Appendix M

Space Thermal Analysis through Reduced Finite Element Modelling

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Abstract

The finite element method (FEM) is widely used in mechanical engineering, especially for space structure design. However, FEM is not yet often used for thermal engineering of space structures where the lumped parameter method (LPM) is still dominant.

LPM offers more accurate surfaces and fewer nodes to generate the radiative links while the FEM has automatic meshing tools and generation of conductive links. Coupled thermo-structural analyses are made straightforward if the same mesh can be used.

The proposed method brings together FEM and LPM by taking advantages on both sides. The structural FE mesh is reduced and the concept of super-node introduced. The reduction provides accurate conductive links and reduces the number of faces to compute the radiative links with Monte Carlo raytracing. The reduced model can integrate user logic in the exact same way a LPM model would do. Once the reduced model is solved using standard techniques, reduction matrices are exploited again to derive the detailed mesh temperatures for thermo-mechanical analyses.

To further reduce the computation time, quasi-Monte Carlo ray-tracing acceleration techniques were presented in the previous editions of the workshop, providing between 50% and one order of magnitude reduction of the number of rays required for a given accuracy. Combined with this acceleration technique, quadric surface fitting of selected regions in the FE mesh is performed to alleviate the FE mesh surface accuracy issue.

This presentation will summarise the research project developments carried out for the last four years. The end-to-end procedure will be detailed with actual space structures.

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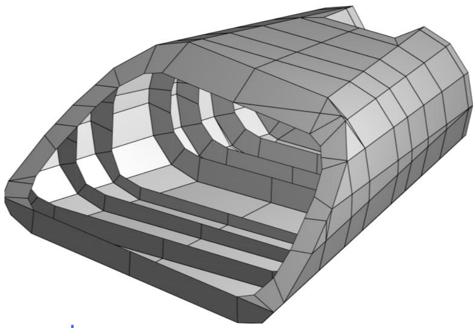
Finite Element vs. Lumped Parameter



	FEM		LPM	
# nodes		10^4 - 10^6		10^1 - 10^3
Conductive links computation	✓	Automatic	✗	Manual, error-prone
Radiative links computation	✗	Prohibitive	✓	Affordable
Surface accuracy for ray-tracing	✗	FE facets	✓	Primitives
User-defined components	✗	Difficult	✓	Easy
Thermo-mech. analysis	✓	Same mesh	✗	Mesh extrapolation

2

Reconciliation through a global approach

Radiative links computation

- Reduce # of rays: quasi-Monte Carlo method (isocell, Halton)
- Reduce # of facets: super-face concept (mesh clustering)

Surface accuracy for ray-tracing

- Quadrics fitting

Conductive links, thermo-mech. analysis and user-defined compts.

- Reduce detailed FE mesh (keep conductive info. of the detailed geometry)
- Able to recover detailed T° from reduced
- Transform reduced FE model to LP model to enable user-defined comp.

3

Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives

4

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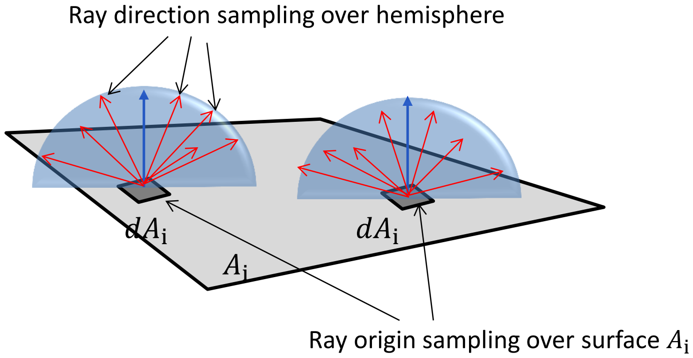
5

Ray-tracing: origin + direction sampling

$$F_{ij}(B_{ij}) = \frac{\text{Number of rays emitted by facet i, directly (finally) hitting j}}{\text{total number of rays emitted by facet i}}$$



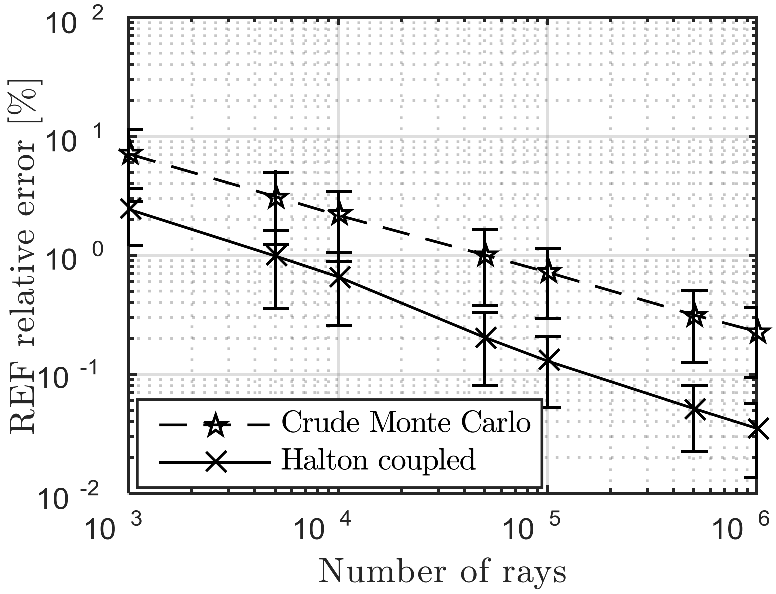
Reference solution: ESATAN-TMS

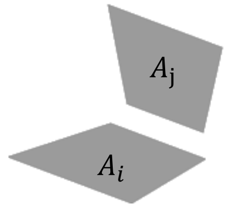
→ crude Monte Carlo: random direction & origin sampling, 1 ray / origin

