INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Opale

Optimization and Control, Numerical Algorithms and Integration of Multidisciplinary Complex P.D.E. Systems

Sophia Antipolis - Méditerranée, Grenoble - Rhône-Alpes

Theme : Computational models and simulation

Activity Report

2009

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2. Overall Objectives

2.1. Research fields

Optimizing a complex system arising from physics or engineering covers a vast spectrum in basic and applied sciences. Although we target a certain transversality from analysis to implementation, the particular fields in which we are trying to excell can be defined more precisely.

From the *physical analysis* point of view, our expertise relies mostly on Fluid and Structural Mechanics and Electromagnetics. In the former project Sinus, some of us had contributed to the basic understanding of fluid mechanical phenomena (Combustion, Hypersonic Non-Equilibrium Flow, Turbulence). More emphasis is now given to the coupling of engineering disciplines and to the validation of corresponding numerical methodologies.

From the *mathematical analysis* point of view, we are concerned with functional analysis related to partial-differential equations, and the functional/algebraic analysis of numerical algorithms. Identifying the Sobolev space in which the direct or the inverse problem makes sound sense, tailoring the numerical method to it, identifying a functional gradient in a continuous or discrete setting, analyzing iterative convergence, improving it, measuring multi-disciplinary coupling strength and identifying critical numerical parameters, etc constitute a non-exhaustive list of mathematical problems we are concerned with.

Regarding more specifically the *numerical aspects* (for the simulation of PDEs), considerable developments have been achieved by the scientific community at large, in recent years. The areas with the closest links with our research are:

1. *approximation schemes*, particularly by the introduction of specialized Riemann solvers for complex hyperbolic systems in Finite-Volume/Finite-Element formulations, and highly-accurate approximations (e.g. ENO schemes),
2. *solution algorithms*, particularly by the multigrid, or multilevel and multi-domain algorithms best-equiped to overcome numerical stiffness,
3. *parallel implementation and software platforms*.

After contributing to some of these progresses in the former project Sinus, we are trying to extend the numerical approach to a more global one, including an optimization loop, and thus contribute, in the long-term, to modern scientific computing and engineering design. We are currently dealing mostly with *geometrical optimization*.

Software platforms are perceived as a necessary component to actually achieve the computational cost-efficiency and versatility necessary to master multi-disciplinary couplings required today by size engineering simulations.

2.2. Objectives

The project has several objectives : to analyze mathematically coupled PDE systems involving one or more disciplines in the perspective of geometrical optimization or control; to construct, analyze and experiment numerical algorithms for the efficient solution of PDEs (coupling algorithms, model reduction), or multi-criterion optimization of discretized PDEs (gradient-based methods, evolutionary algorithms, hybrid methods, artificial neural networks, game strategies); to develop software platforms for code-coupling and for parallel and distributed computing.

Major applications include : the multi-disciplinary optimization of aerodynamic configurations (wings in particular) in partnership with Dassault Aviation and Piaggio Aero France; the geometrical optimization of antennas in partnership with France Télécom and Thalès Air Défense (see Opratel Virtual Lab.); the development of *Virtual Computing Environments* in collaboration with CNES and Chinese partners (ACTRI).

2.3. Highlights of the year

A new activity has been launched by J.P. Zolesio and collaborators related to the control of Maxwell equations to locate radar targets by using a strong solution to the Hamilton-Jacobi equation.

The collaboration with ONERA (The French Aerospace Laboratory) was initiated by J.-A. Désidéri as a consultant in the Numerical Simulation in Aerodynamics and Aeroacoustics Department (DSNA, Châtillon s/ Bâgneux). This collaboration develops along the following major areas of interest in aerodynamic optimization : adjoint equations for coupled aero-structural models, fast multigrid solvers for adjoint equations, global multilevel optimization, reduced models for shape optimization and control of numerical uncertainties, game strategies for multidisciplinary optimization. This year, the collaboration has been extended to the Department of Aerodynamic Applications (DAAP, Meudon) with a special focus on aerodynamic optimization coupled with structural design, or acoustic criteria.

3. Scientific Foundations

3.1. Numerical optimization of PDE systems

Optimization problems involving systems governed by PDEs, such as optimum shape design in aerodynamics or electromagnetics, are more and more complex in the industrial setting.

In certain situations, the major difficulty resides in the costly evaluation of a functional by means of a simulation, and the numerical method to be used must exploit at best the problem characteristics (regularity or smoothness, local convexity).

In many other cases, several criteria are to be optimized and some are non differentiable and/or non convex. A large set of parameters, sometimes of different types (boolean, integer, real or functional), are to be taken into account, as well as constraints of various types (physical and geometrical, in particular). Additionally, today's most interesting optimization pre-industrial projects are multi-disciplinary, and this complicates the mathematical, physical and numerical settings. Developing *robust optimizers* is therefore an essential objective to make progress in this area of scientific computing.

In the area of numerical optimization algorithms, the project aims at adapting classical optimization methods (simplex, gradient, quasi-Newton) when applicable to relevant engineering applications, as well as developing and testing less conventional approaches such as Evolutionary Strategies (ES), including Genetic or Particle-Swarm Algorithms, or hybrid schemes, in contexts where robustness is a very severe constraint.

In a different perspective, the heritage from the former project Sinus in Finite-Volumes (or -Elements) for nonlinear hyperbolic problems, leads us to examine cost-efficiency issues of large shape-optimization applications with an emphasis on the PDE approximation; of particular interest to us:

- best approximation and shape-parameterization,
- convergence acceleration (in particular by multi-level methods),
- model reduction (e.g. by *Proper Orthogonal Decomposition*),
- parallel and grid computing; etc.

3.2. Geometrical optimization

In view of enhancing the robustness of algorithms in shape optimization or shape evolution, modeling the moving geometry is a challenging issue. The main obstacle between the geometrical viewpoint and the numerical implementation lies in the basic fact that the shape gradients are distributions and measures lying in the dual spaces of the shape and geometrical parameters. These dual spaces are usually very large since they contain very irregular elements. Obviously, any finite dimensional approach pertains to the Hilbert framework where dual spaces are identified implicitly to the shape parameter spaces. But these finite-dimensional spaces sometimes mask their origin as discretized Sobolev spaces, and ignoring this question leads to well-known instabilities; appropriate smoothing procedures are necessary to stabilize the shape large evolution. This point is sharp in the "narrow band" techniques where the lack of stability requires to reinitialize the underlying level equation at each step.

The mathematical understanding of these questions is sought via the full analysis of the continuous modeling of the evolution. How can we "displace" a smooth geometry in the direction opposite to a non smooth field, that is going to destroy the boundary itself, or its smoothness, curvature, and at least generate oscillations.

The notion of *Shape Differential Equation* is an answer to this basic question and it arises from the functional analysis framework to be developed in order to manage the lack of duality in a quantitative form. These theoretical complications are simplified when we return to a Hilbert framework, which in some sense, is possible, but to the undue expense of a large order of the differential operator implied as duality operator. This operator can always be chosen as an *ad hoc* power of an elliptic system. In this direction, the key point is the optimal regularity of the solution to the considered system (aerodynamical flow, electromagnetic field, etc.) up to the moving boundary whose regularity is itself governed by the evolution process.

We are driven to analyse the fine properties concerning the minimal regularity of the solution. We make intensive use of the “extractor method” that we developed in order to extend the I. Lasiecka and R. Triggiani “hidden regularity theory”. For example, it was well known (before this theory) that when a domain Ω has a boundary with continuous curvatures and if a “right hand side” f has finite energy, then the solution u to the potential problem $-\Delta u = f$ is itself in the Sobolev space $H^2(\Omega) \cap H^1_0(\Omega)$ so that the normal derivative of u at the boundary is itself square integrable. But what does this result become when the domain boundary is not smooth? Their theory permitted for example to establish that if the open set Ω is convex, the regularity property as well as its consequences still hold. When the boundary is only a Lipschitzian continuous manifold the solution u loses the previous regularity. But the “hidden regularity” results developed in the 80’s for hyperbolic problems, in which the $H^2(\Omega)$ type regularity is never achieved by the solution (regardless the boundary regularity), do apply. Indeed *without regularity assumption on the solution* u, we proved that its normal derivative has finite energy.

In view of algorithms for shape optimization, we consider the continuous evolution Ω_t of a geometry where t may be the time (governing the evolution of a PDE modeling the continuous problem); in this case, we consider a problem with dynamical geometry (non cylindrical problem) including the dynamical free boundaries. But t may also be the continuous version for the discrete iterations in some gradient algorithm. Then t is the continuous parameter for the continuous *virtual* domain deformation. The main issue is the validity of such a large evolution when t is large, and when $t \to \infty$. A numerical challenge is to avoid the use of any “smoother” process and also to develop “shape-Newton” methods [65]. Our evolution field approaches permit to extend this viewpoint to the topological shape optimization ([67]).

We denote $G(\Omega)$ the shape gradient of a functional J at Ω. There exists $s \in \mathbb{R}^+$ such that $G(\Omega) \in H^{-s}(D, \mathbb{R}^N)$, where D is the universe (or “hold all”) for the analysis. For example $D = \mathbb{R}^N$. The regularity of the domains which are solution to the shape differential equation is related to the smoothness of the *oriented distance* function b_Ω which turns out to be the basic tool for intrinsic geometry. The limit case $b_\Omega \in C^{1,1}(\mathcal{U})$ (where $\mathcal{U}$ is a tubular neighborhood of the boundary Γ) is the important case.

