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Project-Team Opale

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

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1. Team

Research Scientist

Jean-Antoine Désidéri [DR, INRIA Sophia Antipolis, HdR]
Régis Duvigneau [CR, INRIA Sophia Antipolis]
Toan Nguyen [DR, INRIA Rhône-Alpes, HdR]
Jean-Paul Zolésio [DR, CNRS, HdR]

Faculty Member

Paola Goatin [Maître de Conférences, On leave from University of Toulon]
Abderrahmane Habbal [Maître de Conférences, University of Nice–Sophia Antipolis, HdR]

External Collaborator

John Cagnol [Prof, Pôle Léonard de Vinci, HdR]
Raja Dziri [Université de Tunis, HdR]
Michel Delfour [Centre de Recherches Mathématiques, Montréal, HdR]
Jacques Périaux [UPC, Barcelona, Spain; TEKES Distinguished Professor, Univ. Jyväskyla, Finland, HdR]
Jan Sokolowski [Institut Poincaré, University of Nancy, HdR]

Technical Staff

Nikolas Mauny [INRIA Sophia Antipolis, from October 2008]

PhD Student

Abdou Wahidi Bello [University of Cotonou, Cotonou (Benin) until March 2008]
Manuel Bompard [ONERA, University of Nice–Sophia Antipolis, from October 2008]
Benoit Chaigne [University of Nice–Sophia Antipolis]

Post-Doctoral Fellow

Abderrahmane Benzaoui [INRIA Sophia Antipolis, from June 2008]
Praveen Chandrashekarappa [INRIA Sophia Antipolis, until August 2008]
Xavier Hachair [INRIA Sophia Antipolis, from Mai 2008]
Luigi Manca [INRIA Sophia Antipolis, from September 2008]
Massimiliano Martinelli [INRIA Sophia Antipolis]

Visiting Scientist

Frank Strauss [Karlsruhe Insitute of Technology]

Administrative Assistant

Montserrat Argente [INRIA Sophia Antipolis]

Other

Dalhia Ibrahim [ENSTA, May-August]
Julien Niel [Master, University of Nice-Sophia Antipolis, May -September]

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-equipped 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.

A new collaboration with the Numerical Simulation in Aerodynamics and Aeroacoustics Department, DSNA, of ONERA (The French Aerospace Laboratory) has been initiated by J.-A. Désidéri as a consultant. The major areas of this collaboration are: 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.

3. Scientific Foundations

3.1. Numerical optimization of PDE systems

Keywords: *Partial Differential Equations (PDEs)*, *Proper Orthogonal Decomposition (POD)*, *finite volumes/elements*, *geometrical optimization*, *gradient-based/evolutionary/hybrid optimizers*, *hierarchical physical/numerical models*, *multi-point/multi-criterion/multi-disciplinary optimization*, *optimum shape design*, *shape parameterization*.

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 [66]. Our evolution field approaches permit to extend this viewpoint to the topological shape optimization ([69]).

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 $t \rightarrow \infty$) 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 [68]. 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. [70].

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

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

- a parameterization module implementing a 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 CFD solvers ;
- 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).

To facilitate the development of the software and collaborative work between the different developers, a code managing framework based on the SVN version control system has been set up. The code is presently hosted at the inriaGforge.

The FAMOSA platform has been linked to the compressible Navier-Stokes solver NUM3SIS developed by Opale and Smash (see below), the Euler code NS3D used by Tropics for automatic differentiation tests and the incompressible flow solver ISIS developed at the Ecole Centrale de Nantes.

5.2. Compressible Navier-Stokes solver NUM3SIS

The NUM3SIS flow solver has been developed by Smash and Opale Project-Team for two years. This work is 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 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.

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.

6. New Results

6.1. Computational methods, numerical analysis and validation

6.1.1. Numerical simulation of shallow-water equations

Participants: Abdou Wahidi Bello, Jean-Antoine Désidéri, Aurélien Goudjo [University of Cotonou, Benin], Côme Goudjo [University of Cotonou, Benin], Hervé Guillard [Smash Project Team].