$$error \propto \frac{1}{\sqrt{N_{rays}}}$$

6

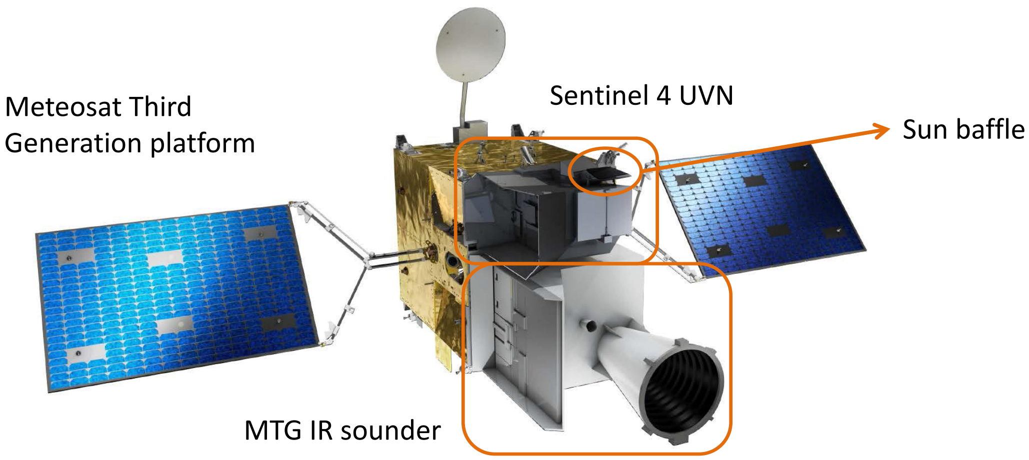
4-D QUASI-MC SAMPLING: 2 QUADRANGLES





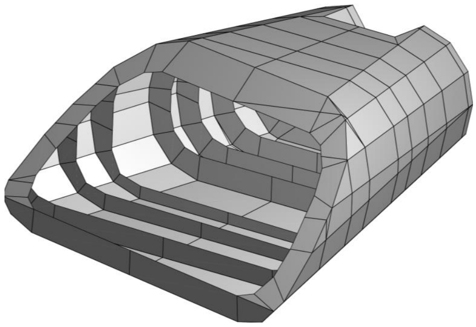
7

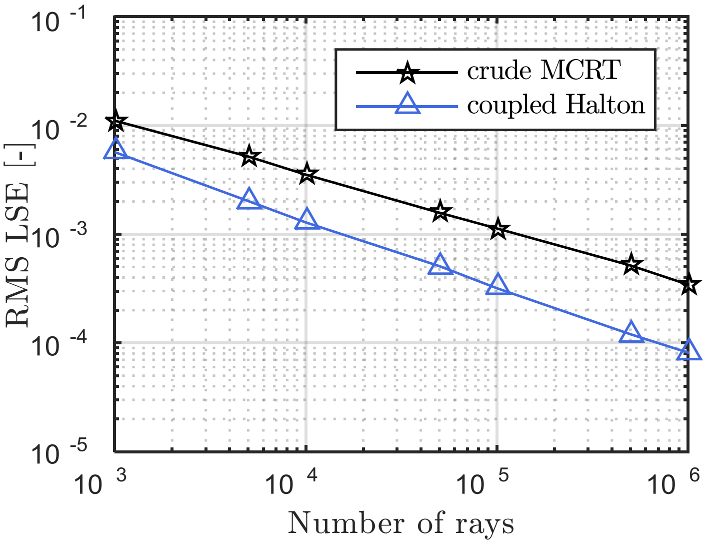
4-D QUASI-MC SAMPLING



8

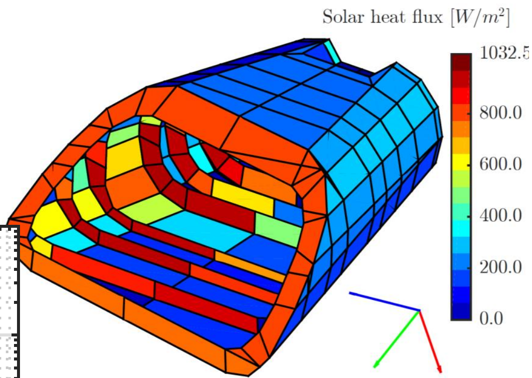
4-D QUASI-MC SAMPLING

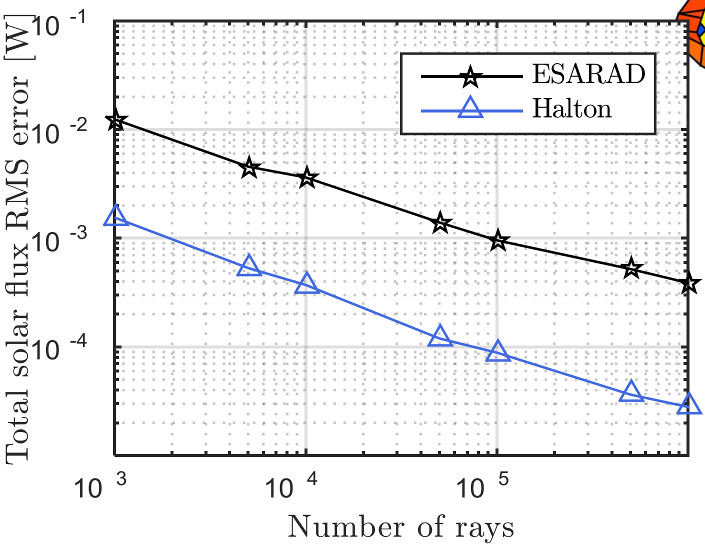




9

APPLIED TO SOLAR HEAT FLUXES





10

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Ray-tracing enhancement

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Super-face ray-tracing

Integrating the developments

Conclusions & perspectives

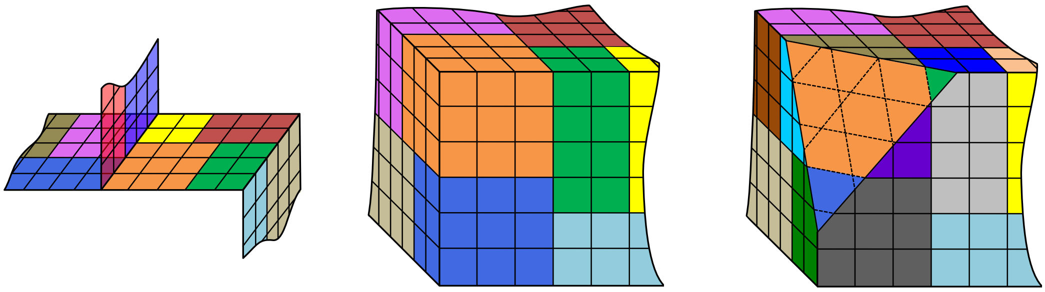
11

Philosophy

2D parts: avoid crossing sharp edges

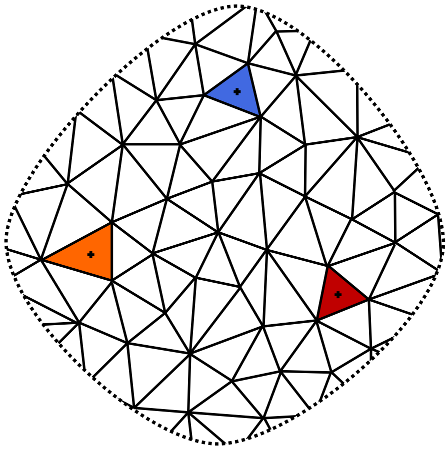
3D parts:

- high k: single super-node for volume and faces
- low k: consider external faces separately



