RESEARCH CENTRE

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Office national d'études et de recherches aérospatiales

2024

ACTIVITY REPORT

Project-Team GAMMAO

Adaptive Mesh Generation and Advanced Numerical Methods

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Numerical schemes and simulations

Contents

Project-Team GAMMAO

Creation of the Project-Team: 2023 January 01

Keywords

Computer sciences and digital sciences

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1 Team members, visitors, external collaborators

Research Scientists

- Frederic Alauzet [Team leader, INRIA, Senior Researcher]
- Paul Louis George [INRIA, Emeritus]
- Guillaume Puigt [ONERA R&D, from Apr 2024]
- Julien Vanharen [INRIA, Senior Researcher]

Post-Doctoral Fellow

- Cosimo Tarsia Morisco [INRIA, Post-Doctoral Fellow, from Sep 2024]

PhD Students

- Thomas Gauchery [INRIA]
- Andrea Gobbi [INRIA]
- Eloi Guilbert [INRIA]

Technical Staff

- Loic Marechal [INRIA, Engineer]
- Matthieu Maunoury [INRIA, Engineer]
- Cosimo Tarsia Morisco [INRIA, Engineer, until Feb 2024]

Interns and Apprentices

- Alexandra Krzeminski [INRIA, Intern, from Aug 2024]

Administrative Assistant

- Mariana De Almeida [INRIA]

Visiting Scientist

- Cosimo Tarsia Morisco [NASA, from Mar 2024 until Aug 2024]

External Collaborators

- Francois Pechereau [ONERA]
- Christophe Peyret [ONERA, from Nov 2024]

2 Overall objectives

Numerical simulation has been booming over the last thirty years, thanks to increasingly powerful numerical methods, computer-aided design (CAD) and the mesh generation for complex 3D geometries, and the coming of supercomputers (HPC). The discipline is now mature and has become an integral part of design in science and engineering applications. This new status has led scientists and engineers to consider numerical simulation of problems with ever increasing geometrical and physical complexities. A simple observation of this chart

$$\text{CAD} \longrightarrow \text{Mesh} \longrightarrow \text{Solver} \longrightarrow \text{Visualization / Analysis}\,.$$

shows: **no mesh = no simulation** along with **"bad" mesh = wrong simulation**. We have concluded that the mesh is at the core of the classic computational pipeline and a key component to significant improvements. Therefore, the requirements on meshing methods are an ever increasing need, with increased difficulty, to produce high quality meshes to enable reliable solution output predictions in an automated manner. These requirements on meshing or equivalent technologies cannot be removed and all approaches face similar issues.

Gamma's research program is motivated by four grand challenges in order to achieve certification and high-fidelity in the numerical simulation pipeline. The goal is to deliver innovative and ground-breaking solutions to each step of the adaptive numerical simulation pipeline. Not surprisingly, these challenges (and the themes that result) are clearly indicated in the NASA CFD Vision 2030 Study [41] and have been mentioned recurrently during the previous evaluations of the Gamma3 team where they have been judged as very ambitious and long-term. The four grand challenges are:

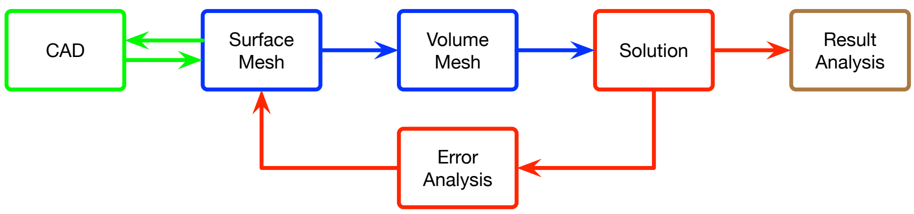
1. Geometric modeling. The goal is to address geometry modeling issues and their interactions with the meshing pipeline. To this end, Gamma will develop more versatile and robust geometry and modeling processes to be embedded within meshing tools.

