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Block-structured quad meshing for supersonic flow simulations

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FROM RESEARCH TO INDUSTRY

Block-structured quad meshing for supersonic flow simulations

March 8, 2023

Claire ROCHE

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- 2 Block Structure Generation
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 - Subsonic NACA0012 Airfoil
 - Supersonic Diamond Airfoil
- 5 Conclusion

Context

- This work aims to provide a solution to generate 3D meshes automatically for a legacy Computational Fluid Dynamics (CFD) code developed for atmospheric re-entry.

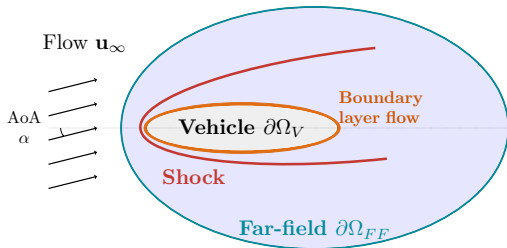


Fig. Flow around a supersonic vehicle

Ideal meshes:

- ◆ Near-wall **orthogonality**
- ◆ **Thin cells** in the boundary layer
- ◆ Smooth mesh **size transition**

Input meshes for the code:

- ◆ **Block-structured** meshes

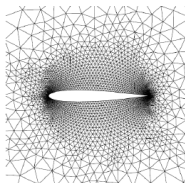
Hypotheses on the domain:

- ◆ Vehicles are **completely immersed** in the fluid
- ◆ Far-field is a **smooth boundary**
- ◆ **Single wall** vehicle

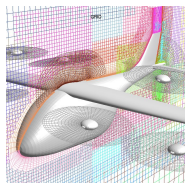
Our meshing algorithm is freely available and implemented in the open-source C++ meshing framework GMDS [LWB]^a.

^a<https://github.com/LIHPC-Computational-Geometry/gmds>.

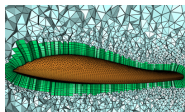
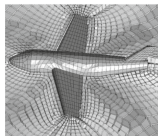
State of the art

CFD Meshes [CDT16]

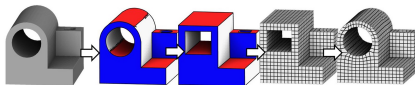
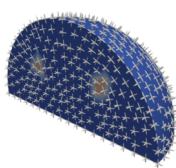
(a) Unstructured mesh [MACP10]



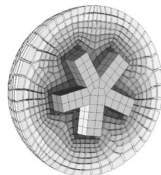
(b) Over-set grid [SBM21]

(c) Hybrid mesh¹(d) **Hex mesh** [RGRS12]Hexahedral mesh generation methods

- Full surveys 2D [BLP⁺13], 3D surfaces [Cam17] and 3D [PCS⁺22]

(a) Polycube [PRR⁺22]

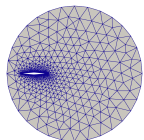
(b) Frame fields [KLF14]

(c) **Advancing front** [RGRS12]

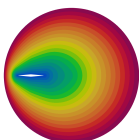
1. <https://www.pointwise.com/>

[RGRS12] Ruiz-Gironés E, Roca X, Sarrate J. The receding front method applied to hexahedral mesh generation of exterior domains. *Engineering with computers*, vol. 28, no. 4, 391-408, 2012.

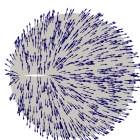
The main stages of our 2D approach



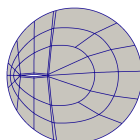
(a) Triangulation



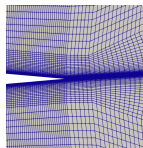
(b) Distance Field



(c) Vector Field



(d) Blocks



(e) Mesh



(f) Results

- ◆ Starting from a triangulation of the domain (a)
- ◆ We first generate and combine distance fields (b)
- ◆ And build a vector field that ensure wall orthogonality and the alignment with the angle of attack (c)
- ◆ Using those fields, we generate curved blocks (d)
- ◆ And a final quad mesh where the element size is carefully controlled in the boundary layer (e)
- ◆ Numerical simulation can then be launched (f)