If the domains are Sobolev domains, that is if $b_\Omega \in H^r(\mathcal{U})$, then we consider a duality operator, $\mathcal{A} \in \mathcal{L}(H^r, H^{-s})$ satisfying: $< \mathcal{A}\phi, \phi > \geq |\phi|^2_H$ where H denotes a root space. We consider the following problem: given Ω_0, find a non autonomous vector field $V \in C^0([0, \infty[, H^r(D, \mathbb{R}^N)) \cap C([0, , \infty[, L^\infty(D, \mathbb{R}^N))$ such that, $T_t(V)$ being the flow mapping of V,

$$\forall t > 0,\ \ \mathcal{A}.V(t) + G(T_t(V)(\Omega_0)) = 0$$

Several different results have been derived for this equation under *boundedness* assumptions of the following kind:

$$\text{there exists}\ \ M > 0 \ \ \text{so that,}\ \forall \Omega,\ \ ||G(\Omega)|| \leq M$$

The existence of such bound has first been proved for the problem of best location of actuators and sensors, and have since been extended to a large class of boundary value problems. The asymptotic analysis (in time $t \to \infty$) is now complete for a 2D problem with help of V. Sverak continuity results (and extended versions with D. Bucur). These developments necessitate an intrinsic framework in order to avoid the use of Christoffel symbols and local mappings, and to work at *minimal* regularity for the geometries.

The intrinsic geometry is the main ingredient to treat convection by a vector field V. Such a non autonomous vector field builds up a tube. The use of BV topology permits these concepts to be extended to non smooth vector fields V, thus modeling the possible topological changes. The *transverse field* concept Z has been developed in that direction and is now being applied to fluid-structure coupled problems. The most recent results have been published in three books [2], [13], [1].

3.3. Integration platforms

Developing grid computing for complex applications is one of the priorities of the IST chapter in the 6th Framework Program of the European Community. One of the challenges of the 21st century in the computer science area lies in the integration of various expertise in complex application areas such as simulation and optimisation in aeronautics, automotive and nuclear simulation. Indeed, the design of the reentry vehicle of a space shuttle calls for aerothermal, aerostructure and aerodynamics disciplines which all interact in hypersonic regime, together with electromagnetics. Further, efficient, reliable, and safe design of aircraft involve thermal flows analysis, consumption optimisation, noise reduction for environmental safety, using for example aeroacoustics expertise.

The integration of such various disciplines requires powerful computing infrastructures and particular software coupling techniques. Simultaneously, advances in computer technology militate in favour of the use of massively parallel PC-clusters including thousands of processors connected by high-speed gigabits/sec wide-area networks. This conjunction makes it possible for an unprecedented cross-fertilisation of computational methods and computer science. New approaches including evolutionary algorithms, parameterization, multi-hierarchical decomposition lend themselves seamlessly to parallel implementations in such computing infrastructures. This opportunity is being dealt with by the OPALE project since its very beginning. A software integration platform has been designed by the OPALE project for the definition, configuration and deployment of multidisciplinary applications on a distributed heterogeneous infrastructure [66]. Experiments conducted within European projects and industrial cooperations using CAST have led to significant performance results in complex aerodynamics optimisation test-cases involving multi-elements airfoils and evolutionary algorithms, i.e. coupling genetic and hierarchical algorithms involving game strategies. [68].

The main difficulty still remains however in the deployment and control of complex distributed applications on grids by the end-users. Indeed, the deployement of the computing grid infrastructures and of the applications in such environments still requires specific expertise by computer science specialists. However, the users, which are experts in their particular application fields, e.g. aerodynamics, are not necessarily experts in distributed and grid computing. Being accustomed to Internet browsers, they want similar interfaces to interact with grid computing and problem-solving environments. A first approach to solve this problem is to define component-based infrastructures, e.g. the Corba Component Model, where the applications are considered as connection networks including various application codes. The advantage is here to implement a uniform approach for both the underlying infrastructure and the application modules. However, it still requires specific expertise not directly related to the application domains of each particular user. A second approach is to make use of grid services, defined as application and support procedures to standardise access and invocation to remote support and application codes. This is usually considered as an extension of Web services to grid infrastructures. A new approach, which is currently being explored by the OPALE project, is the design of a virtual computing environment able to hide the underlying grid-computing infrastructures to the users. It is currently deployed within the Collaborative Working Environments Unit of the DG INFSO F4 of the European Commission. It is planned to include Chinese partners from the aeronautics sector in 2009 to set up a project for FP7.

4. Application Domains

4.1. Aeronautics and space

The demand of the aeronautical industry remains very strong in aerodynamics, as much for conventional aircraft, whose performance must be enhanced to meet new societal requirements in terms of economy, noise (particularly during landing), vortex production near runways, etc., as for high-capacity or supersonic aircraft of the future. Our implication concerns shape optimization of wings or simplified configurations.

Our current involvement with Space applications relates to software platforms for code coupling.

4.2. Electromagnetics

In the context of shape optimization of antennas, we can split the existing results in two parts: the two-dimensional modeling concerning only the specific transverse mode TE or TM, and treatments of the real physical 3-D propagation accounting for no particular symmetry, whose objective is to optimize and identify real objects such as antennas.

Most of the numerical literature in shape optimization in electromagnetics belongs to the first part and makes intensive use of the 2-D solvers based on the specific 2-D Green kernels. The 2-D approach for the optimization of *directivity* led recently to serious errors due to the modeling defect. There is definitely little hope for extending the 2-D algorithms to real situations. Our approach relies on a full analysis in unbouded domains of shape sensitivity analysis for the Maxwell equations (in the time-dependent or harmonic formulation), in particular, by using the integral formulation and the variations of the Colton and Kreiss isomorphism. The use of the France Telecom software SR3D enables us to directly implement our shape sensitivity analysis in the harmonic approach. This technique makes it possible, with an adequate interpolation, to retrieve the shape derivatives from the physical vector fields in the time evolution processes involving initial impulses, such as radar or tomography devices, etc. Our approach is complementary to the "automatic differentiation codes" which are also very powerful in many areas of computational sciences. In Electromagnetics, the analysis of hyperbolic equations requires a sound treatment and a clear understanding of the influence of space approximation.

4.3. Biology and medecine

A particular effort is made to apply our expertise in solid and fluid mechanics, shape and topology design, multidisciplinary optimization by game strategies to biology and medecine. Two selected applications are priviledged : solid tumours and wound healing.

Opale's objective is to push further the investigation of these applications, from a mathematical-theoretical viewpoint and from a computational and software development viewpoint as well. These studies are led in collaboration with biologists, as well as image processing specialists.

4.4. Multidisciplinary couplings

Our expertise in theoretical and numerical modeling, in particular in relation to approximation schemes, and multilevel, multiscale computational algorithms, allows us to envisage to contribute to integrated projects focused on disciplines other than fluid dynamics or electromagnetics such as biology and virtual reality, image processing, in collaboration with specialists of these fields.

5. Software

5.1. Shape optimization platform FAMOSA

Participants: Praveen Chandrashekarappa [former Post-doct], Régis Duvigneau, Antoine Maurice.

Opale team is developing the platform FAMOSA, designed for shape optimization of 2D/3D bodies. It integrates the following components:

- a parameterization module implementing a 2D/3D multi-level and adaptive Bézier parameterization (Free-Form Deformation) that allows to deform simultaneously the shape and the CFD mesh ;
- an optimization library composed of various algorithms, such as the Multi-directional Search Algorithm from V. Torczon (deterministic), a Particle Swarm Optimization method (semi-stochastic) and a Kriging-based algorithm (global optimization) ;
- a module managing the calls to various solvers, including tools for statistical estimations used in robust design ;

- a metamodel library that contains tools to build a database and kriging models that are used to approximate the objective function and constraints (multi-level modelling technique) ;
- a parallel library implementing the evaluations of the objective function in parallel (independent shapes or independent flow conditions).

The FAMOSA platform has been linked to the compressible Navier-Stokes solver NUM3SIS developed by Opale, the Euler code NS3D used by Tropics team for automatic differentiation tests, the open-source 2D Navier-Stokes code NUWTUN and the incompressible flow solver ISISCFD developed at the Ecole Centrale de Nantes.

The software development has been supported by an ATT (Action de Transfert Technologique) program, which funded the work of Antoine Maurice. The objective was to adapt the FAMOSA platform to hydrodynamic design test-cases, such as ship hull optimization or mast design for sailing boats, in collaboration with K-Epsilon company (http://www.k-epsilon.com).

5.2. Compressible Navier-Stokes solver NUM3SIS

Participants: Praveen Chandrashekarappa [former Post-doct], Régis Duvigneau, Nikolas Mauny.

The NUM3SIS flow solver has been developed by Opale and Smash Project-Teams for three years.

The compressible Navier-Stokes solver has been designed for large scale parallel computations using the MPI library. Main features are:

- Euler / Navier-Stokes modelling ;
- Laminar / turbulent flows (Spalart-Allmaras turbulence model) ;
- Multi-phase flows ;
- Mixed finite-volume and finite-element spatial discretization (cell-vertex method)
- High-order reconstruction schemes (MUSCL reconstruction, Beta scheme, V6 scheme)
- Physical fluxes (Godunov, Van-leer flux splitting, HLLC, AUSM+)
- Explicit (Backward explicit, Runge-Kutta) or implicit (Matrix-free, residuals linearization, dual time stepping);
- Domain decomposition method for parallel computing.

The code has been validated on various large-scale computing facilities (Linux cluster, IBM and Bull supercomputers) for a use of several hundreds of processors.

This work is being carried out with the support of a software development engineer since October 2008 in the framework of the ADT (Action de Développement Technologique) program. The objective is to implement a platform architecture that manages the computational tasks, which are considered as plugins loaded according to a computational scenario.

5.3. Numerical modules for gradient computations in electromagnetics

Participants: Claude Dedeban [France Télécom, La Turbie], Pierre Dubois [former PhD], Jerôme Picard [former engineer], Jean-Paul Zolésio.

Shape gradients with respect to 3D geometries in electromagnetic fields are computed by numerical code developments peripherical to the France Télécom SR3D code for the solution of the Maxwell equations. These developments, combined with interpolation in the frequency domain, permit to compute the derivative w.r.t. the frequency.

Additionally, a self-sufficient FORTRAN code is being developed for antenna optimization by parameterized level-set techniques. This code is to be latter interfaced with the code for array antenna optimization.

5.4. Axel plugins for isogeometric analysis and design

Participants: Régis Duvigneau, Xu Gang [Galaad team].