2. Enhanced generic meshing algorithms. Gamma will pursue its work on state-of-the-art meshing technologies which should fulfill these three requirements: adaptation, high-order and large size. Mesh adaptation and high-order meshing will be based on the well-posed metric-based mathematical framework. The generation of large size mesh will be achieved with hybrid parallelism (multi-thread and MPI).

3. Toward certified numerical solutions to the Navier-Stokes equations. This research axis will focus on error estimates and robust numerical schemes (flow solver). Gamma will primarily focus on the design of uncertainty aware RANS error estimates. We will pursue the work on anisotropic mesh adaptation for the turbulent Navier-Stokes equations with moving geometries. We envision to develop a new high-order mesh-adaptive solution platform which requires to design high-order error estimates and a high-order flow solver.

4. Advanced visualization of mesh and solution. High-order representations (both on the solver and meshing sides) use higher-degree polynomials to interpolate solution data. The challenge is to develop algorithms for pixel exact rendering of high-order meshes and solutions which will provide the potential to reveal features that otherwise might be masked by classic visualization approaches. The visualization software will be used for pre and post processing by interfacing all the Gamma's software components.

These four grand challenges cover the whole numerical simulation pipeline depicted below. The geometric modeling is represented by the green part, the enhanced generic meshing algorithms by the blue part, the certification of Navier-Stokes simulations by the red part, and the advanced mesh and solution visualization by the brown part. We can also see the clear interaction between each research axis.



Most of the proposed meshing developments and technologies are generic and can be applied to a broader field of applications in order to increase the impact of this research program. Flow solver developments and technologies focus specifically on CFD with applications to aerospace, turbomachinery, and defense.

3 Research program

The main axes are:

- Geometric Modeling:
  - High-fidelity discrete CAD kernel.
  - Continuous parametric CAD kernel.
- Enhanced Generic Meshing Algorithm:
  - Adaptation (extreme anisotropy, metric-aligned, metric-orthogonal).
  - High-order (tetrahedra, hexahedra, boundary layer, adapted).
  - Large meshes (tetrahedra, hexahedra, adapted).
  - Moving mesh methods for moving geometries.
- Toward Certified Solutions to the Navier-Stokes Equations:
  - Flow solver and adjoints (Finite Volumes, Finite Elements, Flux Reconstruction).
  - Error estimates and correctors.
- Advanced Mesh and Solution Visualisation:
  - Pixel exact rendering (High-Order mesh, High-Order solution).
  - Pre-processing and post-processing.

4 Application domains

Our research in mesh generation, mesh adaptation and certification of the Numerical Simulation Pipeline finds applications in several different domains such as aviation and aerospace but also all fields where computation and simulation are used: fluid mechanics, solid mechanics, solving wave equations (acoustic, electromagnetism...), energy or biomedical.

5 New software, platforms, open data

5.1 New software

5.1.1 GHS3D

Keywords: Tetrahedral mesh, Delaunay, Automatic mesher

Functional Description: GHS3D is an automatic volume mesher

URL: https://team.inria.fr/gamma/gamma-software/ghs3d/

Contact: Frederic Alauzet

Participants: Paul Louis George, Adrien Loseille, Frederic Alauzet

5.1.2 HEXOTIC

Keywords: 3D, Mesh generation, Meshing, Unstructured meshes, Octree/Quadtree, Multi-threading, GPGPU, GPU

Functional Description: Input: a triangulated surface mesh and an optional size map to control the size of inner elements.

Output: a fully hexahedral mesh (no hybrid elements), valid (no negative jacobian) and conformal (no dangling nodes) whose surface matches the input geometry.

The software is a simple command line that requires no knowledge on meshing. Its arguments are an input mesh and some optional parameters to control elements sizing, curvature and subdomains as well as some features like boundary layers generation.

