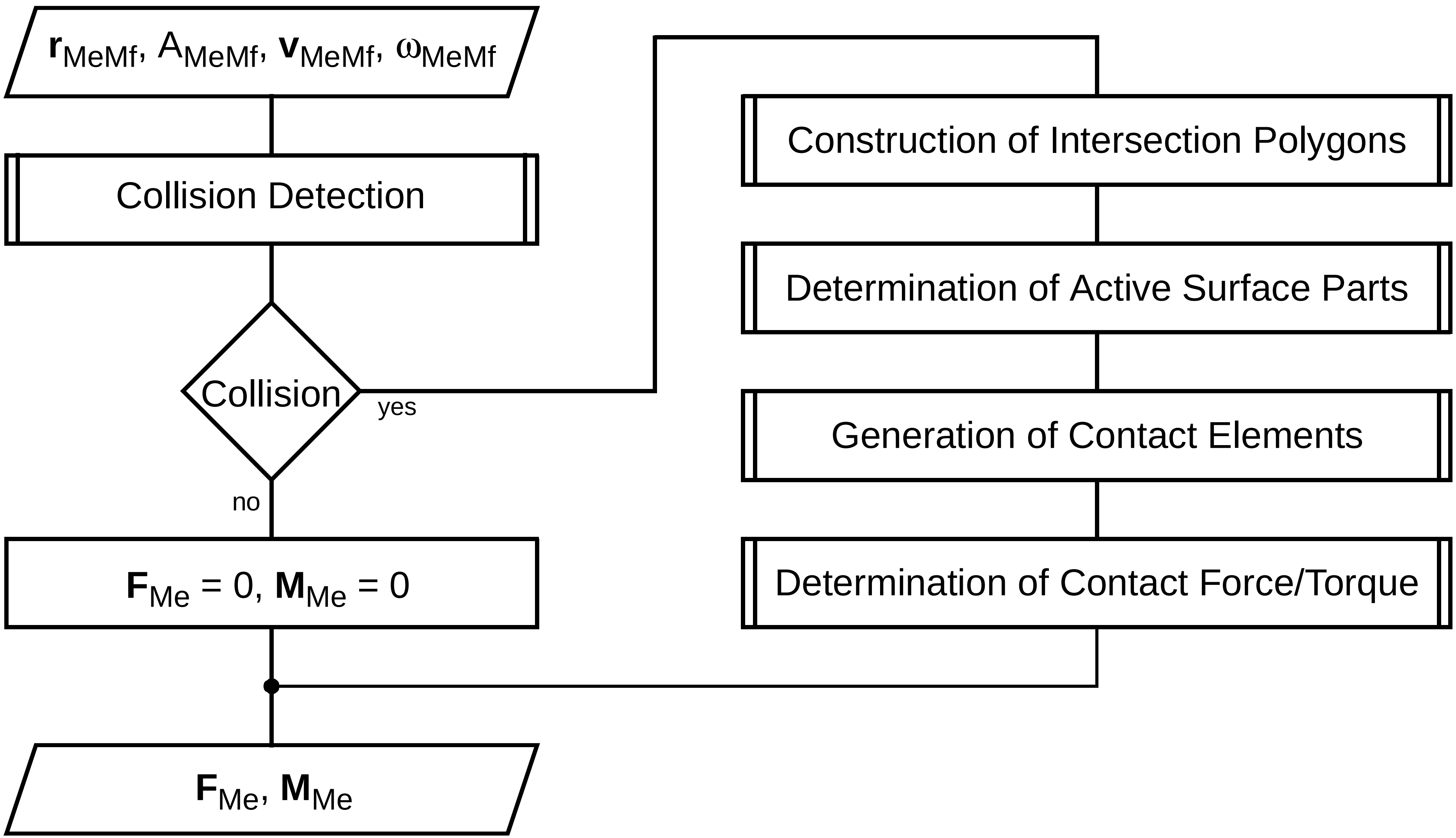








Algorithm Overview



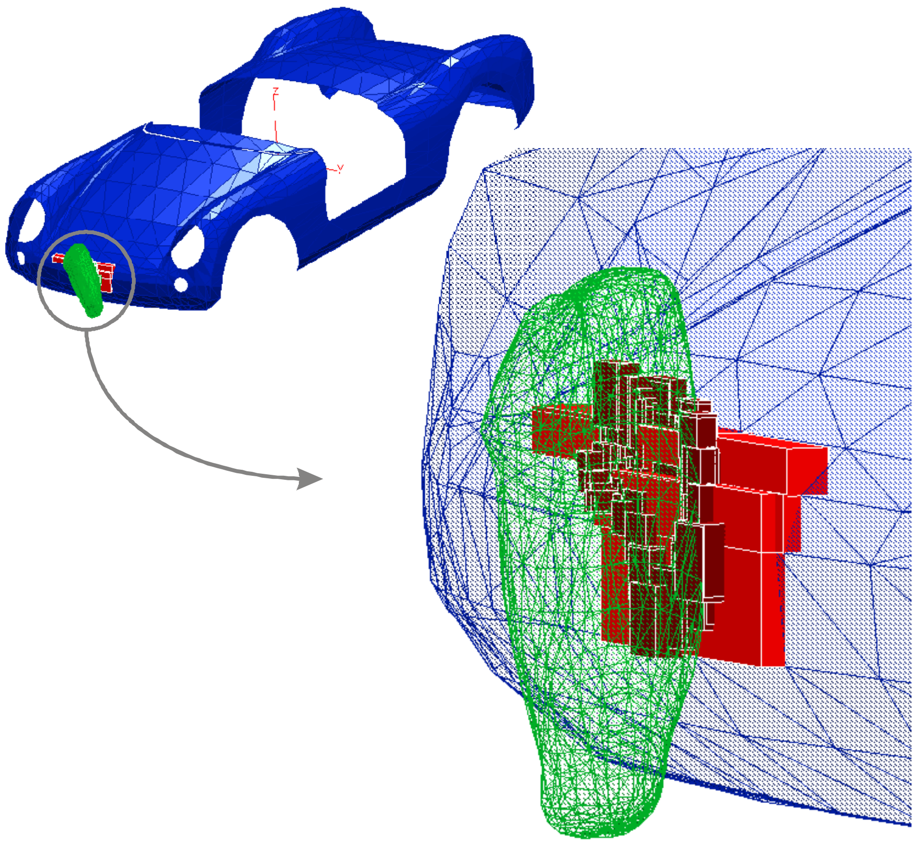
Collision Detection

- Task:
  Determination of all intersection lines of two polygon meshes

- Basic operation:
  Determination of intersection line of two triangles in 3D-space (76-181 FLOPs)

- Brute force method:
  Basic operation for all possible polygon pairings ($O(n^2)$)