Opale team is developing plugins in the framework of the algebraic modeler Axel, whose development is carried out by Galaad team. These plugins aim at implementing a prototype of isogeometric solver and optimizer, in interaction with the CAD library contained in Axel platform.

A simulation tool for heat conduction equation has been implemented, in conjunction with a deterministic and a semi-stochastic optimization algorithm for optimum-shape design.

6. New Results

6.1. Computational methods, numerical analysis and validation

6.1.1. Analysis and numerical approximation of macroscopic models of vehicular traffic

Participant: Paola Goatin.

Paola Goatin is part-time on secondment from University of Toulon.

Present research is focused on the mathematical analysis of traffic flow models on road networks or subject to unilateral constraints. In particular, [25] is devoted to a hyperbolic 2 phase model for traffic flow on a network. The model is rigorously described and the existence of solutions is proved, without any restriction on the network geometry.

In [31], we deal with the mathematical description of toll gates along roads, or of the escape dynamics for crowds. This problem requires the introduction of unilateral constraints on the observable flow. We present a rigorous approach to these constraints, and numerical integrations of the resulting models are included to show their practical usability.

Paola Goatin defended her Habilitation thesis on the "Analysis and numerical approximation of some macroscopic models of vehicular traffic" [24].

A new project entitled "Traffic management by macroscopic models" has been submitted to the ERC Starting Grant, in which the INRIA Sophia Antipolis Méditerranée Center has been proposed as the host institution.

6.1.2. Isogeometric analysis and design

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Frédéric Moresmau, Bernard Mourrain [Galaad Project-Team], Mohammed Ziani.

Design optimization stands at the crossroad of different scientific fields (and related software): Computer-Aided Design (CAD), Computational Fluid Dynamics (CFD) or Computational Structural Dynamics (CSM), parametric optimization. However, these different fields are usually not based on the same geometrical representations. CAD software relies on Splines or NURBS representations, CFD and CSM software uses grid-based geometric descriptions (structured or unstructured), optimization algorithms handle specific shape parameters. Therefore, in conventional approaches, several information transfers occur during the design phase, yielding approximations and non-linear transformations that can significantly deteriorate the overall efficiency of the design optimization procedure.

The isogeometric approach proposes to definitely overcome this difficulty by using CAD standards as a unique representation for all disciplines. The isogeometric analysis consist in developing methods that use NURBS representations for all design tasks:

- the geometry is defined by NURBS surfaces;
- the computation domain is defined by NURBS volumes instead of meshes;
- the solution fields are obtained by using a finite-element approach that uses NURBS basis functions instead of classical Lagrange polynomials;
- the optimizer controls directly NURBS control points.

Using such a unique data structure allows to compute the solution on the exact geometry (not a discretized geometry), obtain a more accurate solution (high-order approximation), reduce spurious numerical sources of noise that deteriorate convergence, avoid data transfers between the software. Moreover, NURBS representations are naturally hierarchical and allows to define multi-level algorithms for solvers as well as optimizers.

A prototype of isogeometric solver and design optimizer has been developed in collaboration with Galaad team. The heat conduction equation (elliptic) has been first considered to assess the convergence properties (high-order approximation schemes) and test the possible refinement preocedures (h- and p-refinement) [57]. The study of hierarchical optimization strategies for modelling and parameterization has been initiated. Moreover, collaborations with the Technical University of Munich for application to structural design and with National Technical University of Athens for application to hydrodynamic design are in progress. In the near future, the Euler equations for compressible aerodynamics (hyperbolic) will be studied to extend the method to more complex applications. (See Figure 1 for an illustration.)

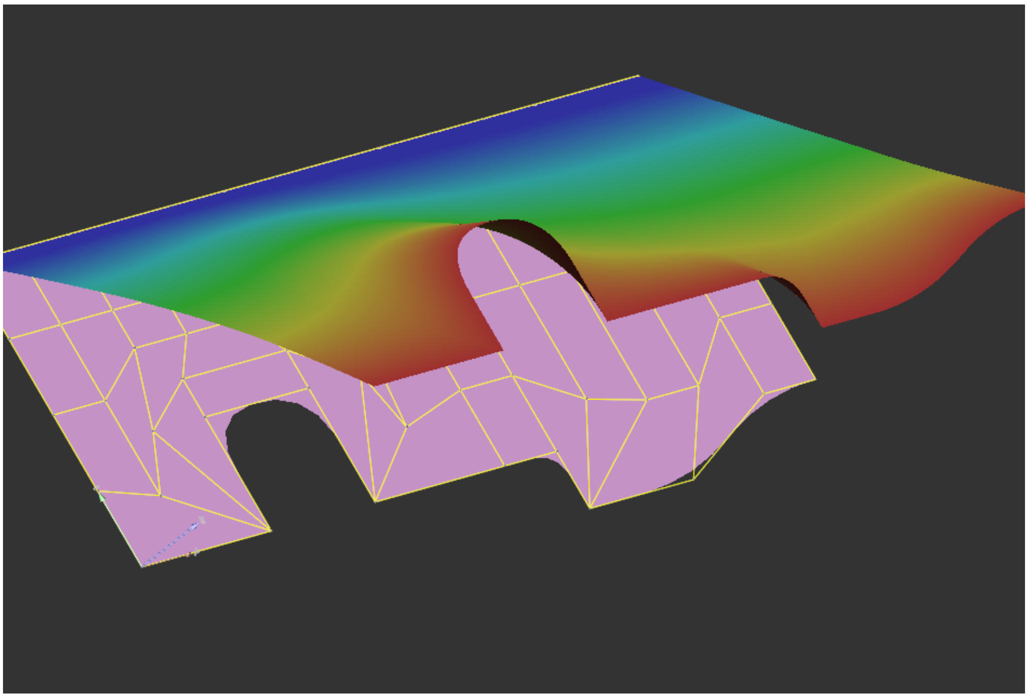


Figure 1. Example of isogeometric simulation in thermal conduction. The computational domain is defined as a plane NURBS surface (pink) specifed by a net of control points (yellow). The solution field is also defined as a NURBS surface, colored according to the temperature value (cold in blue at the top, hot in red at the bottom).

6.2. Numerical algorithms for optimization and optimum-shape design

Our research themes are related to optimization and control of complex multi-disciplinary systems governed by PDEs. They include algorithmic aspects (shape parameterization, game strategies, evolutionary algorithms, gradient/evolutionary hybridization, model reduction and hierarchical schemes), theoretical aspects (control and domain decomposition), as well as algorithmic and software aspects (parallel and grid computing).

These general themes for Opale are given some emphasis this year through the involvement of our project in the ANR/RNTL National Network on Multi-Disciplinary Optimization "OMD”.

6.2.1. Hierarchical (multilevel) and adaptive shape parameterization

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Abderrahmane Benzaoui.

6.2.1.1. Multilevel shape optimization algorithms and application to 3D aerodynamic Problems

We have proposed to exploit the classical degree-elevation process to construct a hierarchy of nested Bézier parameterizations. The construction yields in effect a number of rigorously-embedded search spaces, used as the support of multilevel shape-optimization algorithms mimicking multigrid strategies. In particular, the most general, *FAMOSA, Full Adaptive Multilevel Optimum Shape Algorithm*, is inspired by the classical *Full Multigrid Method*.

The *FAMOSA* method has been applied to the context of three-dimensional flow for the purpose of shape optimization of a transonic aircraft wing (pressure-drag minimization problem) [52] using the Free-Form Deformation (FFD) approach to handle nested levels of parameterization (see Figure 2).

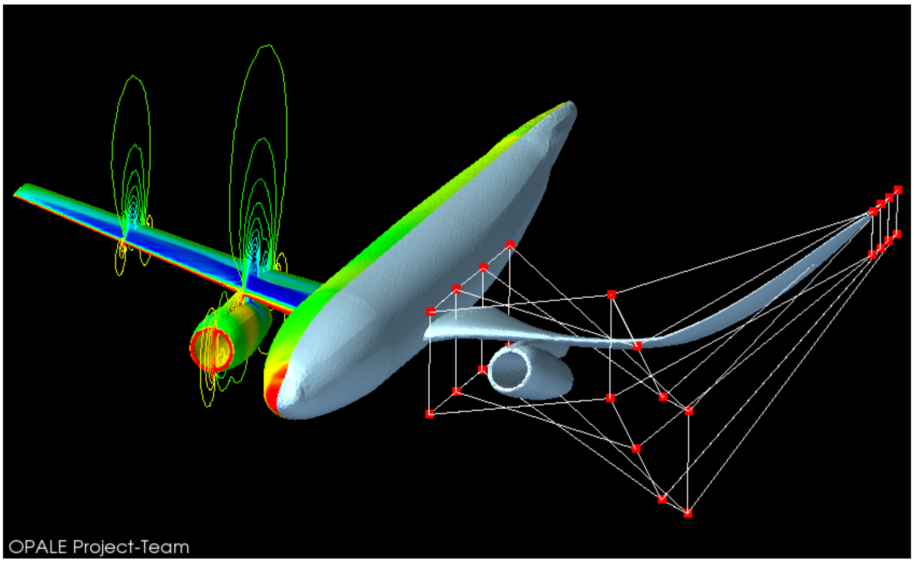


Figure 2. This figure illustrates, on the left side, the simulation of a transonic flow by finite-volume solution of the Euler equations, and on the right side, the potential of the Free-Form Deformation (FFD) approach to produce smooth geometrical deformations, even unrealistically large, at constant topology. The FFD technique has been extensively used to define multilevel algorithms in the FAMOSA platform.

6.2.1.2. Multi-level algorithms based on an algebraic approach

The previous hierarchical approach, based on the degree-elevation property of Bézier curves, has been extended to other parameterization types in order to be able to solve general parametric optimization problems. The proposed approach rely on the construction of a hierarchical basis of the design space, originating from the eigenmodes of the Hessian matrix of the cost functional.

