First Steps of Numerical Simulation using Artificial Intelligence

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Geometric modeling of 3D scenes from measurement data
- Analysis, reconstruction, approximation
- Computational geometry, geometry processing, machine learning
CONTEXT AND MOTIVATIONS

- Additive manufacturing yields increasingly complex objects
  - Reduced weight via topology optimization
  - Many more facets elements are required to describe these free-form shapes, which are later added to the full satellite model.

Image from www.eos.info
CONTEXT AND MOTIVATIONS

‣ Context of real-time simulation & sensibility
  ‣ Radiative thermal simulation is time-consuming: $O(n^2)$ complexity for the view factors, with $n$ the number of faces of the mesh.
  
  ‣ Full simulation intractable on the complete satellite model, in a reasonable time.
  
  ‣ A thermal-aware geometric approximation process is required, allowing real-time simulation and beyond (multi-physics simulation and predictions).
PROBLEM STATEMENT

- **Input**: Complex surface mesh (many facets and occlusions, created by a CAD software)

- **Output**: Approximated model respecting the view factors of the thermal nodes

- **Guarantees**: Error bounds under wide range of configurations and conditions

- **Goal**: Optimize trade-off between accuracy and time
Topics of Ph.D. thesis: Design a geometric approximation method preserving a *simulation-aware* error metric rather than a *geometric* error metric.

Application to space thermal analysis: view factor computation and model reduction

Goals:
- Compute reference view factors
- Compare with approximated view factors
- Evaluate simulation with approximation
- Utilize supervised machine learning to automate the reduction process, leveraging a large training dataset.
VIEW FACTOR

\[ F_{1 \rightarrow 2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi s^2} \ dA_2 \ dA_1 \]

\[ dF_{1 \rightarrow 2} = \frac{\cos \theta_1 \cos \theta_2}{\pi s^2} \ dA_2 \]

View factors depend on 3 components:
- area of the faces
- distance between them
- orientation
RELATED WORK

- Accelerating computation of view factors
  - Jacques, Masset, Kerschen: Ray tracing enhancement for space thermal analysis: isocell method, 27th Space Thermal Analysis Workshop, ESTEC.
RELATED WORK

- **Schröder, Hanrahan**: On the Form Factor between Two Polygons. Proceedings of ACM SIGGRAPH 1993. → Closed form solution for the view factor between two convex polygons

ACHIEVEMENTS

- **Hierarchical geometric data structure**: AABB-tree (fast intersection queries)

- **Closed form solution** when full visibility (Schröder)

- **Quadrature in the presence of occlusions**:
  - Point-based (via bounded centroidal Voronoi diagrams)
  - Triangle-based (recursive longest bisection)
Bounded Centroidal Voronoi Diagrams (CVD)

Tournois, Alliez, Devillers: 2D Centroidal Voronoi Tessellations with Constraints.
VIEW FACTORS (VF)
COMPARISONS

Maximum difference of view factors

Max error with e-Therm [Dorea]
Max error with View3D [Walton]
Min error with both

#quadrature points
COMPARISONS

Standard deviation of view factor

Comparison with e-Therm \([\text{Dorea}]\)
Comparison with View3D \([\text{Walton}]\)
COMPARISONS

Average error of view factor

Comparison with e-Therm [Dorea]
Comparison with View3D [Walton]

#quadrature points
Random uniform sampling

Bounded Centroidal Voronoi

Results with two random triangles configuration and an obstacle between them

View factor value

# quadrature points

Random uniform sampling

Bounded Centroidal Voronoi

View factor exact value
Random uniform sampling vs CVD

Results with two random triangles configuration and an obstacle between them

View factor value

Lloyd 100 obstacle 4
Lloyd 100 obstacle 5

#quadrature points

Random uniform sampling
Bounded Centroidal Voronoi
View factor exact value
Results with two random triangles configuration and an obstacle between them

View factor value

Fixed quad points, incrementing Lloyd iterations (with obstacle)
Approximation method guided by preservation of the view factors. We keep the constraint of the thermal nodes in order to compare the matrices of the radiative surfaces per nodes.
ON-GOING WORK

» **Simplification** via face clustering in order to best approximate the thermal nodes.

» **Comparison with the reference calculation thanks to thermal nodes:**
  » Main idea: compare the radiative surfaces by node matrices from the reference calculation case and the approximation one.
WHAT'S NEXT: SUPERVISED MACHINE LEARNING

‣ **Goal:** learn geometric error metric able to govern an automatic approximation algorithm so that the resulting thermal simulation is as accurate as possible to a reference calculation.

‣ **Constraints** = thermal nodes, so we can compare the radiative surfaces of each node before and after approximation.

[Jacobson] Thingie10K (training dataset)
THANK YOU

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