- Efficiency improved by about four orders of magnitude by pre-selection of test pairings by Bounding Volume (BV) hierarchies



	Brute Force	BV-Hierarchy
BV-Checks	0	1537
Tr-Checks	1890336	330
Intsec-Lines	35	35

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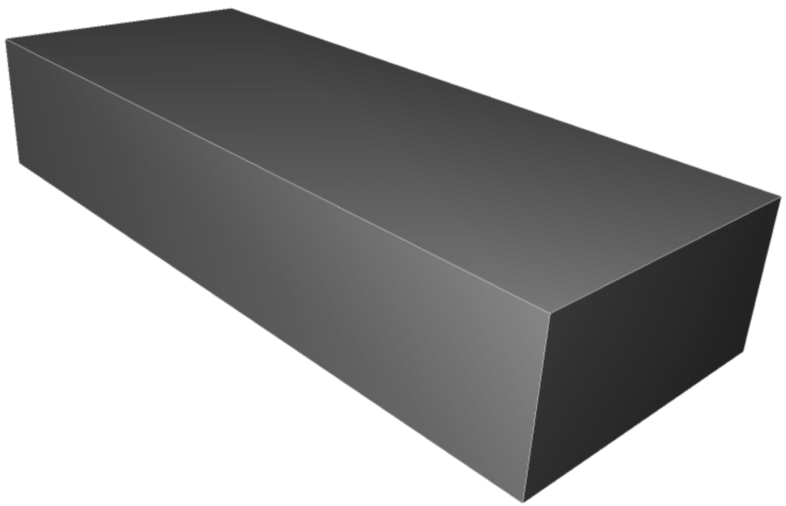
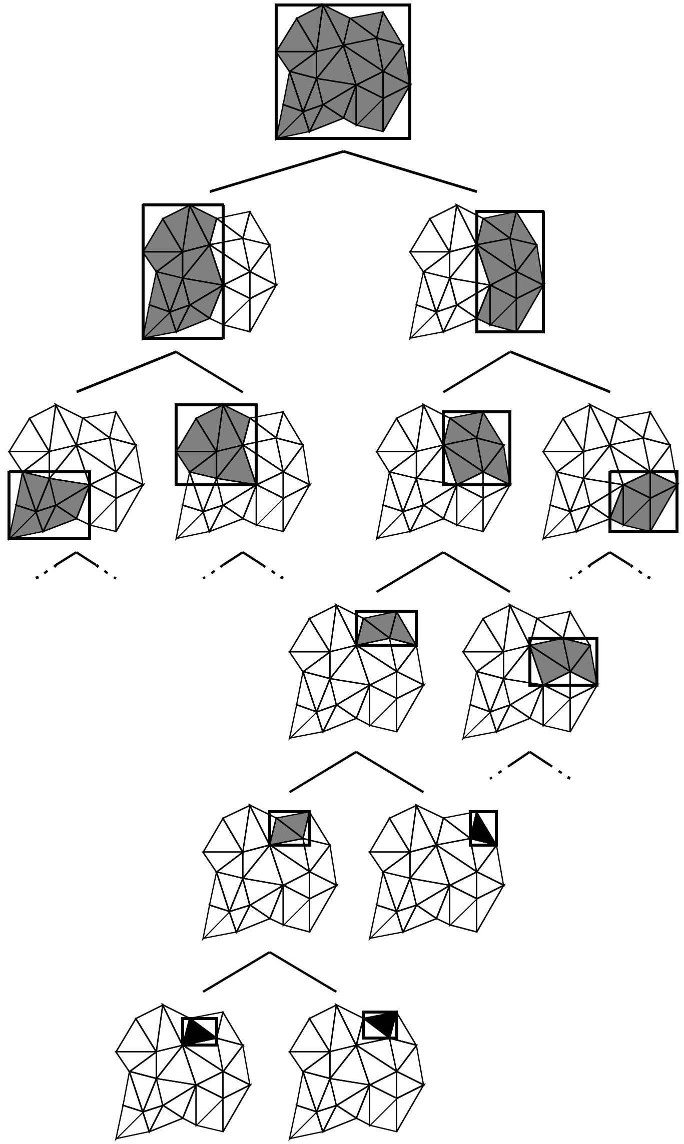
Collision Detection: Bounding Volume Hierarchy