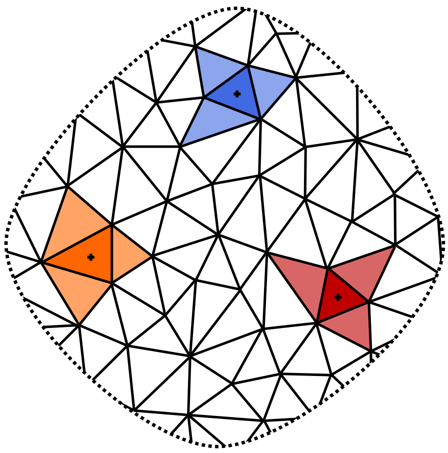
12

K-mean clustering initialization



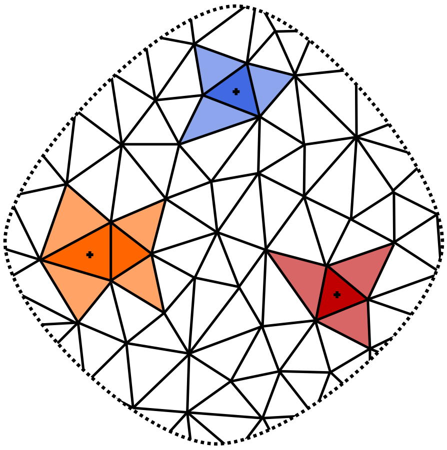
13

Greedy region growing



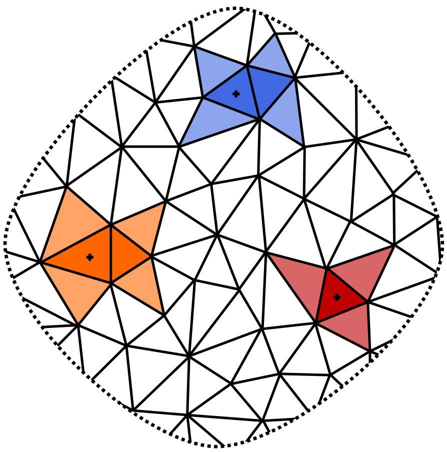
14

Greedy region growing



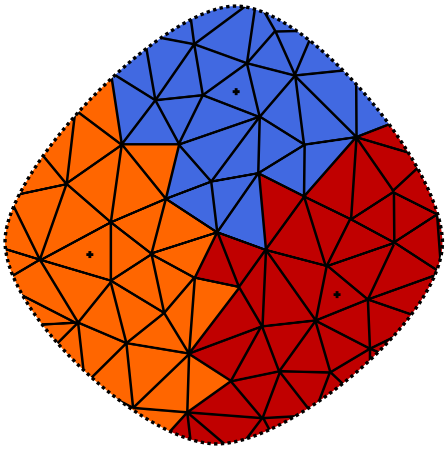
15

Greedy region growing



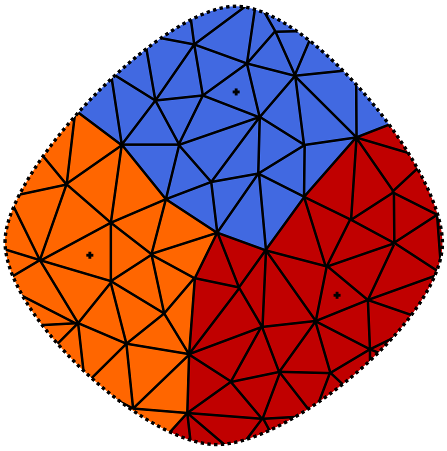
16

Greedy region growing



17

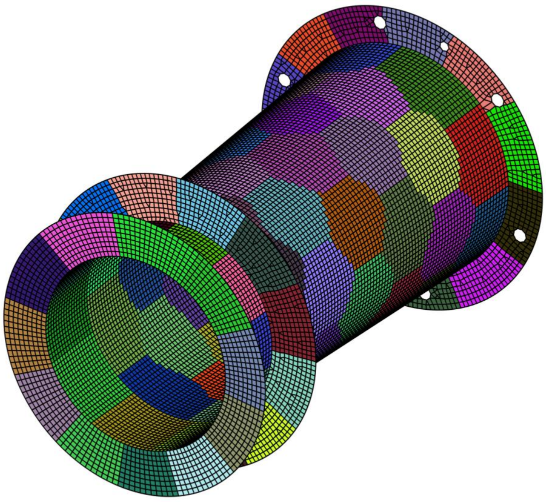
Boundary smoothing



18

Applied to EUI entrance baffle str. mesh

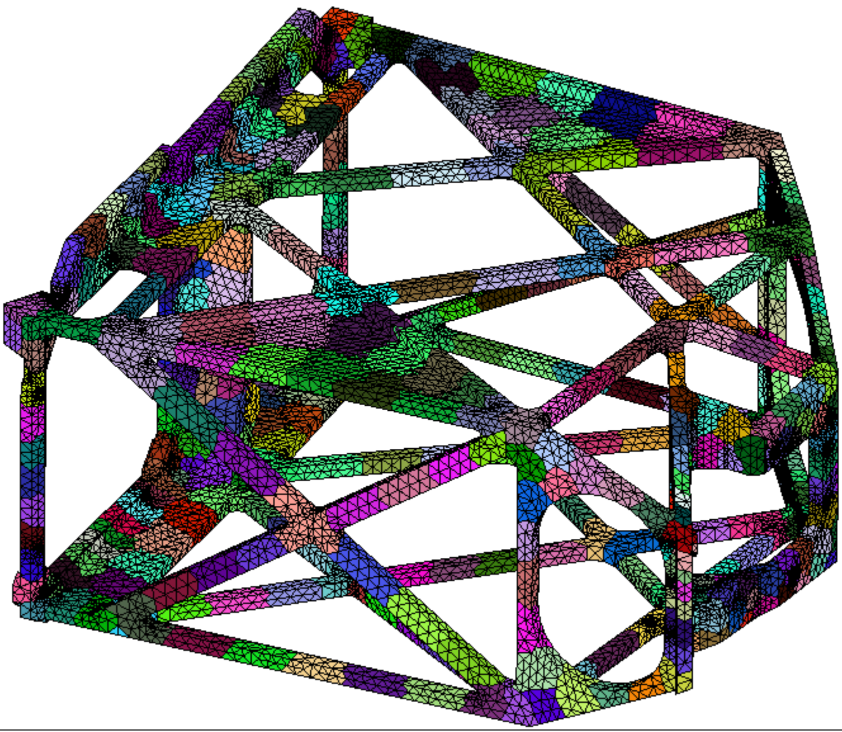
10 super nodes



100 super nodes

19

MTG back telescope assembly



20

Create new "super-nodes" (SINAS)

Not picking a representative node of the cluster but creating new nodes

A super-node = weighted (area, volume) average each node cluster

$$\mathbf{T_{SN}} = \mathbf{AT}$$

$$T_{SN_i} = \sum_{j=1}^{N} A_{ij} T_j \qquad \sum_{j=1}^{N} A_{ij} = 1$$

21

Reduction assumes uniform load