URL: https://team.inria.fr/gamma/gamma-software/hexotic/

Contact: Loic Marechal

Participant: Loic Marechal

Partner: Distene

5.1.3 FEFLOA-REMESH

Keywords: Scientific calculation, Anisotropic, Mesh adaptation

Functional Description: FEFLOA-REMESH is intended to generate adapted 2D, surface and volume meshes by using a unique cavity-based operator. The metric-aligned or metric-orthogonal approach is used to generate high quality surface and volume meshes independently of the anisotropy involved.

URL: https://team.inria.fr/gamma/feflo-a/

Contact: Adrien Loseille

Participants: Adrien Loseille, Frederic Alauzet, Rémi Feuillet, Lucien Rochery, Lucille-Marie Tenkes

5.1.4 Metrix

Name: Metrix: Error Estimates and Mesh Control for Anisotropic Mesh Adaptation

Keywords: Meshing, Metric, Metric fields

Functional Description: Metrix is a software that provides by various ways metric to govern the mesh generation. Generally, these metrics are constructed from error estimates (a priori or a posteriori) applied to the numerical solution. Metrix computes metric fields from scalar solutions by means of several error estimates: interpolation error, iso-lines error estimate, interface error estimate and goal oriented error estimate. It also contains several modules that handle meshes and metrics. For instance, it extracts the metric associated with a given mesh and it performs some metric operations such as: metric gradation and metric intersection.

URL: https://pages.saclay.inria.fr/frederic.alauzet/software.html#Metrix

Contact: Frederic Alauzet

Participants: Adrien Loseille, Frederic Alauzet

5.1.5 Wolf

Keyword: Scientific calculation

Functional Description: Numerical solver for the Euler and compressible Navier-Stokes equations with turbulence modelling. ALE formulation for moving domains. Modules of interpolation, mesh optimisation and moving meshes. Wolf is written in C++, and may be later released as an opensource library. FELiScE was registered in July 2014 at the Agence pour la Protection des Programmes under the Inter Deposit Digital Number IDDN.FR.001.340034.000.S.P.2014.000.10000.

URL: `https://pages.saclay.inria.fr/frederic.alauzet/software.html#Wolf`

Contact: Frederic Alauzet

Participants: Frederic Alauzet, Adrien Loseille, Rémi Feuillet, Lucille-Marie Tenkes, Francesco Clerici, Cosimo Tarsia Morisco

5.1.6 ViZiR4

Name: ViZiR4

Keywords: Visualization, Pixel-exact rendering, Instant rendering, High order methods

Functional Description: Its main features are: - Light, simple and interactive visualization software. - Surface and volume (tetrahedra, pyramids, prisms, hexahedra) meshes. - Pixel exact rendering of high-order solutions on straight elements. - Almost pixel exact rendering on curved elements (high-order meshes). - Post-processing tools, such as picking, isolines, clipping, capping.

URL: `https://pyamg.saclay.inria.fr/vizir4.html`

Publications: hal-01686714, hal-02950321, hal-03539257

Contact: Adrien Loseille

Participants: Adrien Loseille, Matthieu Maunoury, Frederic Alauzet

6 New results

6.1 Evaluation of heat transfert performance of a film-cooled turbine vane using metric-based anisotropic mesh adaptation

Participants: Frederic Alauzet *(correspondant)*.

We show the ability of metric-based anisotropic mesh adaptation to accurately predict the flow field on a particularly complex test case: a film-cooled turbine vane. Film-cooled turbine blades are very complex turbomachinery geometries because they are composed of a cooling network and many different-shaped film-cooling holes which makes these geometries extremely complex to mesh with structured meshing approaches (like multi-block hexahedral meshing methods). Consequently, metric-based anisotropic mesh adaptation seems quite appropriate for such applications as it has demonstrated that it provides automation of the whole process and it allows significant gains in terms of simulation accuracy by capturing coherent flow features proper to the turbomachinery physics. The film-cooled turbine vane simulation was made possible because the mesh-adaptive solution platform was successfully extended to periodic flows and domains.