This activity corresponds to A. W. Bello's thesis work in co-direction between the University of Cotonou, Benin, and INRIA, with the support of the French Embassy in Cotonou. The study aims at developing a numerical simulation method of the water network in the city of Cotonou. This network includes a canal connecting Lake Nokoué to the Atlantic Ocean, and various ducts in the city itself. This network is chronically flooded when important rains occur. In our perspective, the simulation code is meant to be used in the future as a control tool to identify ways to prevent flood, or reduce the damages it causes.

The flow has been simulated by solving the shallow-water equations with topography and friction by a finite-volume method, as it is customary in estuary-flow-type simulations. The computational domain is the space occupied by water and the floodplains. It is projected on a horizontal plane of reference, and discretized, and the governing equations are integrated on each grid cell. The numerical integration is carried out by a Godunov-type scheme using a two-step Riemann approximate solver of HLLC type which preserves the positivity the water height and which is well adapted to the treatment of the shock waves. To determine the height of the intermediate state in the Riemann solver, we propose an algorithm in a celerity-speeds formulation in which the governing equations are linearized; as a result, the positivity of the height is preserved, and this then allows to compute the speeds of the fastest waves.

The simulation method has been tested on academic problems first to demonstrate its adequacy. Then, a more realistic case has been treated to model the phenomenon of flood in the city of Cotonou (BENIN) by the water risings in the lagoon. The thesis was successfully defended in March [22].

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

Participant: Paola Goatin.

Paola Goatin is on part-time leave from University of Toulon. She is preparing her Habilitation thesis on the "Analysis and numerical approximation of some macroscopic models of vehicular traffic". At present, she is working on a traffic flow model with phase transitions on a road network[26], [24], [37], and on the numerical approximation of scalar conservation laws with unilateral constraints to model highway gates. These studies are intended to contribute to the development of numerical schemes devised to model real traffic situations.

6.1.3. Isogeometric analysis and design

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

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 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.

In the context of the EXCITING European project, Opale has initiated the development of a model finite-element solver based on isogeometric concepts, in collaboration with Galaad Project-Team, to study hierarchical strategies for modelling and parameterization in this framework. This activity gives the project-team an opportunity to develop our expertise in numerical approximation schemes for hyperbolic equations in a new application area.

6.1.4. Development and validation of the NUM3SIS flow solver

Participants: Praveen Chandrashekarappa, Régis Duvigneau, Thibaud Kloczko [Smash Project-Team], Nikolas Mauny.

The NUM3SIS flow solver has been developed by Smash and Opale Project-Team for two years. This work has been carried out with the support of a software development engineer since October 2008.

Some specific developments have been achieved in order to link the solver with the shape optimization platform FAMOSA and solve more complex aerodynamic problems (implementation of Spalart-Allmaras turbulence model, dual time-stepping procedure for unsteady flows).

A study of parallel performance has been carried out on National computational facilities (IDRIS, CINES, CCRT), including computations using large grids (until 16 millions nodes for 512 processors) [67].

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: Badr Abou El Majd, 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). This complex iterative strategy has been compared with the basic one-level method, and with the simple "one-way-up" algorithm based on degree–elevation only (without coarse-parameterization correction steps). The *FAMOSA* method was found superior to both simpler alternatives[23].

Multi-level parameterization algorithms have been developed also in the framework of semi-stochastic optimization methods. In particular, we have experimented with success a Particle-Swarm Optimization (PSO) algorithm based on searches in design spaces of increasing dimension[56]. PSO is inspired from the collective intelligence of birds flocks for food seeking or predators avoiding and is based on underlying rules that enable sudden direction changes, scattering, regrouping, etc. The developed multilevel algorithm relies on the use of the *swarm memory* to transfer information from one level to the next. This strategy has been found very effective for a simple degree increase strategy. Especially, it was shown that the multilevel algorithm permits to use swarms of smaller size yielding a significant computational time reduction .