$$\begin{cases} \mathrm{K_L T = Q} \\ \mathrm{T}_{SN} = \mathrm{AT} \end{cases} \Leftrightarrow \begin{bmatrix} K & \mathrm{A^T} \\ \mathrm{A} & 0 \end{bmatrix} \begin{Bmatrix} \mathrm{T} \\ 0 \end{Bmatrix} = \mathrm{M} \begin{Bmatrix} \mathrm{T} \\ 0 \end{Bmatrix} = \begin{Bmatrix} \mathrm{Q} \\ \mathrm{T_{SN}} \end{Bmatrix}$$

$$\begin{Bmatrix} \mathrm{T} \\ 0 \end{Bmatrix} = \mathrm{M}^{-1} \begin{Bmatrix} \mathrm{Q} \\ \mathrm{T_{SN}} \end{Bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{Y^T} \\ \mathrm{Y} & \mathrm{Z} \end{bmatrix} \begin{Bmatrix} \mathrm{Q} \\ \mathrm{T_{SN}} \end{Bmatrix}$$

$$\mathrm{YA^T = I = AY^T}$$

$$0 = \mathrm{YQ + ZT_{SN}}$$

If the load is uniform over each super-node ($\mathrm{Q = A^T Q_{SN}}$): $\mathrm{YQ = Q_{SN}}$

$$-\mathrm{ZT_{SN} = Q_{SN}}$$

$$\boxed{\mathrm{K_{SN} = -Z}}$$

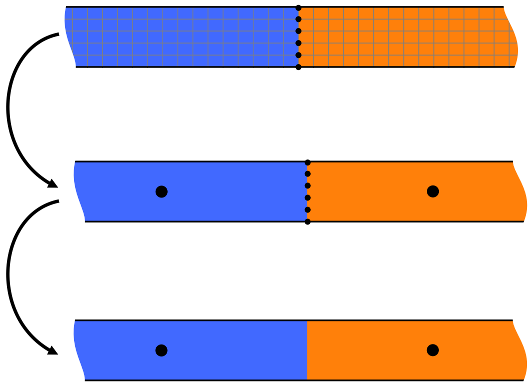
And the detailed T° can be recovered:

$$\mathrm{T = XQ + Y^T T_{SN}}$$

22

M is difficult to invert! → Local inversion

Local inversion of **M** : add super-node & keep all detailed IF nodes



Detailed IF nodes elimination through Guyan condensation

Detailed T° recovery by inverse procedure: no need to store full **X** and **Y**

23

Sources of non-uniformity

Internal radiative heat exchanges

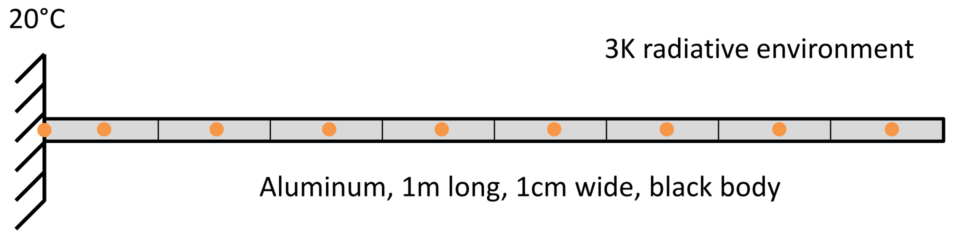
Environmental (solar, albedo, IR) heat loads

Internal dissipations

Internal energy variations (transients)

24

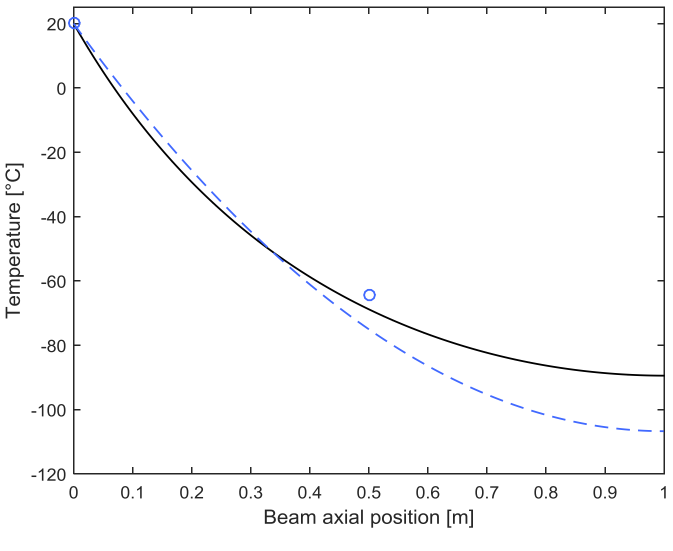
Thermal radiative cantilever beam



$$K_L T + K_R T^4 + Q_{ext} + C\frac{dT}{dt} = 0$$

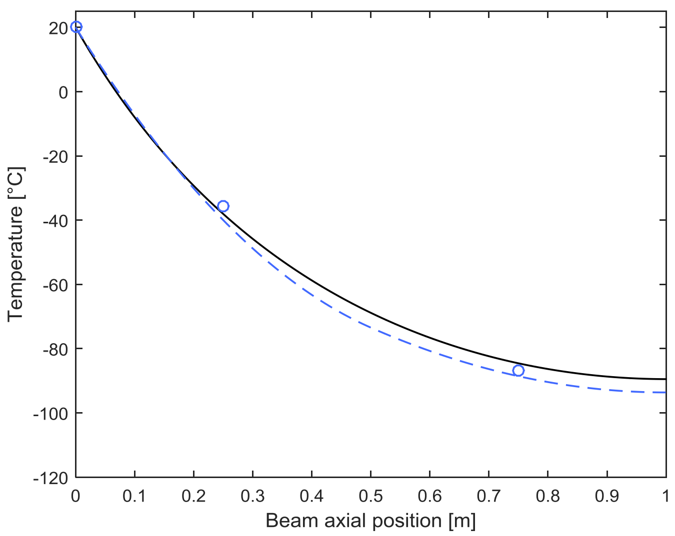
25

1 node



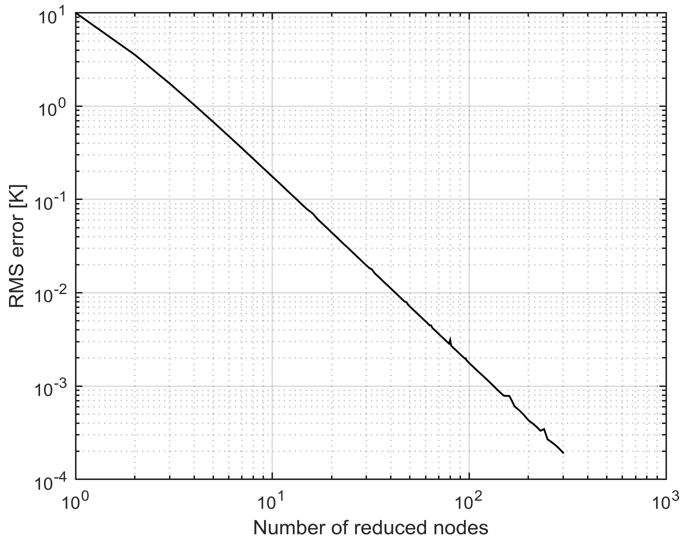
26

2 nodes



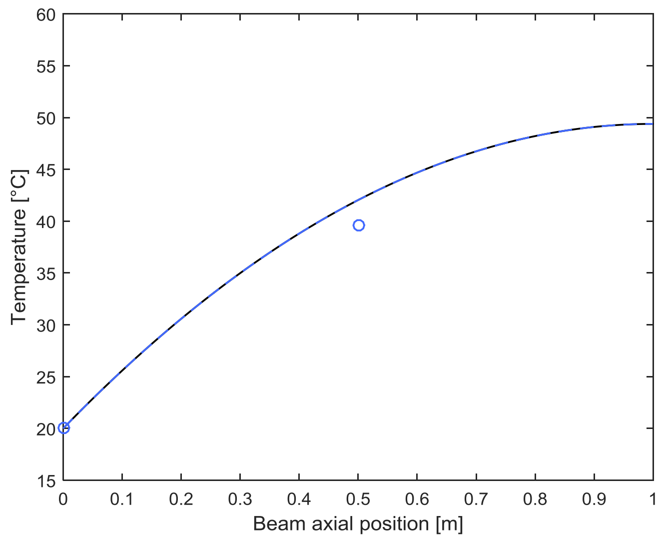
27

Convergence

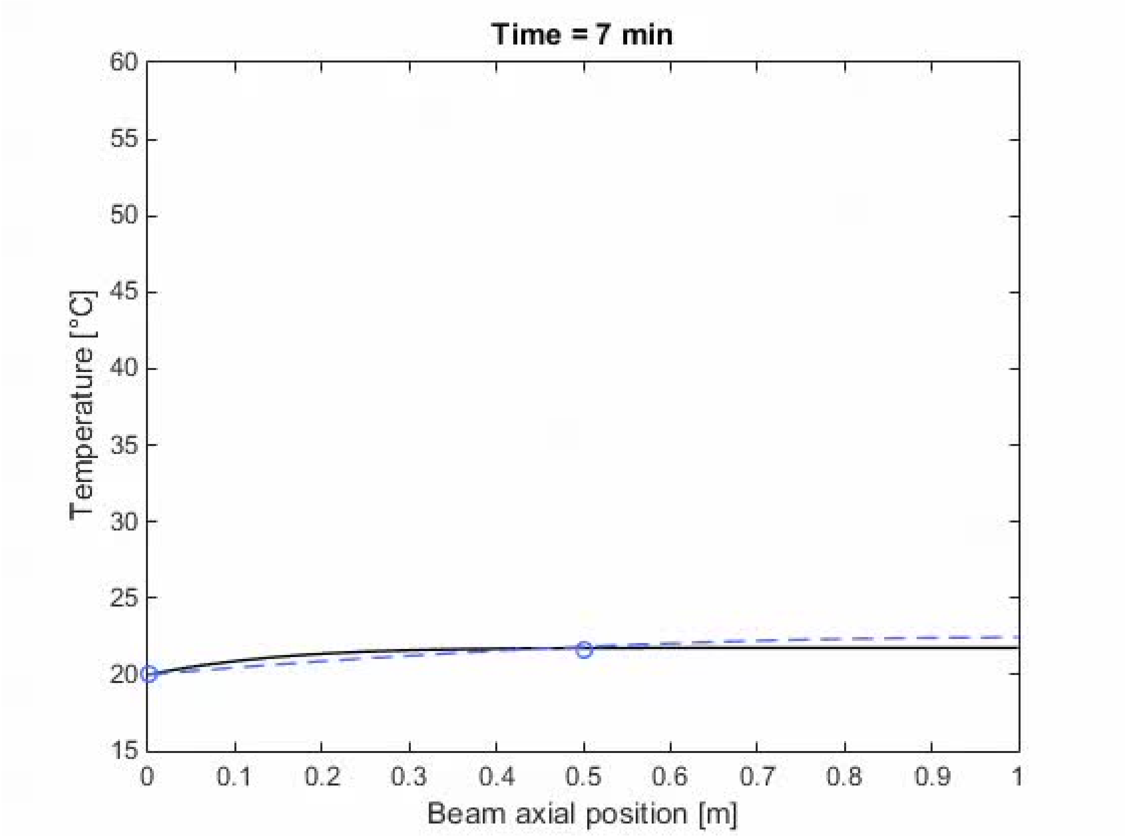


28

Transient solution (no rad)



29



Save the attachment to disk or (double) click on the picture to run the movie.

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30

Selective quadric fitting