6.2 Mixed-element mesh and Anisotropic adapted mesh comparison

Participants: Frederic Alauzet, Cosimo Tarsia Morisco *(correspondant)*.

In order do to a fair comparison, the same numerical strategy must be used when dealing full-tetrahedral meshes as well as hybrid/structured meshes. For these reason, an appropriate numerical strategy was elaborated for extending the Mixed Finite Element-Finite Volume (MEV) scheme to adapted meshes composed of both triangular and quadrangular elements, called *hybrid* meshes [23, 22] (also named *mixed-element* meshes [37, 39]). Particularly, in the context of mesh adaptation, a specific metric gradation process is proposed to favor the clustering of structured elements at wall boundaries. The details are given in [40].

One important challenge is the accurate discretization of turbulence. In the context of RANS simulations, we investigated the numerical behavior of the Spalart-Allmaras SA-neg-QCR2000-R one-equation turbulence model for the anisotropic mesh adaptation process. The solutions obtained on the adapted unstructured meshes are compared with those obtained on some "best-practice" structured/hybrid meshes. Same numerical schemes are adopted to perform a fair comparison. Three test cases of the High-Fidelity Prediction Workshop [7] are considered: a two-dimensional subsonic flow past a Joukowski airfoil, a subsonic three-dimensional flow past the wing-body configuration developed for the High-Lift Prediction Workshop and a subsonic three-dimensional flow past an extruded NACA 0012 wing in a tunnel.

6.3 Pixel-exact rendering for high-order meshes and solutions

Participants: Adrien Loseille, Matthieu Maunoury *(correspondant)*.

We are developing `ViZiR 4`, a visualization software with pixel exact rendering to address the high-order visualization challenges [34, 8]. `ViZiR 4` is bundled as a light, simple and interactive high-order meshes and solutions visualization software. It is based on OpenGL 4 core graphic pipeline. The use of OpenGL Shading Language (GLSL) allows to perform pixel exact rendering of high order solutions on straight elements (without extra subdivision or ray casting) and almost pixel exact rendering on curved elements (high-order meshes). `ViZiR 4` enables the representation of high order meshes (up to degree 4) and high order solutions (up to degree 10) with pixel exact rendering. Unlike other visualization software (ParaView [20], TecPlot [21], Medit [9], Vizir (OpenGL legacy based version) [29], Gmsh [18]), there is no subdivision process that is expensive nor visualization error that has to be controlled. Moreover, the subdivision of the curved entities is done on the fly on GPU which leaves the RAM memory footprint at the size of the loaded mesh. Furthermore, in comparison with standard visualization techniques based on legacy OpenGL, the use of OpenGL 4 core version improves the speed of rendering, reduces the memory footprint and increases the flexibility. Many post-processing tools, such as picking, hidding surfaces, isolines, clipping, capping, are integrated to enable on the fly the analysis of the numerical results.

6.4 Development of algorithms for interactive mesh modifications in a visualization software

Participants: Alexandra Krzeminski, Matthieu Maunoury *(correspondant)*.

GammaO software are acknowledged by the international community as among the most powerful and modern mesh generators. If we consider the automatic generation of a volume mesh (by means of tetrahedra) from a surface mesh (by means of triangles), most of the cases can now be handled. However, it happens that we can have difficulties to automatically generate the volume mesh for some specific cases: complex surface mesh geometry, large size and huge difference of edge lengths. Furthermore, sometimes the surface might be locally of poor quality or even wrong. Thus, it would be useful to have local operators in order to modify the (surface) mesh and avoid problems. It is natural to think of this operation in the visualization software as visualization helps to understand where the problems occur and often a local topological modification might help.

We added several operators: edge swap (also called edge flip), edge split (insert a new vertex to form two edges), edge collapse (cancel an edge by merging its two vertices together) or vertex relocation (modify only the coordinates of a vertex). Except for vertex relocation, the other operations lead to topological changes and a mesh modification (the number of triangle is modified as well as the connectivity and some vertices might be added or removed).

