INRIA, Evaluation of Theme
Computational Models and Simulation

Project-team OPALE

March 2009

Project-team title: Optimization and control, numerical algorithms and integration of complex multidisciplinary systems governed by PDE.

Scientific leader: Jean-Antoine Désidéri

Research center: Sophia-Antipolis Méditerranée and Grenoble Rhône-Alpes

Common project-team with: CNRS and UNSA (University of Nice - Sophia-Antipolis)
1 Personnel

Personnel (September 2004)

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(1) “Senior Research Scientist (Directeur de Recherche)”
(2) “Junior Research Scientist (Chargé de Recherche)”
(3) “Civil servant (CNRS, INRIA, ...)”
(4) “Associated with a contract (Ingénieur Expert or Ingénieur Associé)”

Personnel (March 2009)

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Changes in staff

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Comments :
Régis Duvigneau was recruited as CR2 in October 2005.
Paola Goatin (Maitre de Conférences, University of Toulon), is part-time in secondment in Opale team.
Marwan Moubachir (formerly in secondment) left INRIA in October 2005.

Current composition of the project-team (March 2009):
Permanent members
- Jean-Antoine Désidéri (DR, INRIA Sophia Antipolis, HdR), Head of project-team
• Toan Nguyen (DR, INRIA Rhône-Alpes, HdR), Vice-head of project-team
• Régis Duvineau (CR, INRIA Sophia Antipolis)
• Abderrahmane Habbal (Maître de Conférences, University of Nice - Sophia Antipolis, HDR)
• Jean-Paul Zolésio (DR, CNRS, HDR)
• Montserrat Argente (INRIA Sophia Antipolis), Administrative assistant of Opale, Smash and Nachos project-teams

STAFF ON SECONDMENT
• Paola Goatin (Maître de Conférences, University of Toulon)

POST-DOCTORAL FELLOWS
• Abderrahmane Benzaoui (INRIA Sophia Antipolis)
• Xavier Hachair (INRIA Sophia Antipolis)
• Luigi Manca (INRIA Sophia Antipolis)
• Mohammed Ziani (INRIA Sophia Antipolis)

PhD STUDENTS
• Benoit Chaigne (INRIA Sophia Antipolis)

TECHNICAL STAFF
• Nikolas Mauny (INRIA Sophia Antipolis)

COLLABORATORS
• John Cagnol (Pôle Léonard de Vinci)
• Praveen Chandrashekaraappa (Tata Institute of Fundamental Research, India)
• Raja Dziri (University of Tunis, Tunisia)
• Michel Delfour (Centre de Recherche en Mathématiques, Montreal, Canada)
• Jacques Périaux (UPC, Barcelona, Spain and University of Jyväskyla, Finland)
• Jan Sokolowski (University of Nancy)
Current position of former project-team members (including PhD students during the 2004-2009 period):

- Abdou Wahidi Bello, student in Master of Information Technology, University of Nice, France
- Louis Blanchard, post-doctoral fellow, France-Telecom, La Turbie, France
- Pierre Dubois, Engineer, France-Telecom, France
- Badr Abou El Majd, post-doctoral fellow, Dept. Math., University of Avignon, France
- Marwan Moubachir, financial mathematics
- Lizhe Wang, research assistant at Service-Oriented Cyberinfrastructure Lab., Rochester Institute of Technology, Rochester (NY), USA.

Last INRIA enlistments

- Régis Duvigneau was recruited in October 2005 as CR2

Other comments:

In spite of an increasing industrial solicitation (See Section 3, External Funding), our community experiences great difficulty in recruiting doctoral students. The number of good applications from the University of Nice is very small; the contingent from French or European extraction is somewhat larger but still insufficient; other students are subject to confidentiality restrictions. We thus operate more easily with post-doctoral associates. Nevertheless, we expect to recruit two new doctoral students in September 2009.

