Simulation for assembly-oriented design and digital validation of cables and hoses

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Simulation based design, assembly and validation of cables, hoses and wiring harness

- Introduction Fraunhofer ITWM
  - related activities
- Fast and accurate simulation of flexible structures
- IPS Cable Simulation
  - features & benefits
  - Application cases
- Summary
  - and outlook
Fraunhofer-Institute for Industrial Mathematics ITWM

Activities mainly in the context of engineering applications:

- Dynamics and durability
- Fluid dynamics, flow in complex structures
- Image processing and quality assurance
- Optimization, adaptive systems
- High Performance Computing

260 employees
budget 2013: 22,0 Mio Euro

Simulation of cables, hoses and wiring harness - related Fraunhofer ITWM activities

- Simulation of flexible structures
  - IPS Cable Simulation
  - CDTire
- Vehicle System Simulation
  - MBS / co-simulation / FMI/FMU
  - realtime & hybrid simulation
  - RODOS – Interactive driver and operator simulation
- VMC – Virtual Measurement Campaign
  - Geo-referenced model of the world for vehicle engineering
  - Simulation of usage variability
Fraunhofer ITWM activities

Tire simulation

- **CDTire** – Tire model for comfort, durability, safety and NVH
  - Available with ADAMS, ALTAIR MotionSolve, LMS Virtual.lab, SIMPACK, Matlab/Simulink
  - flexible rim
- **CDTire / Realtime**
  - real time capable / up to 150 Hz
- **CDTire / 3D** shell based detailed model of side-walls and belt

Vehicle System Simulation / MBS

- System modelling and simulation for load path and energy flow
- Multibody System Simulation of full vehicles and subsystems at different complexity levels
- Invariant Loads
  - Identification of road-profiles based on measured wheel-loads, tire-models and optimal-control methods
  - ITWM-I6D-approach, derivation of geometrical road-profiles for / with CDTire
- On-board / realtime simulation and simulation-based monitoring

contact: Michael Burger & Manfred Bäcker
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Simulation of “very” flexible structures

Challenges
- cables and wiring harnesses
- hoses
- ceiling / roof interior
- tires
- rubber mounts
- ...

New Fraunhofer technology – available in **IPS Cable Simulation**
- Fast and physically correct simulation of large non-linear deformations
- Special focus on interactive virtual assembly of cables and hoses
Simulation based design, assembly and validation of cables, hoses and wiring harness

Technology development by dedicated groups of experts at ITWM and FCC since 2005

- based on geometrically nonlinear beam theory
- variational discretization
- special numerical methods:
  - "geometric finite differences"
    - discrete differential geometry: discretization of differential invariants
  - such that even for relatively coarse discretization the bending and torsion energy will be determined physically correct
Basic Cosserat rod kinematics: Configurations

- **Configuration variables:**
  - Centerline curve: \( \Phi: [0, L] \times \mathbb{R} \rightarrow \mathbb{R}^3 \)
  - Moving frame: \( \mathbf{R}(s, t) = a^{(i)}(s, t) \otimes e_i \in SO(3) \)
  - Curve parameter: \( s \in [0, L] \), time: \( t \in \mathbb{R} \)
  - Cross section coordinates: \( (\xi_1, \xi_2) \in A_0 \subset \mathbb{R}^2 \)

- **Current (deformed) configuration:**
  \[
  X(\xi_1, \xi_2, s, t) = \Phi(s, t) + \xi_a a^{(a)}(s, t)
  \]

- **Reference configuration:**
  \[
  X(\xi_1, \xi_2, s) = \Phi_0(s) + \xi_a a^{(a)}(s)
  \]
  \[
  \partial_s \Phi_0(s) = a_0^{(3)}(s)
  \]

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Differential geometry of Cosserat curves in space

- **Framed space curve:** \( (\varphi, \dot{\mathbf{R}}): [0, L] \rightarrow \mathbb{R}^3 \times SO(3) \)
  - regular curve (arc length parametrization)
  - general frame field: \( \dot{\mathbf{R}}(s) = (d_1, d_2, d_3) \in SO(3) \)