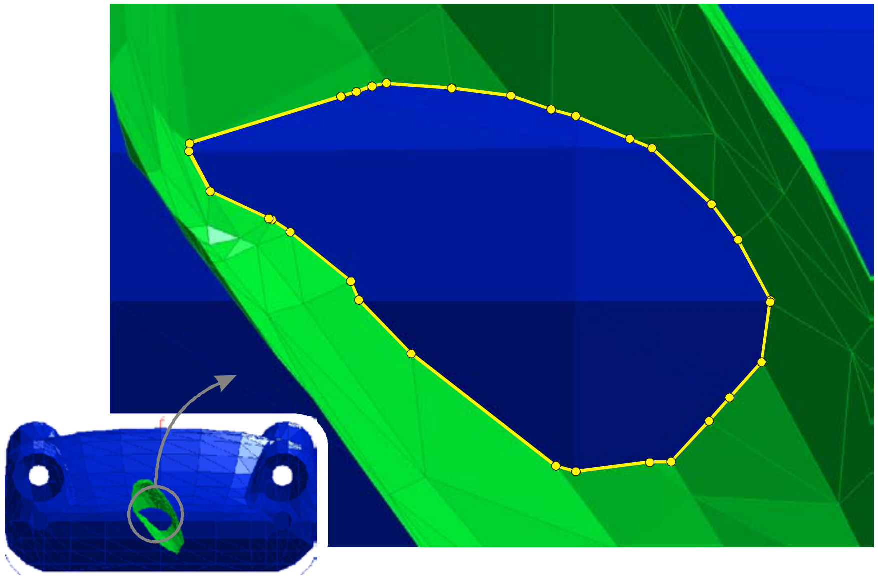
- Binary tree data structure
- Calculation once per surface (preprocessing)
- Elements: Axis-aligned cuboids representing convex hulls of contiguous surface parts
- Spacial refinement from root (whole surface) to leaves (solitary polygons)
- Efficient collision test of two BVs (12-36 FLOPs)