We have experimented the method on simple analytic functions and then on shape reconstruction problems, using various approximations of the Hessian matrix (exact, finite-difference, local metamodel, global least-squares) [53].

Finally, this approach has been applied to the multidisciplinary design of a supersonic business jet (aerodynamics, structure, propulsion, flight mechanics), proposed by Dassault-Aviation as multi-disciplinary optimization benchmark for "OMD" project [29], [41].

6.2.2. Multidisciplinary optimization

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Aurélien Goudjo [Univ. of Abomey-Calavi, Bénin, from October to December 2009], Abderrahmane Habbal, Malik Haris [Erasmus Mundus International Master in Mathematical Engineering 'MathMods'].

In the most competitive engineering fields, such as aeronautics, multicriterion and multidisciplinary design has gained importance in order to cope with new and acute needs of society. In the literature, contributions to single discipline and/or single-point design optimization abound. In recent years, for purely-aerodynamic design, we had proposed to introduce a new approach combining the adjoint method with a formulation derived from game theory for multipoint design problems [22]. Transonic flows around lifting airfoils were analyzed by Euler computations. Airfoil shapes were optimized according to various aerodynamic criteria. The notion of player was introduced. In a competitive Nash game, each player attempts to optimize its own criterion through a symmetric exchange of information with others. A Nash equilibrium is reached when each player constrained by the strategy of the others, cannot improve further its own criterion. Specific real and virtual symmetric Nash games were implemented to set up an optimization strategy for design under conflict.

When devising a numerical shape-optimization method in the context of a practical engineering situation, the practitioner is faced with an additional difficulty related to the participation of several relevant physical criteria in a realistic formulation. For some problems, a solution may be found by treating all but one criteria as additional constraints. In some other problems, mainly when the computational cost is not an issue, Pareto fronts can be identified at the expense of a very large number of functional evaluations. However the difficulty is very acute when optimum-shape design is sought w.r.t. an aerodynamic criterion as well as other criteria for two main reasons. The first is that aerodynamics alone is costly to analyze in terms of functional evaluation. The second is that generally only a small degradation of the performance of the absolute optimum of the aerodynamic criterion alone is acceptable (suboptimality) when introducing the other criteria.

We have proposed a numerical methodology for the treatment of such problems of concurrent engineering [8]. After completion of the parametric, possibly-constrained minimization of a single, primary functional J_A, approximations of the gradient and the Hessian matrix are available or calculated using data extracted from the optimization loop itself. Then, the entire parametric space (a subset of $\mathbb{R}^{n+1}$) is split into two supplementary subspaces on the basis of a criterion related to the second variation. The construction is such that from the initial convergence point of the primary functional, normalized perturbations of the parameters lying in one of the two subspaces, of specified dimension $p \leq n$, cause the least possible degradation to the primary functional. The latter subspace is elected to support the parameterization of a secondary functional, J_B, in a concurrent optimization realized by an algorithm simulating a Nash game between players associated with the two functionals. We prove a second result indicating that the original global optimum point of the full-dimension primary problem is Pareto-optimal for a trivial concurrent problem. This latter result permits us to define a continuum of Nash equilibrium points originating from the initial single-criterion optimum, in which the designer could potentially make a rational election of operating point.

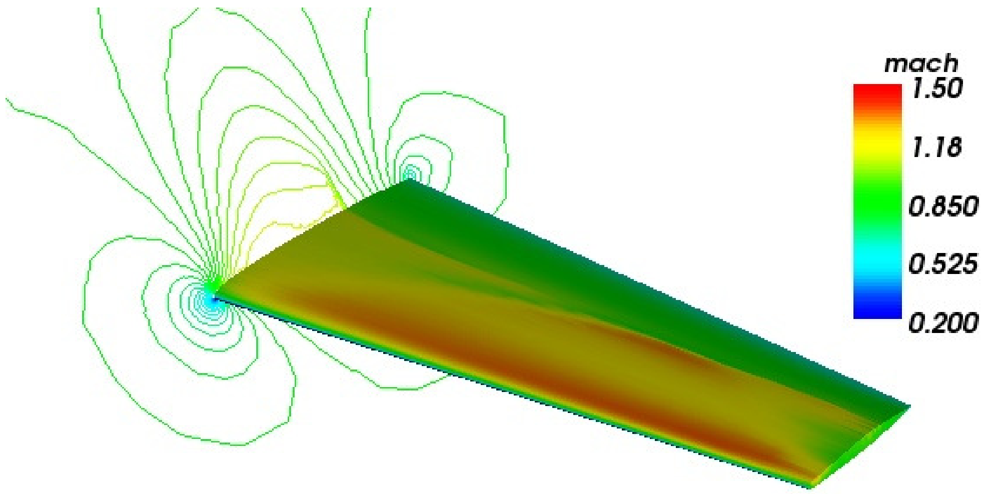
Following the thesis of B. Abou El Majd, a wing-shape aero-structural optimization was successfully realized despite the strong antagonism of the criteria in conflict in the concurrent reduction of the wing drag in Eulerian flow and a stress integral of the structural element treated as a shell subject to linear elasticity [51] and [40] (see Figure 3).

The technique of territory splitting is currently being extended to encompass cases where all the criteria are of comparable importance ("equitable splits"). In a more global optimization process under developement, the optimization is carried out in two phases. In the first, said to be "cooperative", all the criteria under consideration are iteratively improved. This phase relies on a general result of convex analysis yielding to the definition of the so-called Multiple-Gradient Descent Algorithm [58]. In the second phase, said to be "competitive", viable trade-offs are identified as particular Nash equilibrium points in the smooth continuation of the termination point of the MGDA phase [32].

6.2.3. Metamodel-based optimization

Participants: Praveen Chandrashekarappa, Régis Duvigneau.

a) Initial aerodynamic optimum solution



b) Aerostructural Nash game solution using the orthogonal decomposition

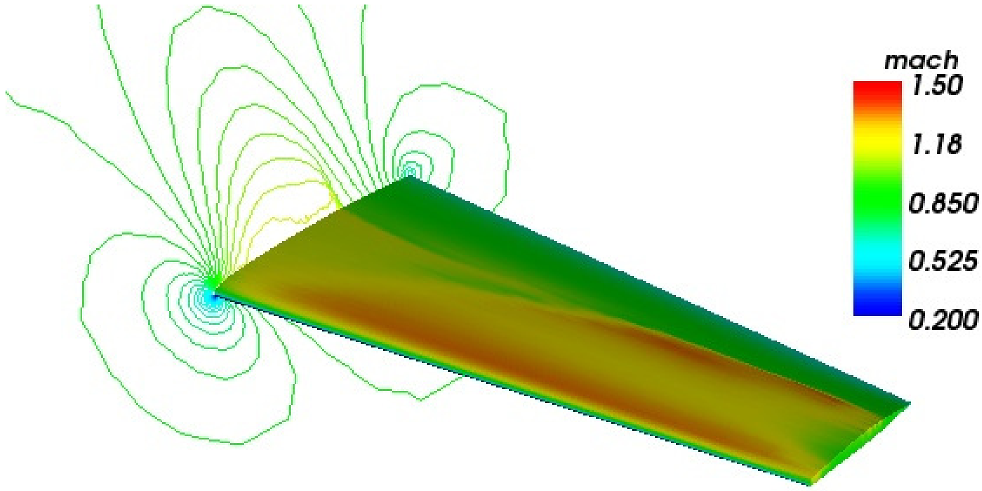


Figure 3. Illustration of a Nash game with an adapted split of territory. On top, the Mach number field corresponding to the aerodynamic global optimum solution. Below, the aerostructural Nash equilibrium solution, demonstrating a minor aerodynamic degradation (slightly-increased shock intensity). As a structural element, the wing is treated as a shell of given thickness under aerodynamic forces and subject to linear elasticity. The game has been organized in an orthogonal basis of parameters and devised to best preserve the aerodynamic criterion, thus suboptimality, while reducing significantly a stress-tensor-based structural criterion.

Design optimization in Computational Fluid Dynamics or Computational Structural Mechanics is particularly time consuming, since several hundreds of expensive simulations are required in practice. Therefore, we are currently developing approaches that rely on *metamodels*, i.e. models of models, in order to accelerate the optimization procedure by using different modelling levels. Metamodels are inexpensive functional value predictions that use data computed previously and stored in a database. Different techniques of metamodelling (polynomial fitting, Radial Basis Functions, Kriging) have been developed and validated on various engineering problems[54]. Our developments have been particularly focused on the construction of algorithms that use both metamodels and models based on PDE's solving to drive a semi-stochastic optimization, with various couplings :

- A strong coupling approach consists in using metamodels to pre-evaluate candidate designs and select those which are exactly evaluated by simulation at each iteration. Then, the optimization algorithm relies only on exact evaluations. For the Particle-Swarm Optimization (PSO) algorithm, an adaptive method has been proposed, that allows the algorithm to automatically adjust the number of exact evaluations required at each iteration[26].
- A weak coupling approach consists in using metamodels only to solve a set of optimization subproblems iteratively. In that case, kriging is employed to predict both function value and modelling error. The subproblems considered (lower bound minimization, probability of improvement maximization, expected improvement maximization) indicate which simulations should be performed to improve the model as well as determine the best design[62].

The efficiency of these approaches has been studied on two benchmark test-cases proposed in the framework of the "Design Database Workshop" organized in December by University of Jyvaskyla (Finland): an inverse problem (pressure reconstruction) using a three-body airfoil[45], and a flow control problem for a transonic airfoil[47].

6.2.4. Uncertainty estimation and robust design

Participants: Régis Duvigneau, Massimiliano Martinelli.

A major issue in design optimization is the capability to take uncertainties into account during the design phase. Indeed, most phenomena are subject to uncertainties, arising from random variations of physical parameters, that can yield off-design performance losses.

To overcome this difficulty, a methodology for *robust design* is currently developed and tested, that includes uncertainty effects in the design procedure, by maximizing the expectation of the performance while minimizing its variance.