- **Generalized Frenet equations:**
  \[
  d'_k = u \times d_k
  \]
  - Darboux vector \( u(s) = \sum_{i=1}^3 U_i(s) d_i(s) \)
  - Curvatures \( U_i(s) \) given w.r.t. the frame directors \( d_i(s) \)

- **Curve tangent components \( V_i(s) \) w.r.t. the frame directors \( d_i(s) \):**
  \[
  \varphi'(s) = \sum_{i=1}^3 V_i(s) d_i(s)
  \Rightarrow V_i(s) = d_i(s) \cdot \varphi'(s)
  \]

- **Natural equations / principal theorem:**
  »If the curvatures \( U_i(s) \) and tangent components \( V_i(s) \) are given as functions of the reference arc length, the curve and its frame are determined up to a rigid body motion!«

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Ref.: Simo (1985), Antman (2005)

Ref.: Antman (1974, 2005)
Basic Cosserat rod kinematics: invariant strain measures

- **Transverse shear & extension / dilation:**
  \[ \partial_s \Phi(s,t) = V_k(s,t) a^{(k)}(s,t) \]
  - Transverse shearing: \( V_a = a^{(a)} \cdot \partial_s \Phi \), \( V_a = 0 \)
  - Extension / dilatation: \( V_3 = a^{(3)} \cdot \partial_s \Phi \), \( V_3 = 1 \)

- **Curvature & twist:**
  \[ \partial_s a^{(k)}(s,t) = u(s,t) \times a^{(k)}(s,t) \]
  - Darboux vector: \( u(s,t) = U_k(s,t) a^{(k)}(s,t) = \hat{R}(s,t) \cdot U(s,t) \)
  - Bending curvatures: \( U_a = a^{(a)} \cdot u = a^{(a)} \cdot (a^{(3)} \times \partial_s a^{(3)}) \)
  - Twisting curvature: \( U_3 = a^{(3)} \cdot u = a^{(2)} \cdot \partial_s a^{(4)} = -a^{(4)} \cdot \partial_s a^{(2)} \)

- **Reference strain measures:**
  \[ V_0(s) = (0,0,1)^T, \quad U_0(s) = \hat{R}_0(s) \cdot u_0(s) \]

**Ref.:** Simo (1985)  
**Source:** Antman (2005)

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Cosserat rod: Mechanical energy

- **Kinetic energy:**
  \[ W_{bin}^{(CR)} = \int_0^L ds \frac{1}{2} \rho_0 [A(\partial_s \Phi)^2 + I_k \Omega_k^2] \]

- **Elastic energy:**
  \[ W_{el}^{(CR)} = \int_0^L ds \frac{1}{2} [\Delta V \cdot \hat{C}_F \cdot \Delta V + \Delta U \cdot \hat{C}_M \cdot \Delta U] \]

- Change in the vectorial strain measures:
  \( \Delta V(s,t) := V(s,t) - U_0(s) \), \( \Delta V(s,t) := V(s,t) - (0,0,1)^T \)
- Effective stiffness matrices (if homogeneous, isotropic material):
  \( \hat{C}_F = \text{diag}( GA_1, GA_2, EA) \), \( \hat{C}_M = \text{diag}(EI_1, EI_2, GJ_3) \)
Cosserat rod: Viscous stress power

- Dissipation function for Kelvin-Voigt damping:

\[
D_{KV}^{(CR)} = \int_0^L ds \left[ \frac{1}{2} \left( \frac{\partial}{\partial t} \mathbf{V} : \mathbf{\dot{V}}_F + \mathbf{\dot{V}}_F : \frac{\partial}{\partial t} \mathbf{V} + \frac{\partial}{\partial t} \mathbf{U} : \mathbf{\dot{V}}_F + \mathbf{\dot{V}}_F : \frac{\partial}{\partial t} \mathbf{U} \right) \right] = \frac{1}{2} P_{\text{visc}}^{(CR)}
\]

- Effective viscosity matrices / damping parameters:

\[
\mathbf{V}_F = \text{diag}(\eta_A, \eta_A, \eta_A) = \mathbf{\hat{C}}_F \cdot \text{diag}(\tau_S, \tau_S, \tau_E)
\]

\[
\mathbf{V}_M = \text{diag}(\eta_E I_1, \eta_E I_2, \eta_E I_3) = \mathbf{\hat{C}}_M \cdot \text{diag}(\tau_E, \tau_E, \tau_S)
\]