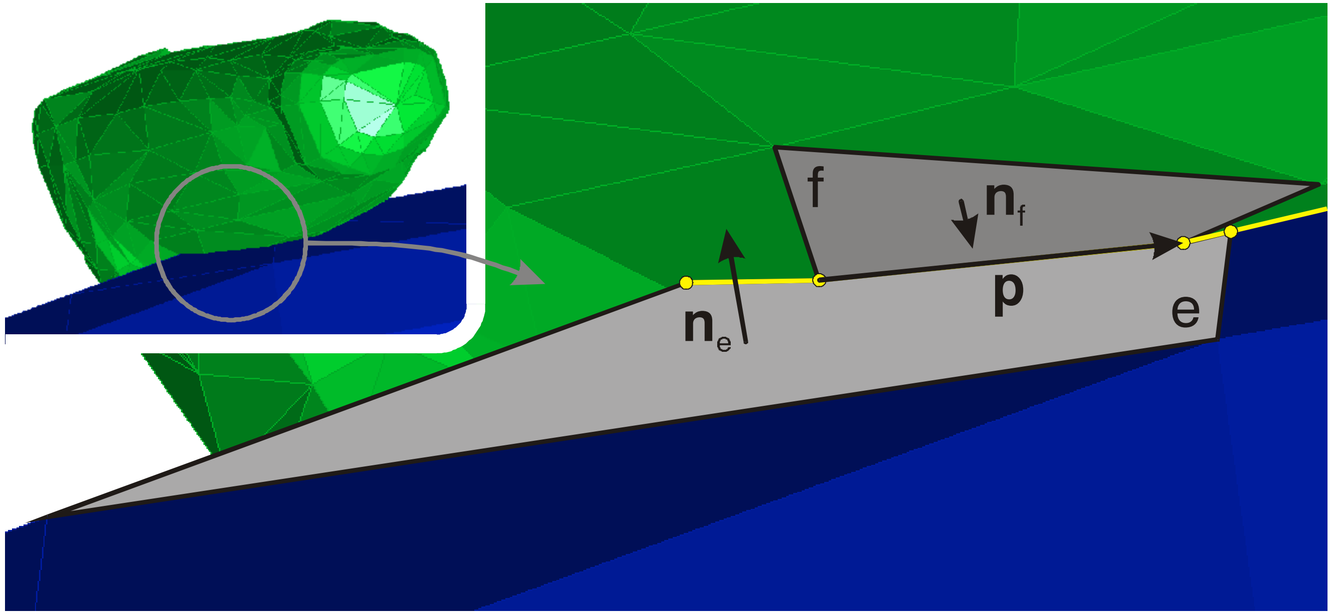




Construction of Intersection Polygons

- Collision detection determines intersection lines in irregular order
- Construction of intersection polygons by distance calculation of end points in pairs
- Circulation direction results from surface orientation





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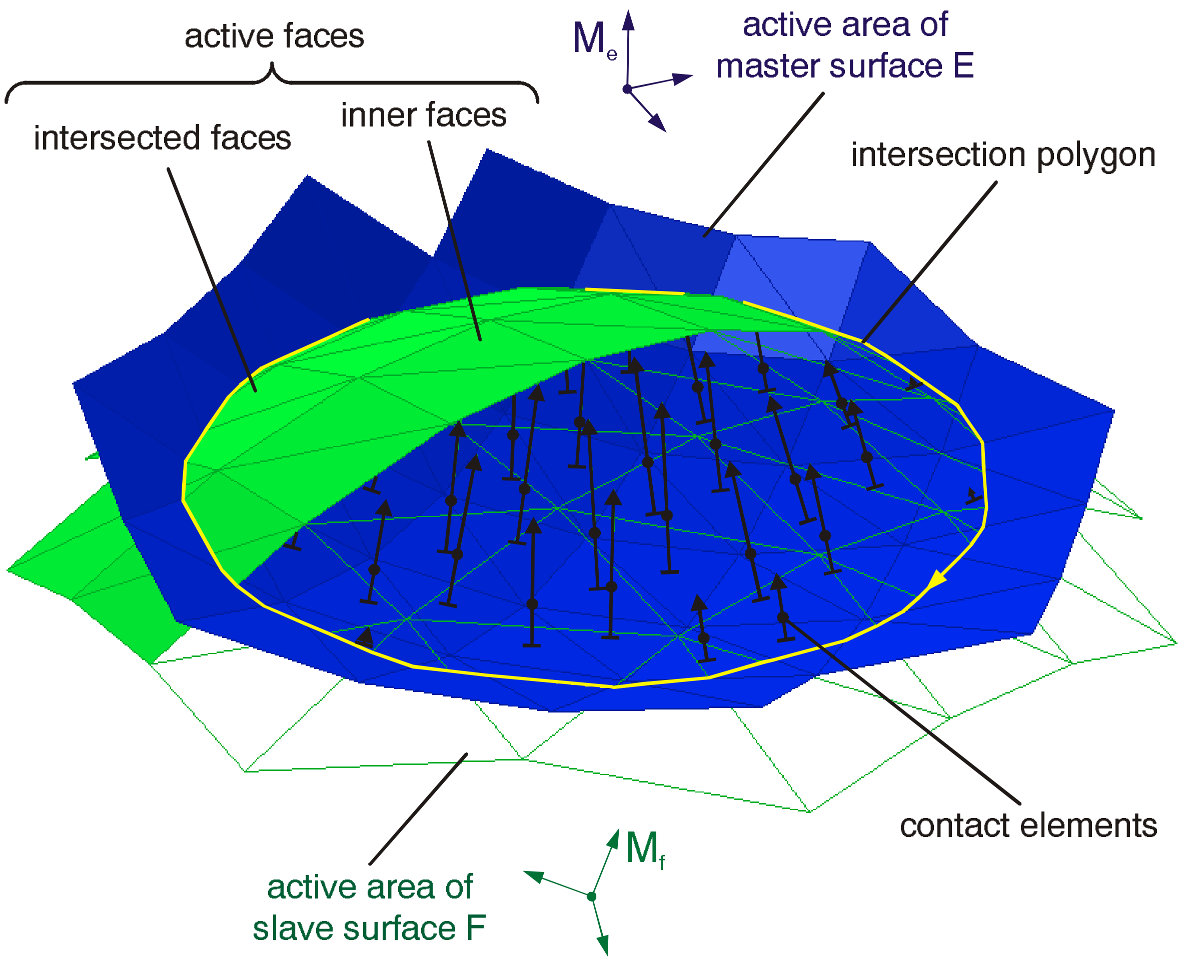
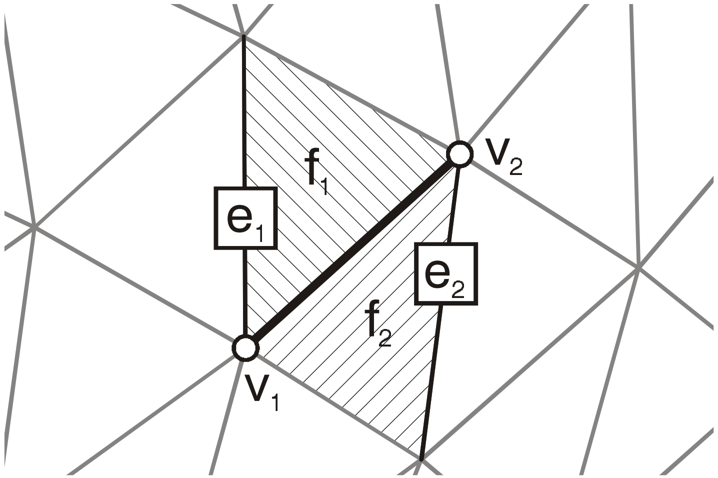
Determination of Active Surface Parts