J.-A. Désidéri was promoted Directeur de Recherche INRIA, 1st class, in 2005. J.P. Zolésio was promoted Directeur de Recherche CNRS, 1st class, in 2006. R. Duvigneau was promoted Chargé de Recherche INRIA, 1st class, in 2008.
2 Work progress

2.1 Keywords
Shape and topology optimization, multigrid, multilevel, multiobjective, multidiscipline, Nash games, gradient-based optimization, automatic differentiation, simplex method, genetic algorithm, particle-swarm, hybridization, metamodels, artificial neural network, Kriging, robustness, uncertainties, method of moments, high-performance computing, distributed and parallel computing, collaborative platforms, optimum design, concurrent engineering, compressible aerodynamics, computational electromagnetics, antennas, gradients in functional space, wound healing, cell and tissue dynamics

2.2 Context and overall goal of the project
The project-team has several objectives: to analyze mathematically coupled PDE systems involving one or more disciplines for purpose 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 Thales Air Défense (see Opratel Virtual Lab.); multi-criterion optimization of structural elements in partnership with Arcelor-Mittal (Automotive Center); the development of Virtual Computing Environments in collaboration with CNES (French Space Research Agency) and the European Airframe Company EADS (Common Research Center).

2.3 Objectives for the evaluation period
Objective 1: Computational methodologies for the simulation and optimization of multidisciplinary PDE systems in applied sciences:

1. Multilevel shape optimization algorithms
2. Hybrid Optimizers
3. Coordination of physical models
4. Neural networks and Kriging methods
5. Robust Design

Objective 2: Mathematical Analysis of Geometrical Optimization

1. Control of Dynamical Domains in coupled fluid-structure devices
2. Shape stabilization of wave equation
3. e-lab OpRaTel
Objective 3 : Computing environment

1. Design, deployment and experiment of distributed computing environments
2. Simplification of the access to distributed computing resources
3. Virtualization techniques for the design and deployment of distributed workflow systems
4. Contribution to scientific networking in national and international projects

Objective 4 : Application of shape and topology design to biology and medicine

1. Anti-angiogenesis for Solid Tumours
2. Wound Healing

2.4 Computational methodologies for the simulation and optimization of multidisciplinary PDE systems in applied sciences : Executive summary

2.4.1 Personnel

- Permanent staff: J.-A. Désidéri, R. Duvigneau, A. Habbal
- PhD students: B. Abou El Majd, B. Chaigne
- Post-Doct associates: A. Benzaoui, P. Chandrashekarappa, J. Zhao

2.4.2 Project-team positioning

2.4.3 Scientific achievements

Multilevel shape optimization algorithms This research axis was inspired by our former involvement in the development of multigrid and algebraic multilevel methods. Those methods are well-known for demonstrating optimal linear convergence rate. This means that for the Full Multi-Grid (FMG) method, when all numerical parameters (fine-grid smoothing and coarse-grid correction operators, transfer operators, termination criteria, etc) are ideally chosen, the computational cost for solving a PDE can be made (only) proportional to the total number of degrees of freedom associated with the fine grid, or grid size. These methods have been developed to great extent by the scientific community of numerical analysts and computational experts and applied to various types of PDEs, including the nonlinear hyperbolic equations of gas dynamics (steady Euler equations) and the full Navier-Stokes equations.

With these notions in mind, we have developed an analogy between grids used to solve PDEs, and shape, or shape-deformation parameterizations used to optimize functionals of flows subject to distributed PDEs, themselves solved on a grid of given topology. The latter solution could itself be of multigrid type, in which case two nested hierarchical
concepts would be coupled, but we have not yet developed this option, thus focusing hierarchical optimization via multilevel shape-deformation parameterization.

More specifically, we have exploited the classical degree-elevation process of parametric curves to construct an a priori hierarchy of embedded Bézier parameterizations as the support of a number of multi-level optimization algorithms, including one inspired from the FMG concept, and referred to as the Full and Adaptive Multi-Level Optimum-Shape Algorithm (“FAMOSA”). Our construction yields rigorously-nested optimization search spaces. Our main contributions are the following:

