The potential of Isogeometric Analysis for improved simulation of environmental impact on large structures

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### Objective of 3D models and the used 3D representations

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<th>State-of-the-art:</th>
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<td>Computer Graphics</td>
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<td>Animation movies</td>
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<td>Computer Aided Design (CAD)</td>
<td>Face connectivity and Shape accuracy</td>
<td>Boundary structures of elementary and NURBS surfaces</td>
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<td>Suitable for production</td>
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<td>Manufacturing &amp; robotics (CAM)</td>
<td>Proper control of movements</td>
<td>Curves to control movement Shape as Triangulations (STL) or CAD-surfaces</td>
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<td>Finite Element Analysis (FEA)</td>
<td>Volume block connectivity</td>
<td>Structures of 3-variate parametric polynomials, most often of degree 1 or 2.</td>
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<td>Model refinement in critical regions</td>
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In current simulation processes for large structures many instances, representations and qualities of the same information is used.
Improved simulation of environmental impact on large structures - Requirements

- Model quality
  - CAD model shape accuracy
    - Updated to represent “As-is” (CAD-models describe “As-planned”)
    - Unnecessary details removed
  - FEA model connectivity
    - Watertight models (Correct connectivity/topology)
    - Simulation model refined as needed in critical regions
    - Grids for coupled systems
- Simulation quality
  - Higher order methods to better reflect the physics involved
  - Coupled problems, systems, e.g., fluid structure interaction
- Visualization
  - High end 3D graphics
  - Visual impression as in games and movies
Traditional simulation pipeline

**Bottleneck**
- Shape approximation
- Gap removal
- From surface to 3-variate representation

CAD Model → Surface Meshing → Surface Mesh → Volume Meshing → Volume Meshing → Definition of Boundary conditions → Shape Simplification → Solving → Simulation Post Processing → Graphics Model
Simulation on large structures– Future Information flow

As-is shape model

CAD Model + 3D measurement

3-Variate Rational Spline Model

Update isogeometric CAD-model

Direct visualization

Simulation Post Processing

Isogeometric solution

Solving

Simplified Isogeometric model

Refinement (Meshing)

Definition of Boundary conditions

Model for isogeometric simulation

Shape Simplification

Technology for a better society
Challenge 1: Create “as-is” model

- CAD-models describes the object as planned
  - Combines elementary surfaces (plane, cylinder, cone, sphere, torus and NURBS)
- Models aimed at visual purpose most often represent shape by (texture mapped) triangulations
- Laser scanning efficiently produce millions of points on the geometry
  - Extracting information from 3D datasets is complex
  - A industry is established related to model building from laser scans
  - Using the datasets for validation and updating of 3D models (CAD) is challenging
- The project “3D Airports for Remotely Operated Towers” in SESAR JU (EU) partly addresses these challenges for airports
  - The novel Locally Refined Splines will be explored.
The "As-is" shape model describes mathematically only the inner and outer hulls (surfaces) of the object using triangulations, elementary surfaces or NURBS surfaces.

The isogeometric model is analysis/simulation suitable and describes the volumes mathematically by watertight structures of blocks of 3-variate rational splines.

Building an isogeometric model is a challenge:
- There is a mismatch between the surface patch structure of the "As-is" model, and a suited block structure of an Isogeometric 3-variate rational spline model.
- Augmented spline technology is needed such as the novel Locally Refined Splines.

Projects addressing this:
- Isogeometry (2008-2012)- KMB project funded by the Norwegian Research council
- TERRIFIC (2011-2014) – STREP funded by the EU ICT under contract negotiations
Example: Isogeometric tube joint - Intersection

- Two independent pipes coming from CAD and described as 3-variate volumes
- The intersection of the pipes calculated.
  - The original large pipe is split in 3 volumes
- The intersection of the pipes calculated.
  - The original small pipe is split in 3 volumes

Example by: Vibeke Skytt, SINTEF IKT
Example: Isogeometric tube joint – Composing volumes

- The relations between the sub volumes produced by the intersection are established.
- These volumes do not satisfy the hexahedral (box structure) of the need isogeometric sub volumes.
- The volumes split to produce hexahedral volumes.
- The internal faces produced by the splitting process.

Example by: Vibeke Skytt, SINTEF IKT
Example: Isogeometric tube joint – match spline spaces

- Spline space refined to have matching lines in each hexahedral NURBS-block to produce a watertight representation
- Same as to the left, different view
- The final isogeometric tube joint.

Example by: Vibeke Skytt, SINTEF IKT
Challenge 3: Isogeometric analysis

First introduced in 2005 by T.J.R. Hughes, Univ. Texas

- Replace traditional Finite Elements by NURBS - NonUniform Rational B-splines
- Accurate representation of shape
- Allows higher order methods
- Perform much better than traditional Finite Elements on benchmarks
- Refinement of analysis models without remeshing
- Exact coupling of stationary and rotating grids
- Augmented spline technology is needed, e.g., Locally Refined Splines

Projects:
- ICADA (2009-2014)– KMB Project funded by Norwegian Research Council and Statoil
- Exciting (2008-2011) – STREP Project EU’s Transport program
Why has isogeometric analysis not been introduced before?

Independent evolution of CAD and FEM

- CAD (NURBS) and Finite Elements evolved in different communities before electronic data exchange
  - FEM developed to improve analysis in Engineering
  - CAD developed to improve the design process
  - Information exchange was drawing based, consequently the mathematical representation used posed no problems
  - Manual modelling of the element grid
  - Implementations used approaches that best exploited the limited computational resources and memory available.
- FEA was developed before the NURBS theory
  - FEA evolution started in the 1940s and was given a rigorous mathematical foundation around 1970 (E.g., 1973: Strang and Fix’s An Analysis of The Finite Element Method)
  - B-splines: 1972: DeBoor-Cox Calculation, 1980: Oslo Algorithm
Free vibration of a Tubular Joint
- 3-variate NURBS elements

Example by: Knut Morten Okstad, SINTEF IKT
Free vibration of a Nut
– 3-variate NURBS elements

Example by: Knut Morten Okstad,
SINTEF IKT
Challenge 4: Isogeometric visualization

• Current visualization technology address low order elements
  • Currently the isogeometric model has to be approximated with lower order representation (elements) for visualization
  • Results are degraded and information lost
• Need for visualization solutions exploiting the higher order representations
  • Higher order representations are more advanced and can better represent singularities in the solution
  • Direct ray tracing on the GPU:
• Cloudviz (2011-2014) – KMB project funded by Norwegian Research Council, Statoil, Ceetron,....
Direct rendering of advanced shapes on the GPU – avoiding tessellation

Eurographics 2008
Video: Johan S. Seland, SINTEF IKT, and Martin Reimers, UiO

Frames per second
Summing up:

- Efficient simulation of environmental impact on large structures requires an holistic approach to:
  - Creating a validated structure description
  - Creating an analysis suitable model
  - Handling coupled models and system
  - High quality visualization

- Current technologies are fragmented and require significant human intervention to work in an integrated way

- Isogeometric analysis has a potential of providing interoperability of shape representation (CAD) and FEA. However, augmented technology is needed for
  - Locally Refined Splines
  - Combining measurements of shape “as-is” with existing synthetic models (CAD)
Isogeometric Eigen frequency analysis of Chess Queen

The Eigen frequency analysis and consequently the animation is based on an isogeometric volumetric NURBS representation. Consequently the surface is a NURBS surface at all times, and can be translated back to CAD exactly as it is for any time step.

Animation by: Kjetil A. Johannessen PhD-fellow, NTNU