- Active surface parts represent the boundaries of the intersection volume
- Intersected polygons given by collsion detection
- Determination of inner polygons by searching along active surface parts using Doubly Connected Edge Lists (DCEL)





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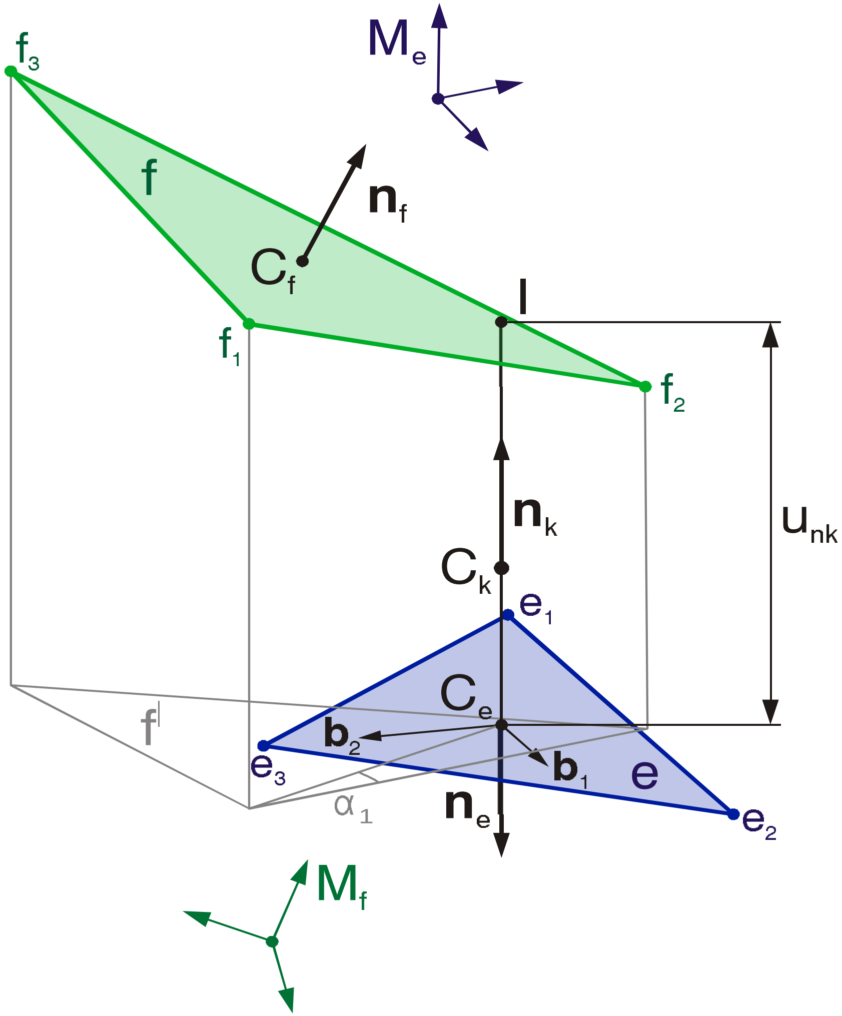
Generation of Contact Elements