Two strategies to *propagate the uncertainty* are currently under study :

- the use of metamodels to predict the uncertainties of the objective function from the uncertainties of the input parameters of the simulation tool. During the optimization procedure, a few simulations are performed for each design variables set, for different values of the uncertain parameters in order to build a database used for metamodels training. Then, metamodels are used to estimate some statistical quantities (expectation and variance) of the objective function and constraints, using a Monte-Carlo method.
- the use of the automatic differentiation tool Tapenade (developped by Tropics Project-Team) to compute first and second order derivatives of the performance with respect to uncertain parameters. The first order derivatives are computed by solving the adjoint system, that is built by using Tapenade in reverse mode. For the computation of the second derivatives, two strategies can be employed: the use of two successive tangent mode differentiations or the use of the tangent mode on the result of the reverse mode differentiation. The efficiency of these strategies depends on the number of the parameters considered. Once these derivatives have been computed, one can easily derive statistic estimations by integrating the Taylor series expansion of the performance multiplied by the probability density function. This work is carried out in collaboration with Tropics Project-Team.

Uncertainty estimation has been carried out in the particular framework of flow control, for an oscillatory rotating cylinder, in order to measure the sensitivity of optimal control parameters (frequency, amplitude) to variable flow conditions[43].

Various robust optimization approaches (statistical, min-max, multi-point) have been compared for the optimization of the wing shape of a Falcon business aircraft subject to four uncertain parameters: free-stream velocity, angles of attack, yaw and pitch[42].

6.2.5. Application of shape optimization algorithms to naval hydrodynamics

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Antoine Maurice, Yann Roux [K-Epsilon].

The shape optimization algorithms developed by Opale have been applied to challenging problems in naval hydrodynamics.

In the framework of the collaboration with K-Epsilon company, the optimization of a mast section for a sailing race boat has been performed, on the basis of unsteady Navier-Stokes simulations. We have also initiated the study of bow design optimization for fishing boats, in order to minimize the flow resistance induced by free-surface elevation [61] (see Figure 4).

A collaboration with the fluid mechanics laboratory of Ecole Centrale de Nantes (CNRS UMR 6598), is currently setting-up in order to develop optimization strategies adapted to this particular context.

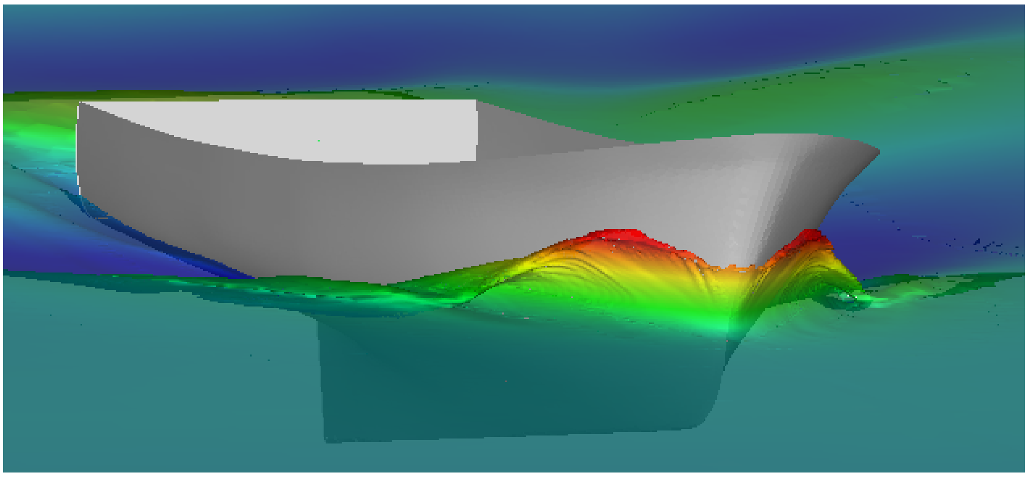


Figure 4. Simulation of the free-surface flow around a fishing boat in preparation of the optimization of a bow-device to reduce the wave drag. This study is conducted in cooperation with the K-Epsilon company.

6.2.6. Multiobjective Shape optimization applied to Nonlinear Structural Dynamics

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Abderrahmane Habbal, Gaël Mathis [Arcelor Mittal Automotive Research Division], Zahra Shirzadi.

The reduction of the carbon dioxide CO2 emitted by cars is directly related to the reduction of their overall weight. When designing vehicles which comply to "green" environment standards, the automotive industry has however to fulfil security requirements, particularly those involving crash and fatigue. The so-called high performance steel -HPS- is therefore a promising material, since it allows to design very thin structures which demonstrate good mechanical properties. The metal forming process of such a steel pieces is however complex and requires the development of new and efficient numerical tools permitting a good understanding as well as for an optimal control of the mechanical behavior. In collaboration with Arcelor Mittal Automotive Research

Division, the Opale team is conducting research activity in the framework of multidisciplinary optimisation of HPS structures.

In a first step, via Z. Shirzadi's internship, we led a study related to the design of the shape of a beverage can, using an axisymmetric elastoplastic model. The aim was to design a can with respect to dome reversal -DR- and reversal pressure -RP- criteria. We have used a metamodel approach, based on Neural Networks, to capture the Pareto Front of the problem. The database was built by means of the direct simulation code LS-DYNA (to compute exact nonlinear responses). The first results have proved that the considered costs are antagonistic, and allowed us to capture a part of the front. Perspectives are to push further the can design case, taking profit from the axisymmetric 2D computations (much more economical than the 3D counterpart in the nonlinear dynamic case), to implement the normal boundary intersection method -NBI- in order to efficiently capture the Pareto Front (see Figure 5). In a longer term perspective, it is envisaged to develop efficient algorithms to compute (in particular) Nash equilibria for games involving criteria representative of crash, fatigue, blank holder force, forming defects, and so on, and to apply the methodology to the design of complex 3D steel elements. Such work will be carried out through a doctoral program within the Opale team.

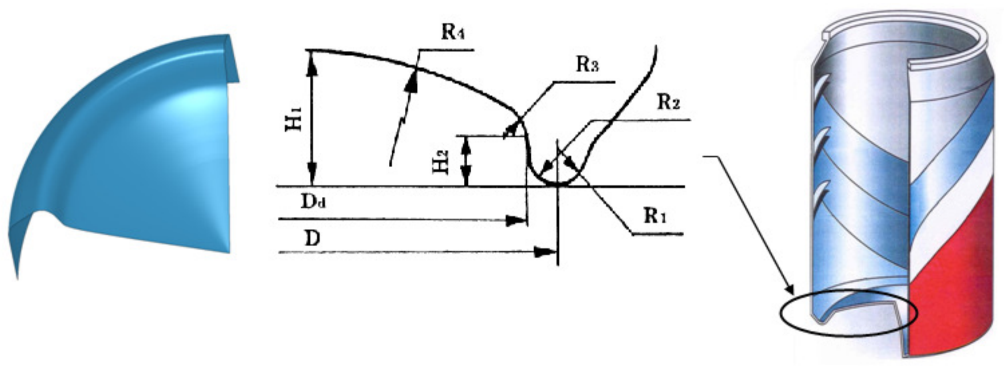


Figure 5. Multidisciplinary shape optimization for Nonlinear structural dynamics. Optimal use of natural resources among which are metals leads to design thinner and lighter structures, that are yet prescribed to fulfil function and safety requirements. The multidisciplinary shape optimization techniques applied to structural mechanics yield new designs that are optimal with respect to many criteria. In the picture "high-tech" beverage cans are designed through the optimization of the shape of their bottom. (Courtesy of ArcelorMittal)

6.2.7. Numerical shape optimization of axisymmetric radiating structures

Participants: Benoît Chaigne, Claude Dedeban [France Télécom R & D], Jean-Antoine Désidéri.

This activity aims at constructing efficient numerical methods for shape optimization of three-dimensional axisymmetric radiating structures incorporating and adapting various general numerical advances [69] (multi-level parameterization, multi-model methods, etc) within the framework of the time-harmonic Maxwell equations.

The optimization problem consists in finding the shape of the structure that minimizes a criterion related to the radiated energy. In a first formulation, one aims at finding the structure whose far field radiation fits a target radiation pattern. The target pattern can be expressed in terms of radiated power (norm of the field) or directivity (normalized power). In a second formulation, we assume that the structure is fed by a special device named the waveguide. In such a configuration, one wishes to reduce the so-called reflexion coefficient in the waveguide. Both formulations make sense when the feeding is monochrome (single frequency feeding). For multiple frequency optimization, several classical criteria have been used and various multipoint formulations considered (min-max, aggregated criterion, etc.).

Concerning the numerical simulation, two models have been considered: a simplified approximation model known as “Physical Optics” (PO) for which the far field is known explicitly for a given geometry; a rigorous model based on the Maxwell equations. For the latter, the governing equations are solved by SRSR, a 3D solver of the Maxwell equations for axisymmetric structures provided by France Télécom R&D.

A parametric representation of the shape based on *Free-Form* deformation (FFD) has been considered. For the PO model, the analytical gradient w.r.t. the FFD parameters has been derived. An exact Hessian has been obtained by Automatic Differentiation (AD) using Tapenade (developed by Tropics Project-Team). Both gradient and Hessian have been validated by finite differences. For the Maxwell equations model, the gradient is computed by finite differences.

Both global and local points of view have been considered for solving the optimization problem. An original multilevel semi-stochastic algorithm [64] showed great robustness for global optimization. In the case of an optimization with multiple frequency w.r.t. the radiation diagram, numerical experiments showed that an algorithm treating the frequency points hierarchically demonstrated improved robustness. For local optimization, a quasi-Newton method with BFGS update of the Hessian and linear equality constraints, has been developed. A numerical spectral analysis of the projected Hessian or quasi-Hessian for some shapes has exhibited the geometrical modes that are slow to converge. Based on this observation, several multi-level strategies to facilitate the convergence of these modes precisely, have been proposed and tested. Successful results have been obtained for both PO and Maxwell model.