6.5 Easy multithreaded parallelisation of solvers dealing with unstructured meshes

Participants: Loïc Maréchal.

The LPlib has been successfully used for a long time to parallelize many codes developed by the GammaO team. However, recent advances in high aspect ratio anisotropic mesh generation proved to be challenging to the library's Hilbert block scheduler. Thanks to the work of T.Gauchery, we implemented a colored-block approach that partitions the mesh into mid-sized blocks called grains and assign each a unique color so that no other neighboring grain (i.e., sharing a common element) is assigned the same color. Consequently, all grains belonging to the same color can be safely processed in parallel by a single thread without any need for synchronization between all threads. Such partitioning scheme proved to be much less sensitive to the anisotropy of the mesh and scales pretty well on a 64-core processor. Furthermore, we think that this coloring scheme is perfectly suited for GPU computing and we plan on using it to distribute the workload on multiple GPU by processing each grain on a single GPU without the need for costly inter GPU synchronizations. After the processing of all grains belonging to the same color, data shared by neighboring grains will need to be transferred before processing the next color's grains.

6.6 Fast sparse matrix-vector multiplication on GPU with sliced matrices

Participants: Loïc Maréchal.

The GMlib has been implemented to ease the development of explicit solvers on GPU but it was lacking any linear algebra capacities to handle implicit solvers. Linear algebra on sparse matrices derived from unstructured meshes is efficient on CPUs but very challenging on GPUs which are best suited to handle structured data. We developed a slicing scheme that sorts the mesh vertices against their degree (i.e., number of incident elements) and splits up the main matrix into several sub matrices each with a constant width. Such constant width matrices are highly efficient to process on GPU and we were able to reach more than 80% of the theoretical CPU memory bandwidth with our first experiments. With the help of colored grains partitioning, we hope to efficiently run our implicit flow solver on multiple GPU with the next GMlib version in 2025.

6.7 Accuracy analysis for a Mixed Element Volume scheme

Participants: Andrea Gobbi, Julien Vanharen, Cosimo Tarsia Morisco.

We performed a deep accuracy analysis of a Mixed Element Volume (MEV) numerical scheme [42, 5], namely the V4 scheme [6], by studying it on the 2D linear advection equation and comparing the results between structured and unstructured triangular meshes of different regularity. The scheme in fact achieves third order accuracy on this equation with cartesian Friedrichs-Keller triangular meshes, and second order accuracy on the 3D Euler equations with anisotropic adapted meshes [4]. A solver was specifically implemented for this analysis, in order to compare the results between structured Friedrichs-Keller meshes and unstructured Delaunay ones. After that we considered more irregular unstructured meshes obtained by taking the ones used previously and perturbing them at different levels. These new meshes were then tested in order to compare the accuracy, in particular with another convergence study, obtaining a second order accuracy. An analysis of the local truncation error followed, by means of an algorithm that computes automatically the coefficients of the derivatives in the error terms. These coefficients were computed for all the families of meshes studied, in an attempt to explain the global errors computed through the local ones. The results were a third order of local accuracy for the regular meshes, and a first order for the perturbed ones, in opposition to the second order for the global error. This difference will be investigated with further studies.

6.8 Addition of Mixing Plane in Wolf

Participants: Frédéric Alauzet, Eloi Guilbert *(correspondant)*.

The mixing plane method is used typically on turbomachinery in order to model the interaction between a rotor (rotating part) and a stator (static part). Each row (stator, rotor) has its own computation which is coupled with his surroundings rows with the mixing plane. The idea is to average quantities along the pitch direction at the outlet of a row, those averaged values are transferred to the next row. The same process is done at the inlet of a row and transferred at the previous row. Associating mesh adaptation with mixing planes requires that the position and the distribution radial discretization must be automatic and consistent with the current adapted mesh. Therefore, after each mesh adaptation, a specific radial discretization for the mixing plane is built based on the current adapted mesh size. These radial discretizations are different on either side of the mixing plane as the adapted meshes do not match on either side. It allows removing the dependency of the results on the relative position between the rotor and the stator. Thus, RANS simulation can be used, even if the problem is naturally unsteady.