- Contact elements result from active polygons e of master-surface E
- Determination of corresponding polygon f by projection of active slave-polygons to plane of e -> C_e is located inside of $f^{|}$
- Calculation of u_{nk} using normal form of plane of e
- C_k is reference position of relative velocity calculation and force vector



$$A_k = A_e \qquad u_{nk} = \frac{\boldsymbol{n}_f \cdot \boldsymbol{r}_{CeCf}}{\boldsymbol{n}_e \cdot \boldsymbol{n}_f}$$

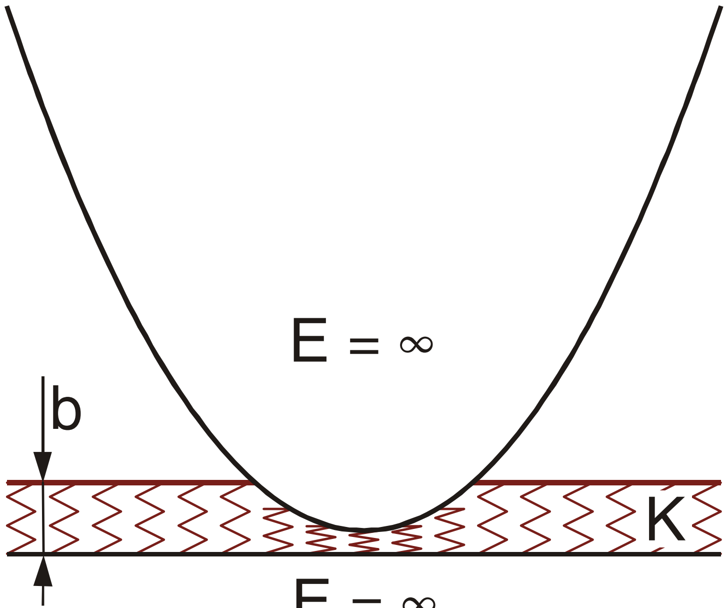
$$\boldsymbol{n}_k = -\boldsymbol{n}_e$$

$$\boldsymbol{r}_{Ck} = \boldsymbol{r}_{Ce} + \frac{c_F}{c_E + c_F} \cdot u_{nk} \cdot \boldsymbol{n}_k$$

Normal Force Law of Contact Elements

1. Elastic Foundation Model

$$F_{ck} = c_l \cdot A_k \cdot u_{nk} \qquad c_l = \frac{K_l}{b_l} = \frac{1}{\dfrac{b_E}{K_E} + \dfrac{b_F}{K_F}}$$



2. Aereal Damping

$$F_{dk} = \begin{cases} d_l \cdot A_k \cdot v_{nk} & u_{nk} \geq u_d \\ d_l \cdot A_k \cdot v_{nk} \cdot \dfrac{u_{nk}}{u_d} & u_{nk} < u_d \end{cases}$$

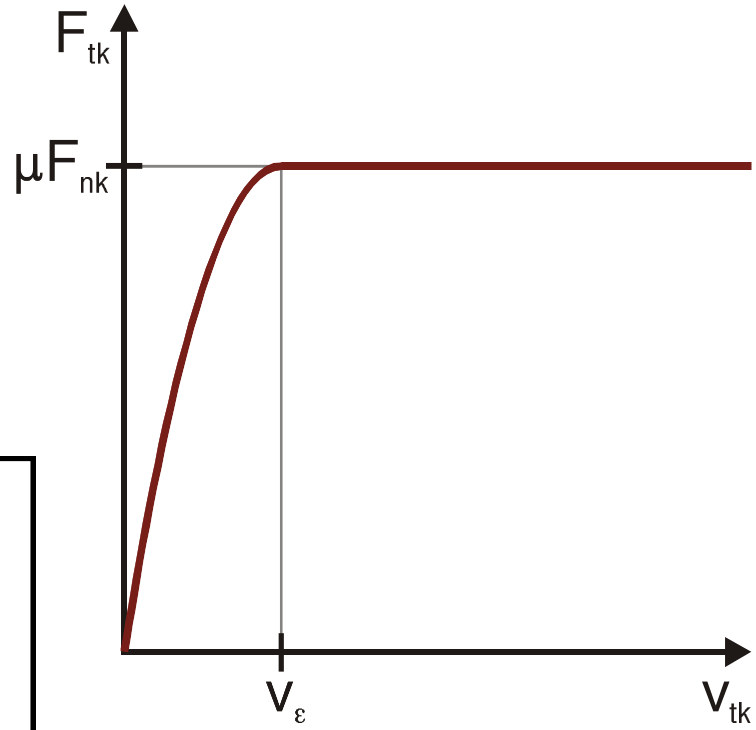
3. Adhesion Avoidance

$$F_{nk} = \begin{cases} F_{ck} + F_{dk} & F_{ck} + F_{dk} > 0 \\ 0 & F_{ck} + F_{dk} \leq 0 \end{cases}$$