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Distance field computation

Distance field computation solving Eikonal equation [RGRS12]:

$$\begin{cases} \|\nabla d_V\| &= 1 \text{ in } \Omega \\ d_V|_{\partial\Omega_V} &= 0 \end{cases}$$

$$\begin{cases} \|\nabla d_{FF}\| &= 1 \text{ in } \Omega \\ d_{FF}|_{\partial\Omega_{FF}} &= 0 \end{cases}$$

$$d = \frac{d_V}{d_V + d_{FF}}$$

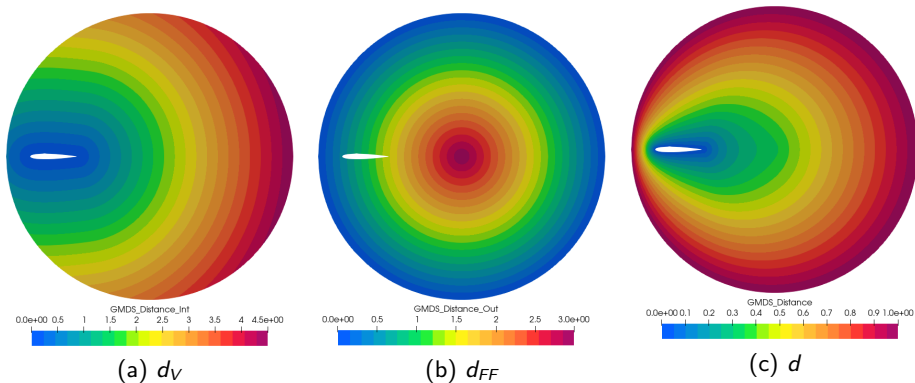


Fig. The distance fields on the NACA 0012 airfoil geometry.

Vector field computation

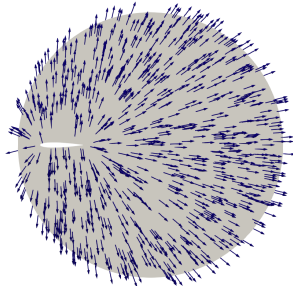
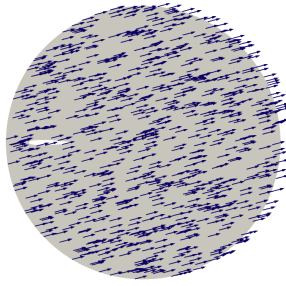
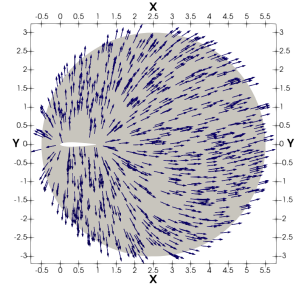
(a) ∇d_v (b) \mathbf{u}_∞ (c) \mathbf{v}

Fig. Vector fields computed on the NACA 0012 geometry. The vector field (c) is a mixed from ∇d_v (a), and \mathbf{u}_∞ (b).

For each node n_i at position $p_i = (x_i, y_i)$:

$$\begin{cases} \mathbf{v}_i = \nabla d_v & \text{if } x_i < 1.5 \\ \mathbf{v}_i = \mathbf{u}_\infty & \text{if } x_i > 5.0 \\ \mathbf{v}_i = \theta \nabla d_v + (1 - \theta) \mathbf{u}_\infty & \text{otherwise, with } \theta \in [0, 1] \end{cases}$$

Block layer generation

Regular layer computation

Each node of the front \mathcal{L}_i computes its ideal next node position in the layer \mathcal{L}_{i+1} following the **vector field** \mathbf{v} until the target distance d_{i+1} is reached in the **combined distance field** d . A 4th order Runge-Kutta method is used.

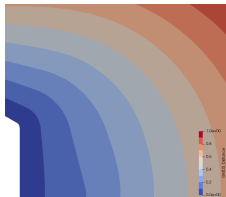


Fig. a Distance field

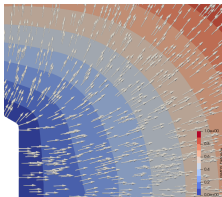


Fig. b Vector field

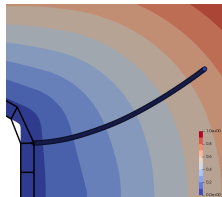


Fig. c Advected node

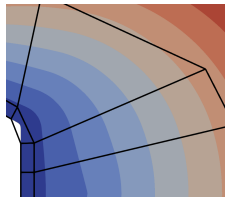


Fig. d New blocks

- All the nodes of the same layer \mathcal{L}_i are at an equal distance d_i in the combined distance field d
- A front cannot separate
- Need to solve conflicts due to expansion/contraction in a layer