- Definition of algorithms and basic validation of concept by numerical experiments\[30\]
- Analysis of algebraic model problem (shape reconstruction)\[80\]
- Size experiments in compressible aerodynamics using 3D Free-Form Deformation (FFD) approach\[12, 37, 32\]
- Parameterization self-adaption procedures \[12, 36\]
- Adaptation of the methodology to shape optimization of antennas (improved global and local optimization algorithms in terms of robustness and convergence rate; thesis by B. Chaigne)
- Software: development of the FAMOSA platform implementing a general multi-level algorithm for 3D aerodynamics and contribution to the OMD Scilab platform
- Extension: definition of a hierarchical basis from purely algebraic sensitivity analysis and preliminary experiments
- Two participations in European short courses on invitation and invited conference at the DLR

**Hybrid Optimizers** Finally, it has been found that the proposed multilevel parameterization approach defines a suitable framework for hybrid optimization, by combining an evolutionary search in spaces of progressively larger dimension, with a deterministic search in the space of largest dimension.

The application to the optimization of the wing shape of a supersonic business jet has shown that the hybrid approach is far more efficient than deterministic or evolutionary methods alone. Especially, the exploration of the design space as well as the accuracy of the search are improved\[32\].

**Coordination of physical models** (in an optimization); **Concurrent Engineering**

Wing-shape optimization in compressible aerodynamics offer a number of prototypical example problems of a complex optimization because it is

- multi-objective, since all aerodynamic coefficients can be treated as criteria to be optimized or treated as constraints,
- multi-point, since these coefficients are critical in different phases of flight (e.g. lift at take-off and landing subsonic-flow conditions, drag in cruise transonic or supersonic-flow conditions),
- multi-disciplinary, since criteria originating from other disciplines such as structural stresses, thermal loads, noise criteria, etc, are essential to a relevant optimization,
not even mentioning manufacturing constraints. Thus, a great challenge to the computational expert is to devise general and efficient methods capable of confronting “concurrently” several criteria, each one of which is a functional of a physical field (costly) evaluated by the discrete solution of a distributed PDE system. In certain communities, this problem is referred to as “concurrent engineering”, and contributing to robust numerical methodologies in this area is one of our main research objectives. We aim at devising efficient alternatives to the costly and logically complicated identification of the Pareto-equilibrium front.

Originally under the thrust of our collaborator, J. Périaux (now associated with the Technical University of Catalunya, Spain, and the University of Jyväskyla, Finland), and a number of former students now at NUAA (Nanjing University of Aeronautics and Astro-
nautics), we have investigated the possibility of using the analogy of dynamic Nash games to achieve successful practical multi-objective optimizations in aeronautics (multi-point aerodynamics, aerodynamics coupled with electromagnetics, etc). Indeed 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 can be implemented to set up an optimization strategy for design under conflict.

The originality of our approach compared with standard Nash games resides in the fact that ours are artificial dynamic games in which the distribution of variables to the players (or agents) is not given a priori by the physical or societal model, but is the main free parameter by which we can realize physical couplings that are sensible or not. This is what we call the split of territory, and we believe that we have made an original contribution in this area, by relating the split to an appropriate eigenvalue problem.

Our main contributions have been:

- Proof of concept in compressible aerodynamics, implementation in a parallel environment [56]
- Theoretical split of territory:
  - The fundamental case of a preponderant discipline[29, 139]
  - Extension to the general case[87]
- Assessment of game strategies for the aero-structural optimization of an aircraft wing[7]

Meta-models The use of meta-modelling techniques, such as Artificial Neural Networks (ANNs), Radial Basis Functions (RBFs), Gaussian Processes (GPs) or Kriging, has known a growing interest in the last years, because of the computational burden of high-fidelity analyses. We have developed such approaches, to accelerate the optimization procedure or provide additional information to the optimizer. Our developments have been particularly focused on the construction of algorithms that use both meta-models and models based on PDE’s solving to drive a semi-stochastic optimization, with various coupling strategies:

- A strong coupling approach: meta-models are used at each iteration to pre-evaluate candidate designs and select those which will be ”exactly” evaluated by simulation. Then, the optimization algorithm relies only on ”exact” evaluations[55].
- A weak coupling approach: meta-models are used only to solve completely a set of optimization subproblems iteratively. GPs are employed to predict both function value and modelling error. The subproblems considered (lower bound minimization, probability of improvement maximization, expected improvement maximization) indicate which ”exact” evaluations should be performed to improve the model as well as determine the best design.