- Shear & bulk retardation times: \(\tau_S = \eta / G, \tau_B = \zeta / K\)
- Extensional viscosity: \(\eta_E = \zeta(1-2\nu)^2 + \frac{1}{2} \eta(1+\nu)^2\)
- Extensional retardation time: \(\tau_E = \eta_E / E = \frac{1}{2}[(1-2\nu)\tau_B + 2(1+\nu)\tau_S]\)

- Balance of mechanical energy:

\[
\frac{d}{dt} \left[ W_{\text{kin}}^{(CR)} + W_{\text{el}}^{(CR)} \right] = -P_{\text{visc}}^{(CR)}
\]

Application demands on the discrete rod model

- Requirements for the discrete cable model:
  - (sufficiently) correct mechanics ...
  - ... as fast as possible !!!
  - ... suitable for fast simulations
  - »at interactive rates«
  - Compute cable deformations within a few milliseconds!
  - \( \Rightarrow \) The discrete model has to work with as few d.o.f. as possible!

- The »Geometric Finite Differences« approach to the discretization of Cosserat rod models:
  - Discrete Differential Geometry (DDG) of framed curves
  - Discretization of the differential invariants that are qualitatively correct for arbitrarily coarse meshes!
Quaternionic Cosserat rods: Euler parametrization of SO(3)

Euler parametrization:
\[
\begin{pmatrix}
  d_1(p) \\
  d_2(p)
\end{pmatrix} = \begin{pmatrix}
  p_0^2 + p_1^2 - p_2^2 - p_3^2 \\
  2p_0p_3 + 2p_1p_2 \\
  p_0^2 - p_1^2 + p_2^2 - p_3^2 \\
  -2p_0p_2 + 2p_1p_3
\end{pmatrix}
\begin{pmatrix}
  -2p_0p_2 + 2p_1p_3 \\
  2p_0p_3 + 2p_1p_2 \\
  2p_0p_1 + 2p_2p_3
\end{pmatrix}
\]
\[\|p\| = 1, \quad \text{where } p = (p_0, p_1, p_2, p_3) \in \mathbb{H}\]


Quaternionic Cosserat rods: strain measures

\[\mathcal{R}(\Gamma) = 0, \quad \mathcal{S}(\Gamma) = \mathbf{V} - \mathbf{V}_0\]

strain vector
\[
\begin{align*}
\Gamma_1 &= \left\langle d_1(p), \delta \phi \right\rangle \\
\Gamma_2 &= \left\langle d_2(p), \delta \phi \right\rangle \\
\Gamma_3 &= \left\langle d_3(p), \delta \phi \right\rangle - 1
\end{align*}
\]
\[\text{stretching, shearing}\]

curvature vector
\[K = 2 \rho \partial_s \rho\]
\[\text{bending, torsion}\]

angular velocity vector
\[\Omega = 2 \rho \partial_t \rho\]
Discrete quaternionic Cosserat rods


Discrete differential geometry of Cosserat curves

Principal theorem of the DDG of framed curves:
»If the discrete curvatures $K_n$ and discrete shear strains $\Gamma_{n-1/2}$ are given, the discrete curve and its quaternionic frame are determined up to a rigid body motion!«
Discrete Cosserat rod model: Energy & dissipation function

- **Discrete elastic energy:**
  \[
  W_{\text{el}}^{(CR)} \approx \frac{1}{2} \sum_{j=0}^{N} \frac{1}{2} (\Delta s_{j} + \Delta s_{j+1}) \Gamma_{j} \psi_{j} \cdot \Gamma_{j}
  \]

- **Discrete kinetic energy:**
  \[
  W_{\text{kin}} \approx \frac{1}{2} \sum_{j=0}^{N} \frac{1}{2} (\Delta s_{j} + \Delta s_{j+1}) \rho \dot{A}_{j} \dot{s}_{j} + \frac{1}{2} \sum_{j=1}^{N} \frac{1}{2} \Delta s_{j} \Omega_{j} \cdot \rho \dot{\Gamma}_{j} \cdot \Omega_{j}
  \]