Automatic quadric mesh fitting of user selected regions (e.g. optics)

$$f(\mathbf{x}) = \mathbf{C}^{\mathrm{T}}\mathbf{F} \qquad \mathbf{F}(\mathbf{x}) = [1, x, y, z, xy, xz, yz, x^2, y^2, z^2]^{\mathrm{T}}$$

$$\mathbf{C} = [c_0, \dots, c_9]^{\mathrm{T}}$$

$$error \approx \sum_{S_i \in R} \int_{S_i} \frac{f(\mathbf{x})^2}{|\nabla f(\mathbf{x})|^2} d\sigma \approx \frac{\mathbf{C}_0^{\mathrm{T}} M \mathbf{C}_0^{\mathrm{T}}}{\mathbf{C}_0^{\mathrm{T}} N \mathbf{C}_0^{\mathrm{T}}}$$

With $\mathbf{M} = \frac{1}{n} \sum_{\substack{i=1, \\ \mathbf{x}_i \in R}}^{n} \mathbf{F}(\mathbf{x}_i)\mathbf{F}(\mathbf{x}_i)^{\mathrm{T}}$ $\qquad$ $\mathbf{N} = \frac{1}{n} \sum_{\substack{i=1, \\ \mathbf{x}_i \in R}}^{n} \nabla\mathbf{F}(\mathbf{x}_i)\nabla\mathbf{F}(\mathbf{x}_i)^{\mathrm{T}}$

$\mathbf{C}$ is the eigen vector associated with minimum eigen value of

$$\mathbf{M} - \lambda \mathbf{N}$$

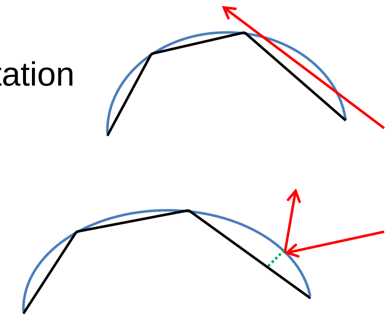
31

Ray-tracing with quadrics

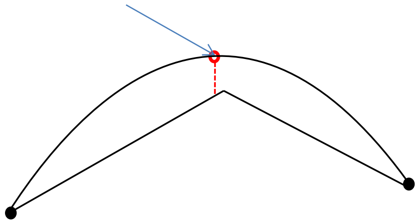
Use directly the quadric for the intersection computation