Tangential Force Law of Contact Elements

4. Regularised Coulomb's Friction

$$F_{tk} = \begin{cases} \mu \cdot F_{nk} & v_{tk} \geq v_{\varepsilon} \\ \mu \cdot F_{nk} \cdot \dfrac{v_{tk}}{v_{\varepsilon}} \cdot \left(2 - \dfrac{v_{tk}}{v_{\varepsilon}}\right) & v_{tk} < v_{\varepsilon} \end{cases}$$



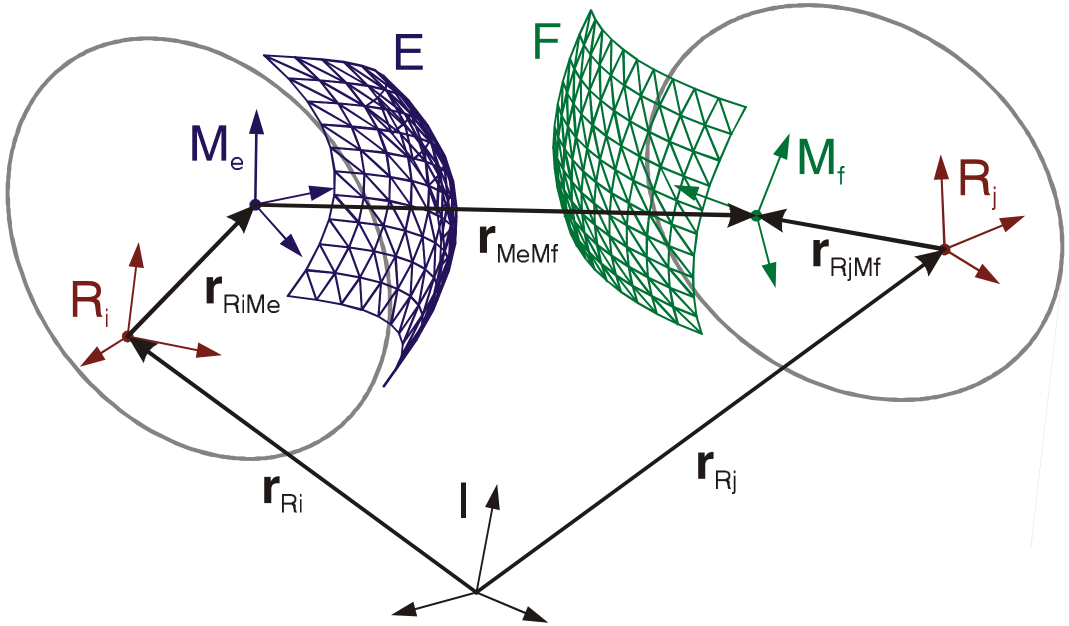
Total Resulting Contact Force & Torque

5. Contact Element Force

$$F_k = F_{nk} \cdot \boldsymbol{n}_k + F_{tk} \cdot \frac{\boldsymbol{v}_{tk}}{v_{tk}}$$