- **Discrete dissipation potential:**
  \[
  D_{\text{RV}}^{(CR)} \approx \frac{1}{2} \sum_{j=0}^{N} \frac{1}{2} (\Delta s_{j} + \Delta s_{j+1}) \Delta K_{j} \cdot \psi_{j} \cdot \Delta K_{j}
  \]

- **Quasistatic equilibrium:**
  \[
  \Omega_{j} = 2\Gamma_{j} \dot{\Gamma}_{j}
  \]

- **Additional terms accounting for external forces & moments**

Discrete Cosserat rod model: dynamic equilibrium equations

\[
L = T - V - g^{T} \lambda
\]

- Lagrange function
- Potential energy \( V \)
- Kinetic energy \( T \)
- Dissipative energy \( D \)
- Constraints \( g = ||p||^{2} - 1 \)
- Exterior forces \( f \) & moments \( m \)

\[
\begin{align*}
\dot{q} & = v \\
M(q) \ddot{v} & = \psi(q, v, t) - G(q)^{T} \lambda \\
0 & = g(q)
\end{align*}
\]

\[
\psi(q, v, t) = \left( \frac{f}{m} \right) - \frac{\partial V}{\partial q} - \frac{\partial D}{\partial v} + \frac{\partial T}{\partial \dot{v}} - \frac{\partial G(Mv)}{\partial q}
\]

Quasistatic equilibrium:
\[
\Rightarrow \text{solve discrete eqns. for } \dot{q} = 0 = \ddot{q}
\]

Discrete Kirchhoff constraints (\( \Rightarrow \text{Lang} \& \text{Arnold, 2009-2011} \)):
- zero transverse shear (and \( f \) or extensional) strains
Simulation based design, assembly and validation of cables, hoses and wiring harness

Technology development by dedicated groups of experts at ITWM and FCC since 2005

- based on geometrically nonlinear beam theory
- variational discretization
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Simulation based design, assembly and validation of cables, hoses and wiring harness

Flexible parts in cars / Electrical System

- between 1 and 3.5 km different types of wires and wiring harnesses
- 60 kg and more depending on configuration
- even more for electric drivelines and hybrid cars
Design, assembly and validation with IPS Cable Simulation

application focus: CAD, digital assembly and digital validation

modeling options, features and benefits
- interactive simulation
- cables and hoses, including non-circular cross sections
- junctions and branches
- car wire harness including various types of clips
- free hanging cable ends with plugs and connectors
- fixtures and clips (also handling the geometric shape)
- collision handling (cable to rigid and cable to cable)
- automatic flexibilization of CAD-defined cables
- huge variety of analysis and post-processing options

Example (AUDI):
Assembly of retractable display in cockpit

3 project steps involving wires
- Assembly simulation of display in cockpit
- Assembly sequence of connectors and variation of clip types
- Functional reliability test and redesign of mount
Assembly simulation of display in cockpit

**Situation**
- Assembly may cause buckling and clamping

**Objectives**
- Optimize length for robust and fast assembly
- Minimize length to save cost and reduce weight

Real-time simulation of Cable with overlength
Assembly simulation of display in cockpit

Conflicting objectives:
- Ease of installation  
  -> longer cable
- Reduction of buckling risk  
  -> shorter cable

Result
- Cable length reduced by 80 mm
- No clamping and sufficient clearance for manual assembly

Assembly optimized cable length (80mm shorter)
Assembly of connectors and variation of clip

**Situation**
- Reduced clearance for manual assembly of connectors and clips
- Last clip could not be mounted correctly

**Objectives**
- Keep length and change clip to reduce load and bending radius
- Check assembly sequence

Assembly simulation of connectors and clips
Assembly simulation of connectors and clips

Result
- Bending radius and tensile stress OK
- Clearance OK for manual installation
- Wires must be installed without crossing
- 180° rotation of display does not cause damage
Variation of clip type

Custom clips from database

- Various clip types with different degrees of freedom are applicable with cables in real-time
- Plug and play
- Realistic look
- Insert from database
Variation of clip type

Result
- Best result achieved by opening one connection
- Bending radius OK
- Lower tension on wires and clip
- Shorter manual installation time
- No risk of damage

Functional reliability and redesign of mount part

Situation
- Signal cable damaged during test
- Bending radius, acting forces and stresses could not be determined easily

Objectives
- Find root cause & redesign
Functional reliability and redesign of mount part

**Result**
- Root cause detected and shape of mount part redesigned
- Bending radius OK -> no damage

**Advantage**
- Product quality assured with efficient time saving process
- Cost reduction by saving prototypes
**Application case (Volvo):**
Design of hydraulic hoses at a driving cab of a truck

Cab moves relative to the chassis at tilting.