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). The application to the multidisciplinary design of a supersonic business jet (aerodynamics, structure, propulsion, flight mechanics) is currently in progress.

6.2.2. Multidisciplinary optimization

Participants: Badr Abou El Majd [now at the University of Avignon], Praveen Chandrashekarappa, Jean-Antoine Désidéri, Régis Duvigneau, Vincent Heuveline, Frank Strauss, Abderrahmane Habbal, Julien Niel, Jacques Périaux, Zhili Tang [Nanjing University of Aeronautics and Astronautics].

6.2.2.1. Multicriterion Aerodynamic Shape Design Optimization and Inverse Problems using Control Theory and Nash Games

Multicriterion design is gaining importance in Aeronautics in order to cope with new needs of society. In the literature, contributions to single discipline and/or single-point design optimization abound. We propose to introduce a new approach combining the adjoint method with a formulation derived from game theory for multipoint aerodynamic design problems. Transonic flows around lifting airfoils are analyzed by Euler computations. Airfoil shapes are optimized according to various aerodynamic criteria. The notion of player is 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 are implemented to set up an optimization strategy for design under conflict.

6.2.2.2. Splitting of territories in concurrent optimization

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 (sub–optimality) 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.

First, 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, [50].

Secondly, at the occasion of a two-month visit of F. Strauss, the stability of a hydrodynamic channel flow governed by the incompressible Navier-Stokes equations has been formulated classically as a problem of control of the positivity of the real part of an appropriate eigenvalue. This case has been treated as a constrained shape optimization problem in which the eigenvalue real part is maximized. By application of the splitting technique certain improvements of the original design have been achieved [42]. This activity was launched to initiate a collaboration with the Karlruhe Institute of Technology.

Thirdly, J. Niel has analyzed a problem of aerodynamic design of a supersonic aircraft proposed by Dassault Aviation within the French Network on Multi-Disciplinary Optimization (OMD). In a classical flight-mechanics model, the main flight characteristics (mass, range, take-off distance, landing velocity) are explicitly related to global aircraft design characteristics by the fundamental laws of aerodynamics, structural and propulsion analyses. These relations have been integrated by Dassault Aviation to the Scilab project platform as explicit functionalities of the dedicated software. J. Niel has conducted a number of optimization experiments by using these functionalities and by applying particle-swarm optimization techniquues and territory splitting, and achieved certain viable designs [63].

The technique of territory splitting is now 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. In the second phase, said to be "competitive", viable trade-offs are identified as particular Nash equilibrium points.

6.2.3. *Metamodel-based optimization*

Participants: Praveen Chandrashekarappa, Régis Duvigneau.

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. 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[55] :

- 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[28], [52].

- 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.

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.

These strategies have been applied to quantify the drag statistics for a wing shape of a business aircraft subject to uncertain flow conditions (Mach number and angle of attack)[46], [49]. It has been shown that the approach based on automatic differentiation is more efficient from a computational point of view, but the metamodel-based approach is more general and more robust[39], [57]. In particular, some difficulties with non-differentiable programs have been reported in case of transonic Eulerian flows when using automatic differentation (due to the use of Roe flux and limiters).

6.2.5. Parallel algorithms for robust aerodynamic design

Participant: Régis Duvigneau.

In order to reduce the computational time required by aerodynamic design procedures, we have developed a sophisticated parallelization strategy, that relies on a three-level parallelization using MPI library. For a robust design optimization in aerodynamics, we compute in parallel:

1. the flow field using a domain decomposition approach (mesh partitionning);
2. the performance for different flow conditions (database filling for metamodel-based Monte-Carlo);
3. the performance for different candidate design (parallel optimizer).

This strategy has been applied for the robust design of a business aircraft using several hundreds of processors[38].

6.2.6. Application of shape optimization algorithms to naval hydrodynamics

Participants: Régis Duvigneau, Michel Visonneau [CNRS, Ecole Centrale de Nantes].