6.9 Localized flux limiting for Mixed Element Volume scheme on anisotropic adapted meshes

Participants: Frédéric Alauzet, Julien Vanharen, Andrea Gobbi *(correspondant)*.

We are working on decreasing the amount of numerical dissipation introduced by flux limiters in a Mixed Element Volume (MEV) scheme, that uses MUSCL extrapolations and the HLLC approximated Riemann solver to solve the convective part of the compressible Navier-Stokes equations. The computations are performed in the context of metric-based anisotropic mesh adaptation, thus it is essential to be both accurate and robust. The numerical approach consists in using the Larsson sensor in order to detect shocks and possibly other unstable regions of the solution, and use the flux limiters locally in those regions. The strategy is being tested for different flow configurations, both transonic, where shocks are expected and need to be treated accordingly, and subsonic, where flux limiters should not be needed. A case with a contact discontinuity is also considered.

6.10 Comparison of several shared-memory parallel linear solvers for the Navier-Stokes primal and adjoint equations on anisotropic adapted meshes

Participants: Frédéric Alauzet, Loïc Maréchal, Julien Vanharen, Thomas Gauchery *(correspondant)*.

We presented and studied a new methodology to improve linear solvers on parallel shared-memory architecture in the context of Reynolds-Averaged Navier-Stokes primal and adjoint equations. The computations are realized in the context of metric-based anisotropic mesh adaptation, thus efficiency and robustness of the new approach are crucial. For this purpose, a domain decomposition approach coupled with coloring algorithm for unstructured meshes is considered. It improves the convergence of the iterative solvers considered to solve the linear systems. The new strategy is validated on multiple realistic test cases to highlight the improved convergence for primal and adjoint problems. The results obtained have been presented during the AIAA SciTech 2025 conference in Orlando [11].

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Participants: Frédéric Alauzet.

Safran Tech

- Duration: 2017 - 2027
- Inria PI: Frédéric Alauzet
- Budget for GammaO: Salary for non-permanent staff, travels
- Objectives: Practical use of metric-based mesh adaptation for turbomachinery industrial applications

8 Partnerships and cooperations

8.1 European initiatives: NumPEx - Should start in 2023-2025

Participants: Loïc Maréchal, Julien Vanharen.

Since COVID crisis the air traffic is getting back to normal with a growing trend. Aeronautical engines' manufacturer did realize this as a critical time for aviation and huge effort should be made to reduce our environmental impact. For instance, The Advisory Council for Aeronautics Research in Europe aka ACARE 2050 objectives set a reduction of 75% in production of CO_2 and of 90% of NO_x. This objective brings to the design of new and groundbreaking parts and requires more efficient and complex numerical tools. To cope with new challenges an increase in simulation complexity and representativity is needed. It leads industrials like Safran to wonder if current numerical toolchains can still address those issues or should we optimize it. Parts, like propellers and turbines are very complex with a large number of technological effect, taking into account all physical aspect is often not possible since it leads to an exponential growth of the number of degrees of freedom with no convergence or accuracy guarantee. Thus designers simplify the geometry to use their traditional old simulation methods. For this reason, SAFRAN is pushing to develop new numerical toolchains that allows to reach better accuracy and scalability on the key design parameters. The recent studies in this sense ([2] is an example of application of remeshing technique with a turbine) highlights how the combination of an anisotropic meshing technique, a robust and accurate solver and the use of a remeshing technology would bring an improvement on physical quantities accuracy and reliability. The need of testing integrated parts, like propellers installed on wide body aircraft or multi-stage turbomachine, shows the interest for industrials of scaling the numerical toolchain to exascale machines in order to have accurate results to real world design problems.