We have also employed meta-modelling techniques for various purposes:

- Provide sensitivity information to optimizer. For instance, they are used to estimate Hessian eigenvectors and eigenvalues required for a split of territories in a Nash game framework.
a) Aerodynamics optimized alone

b) Aero-structural Nash equilibrium

Figure 2: Mach-number surface flowfields: a) single-discipline optimization, and b) aero-structural Nash equilibrium solution. The split of variables has been made in the appropriate orthogonal basis in a way that causes the least perturbation to the original aerodynamic flowfield; nevertheless, the structural criterion has been reduced of 8%.

- Handle inexpensive models for Monte-Carlo simulations in the framework of robust design[91].
- Replace a disciplinary analysis in the framework of multi-disciplinary optimization[7].
Robust design 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 has been developed and tested, that includes uncertainty effects in the design procedure, by maximizing the expectation of the performance while minimizing its variance, subject to probabilistic constraints.

Two strategies to propagate the uncertainty have been studied:

- the use of meta-models to predict the uncertainties of the objective function: during the optimization procedure, a few simulations are performed for each design variables set, for different values of the uncertain parameters to build a database used for meta-models training. Then, meta-models are used to estimate some statistical quantities of the objective function and constraints, using a Monte-Carlo method[90, 99].

- the use of the automatic differentiation tool Tapenade (developed by Tropics Project-Team) to compute first and second order derivatives of the performance with respect to uncertain parameters. Once these derivatives have been computed, one can easily derive statistic estimations by integrating the Taylor series expansion of the performance[108].

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)[96, 109, 39]. Robust design exercises have also been performed, to minimize drag expectation and variance subject to a probabilistic lift constraint [91].

Other contributions

- Flow control

We have applied optimization strategies to flow control problems. In this context, the purpose is to optimize some actuator parameters (e.g. oscillatory jet frequency, direction and position) that allow to control the vortex dynamics. This is a particularly difficult exercise, because of the computational cost of unsteady simulations and the multimodality of the underlying phenomena. Promising results have been obtained by optimizing the characteristics of oscillatory/steady jets for stall control for an airfoil[43, 44, 38]. This work has been carried out in collaboration with the Fluid Mechanics Laboratory of Ecole Centrale de Nantes.

Figure 3: Unsteady vorticity field about a cylinder without control (left), and with metamodel-optimized pulsating-rotation control (right)
• **Shallow-water equations**

A. Bello, student from the University of Abomey-Calavi (Benin), has been partially supported by the INRIA Dept. of International Programs, for three training periods in our project-team under the guidance of J.-A. Désidéri and H. Guillard (Project-team Smash). He developed upwind finite-volume methods for the shallow-water equations, and made a simulation of flood in the canal system of the city of Cotonou, and successfully defended his doctoral thesis[8].

• **Interpolation of infinite sequences by entire functions**

Given an arbitrary set of real numbers associated with the nodes of an infinite lattice in two dimensions, we have proved the existence of (uncountably many) functions of \(x\) and \(t\), entire in each argument, and matching the specified data. We have provided explicit formulas for such interpolants. The construction has been extended to the interpolation of the function and an arbitrary but specified number of its derivatives (Hermitian interpolation)[28].

These results are helpful to support the classical heuristic analysis of accuracy of finite-difference schemes for Cauchy problems\(^1\).

### 2.4.4 Collaborations

Closest groups with whom we collaborate are:

- Tropics project-team for automatic differentiation in gradient-based methods; inclusion of second derivative of functional to account for sensitivity.
- ONERA/DSNA for statistical methods.
- Fluid Mechanics Laboratory of Ecole Centrale de Nantes.
- Mathematical Information Technology, Jyväskyla for alternate algorithms, software and applications. (Newly supported by the 2009 INRIA Associated Team program.)