In order to provide a theoretical basis to this multilevel method, a shape reconstruction problem has been considered. The convergence of an ideal two-level algorithm has been studied. In a first step, the matrix of the linear iteration equivalent to the two-grid cycle is computed. Then, by means of similar transformations and with the help of Maple, the eigenvalues problem has been solved. Hence, the spectral radius of the ideal cycle is deduced. Provided that an adequate prolongation operator is used, we were able to show that the convergence rate is independent of the dimension of the search space. The detailed proof is to be find in [56].

Finally, a two-criterion optimization problem has been considered: both radiation pattern and reflexion coefficient need to be optimized. As an alternative to the classical but costly Multi Objective Evolutionnary Algorithms (MOEA), a two-player Nash game strategy has been adopted. The split of the territory is guided by a preliminary local sensitivity analysis: after a primary criterion has been chosen and optimized, one seeks an appropriate subspace, in which a sensitivity is minimal, using the diagonalization of an approximation of the Hessian matrix (which is positive definite). This subspace is thus assigned to the second player. Consequently, the numerical Nash game allows to reduce the secondary criterion while almost preserving the primary criterion.

All of these multiobjective techniques have been applied and validated on a realistic test-case provided by France Télécom. This required a prototype software to be developed. Details on methods and representative examples are reported in the thesis [23].

6.3. Application of shape and topology design to biology and medecine

Participants: Abderrahmane Habbal, Nicholas Ayache [ASCLEPIOS PROJECT], Grégoire Malandain [ASCLEPIOS PROJECT], H. Barelli [IPMC], B. Mari [IPMC].

In the framework of a research collaborative action COLOR 2005, involving three research teams specialized in cell biology (IPMC), image processing and mathematical modeling (ASCLEPIOS and OPALE project-teams), two test-cases have been defined : angiogenesis and wound healing. The latter application has been given particular emphasis, since experimental results from biology can be obtained more easily.

Thus, several images and movies are quickly collected from experimental results in biology, concerning mono-layer MDCK cell healing. The analysis of these images allows us to observe that the cell migration velocity is constant during the healing.

In order to numerically model the migration, Fisher's model (non-linear parabolic equations) seems relevant to us. Indeed, it is characterized by a constant front velocity. The first results obtained (see Figure 6). are very promising and confirm the adequacy of Fisher's model. As a consequence of this work, new data are provided to biologists (diffusive coefficients) to describe the behavior of MDCK cells in presence of HGF and inhibitors.

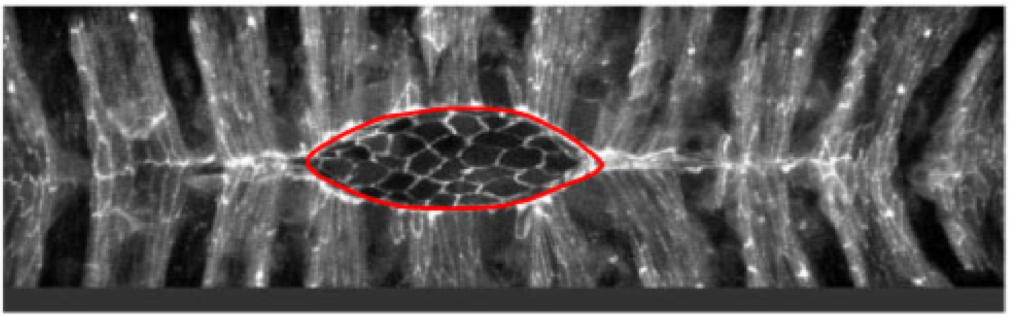


Figure 6. Mathematical modeling of the dorsal closure of Drosophila (DC). Understanding wound dynamics is a keystone in designing healing processes and computational modeling is expected to help specialists with qualitative and quantitative information, as soon as the model is validated. The picture shows a PDE-based theoretical wound (in red) which perfectly fits the biological videoscopy during all the closure duration. (From Almeida-Bagnerini-Habbal-Serman-Noselli.)

6.4. Mathematical analysis in geometrical optimization

6.4.1. Fast algorithm for Maxwell 3D harmonic solution via optimal control approach

Participants: Luigi Manca, Jean-Paul Zolésio.

Using the pseudo differential boundary operator T, "Dirichlet to Neumann" for any outgoing radiating solution of the Maxwell equation in the exterior of a bounded domain D with boundary S, we build an optimal control problem whose solution is the harmonic regime in the domain D. The optimal control is part of the initial data for the time depending solution. Under periodic excitation (with compact support in D) and lateral Neumann boundary condition on S, the operator T is involved. The optimal synthesis involves the time backward adjoint state which is captured by the Ricatti solution. The mathematical proof of the « device » requires sharp regularity analysis on the non homgeneous Neuman problem associated in D with the time depending 3D Maxwell system [60] [33].

6.4.2. Optimal geometry in radar device

Participants: Xavier Hachair, Jean-Paul Zolésio.

This is an confidential approach for the conception of a part of radar device. It involves a specific geometrical optimization.

6.4.3. Hidden sharp regularity and shape derivative in wave and hyperbolic systems

Participants: Michel Delfour, Jean-Paul Zolésio.

After ICIAM 1995 in Hamburg (and several papers) we introduced the so-called “extractor technique” which permit to recover the hidden regularity results in wave equation Under Dirichlet Boundary Condition. These results were a kind of quantified Version of results derived by I.Lasiecka and R. Triggiani using some multiplicator techniques and were power full enough to derive shape dérivative Under weak regularity . Nevertheless this technique failed for the Neumann like boundary conditions. We introduce theew concept of “Pseudo-differential” technique which recentely dropped this limitation. So we develop new sharp regularity results leading for shape dérivative existence for wave Under eumann boundary data in the space of finité energy on the boundary. The intrinsic character of the pseudo extractor permits toextend easily the results to the important situation of free time depending elastic shell equations [27].

6.4.3.1. Non cylindrical dynamical system

Participant: Jean-Paul Zolésio.

Optimal control theory is classicaly based on the assumption that the problem to be controled has solutions and is well posed when the control parameter describes a whole set (say a closed convex set) of some functional linear space. Concerning moving domains in classical heat or wave equations with usual boundary conditions, when the boundary speed is the control parameter, the existence of solution is questionable. For example with homogeneous Neumann boundary conditions the existence for the wave equation is an open problem when the variation of the boundary is not monotonic. We derive new results in which the control forces the solution to exist [48] [37].

6.4.3.2. Shape optimization theory

Participants: Michel Delfour, Jean-Paul Zolésio.

The ongoing collaboration with the CRM in Montreal (mainly with Professor Michel Delfour) led to several extensions to the theory contained in the book [2]. The emphasis is put on two main aspects: in order to *avoid* any relaxation approach but to deal with real shape analysis we extend existence results by the introduction of several new families of domains based on fine analysis. Mainly *uniform cusp* condition, *fat* conditions and *uniform non differentiability* of the oriented distance function are studied. Several new compactness results are derived. Also the fine study of *Sobolev domains* leads to several properties concerning boundaries convergences and boundaries integral convergence under some weak global curvature boundedness [36].

6.4.3.3. Control of coupling fluid-structure devices

Participants: John Cagnol, Raja Dziri, Jean-Paul Zolésio.

The use of the transverse vector field governed by the Lie bracket enables us to derive the “first variation” of a free boundary. This result has led to the publication of a book.

An alternate approach to fluid-structure has been developed with P.U.L.V. (J. Cagnol) and the University of Virginia (I. Lasiecka and R. Triggiani, Charlottesville) on stabilization issues for coupled acoustic-shell modeling [63] [28] [55] [30].

6.4.3.4. Shape gradient in Maxwell equations

Participants: Pierre Dubois, Jean-Paul Zolésio.

It is well known that in 3D scattering, the geometrical singularities play a special role. The shape gradient in the case of such a singularity lying on a curve in 3D space has been derived mathematically and implemented numerically in the 3D code of France Télécom.

This work with P. Dubois is potentially applicable to more general singularities.

6.4.3.5. Shape optimization by level set 3D

Participants: Claude Dedeban [France Télécom], Pierre Dubois, Jean-Paul Zolésio.

The *inverse scattering* problem in electromagnetics is studied through the identification or "reconstruction" of the obstacle considered as a *smooth surface* in R^3. Through measurement of the scattered electric field E_d in a zone θ we consider the classical minimization of a functional $\mathcal{J}$ measuring the distance beetwen E_d and the actual solution E over θ. Then, we introduce the continuous flow mapping T_r, where r is the disturbance parameter which moves the domain Ω in Ω_r. We derive the expression for the shape derivative of the functional, using a $\min\max$ formulation.

Using the Rumsey integral formulation, we solve the Maxwell equation and we compute the shape gradient, verified by finite difference, using the SR3D software (courtesy of the France Telecom company).

Additionally, we have introduced the Level Set representation method in 3 dimensions. This technique, which comes from the image processing community, allows us to construct an optimization method based on the shape gradient knowledge. In this method, the 3D surface, defined by a homogenous triangulation, evolves to reduce the cost functional, easily encompassing certain topological changes. Using this technique, we have studied the inverse problem and evaluated sensibilities w.r.t. quantitative and qualitative criteria.

6.4.4. Shape stabilization of wave equation

Participants: John Cagnol, Jean-Paul Zolésio.

The former results by J.P. Zolésio and C. Trucchi have been extended to more general boundary conditions in order to derive shape stabilization via the energy “cubic shape derivative”. Further extension to elastic shell intrinsic modeling is foreseen.

Passive Shape Stabilization in wave equation. We have developed a numerical code for the simulation of the damping of the wave equation in a moving domain. The *cubic shape derivative* has been numerically verified through a new approximation taking care of the non autonomeous oprator in the order reduction technique.

Active Shape Morphing. The ongoing collaboration on the stability of wave morphing analysis for drones led to new modeling and sensitivity analyses . Any eigenmode analysis is out of the scope for moving domains as we are faced with time depending operators. Then, we develop a new stability approach directely based ont a "Liapounov decay" by active shape control of the wave morphing. This active control implies a backward adjoint variable and working on the linearized state (through the *transverse vector filed* Z which is driven by the Lie brackets) we present a Ricatti-like synthesis for the real time of the morphing.