Block layer insertions & shrinking

- ◆ Insertions rules as in BLACKER ET AL. [BS91], to solve conflicts on a layer
- ◆ Use both geometrical and physical criteria

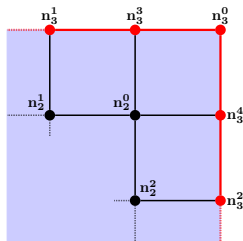
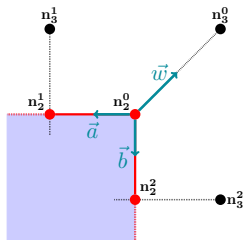


Fig. a Block insertion.

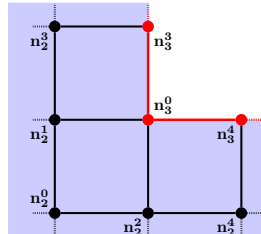
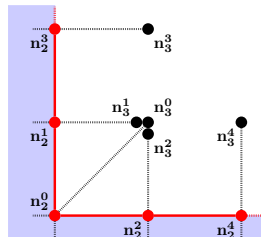


Fig. b Block shrinking.

Block layer insertions & shrinking

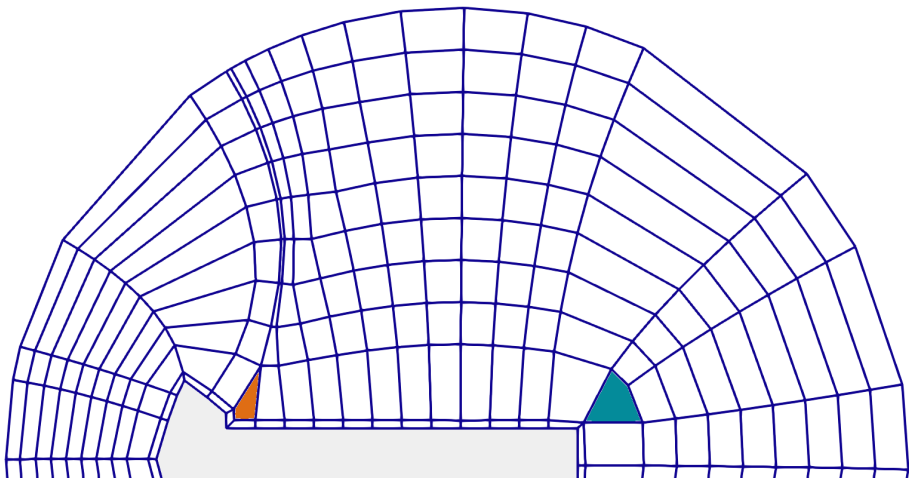


Fig. Block shrinking in orange (—) and insertion in blue (—) on the second layer.

First layer generation

Specific case of the first layer

- ◆ The distance field considered is d_V
- ◆ The thickness of this first layer is higher than the thickness of the boundary layer flow
- ◆ Double block insertions are the only insertions allowed in this layer

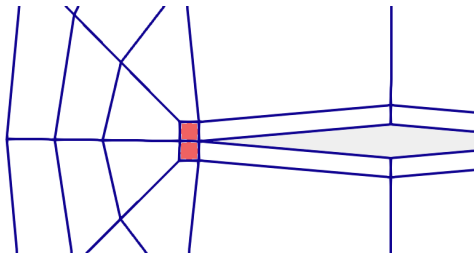


Fig. a Insertion of two blocks (—) on the first layer for the diamond airfoil.

- Ensure the mesh validity

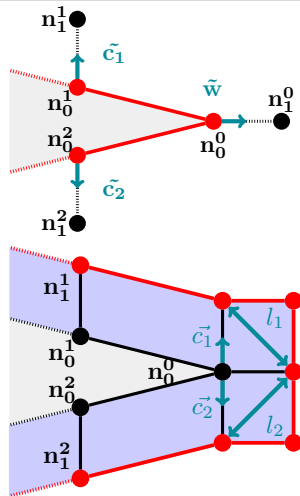


Fig. b Double block insertion on the boundary layer.