Nowadays, industrials such as Airbus, Safran or ArianeGroup, are facing major technological challenges, which include the design of the Airbus A350 high-lift configuration, the cooling system of turbomachinery involving microperforated panels, the Ariane 6 launch vehicle or the consideration of ice accretion on aircraft wings. All of these challenges imply an intensive use of Computational Fluid Mechanics (CFD) in order to alleviate design and manufacturing costs and environmental impacts. However, three technological roadblocks need to be overwhelmed in the coming decades to treat the previous quoted industrial applications: the ability to handle **very complex geometries**, to predict unsteady turbulent flows with a **high-fidelity** and **very quickly**, which necessitates the High-Performance Computing (HPC). The application proposed in this project is out of reach with the present technology. Hence, disruptive methods need to be proposed to maximize the socio-economic impact. The first challenge requires to use the **automatic generation of tetrahedra meshes**, which is developed in our team for more than thirty years [13, 35, 19, 10, 14, 12, 17, 15, 16, 26, 25, 24, 38, 36, 27, 28]. Indeed, it is for instance impossible to generate a structured mesh around a real landing gear and even if it would be possible, it would require an enormous amount of time and resources compared with our automatic unstructured mesh generator. The last two challenges deal with the importance of having **accurate and fast numerical methods** on unstructured tetrahedra meshes to capture unsteady turbulent three-dimensional flows. Last but not least, these challenges have to be **simultaneously** addressed and impose strong constraints on the whole computational workflow. Moreover, **anisotropic mesh adaptation**, developed in our team [32, 31, 30, 33] works like a catalyst since it allows to:

1. efficiently discretize complex industrial geometries,
2. increase accuracy of numerical schemes,
3. reduce the computational time to achieve the same accuracy thanks to the generation of an optimal mesh in terms of degrees of freedom for a given configuration.

Our simulation suite is made of two main softwares: Feflo.a and Wolf. Feflo.a is our robust anisotropic local remeshing software for three-dimensional volume and parametric surface mesh generation conforming in sizes and orientations to a prescribed input metric field. It is based on a unique cavity-based operator [33, 43]. It also includes many components required to generate an initial mesh or generate highly-adapted meshes. It also handles non-manifold geometries and boundary layer mesh generation. Wolf is a mixed Finite Volume Finite Element flow solver for the compressible Euler and Navier Stokes equations with or without moving geometries. It also solves the steady and unsteady adjoint problems. It achieves second-order accuracy in space and up to fourth-order accuracy in time with explicit or implicit schemes. These suite has demonstrated its incredible potential and provided substantial breakthroughs in industrial applications [44, 43, 3].

It is absolutely crucial to keep in mind that the challenge to handle highly anisotropic unstructured meshes arise from the connectivity table needed to represent an unstructured mesh which induces loop indirections and load imbalances during computations and from the anisotropy which invalidates most of the standards geometric algorithms. Very simple standard algorithm such as a cut plane in an anisotropic tetrahedra mesh should be revised to efficiently run on a distributed memory architecture. Furthermore, the GPU algorithm has very little to do with the CPU one which notably increases the development cost to obtain a portable solution.

To continue and improve the capabilities of our suite, we propose a new library GMlib to specifically address the issue of handling anisotropic unstructured meshes on GPU and an industrial test case in agreement with the Safran Tech's roadmap.

8.2 European initiatives: NextAIR - 2023-2026

Participants: Frédéric Alauzet, Eloi Guilbert, Cosimo Tarsia Morisco.

Radical changes in aircraft configurations and operations are required to meet the target of climate-neutral aviation. To foster this transformation, innovative digital methodologies are of utmost importance to enable the optimisation of aircraft performances. NEXTAIR will develop and demonstrate innovative design methodologies, data-fusion techniques and smart health-assessment tools enabling the digital transformation of aircraft design, manufacturing and maintenance. NEXTAIR proposes digital enablers covering the whole aircraft life-cycle devoted to ease breakthrough technology maturation, their flawless entry into service and smart health assessment. They will be demonstrated in 8 industrial test cases, representative of multi-physics industrial design, maintenance problems and environmental challenges and interest for aircraft and engines manufacturers.