6.4.5. Array antennas optimization

Participants: Louis Blanchard [France Telecom R & D], Jean-Paul Zolésio.

We are developing a new approach for modeling array antennas optimization. This method integrates a Pareto optimization principle in order to account for the array and side lobes but also the antenna behavior. The shape gradient is used in order to derive optimal positions of the macro elements of the array antenna.

6.4.6. Parametrized level set techniques

Participants: Louis Blanchard, Xavier Hachair, Jean-Paul Zolésio.

Since a 1981 NATO study from the University of Iowa, we know how to define the speed vector field whose flow mapping is used to build the level set of a time-dependent smooth function F(t,x) in any dimension. We consider the Galerkin approach when $F(t,.)$ belongs to a finite-dimensional linear space of smooth functions over the fixed domain D. Choosing an appropriate basis (eigenfunctions, special polynomials, wavelets, ...), we obtain $F(t,.)$ as a finite expansion over the basis with time-dependent coefficients. The Hamilton-Jacobi equation for the shape gradient descent method applied to an arbitrary shape functional (possessing a shape gradient) yields a nonlinear ordinary differential equation in time for these coefficients, which are solved by the Runge-Kutta method of order four. This Galerkin approximation turns out to be very powerful for modeling the *topological changes* during the domain’s evolution. Within the OpRaTel collaboration, L.Blanchard has used extensively the code formely developed by Jérome Picard, also yielding an optimal partionning procedure that is based on the same Galerkin principle but the use of a brute-force calculus to be avoided. Indeed, if the optimal partionning of a domain (e.g. an antenna) consisted in finding a decomposition by 100 subdomains, the level set approach would lead to 100 Hamilton Jacobi equations. We introduced the concept of "multi-saddle" potential function $F(t,x)$ and through the Galerkin technique we follow the evolution of the saddle points. This technique has been succesfully understood thanks to the various testing campaign developed in the OpRaTel collaboration by L. Blanchard and F. Neyme (Thales TAD). The work has permitted to understand the multi-saddle procedure which turns out to require very delicate parameters tuning. We developed a mathematical analysis to justify that the trial-error method and some existence results have been proved for the crossing of the singularity associated with the toplogical change in the Galerkin approximation (here the finite dimensional character is fundamental) [59].

6.4.7. Shape metrics

Participants: Louis Blanchard, Jean-Paul Zolésio.

We characterize the geodesic for the Courant metric on Shapes. The Courant Metric is described in the book [2]. It furnishes an intrinsic metric for large evolutions. We use the extended weak flow approach in the Euler setting.

It is extended to larger class of sets and using the *transverse flow mapping* (see the book) we derive *evolution equation* which characterises the Geodesic for such differentiable metrics [39] [38].

Applications are being developed for Radar image analysis as well as for various non cylindrical evolution problems including real time control for array antennas.

6.5. Virtual computing environments

6.5.1. Virtual Collaborative Platforms

Participant: Toan Nguyen.

Based on the previous work on Virtual Computing Environments with CNES (2004-2006), the OPALE project/team is working on Virtual Collaborative Platforms which are specifically adapted to Multiphysics Collaborative projects. This is in particular studied in the framework of the European AEROCHINA2 support action. The approach considers not only code coupling for multiphysics applications in aeronautics, but includes also interactions between participant teams, knowledge sharing through numerical databases and communication tools using Wikies. The design of a proof of concept demonstrator is planned in the AEROCHINA2 project, started in October 2007. Indeed, large scale multiphysics problems are expected to be orders of magnitude larger than existing single discipline applications, like weather forcast which involve ocean and atmosphere circulation, environmental disaster prevention and emergency management. Their complexity requires new computing technologies for the management of multi-scale and multi-physics problems, large amounts of data and heterogenous codes. Among these technologies are wide area networks and distributed computing, using cluster and grid-based environments. It is clear that supercomputers, PC-clusters and, to a limited extent wide area grids, are currently used for demanding e-science applications, e.g., nuclear and flight dynamics simulation. It is not so clear however what approaches are currently the best for developing multiphysics applications. We advocate the use of an appropriate software layer called upperware, which, combined with cluster and grid-based techniques, can support virtualization of multidiscipline applications when running multidisciplinary codes and business software, e.g., decision support tools. This paves the way for "Virtual Collaborative Platforms". Unlike Wikis and other collaborative tools widely accepted for document editing, virtual collaborative platforms are used to deploy distributed and parallel multiphysics simulation tools. Their execution may be controlled and monitored by distributed workflow systems that may be hierarchically composed. Work in progress is done on this subject, particularly on workflow management system with fault-tolerance, interaction and exception handling mechanisms, in partnership with other participants to European projects, e.g., AEROCHINA.

6.5.2. Workflow systems for multidiscipline optimization

Participants: Jean-Antoine Désidéri, Toan Nguyen, Laurentiu Trefan.

Workflows systems are the focus of many e-Science applications, ranging from astrophysics to bioinformatics. Among the most popular workflow management systems are Taverna, Kepler, Pegasus, Bonita, YAWL and many others. They complement scientific software programming environments like Dakota, Scilab and Matlab in their ability to provide complex application factories that can be shared, reused and evolved. Further, they support the incremental composition of complex hierarchic composite applications. Providing a control flow approach, they also complement the usual dataflow approach used in programming toolboxes. Another bonus is that they provide seamless user interfaces, masking technicalities of distributed, programming and administrative layers, thus allowing the users and experts to concentrate on their areas of interest.

The OPALE project is investigating the use of the YAWL system for distributed and parallel multidiscipline optimization. The goal is to develop a resilient workflow system for large-scale optimization applications. It is based on extensions to the YAWL system to add resilience and remote computing features on high-performance distributed infrastructures [46] [34] [35]. This includes large-PC clusters connected to broadband networks. It also includes interfaces with the Scilab scientific computing toolbox and the ProActive middleware. A prototype implementation is underway for the OMD2 project ("Optimisation Mutlidiscipline Distribuée") of the French Agence Nationale de la Recherche (ANR). A doctoral program has been launched on this topic.

7. Contracts and Grants with Industry

7.1. Optimization in electromagnetics

- France Télécom (La Turbie); two contracts:
  - *Optimization of antennas*, which has partially supported L. Blanchard's thesis;
  - *Shape Optimization Codes Platform by Hierarchical Methods*, which partially supports B. Chaigne's thesis.
- Thalès (Bagneux) : optimization of the most dangerous trajectories in radar applications.

7.2. Optimized steel solutions

A partnership with industry was launched with the R & D *Automotive Applications Centre* of Arcelor Mittal in Montataire, France. This partnership is related to the optimization of steel (automobile) elements with respect to mechanical criteria (crash, fatigue). The project team was solicited to audit the GEAR2 optimization team in Montataire . Additionally, a student interm from Arcelor, J.-G. Moineau, was hosted and directed at INRIA for a four-months period.

7.3. Optimization in naval hydrodynamics

This year, a new partnership with the company K-Epsilon, specialized in numerical studies for naval hydrodynamic applications, has been initiated. The objective is to apply design optimization methods developed in OPALE to challenging and emerging design problems, such as mast and keel design for sailing race boats or bow design for fishing boats.

This collaboration is supported by the INRIA program ATT (Action de Transfert Technologique), which granted the enrolment of A. Maurice as engineer for a period of six months. This allowed the adaption of the FAMOSA software to the problems treated by K-Epsilon and the achievement of a first study related to mast section design.

8. Other Grants and Activities

8.1. National and regional initiatives

8.1.1. Project "OMD" (Optimisation Multi-Disciplinaire)

Opale participates in the RNTL[1] Project "OMD" for multi-disciplinary optimization (see http://omd.lri.fr). This project was set-up by the CNRT Aéronautique. The involvement of Opale includes two major lines of investigation developed by Post-Doctoral researchers:

1. To establish the status of multilevel strategies in shape optimization;
2. To develop efficient techniques for hierarchical model coupling for optimum-shape design in Aerodynamics.

[1] RNTL: *Réseau National des Technologies Logicielles* (National Network for Software Technologies, a program supported by the National Agency for Research (ANR))

This contract provides the grant supporting the post-doctoral studies of P. Chandrashekarappa, J. Zhao and A. Benzaoui

8.1.2. Project "OMD2" (Optimisation Multi-Disciplinaire Distribuée)

The notion of optimization platform based on distributed and parallel codes is undertaken with a distributed workflow management system running on a grid infrastructure using the ProActive middleware from INRIA, in collaboration with the OASIS project at INRIA Sophia-Antipolis. Renault is the coordinator of this project, which involves also EMSE, ENS Cachan, EC Nantes, Université de Technologie de Compiègne, CD-Adapco, Sirhena, Activeon, and INRIA project TAO, OASIS and OPALE. This contract provides the grant supporting two PhD theses.

8.1.3. E-Lab Opratel

The collaboration with France Télécom and Thalès Défense led to the creation of the e-lab OPRATEL in which we develop models for array antennas for telecommunication purposes. Our activity is divided in two main themes:

- development of models of array antennas for telecommunication purposes; a patent will shortly be deposited;
- frequency allocation, a difficult modeling topic of major importance for our industrial partners.

More specifically, the classical problem of frequency allocation is a main activity. This problem results in a very acute technological challenge today due to the numerous systems operating concurrently (interference of radar, surveillance systems, telephone, radio, television, domestic electronics, electromagnetic noise of WIFI, etc.). Since the channels are limited, special techniques are envisaged to support these systems (orthogonal waves, coding, dynamic occupation of the spectrum).