Curved blocking

- Aims to avoid smoothing on final mesh
- ◆ If the two nodes of a block edge are on a same layer
- ◆ If the edge is not on the wall or on the first layer

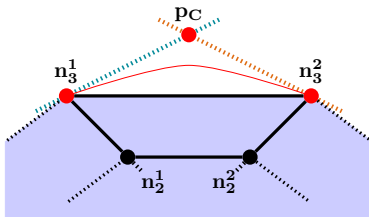


Fig. b Curve block edges as a quadratic Bézier curve.

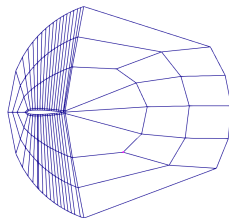


Fig. a Linear blocking

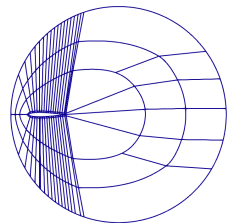


Fig. c Curved blocking

The method

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Interval Assignment

- The aim is to set the discretization of each block edge

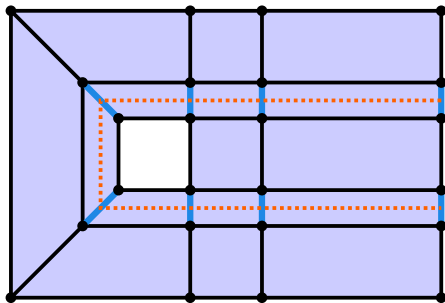


Fig. a Topological chord

- ◆ A topological chord (— —) is a set of opposite block edges (—)
- ◆ All edges of a same topological chord share the same discretization

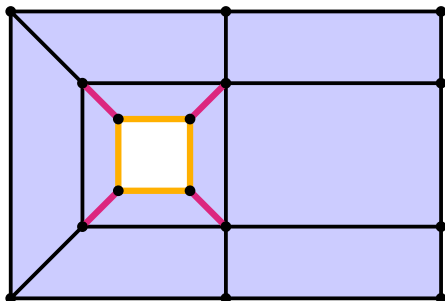


Fig. b Hard constraint

- ◆ (—) edges: s_w , the size of the edges on the wall
- ◆ (—) edges: s_w^\perp , the size of the edges on the first layer, on the wall-normal direction

First layer meshing

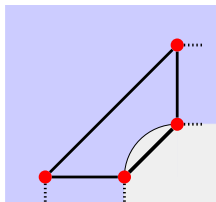


Fig. a

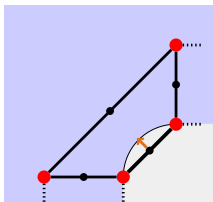


Fig. b

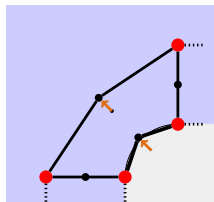


Fig. c

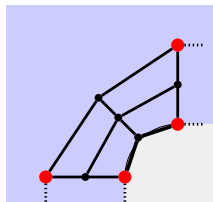


Fig. d

- Set the block edges discretization
- Project nodes on the geometry (b)
- Add the offset on the opposite block edges (c)
- Apply transfinite in each block (d)
- Smoothing to add orthogonality on the wall
- Apply the β refinement