→ avoid lost grazing rays

→ better shadow

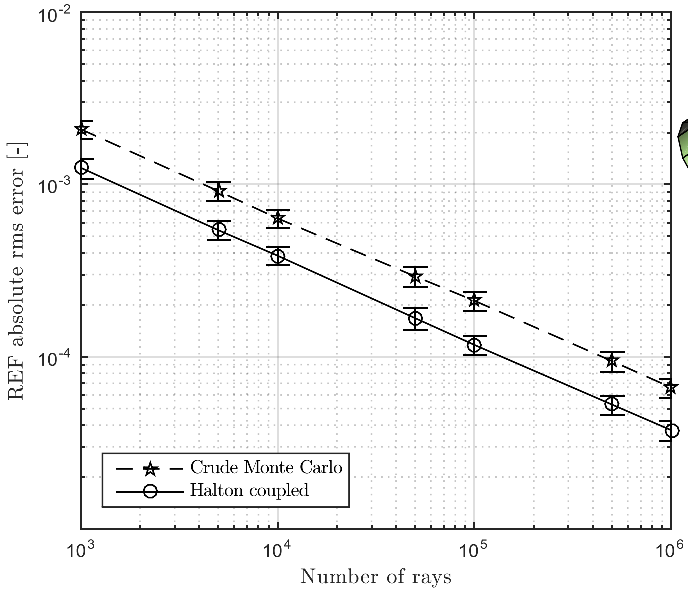


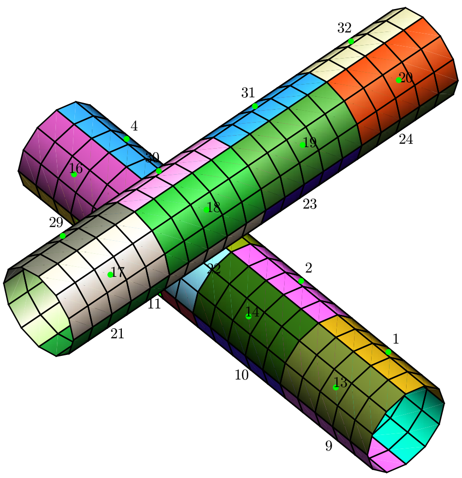
Project normally to the quadric to determine which super-face



32

Fitted cylinder vs. ESARAD cylinder





33

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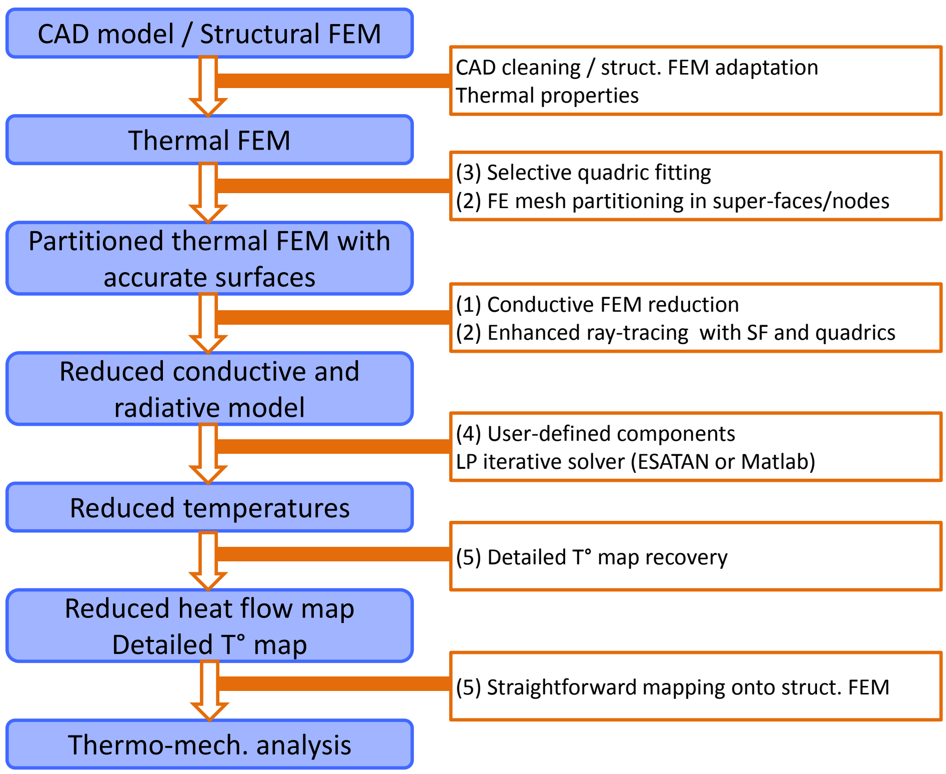
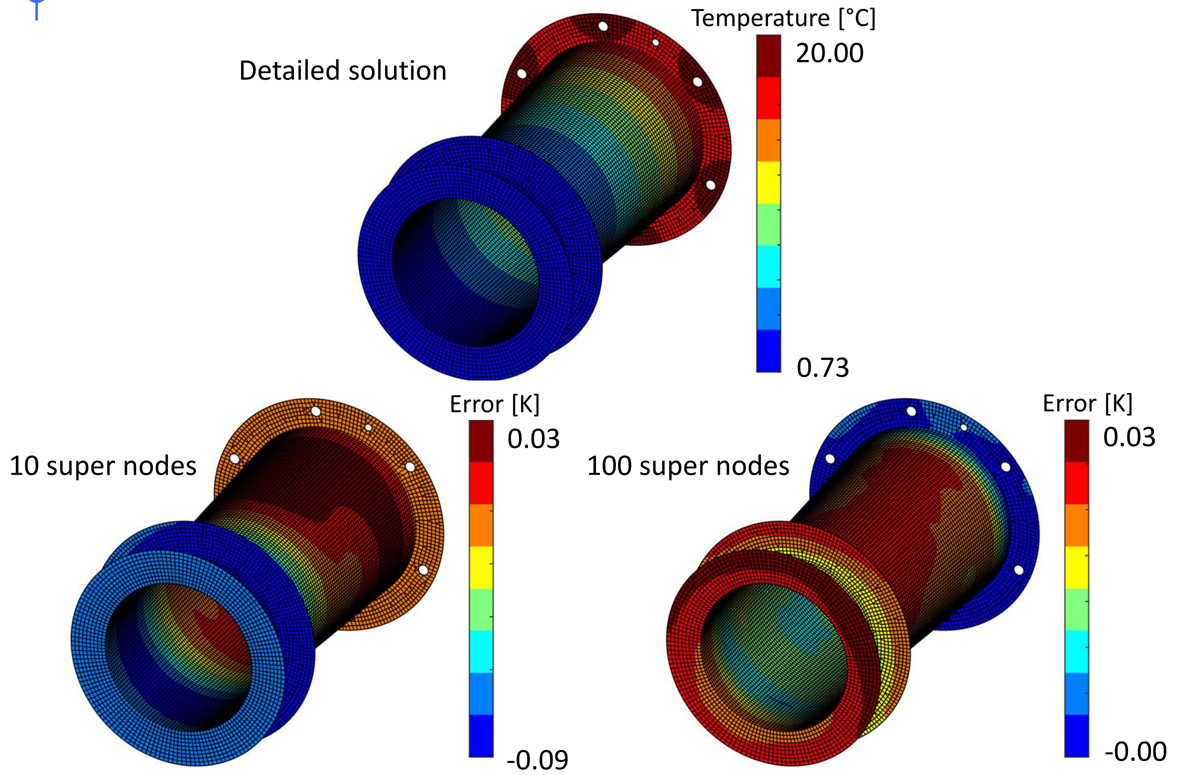
34