8.2. International networks and working groups

8.2.1. Associated team SOUMO with the University of Jyväskylä (Finland)

Opale Project-Team and the Department of Mathematical Information Technology (MIT) at University of Jyväskylä (Finland) have initiated a collaboration in the framework of INRIA Associated Teams program on the topic “Shape Optimization with Uncertainties and Multicriterion Optimization in Concurrent Engineering”. More precisely, the aim is to develop and experiment methodologies for large-scale computations and shape optimization in challenging engineering problems relying on advanced numerical simulation tools, such as compressible CFD (Computational Fluid Dynamics), CEM (Computational Electromagnetics), computational material sciences. More precisely, the objective is to make progress in:

- Numerical methods for two-discipline shape optimization. Establish a better understanding of the relationship between the Pareto equilibrium front and designs originating from Nash games. Treat specific challenging engineering cases involving joint expertise.
- Numerical methods for optimization subject to uncertainties. Assessment of state-of-the-art methods for uncertainty estimation: metamodel-based Monte-Carlo methods, approaches using sensitivity analysis (derivatives evaluated via Automatic Differentiation), etc. Develop new optimization algorithms accounting for these uncertainty estimates as criteria or constraint. Compare numerical strategies on a variety of engineering problems potentially at hand jointly.

This year, OPALE has organized the workshop "Reliable Simulations and Robust Design Methods and Tools in Multiphysics applications", 5-8 October. The Finnish delegation counted about ten persons. This workshop was the opportunity to compare the respective methodologies and applications studied by both teams and establish a program for 2010.

OPALE has also hosted J. Leskinen (PhD student) for a period of two weeks, to initiate a collaboration on the topic of the use of Nash games with distributed computing for design optimization.

8.2.2. Collaboration with China

The OPALE project is a member of the FP7 AEROCHINA2 coordination and support action (2007-2009) on multidiscipline design, simulation and optimization for the aeronautics sector. OPALE is responsible for the Large-scale simulation Working Group 06 and COllaborative Platforms Work Package 07 in this project, formed by five Chinese (ACTRI, NUAA, SADRI, NPU and BUAA) and five European members (Airbus, EADS IW, Alenia, CIMNE, INRIA). Current investigations for the set-up of a proposal answering to the Call 2010 in the Transport and Aeronautics Objective of the FP7 are undertaken concerning Multidiscipline Optimization calling for High performance computing services focused on Active Flow Control devices of interest to the aeronautics sector, e.g. vortex generators, synthetic jets, bumped airfoil profiles. Contacts are also underway to assess the feasibility of a continuation network building on the AEROCHINA2 partnership.

8.2.3. European project EXCITING

Opale and Galaad Project-Teams participate to the European project EXCITING (EXaCt-geometry sImulTIoN for optimized desiGn of vehicules and vessels). The objective is to develop simulation and design methods and software based on the isogeometric concepts, that unify Computer-Aided Design (CAD) and Finite-Elements (FE) representation bases. Applications concern hull shape, turbine and car structure design.

8.2.4. Euromed 3+3 program SCOMU

A. Habbal is the French responsible for the project "Scientific Computing and Multidisciplinary Optimization" (SCOMU), a Euro-Mediterranean Euromed 3+3 program. The project SCOMU involves institutions from France (INRIA, Opale Project, Nice Sophia Antipolis University), Italy (University of Genova), Spain (University of Corogna), Tunisia (ENIT, Tunis) and Morocco (Ecole Mohammedia, University Mohamed V, Rabat). The project is a three-year financed action, 2009-2011. The main goal of the project is to develop and promote collaboration between specialists of scientific computing and specialists of single and multi objective optimization. Application areas include image processing, finance, structural mechanics and mathematical biology.

9. Dissemination

9.1. Education

The members of the OPALE project participate in the Educational effort within different areas at the University of Nice Sophia-Antipolis.

9.1.1. University of Nice Sophia-Antipolis (UNSA)

A. Habbal teaches the following courses:

- Introduction to game theory and its application to economy (Master 1, 47hrs)

9.1.2. Ecole Polytechnique Universitaire (EPU), Nice Sophia-Antipolis

A. Habbal teaches the following courses (“Information Systems”):

- Numerical Engineering methods (first year, 75 hrs)
- Programming mathematics (first year, 16 hrs)
- Shape optimization (15hrs)
- Numerical Methods in Finance (third year, 18 hrs)
- Introduction to biomathematics (2nd year, 14hrs)

J.-A. Désidéri, R. Duvigneau and A. Habbal jointly teach the following course (“Applied Mathematics and Modelling”):

- Shape optimization (third year, 45hrs)

J.-A. Désidéri teaches the following course (“Applied Mathematics and Modelling”):

- Numerical Methods I (first year, 22.5 hrs)

R. Duvigneau teaches the following course (“Applied Mathematics and Modelling”):

- Project on Partial Differential Equations (first year, 20 hrs)

9.2. Participation in international courses

- A. Habbal delivered a short-course: "Introduction to game theory" at the post-graduate level of Ecole Mohammedia of Engineers, Rabat, Morocco, in the framework of Euromed 3+3 program, november 2009.
- J.-A. Désidéri delivered a short-course: “Multisciplinary Optimization”, at the Erasmus Mundus International Master in Mathematical Engineering ’MathMods’.

9.3. Theses and educational trainings

The following trainees have been, or are being supervised by the project:

Manuel Bompard, University of Nice Sophia Antipolis, at ONERA-DSNA (Châtillon s/ Bâgneux); topic: Gradient computations for local optimization and multilevel strategies.

Benoît Chaigne, University of Nice Sophia Antipolis; topic: shape optimization of axisymetric reflectors in electromagnetism.

Imane Ghazlane, University of Nice Sophia Antipolis, at ONERA-DAAP (Meudon); topic: Aerodynamic and structural optimization of a transport aircraft wing shape.

Nouredine Moussaid, “École Mohammedia” Engineering School of Rabat, Marroco; topic: Nash games in topological optimization.

Babacar Ndiaye, University of Nice Sophia-Antipolis; topic: Mathematical modeling of cellular migration.

Laurentiu Trifan, University of Grenoble I (Joseph Fourier); topic: Collaborative platforms for high performance multidiscipline optimization.

9.4. Participation in scientific committees

- J.-A. Désidéri is being appointed by the department of aerodynamics and aeronautics simulation (DSNA) of ONERA Châtillon. This appointment includes a monthly visit at ONERA.
- R. Duvigneau is member of the CFD (Computational Fluid Dynamics) committee of ECCOMAS (European Community for Computational Methods in Applied Science).
- A. Habbal is member of the specialists board for sections 25-26-27 in IUFM of Nice Sophia-Antipolis.
- A. Habbal is member of the executive board of “Ecole Polytech Nice”.
- T. Nguyen is member of the Program Committee of the conference CDVE, Luxembourg, September 2009.
- T. Nguyen is member of the Program Committee of the Fourth International Conference on Advanced Engineering Computing and Applications in Sciences, ADVCOMP 2010, Florence, october 2010.
- J.P. Zolésio is chairman of Working Group IFIP 7.2 *System Modelling and Optimization*.
- J.P. Zolésio belongs to the editorial board of the *Control and Cybernetics Journal*.

9.5. Invited or keynote lectures

- "Split of territory in Nash games for multi-objective optimization", Workshop on Numerical Techniques for Optimization Problems with PDE Constraints, Oberwolfach Mathematisches Institut, January 25th - January 31st, 2009 (J.-A. Désidéri).
- "Optimisation aéro-structurale de la voilure d'un avion d affaires par un jeu de Nash et un partage adapté des variables", MDO Mini Symposium, 9th National Congress on Computational Structures (9e Colloque National en Calcul des Structures, Giens 2009) May 24, 2009 (J.-A. Désidéri).
- "Optimisation multidisplinaire : jeux de Nash et partage de territoire", Colloquium Université de Nantes, CNRS, Centrale Nantes, Laboratoire de mathématiques Jean Leray, 1er Juillet 2009 (J.-A. Désidéri).
- "Hierarchical Shape Optimization : Cooperation and Competition in Multidisciplinary Approaches" (J.-A. Désidéri). This lecture was firstly prepared as a plenary lecture at the 24 th IFIP TC7 conference, Buenos Aires, Argentina, July 27-31, 2009, and has also been delivered on invitation at :
  - Basque Center for Applied Mathematics (BCAM), Bilbao (Spain), 25 September 2009;
  - Database Workshop for multiphysics optimization software validation, University of Jyväskyla, Finland, December 3-4, 2009 (emphasis on *Application to aero-structural business-jet wing-shape optimization*).
- "New trends in aerodynamic design: Multi-disciplinary optimization, robust design and CAD-FEM integration", Workshop on Multi-physics and Policy Meeting EU-China on RTD Collaboration in Aeronautics, Brussels, Belgium, September 2009 (R. Duvigneau);
- "Boundary Control and Shape Stabilization in Non-Cylindrical Wave Equation", IFIP-NSF Conference Honoring A.V. Balakrishnan. UCLA, January 29-31, 2009; plenary lecture (J.P. Zolésio).
- "Variationnal Formulation For Incompressible Euler Flow", CNRS/MITACS/CRM Program, Pacific Institute for Mathematics, UBC, Vancouver, February 2-15, 2009 (J.P. Zolésio).
- "Existence result for shpe functional governed by curvature Under global folding constraints", SIAM Conference on Control and Its Applications (CT09), Denver, Colorado, July 6-10, 2009 (J.P. Zolésio).
- "Variational Solution to Incompressible Euler Flow and application to Shape Metrics", 7th Isaac Congress, Imperial College London, July 13-18, 2009 (J.P. Zolésio).
- "Stability of Shape Geodesic", 12-th Workshop on well - posedness of optimization problems and related topics (Levico), September 12-19, 2009 (J.P. Zolésio).
- "Shape Stabilization for Non cylindrical wave Equation", SIAM Conference on Analysis of Partial Differential Equations, Miami, Florida, December 7-10, 2009 (J.P. Zolésio).
- "Shape linearization of coupled fluid-structure device", ESF Workshop on Computational techniques for optimization problems subject to time-dependent PDEs, Brighton, Sussex, England, December 14-17, 2009 (J.P. Zolésio).

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