**Tasks:**
- Finding the ideal length of the hose.
- Is the designed space sufficient and can an assembly be performed?
- Where and how have the hoses to be fixed and/or bundled by setting clips of various kinds?
- Will the minimal bending radius be violated?
- Is there collision to other parts?
- What is the load on hoses that are assembled between relative to each other moving parts?
- What is the impact of an incorrect assembly (e.g., rotation of the connections)?

**Simulative approach:**
- Interactive tilting of the cab including the assembled flexible hose.
- Determination of the point in time where the highest load occurs.
- For this point in time vary the length of the hose either manually or automatically.
- Determination of the optimal length of the hose by using several analyze features.
- Analysis by stresses, deformations, designed space, position(s) and type(s) of clip(s), bending radius, rotation of connections, ...
**Application case:**
Design of hydraulic hoses at a driving cab of a truck (@ Volvo)

- **Analyzed variants without clips:**
  - Shortest hose 630 mm
  - Longest hose 900 mm
  - All variants between 630 and 900 mm (by an increment of 1 mm) in worst-case position

- **Analysis of von Mises stresses:**
  - Maximum values differ over different lengths.
  - Area, where max. load occurs, changes.
  - Optimal length of hose (without clips) is at approx. 700 mm

Exemplary plotted variants of length 630 mm, 700 mm, 800 mm, 900 mm

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**Application case:**
Design of hydraulic hoses at a driving cab of a truck (@ Volvo)

Comparison of the designed space for different clamping and identical hose length of 700 mm:

- grey: hose without clamping
- blue: fixed clamping
- yellow: guided clamping, sliding and rotation allowed
Application case:
Design of hydraulic hoses at a driving cab of a truck (© Volvo)

- **Results:**
  - Optimal length of hoses for the actual loads during operation.
  - Original hose design could be optimized by 85 cm.
  - Ideal assembly position and type of clamping were determined.
  - Material loads and the necessary designed space could be reduced.

IPS Cable Simulation - Workflow

- Import geometry
- Define and create the cable
- Connect the cable(s) / hose(s)
- Analyze motion and loads
- Export geometry and results
IPS Cable Simulation

Customers / references:
- AUDI
- Bosch
- BMW
- Daimler
- Delphi
- EADS / Cassidian
- FORD
- Fujikura
- GM
- Liebherr
- OPEL
- Saab
- SCANIA
- SEAT
- Stihl
- Volkswagen
- Volvo AB (Truck & CE)
- Volvo Car

Technology development: Beyond own funding out of licence income our development is supported by public funding and specific method development projects financed by industry partners.

Public funding partners include
- VINNOVA (Sweden)
- BMBF
- EU and Rheinland-Pfalz (Fraunhofer Innovation Cluster)
- Fraunhofer Vorlaufforschung

Industry partners involved in method development projects
- Main partners since phase 1 – since 2005: **Volvo, GM, Ford, Delphi, Scania, Saab,…**
- Main partners since phase 2 / since 2010: **AUDI, VW, Daimler,** Bosch, BMW, Toyota, Stihl, Liebherr,…
Simulation based design, assembly and validation of cables, hoses and wiring harness

Summary

- IPS Cable Simulation provides leading technology for design, digital assembly and digital validation of cables, hoses and wiring harness, incl.:
  - interactive simulation of cables and hoses, incl. non-circular cross sections
  - car wire harness, incl. junctions, branches and various types of fixtures and clips
  - free hanging cable ends with plugs and connectors
  - collision handling (cable to rigid and cable to cable)
  - huge variety of analysis and post-processing options
  - Simulation of shell based structures (under development)