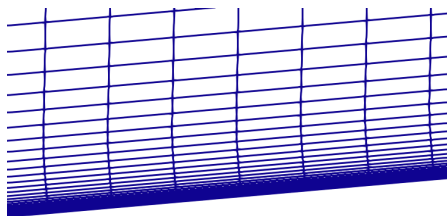
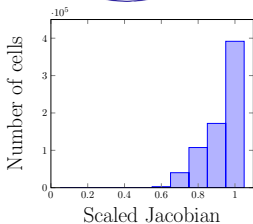
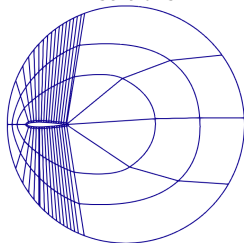
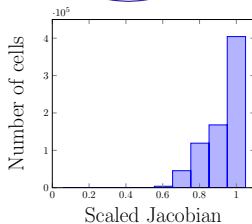
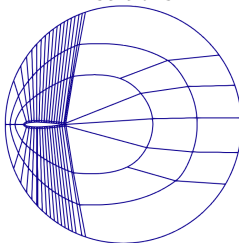
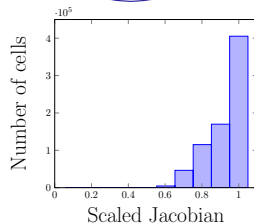
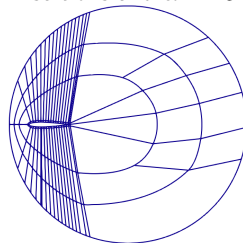


Fig. e Mesh result in near the wall

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Mesh Validity

Fig. a. Blocking without insertions**Fig. b.** Blocking with insertions**Fig. c.** Blocking with insertions and $\alpha = 15^\circ$ 

- The insertions of blocks and the adaptation to the angle of attack α doesn't degrade the mesh quality.

Subsonic NACA0012 Airfoil [Rum21]

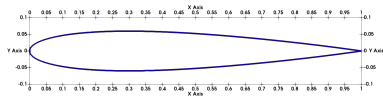


Fig. a NACA 0012 geometry.

M_∞	AoA α	Re	T_∞
0.3	15°	3×10^6	293K

Table - Simulation parameters.

- The simulations are performed using the open multiphysics simulation software SU2 [EPC⁺16]
- Reynolds Averaged Navier-Stokes (RANS) solver
- $k-\omega$ SST turbulence model

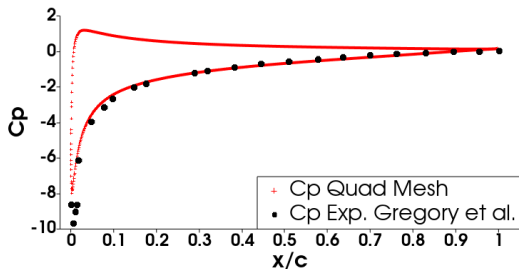


Fig. b Pressure coefficient compared to experimental data set [GO70].

Supersonic Diamond Airfoil

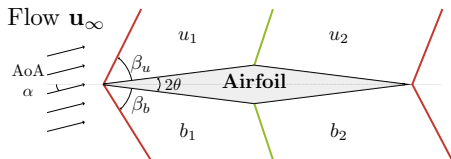


Fig. a Diamond Shaped Airfoil.

M_∞	AoA α	R_e	T_∞
1.5	3°	3×10^6	293K

Table - Simulation parameters.

- ▶ Validation on analytical case
- ▶ Shock angles captured with an error of 1° compared to analytical values
- ▶ Constant Mach number in the area u_1 and b_1 consistent with those given by the tables [rs53]

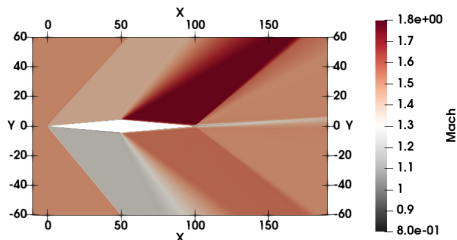


Fig. b Mach-number distribution.

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Summary

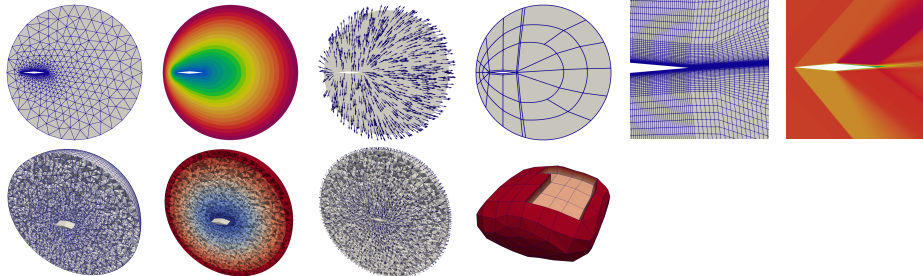
- ◆ This work proposes a solution to automatically generate 2D quad block-structured meshes dedicated to CFD
- ◆ Geometrical shape of the domain is taken into account
- ◆ Simulation parameters are taken into account (e.g the angle of attack and boundary layer thickness)
- ◆ First obtained meshes are usable for subsonic and supersonic flow simulations