NEXTAIR will increase high-fidelity modelling and simulation capabilities to accelerate and derisk new disruptive configurations and breakthrough technologies design. NEXTAIR will also improve the efficiency of uncertainty quantification and robust optimisation techniques to effectively account for manufacturing uncertainty and operational variability in the industrial multi-disciplinary design of aircraft and engine components. Finally, NEXTAIR will extend the usability of machine learning-driven methodologies to contribute to aircraft and engine components' digital twinning for smart prototyping and maintenance.

NEXTAIR brings together 16 partners from 6 countries specialised in various disciplines: digital tools, advanced modelling and simulation, artificial intelligence, machine learning, aerospace design, and innovative manufacturing. The consortium includes 9 research organisations, 4 leading aeronautical industries providing digital-physical scaled demonstrator aircraft and engines and 2 high-Tech SME providing expertise in industrial scientific computing and data intelligence.

9 Dissemination

9.1 INRIA HPC developers day

Participants: Loïc Maréchal.

In October 2024 we organized a two-day event to gather many INRIA's engineers developing numerical simulation software. This event was aimed at building a closer community as all engineers are scattered between different teams and INRIA facilities across the country. Talks were given on topics covering many aspects of HPC software development like, CI/CD, portability of numerical accuracy, data structures and best practices. Round tables were organized to discuss and address common issues like mutualizing linear algebra toolkits or exchanging experiences with new programing languages.

10 Scientific production

10.1 Publications of the year

International journals

[1] B. Sauvage, F. Alauzet and A. Dervieux. 'A space and time fixed point mesh adaptation method'. In: *Journal of Computational Physics* 519 (Dec. 2024), p. 113389. DOI: 10.1016/j.jcp.2024.113389. URL: https://inria.hal.science/hal-04715086.

10.2 Cited publications

[2] F. Alauzet, L. Billon, E. Parente, M. Philit, A. Remigi and D. Papadogiannis. 'Evaluation of heat transfer performance of a film-cooled turbine vane using metric-based anisotropic mesh adaptation'. In: *AIAA SCITECH 2023 Forum*. National Harbor, MD, USA, 2023. DOI: 10.2514/6.2023-1399 (cit. on p. 10).

[3] F. Alauzet, F. Clerici, A. Loseille, M. Maunoury, L. Rochery, C. Tarsia-Morisco, L.-M. Tenkes and J. Vanharen. '4th AIAA CFD High Lift Prediction Workshop results using metric-based anisotropic mesh adaptation'. In: *AIAA Fluid Dynamics Conference*. Chicago, IL, USA, June 2022 (cit. on p. 11).

[4] F. Alauzet, A. Loseille and G. Olivier. 'Time-accurate multi-scale anisotropic mesh adaptation for unsteady flows in CFD'. In: *Journal of Computational Physics* 373 (2018), pp. 28–63 (cit. on p. 9).

[5] P. Arminjon and A. Dervieux. 'Construction of TVD-like artificial viscosities on two-dimensional arbitrary FEM grids'. In: *J Comput Phys* (1993) (cit. on p. 8).

[6] C. Debiez and A. Dervieux. 'Mixed-element-volume MUSCL methods with weak viscosity for steady and unsteady flow calculations'. In: *Computers & Fluids* (2000) (cit. on p. 8).

[7] B. Diskin, Y. Liu and M. C. Galbraith. 'High-Fidelity CFD Verification Workshop 2024: Spalart-Allmaras QCR2000-R Turbulence Model'. In: *AIAA SCITECH 2023 Forum*. 2023, p. 1244 (cit. on p. 7).

[8] R. Feuillet, M. Maunoury and A. Loseille. 'On pixel-exact rendering for high-order mesh and solution'. In: *Journal of Computational Physics* 424 (2021), p. 109860 (cit. on p. 7).

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