The shape optimization algorithms developed by Opale have been applied to challenging problems in naval hydrodynamics, in collaboration with the fluid mechanics laboratory of Ecole Centrale de Nantes (CNRS UMR 6598).

The problem consists in optimizing the hull shape of a carrier cruise ship, with respect to two antagonistic critera : the total flow resistance and the wake caracteristics of the flow at the propeller. Analyses are performed by solving incompressible Reynolds-averaged Navier-Stokes equations on three-dimensional unstructured grids with several millions of nodes, using the ISIS flow solver from Ecole Centrale de Nantes. This is a particularly challenging problem because each evaluation takes several hours on a parallel machine. Moreover, complex and highly non-linear constraints are taken into account, such as constant displacement, room for engine installation, etc. This problem was considered as test-case for a European workshop meeting organized in Lisbon in October, where the leading naval engineering labs in Europe have competed.

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 [71] (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 wants to reduce the so-called reflexion coefficient in the waveguide. Both formulations make sense when the feeding is monochrome (single frequency feeding). For multiple frequencies optimization, several classical criterions used in multipoints optimization are considered (min-max, linear combinaison, etc.).

Two models have been considered for the analysis problem: 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 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 point of view have been considered for solving the optimization problem. An original multilevel semi-stochastic algorithm [65] showed robustness for global optimization. In the case of multiple frequencies optimization w.r.t. the radiation diagram, numerical experiments showed that a hierarchy in the frequency points can improve the robustness. For local optimization, a quasi-Newton method with BFGS update of the Hessian with 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 help this modes to converge have been developed. Successful results have been obtained for both PO and Maxwell model[], [48].

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 bigrid cycle is computed. Then, by mean of similar transformations and with the help of Maple, the eigenvalues problem is solved. Hence, the spectral radius of the ideal cycle is deduced. Provided that an adequate prolongation operator is used we can show the independance of the convergence rate w.r.t. the dimension of the search space.

In addition, it has been observed that better results are obtained when the Bernstein polynomials are replaced by Legendre or Tchebychev polynomials in the FFD formulation.

In the future we intend to consider multi-objective problems together with original approaches based on game theory. Further real-case problems proposed by France Télécom will be considered.

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

Participants: Abderrahmane Habbal, Nicholas Ayache [EPIDAURE PROJECT], Grégoire Malandain [EPIDAURE 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 (EPIDAURE and OPALE projects), two test-cases are defined : angiogenesis and wound healing. This latter application is 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 monolayer 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 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.

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.

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 IIAM 19595 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 « tehcnic 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.

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.

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 boundness.

6.4.3.3. *Control of coupling fluid-structure devices*

Participants: Marwan Moubachir, 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. [64].

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.

6.4.3.6. Shape stabilization of wave equation

Participant: 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.

6.4.3.6.1. 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.

6.4.3.6.2. 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.

6.4.3.7. Array antennas optimization

Participants: Louis Blanchard, 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.

6.4.3.8. Parametrized level set techniques

Participants: Louis Blanchard, Jerôme Picard, 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 non linear ordinary differential equation in time for these coefficients, which are solved by the Runge-Kutta method of order four. This Galerkin approximation turns to be powerful for modeling the *topological changes* during the domains evolution. Jérome Picard has developed a code which is used by L.Blanchard (in the OpRaTel collaboration). Also they have together developed a code for an optimal partionning procedure which is working on the same Galerkin principle but avoiding the use of calculus which would have been developed by the brut force technique. 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 developed by J. Picard and will be exploited in OpRaTel collaboration by L. Blanchard and F. Neyme (Thales TAD). The work of Jérome Picard has been very interactive and very important to understand this multi-saddle procedure which turns out to be very delicate in the parameters tuning. We developed a mathematical analysis to justify that trials-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).

6.4.3.9. 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 caracterises the Geodesic for that differentiable metric.

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

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"[40], [51], [41]. 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.

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

This year, a new 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.

8. Other Grants and Activities

8.1. National and regional initiatives

8.1.1. RNTL network

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.

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

8.1.2. 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:

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

- 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.