Putting the building blocks together

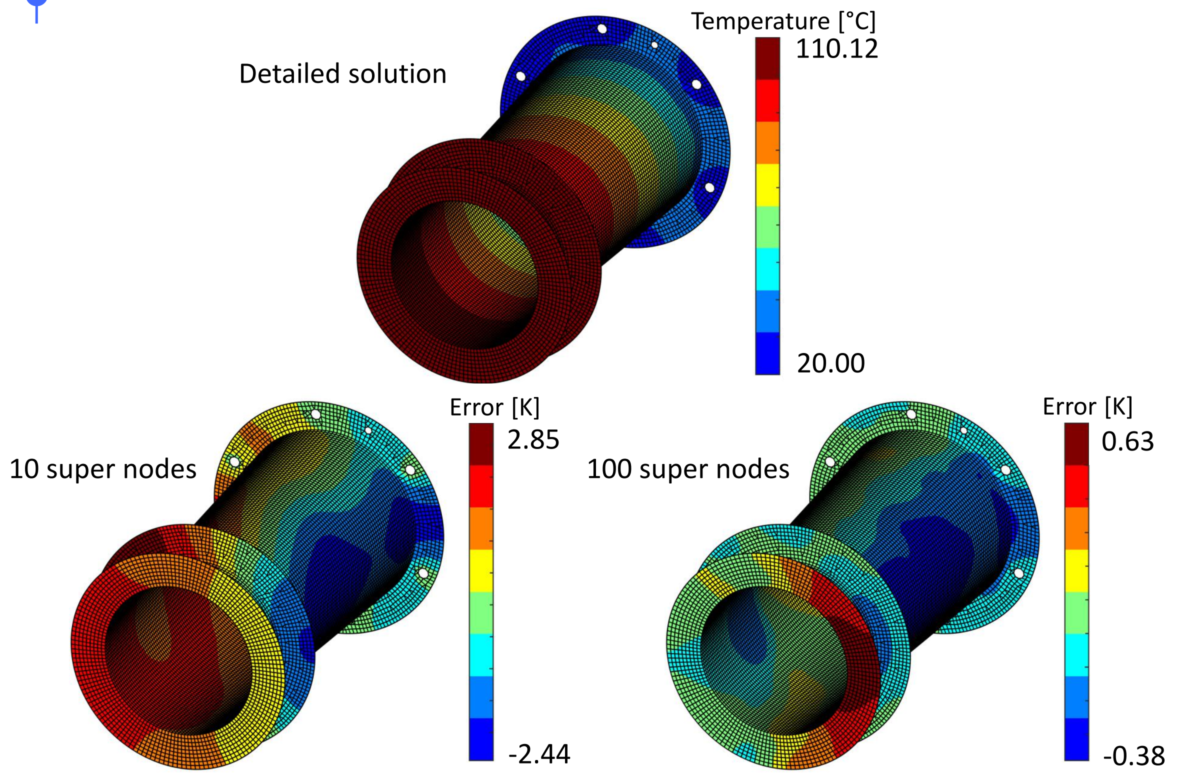


35

Only conduction and radiation



Conduction and radiation + Sun



Conclusions & perspectives

Integrated approach for detailed analysis of complex structures

No GMM needed, no T° mapping → time and costs saving!

Takes advantages of both lumped parameter and finite element methods:

- More accurate conductive links
- Accurate shape recognition used for ray-tracing
- Reduce the gap between thermal and structural analyses

Perspectives:

- Iterative process with automatic refinement in high ΔT regions
- Quadric fitting → opto-thermo-structural analyses

38

Thank you for your attention…

Any question?

39

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40