Limitations of this method

- ◆ Can't handle complex geometries (multi-component, etc)
- ◆ Accuracy of the distance field computation can be improved

Perspectives

- ◆ Improving the mesh size transition
- ◆ Extension of the method to 3D
- ◆ Extend the work of RUIZ-GIRONES ET AL. [RGRS12] to high-order blocks
- ◆ Integrating some smoothing methods for the blocks
- ◆ Improving the mesh generation with a previous result of simulation



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Thank you.

Wall block discretization

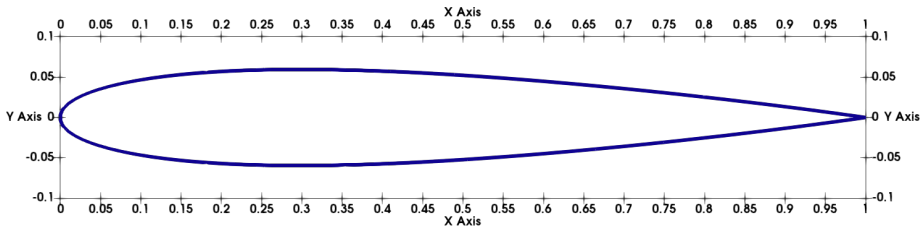
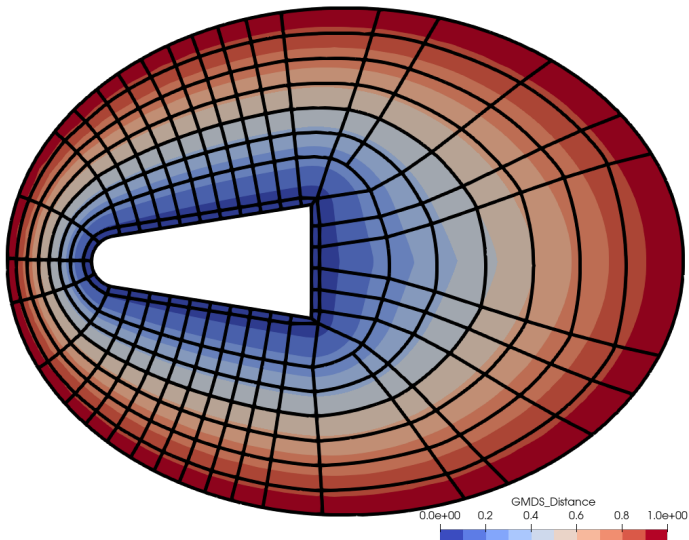


Fig. a NACA 0012 geometry.

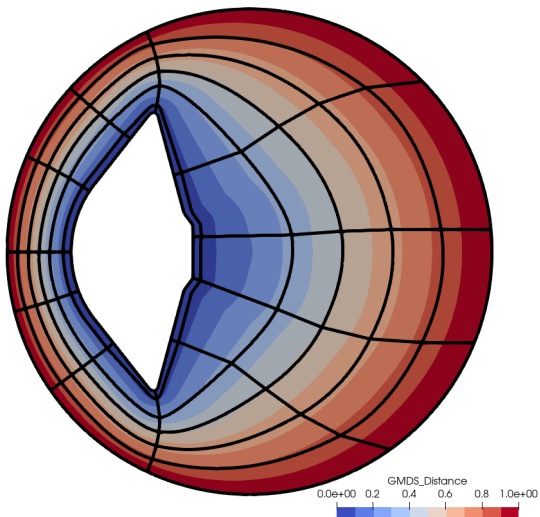
Iteration on the ordered vertices v_i of the triangulation on the wall. We place a block corner on v_i if:

- ◆ v_i is located on an extremum of the boundary profile.
- ◆ v_i is a geometric corner of the boundary.
- ◆ the curvilinear distance from the previous selected vertex and v_i is greater than a limit length given as an input parameter.

Results on RAMCII

**Fig.** Blocking on RAMCII

Results on Orex

**Fig.** Blocking on Orex