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 2009 in the Transport and Aeronautics Objective of the FP7 are undertaken concerning Multidiscipline Optimization calling for High performance computing services.

8.2.3. European project NODESIM

Opale and Tropics Project-Teams participate to the European project NODESIM (NOn DEterministic SIMulation), whose topic is the study of the influence of uncertainty on simulation in aeronautics. Tropics Project-Team is in charge of computing first and second order derivatives of the flow characteristics with respect to uncertain parameters, whereas Opale Project-Team uses these computations to carry out robust design optimization exercises.

8.2.4. 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 iso-geometric concepts, that unify Computer-Aided Design (CAD) and Finite-Elements (FE) representation bases. Applications concern hull shape, turbine and car structure design.

8.2.5. Integrated action project France-Marroco ANOPIC

A. Habbal is the French responsible for the Integrated Action Project France-Morocco *ANOPIC* : new applications in optimization, inverse problems and control, granted from 2005 to 2008 (7650 euros in 2005). The project is gathering several teams from France (INRIA/OPALE, University of Nice, “École des Ponts et Chaussées” and technical University of Compiègne) and Morroco (Engineering School Mohammedia and “ École des Mines”, University Mohammed V in Rabat, and University Chouaib Doukkali in Settat). The research topic is the mathematical and numerical study of parametric, geometry or topology optimization problems.

This project has supported the organization of the workshop “New Applications, Shape Optimization, and Inverse Problems, PDEs and Applications”, Rabat, Morocco, November 7, 2007, during which J.-A. Désidéri delivered an invited opening lecture.

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 teach the following course (“Applied Mathematics and Modelling”):

- Shape optimization (third year, 45hrs)

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

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

B. Chaigne teaches the following courses (“Applied Mathematics and Modelling”):

- Numerical Engineering methods (first year, 24 hrs)

9.2. Participation in international courses

- A. Habbal delivered a short-course: "Introduction to game theory" Post-graduate level at Ecole Mohammedia of Engineers, Rabat, Morocco, during a one month stay in the framework of IMAGEEN European Window Cooperation Program, may 2008.

9.3. Theses and educational trainings

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

Abdou Wahidi Bello, University of Cotonou; topic: Finite-volume methods for the shallow-water equations with application to the simulation of the flow in the ducts system of the city of Cotonou, Benin.

Benoît Chaigne, University of Compiègne; topic: shape optimization of axisymetric reflectors in electromagnetism.

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.

9.4. Participation in scientific committees

- J.-A. Désidéri has been 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 Advisory Board of the French-Finnish Association for Scientific Research.
- T. Nguyen was member of the Scientific and Technical Committee of the Workshop NUAA-Europe held at the Nanjing University of Aeronautics and Astronautics de Nanjing (PR China), 22-24 october 2007.
- J.P. Zolésio is chairman of Working Group IFIP 7.2 *System Modelling and Optimization*.

9.5. Invited or keynote lectures

- “Hierarchical Optimization: Multi-Level Algorithms, Multi-Disciplinary Optimization, Robust Design and Software Environments”, 8th World Congress on Computational Mechanics WCCM8, 5th European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2008, Venice, Italy, 30 June-4 July 2008; Special Technological Session: MDO Tools for High Quality Design in Aeronautics (J.-A. Désidéri);
- “Partage de territoire en optimisation concourante”, ONERA-DSNA, Châtillon sous Bâgneux, France, January 2008 (J.-A. Désidéri);
- “Shape Optimization in Aerodynamics”, Univerity of Abomey-Calavi (Benin), March 2008 (J.-A. Désidéri);
- “Shape-Morphing Metric by Variational Formulation for Incompressible Euler Flow”, International Workshop on Advances in Shape and Topology Optimization, Graz, Austria, October 2008 (J.P. Zolésio);
- “Control Formulation for incompressible Euler Flow in 3D”, 50 Years of Optimal Control, Banach Institute Conference, Bedlewo, Polland, September 2008 (J.P. Zolésio).

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