6. Resulting Torque

$$\boldsymbol{M}_k = \boldsymbol{r}_{MfCk} \times \boldsymbol{F}_k$$



7. Total Force at M_f

$$\boldsymbol{F}_{Me}^{Mf} = \sum \boldsymbol{F}_k$$

8. Total Torque

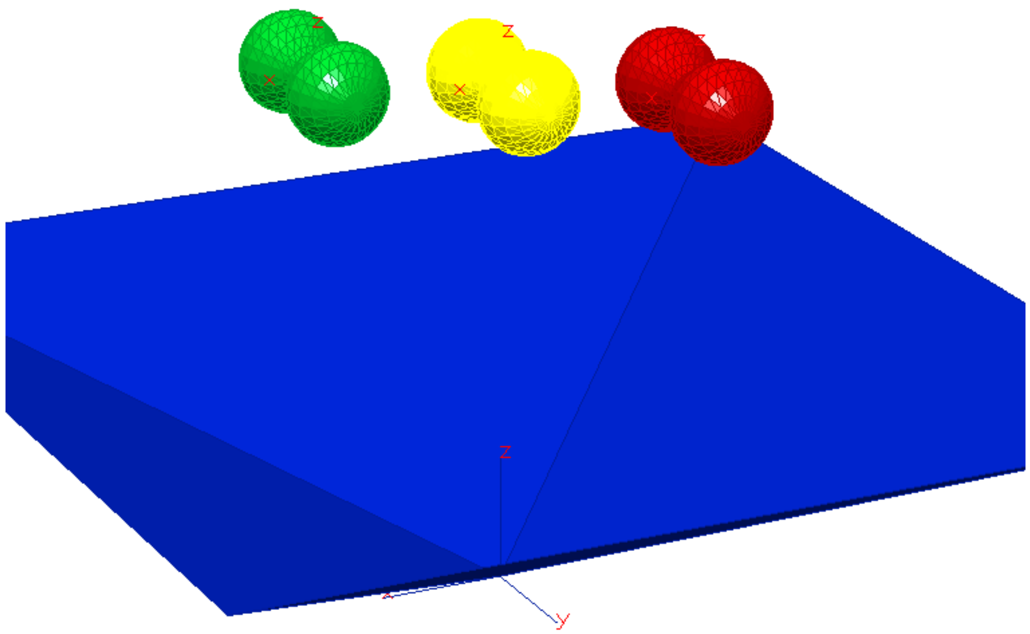
$$\boldsymbol{M}_{Me} = \sum \boldsymbol{M}_k$$

MBS: Applied Forces

$$\begin{aligned} \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}(t) &= \boldsymbol{f}(t, \boldsymbol{q}, \dot{\boldsymbol{q}}, \lambda) - \boldsymbol{G}^T(t, \boldsymbol{q})\lambda \\ 0 &= \boldsymbol{g}(t, \boldsymbol{q}) \end{aligned}$$

Example: Bouncing Bubbles

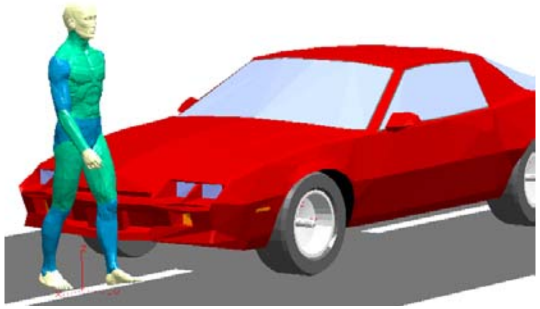
- 3 bodies
- 18 degrees of freedom
- 6 contact pairings
- Bubbles: 950 triangles
- Container: 4 triangles
- Synthetical parameterisation
- Multiple and conforming contacts
- LSODE atol = rtol = 2.0e-4
  - Mean step-size 0.8 ms
  - Real-time factor* 276 s / 3 s = 92

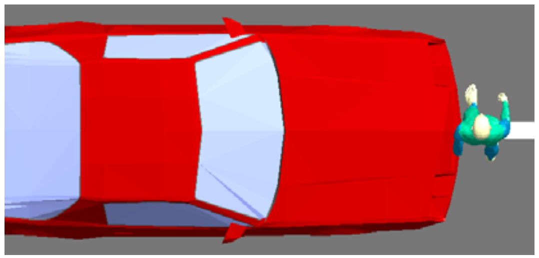


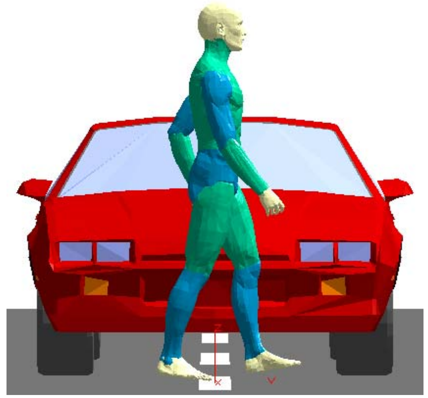
* Mobile PIII 1133 MHz / SIMPACK 8.6 / Win 2k

Example: Pedestrian Crash

- 15+1 bodies
- 29 degrees of freedom
- 27 contact pairings
- Man: 20452 triangles
- Car: 1240 triangles
- Estimated parameterisation
- DOPRI5 atol = rtol = 1.0e-3
  - Mean step-size 2.0 ms
  - Real-time factor* 288 s /1,5 s = 192







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Valuation

Disadvantages

- High quality polygon meshes required
  - Consistent orientation
  - No cracks
  - Discretisation results from resolution
- Non-practical parameters
- Not applicable for elastic bodies
- Neglecting of adhesive friction and shear stresses in contact patch
- Stiff layers cause stiff ODE

Advantages

- Easy providing of contact surfaces
- Complexly shaped contact surfaces
  - Multiple contact patches
  - Multiply bordered contact patches
  - Conforming contact
- Very robust algorithm
- Better approximation than single point models
- Efficiency fits into MBS simulation
- Open source code: www.pcm.hippmann.org