### 2.4.5 External support

- Contract with Dassault Aviation (Parameterization techniques for Shape Optimization in Aerodynamics); partially supported B. Abou El Majd thesis.
- Regional/Industry: doctoral scholarship of B. Chaigue co-financed by the Region Provence-Alpes-Côte d’Azur and France Telecom R & D.
- Industry: a two-phase contract was signed in 2007 with Arcelor-Mittal. In the first phase, now completed, J.-A. Désidéri and A. Habbal audited the GEAR2 optimization team of the Automotive Center in Montataire. The second phase is to support the direction of a thesis by J.-A. Désidéri and A. Habbal (co-director). This phase will start when Arcelor-Mittal succeeds to recruit a doctoral student.
- National: participation in the “OMD” (Multidisciplinary Optimization) project of the National Research Agency, ANR/RNTL (\(2 \times 2\) man-years for Phase 1)
- European:

  1. AEROCHINA 1 and 2 projects (Aeronautics).

2. NODESIM (Aeronautics)
3. EXCITING (Transports)

2.4.6 Self assessment

To our knowledge, the geometrical (and now, algebraic) multilevel approach for parametric shape optimization mimicking multigrid, as well as the usage of game strategies to handle multi-physics optimization are both original methodologies. We believe that “smart splits of variables” based on adequate sensitivity analysis provide an original and powerful tool in this context. We plan to continue our efforts in these directions.

For multi-objective optimization, we are conscious that alternate formulations exist, in particular those relying on the interior-point method. However, they require that at least one functional criterion is handled as a constraint which is seldomly trivial to do. This is a route that we have not investigated thoroughly so far. With the advent of more easily computable gradients (via Automatic Differentiation, in particular), we would, in a larger team, devote more effort to this research direction.

Quantification and control of uncertainties is a relatively new topic that will be amplified, and our strategy is to achieve this in cooperation with ONERA/DSNA for flow simulations. This cooperation should also help us treat multi-physics optimization with higher level of modeling (aero-structural and aero-acoustics design, in particular).

2.5 Mathematical Analysis of Geometrical Optimization : Executive summary

2.5.1 Personnel

- Permanent staff: J.-P. Zolésio
- PhD students: L. Blanchard, P. Dubois
- Post-Doct associates: X. Hachair, L. Manca
- Other: M. Moubachir (on secondment during the year 2005)

2.5.2 Project-team positioning

Many groups in the world are working on inverse problems in electromagnetics but, to our knowledge, we are the only one to use a full 3D analysis for radiating conditions and shape analysis not using the farfield framework in presence of metallic or dielectric obstacles. We are not limited to tomography analysis and/or TE, TM regimes but we derived a full 3D reconstruction of metallic obstacles by 3D level set methods with various topological changes. We are the single one who provided a full shape gradient analysis through the Harmonic integral representation of solution and a complete implementation in the 3D code SR3D of France-Telecom in the OpRaTel collaboration with Thales.

2.5.3 Scientific achievements

They are several. Concerning the inverse problem in electromagnetics the shape gradient analysis for harmonic regime through an integral equation with geometrical singularities is a breakthrough. Also the use of the new Morphic metrics for the geometrical optimization of antennas array using a level set approach. On the theoretical viewpoint, we have proved existence for strong solution to the Hamilton-Jacobi equation associated to the level set method with topological changes. Also the shape geodesic characterization as variational
solutions to incompressible Euler-like flow for the Morphic metrics which extends the so-called Courant metric as a new differentiable metric. We also extend the hidden regularity results for the Maxwell system of electromagnetic and open the shape gradient analysis for singular geometries.

Non cylindrical dynamical system The mathematical analysis in geometrical optimization has been extended to non cylindrical dynamical system. A main result is that, in any dimension, the incompressible Euler flow, associated with exact controllability results concerning the associated transport problem, has global solution in finite time and better than this: has variational solutions[133].

Also we fully succeeded in the smart moving boundary analysis for the drag minimization in a 3D Navier Stokes flow. We have derived the optimality of the PDE system for the moving active boundary in order to minimize some functional in the fluid as the drag and/or the curl norm in a given region of the 3D fluid[5]. We also give existence result for this system and parametric analysis in order to deal with quasi-periodical boundary motions and/or quasi rigid body motions framework. This kind of results have been also applied to elasto-plastic quasi-steady free boundaries in Norton-Hopff flow[47, 48].

Two new basic ingredients that we developed in this period for deriving these results are connected to the so-called Transverse Field Z those Lie Brackets govern the non cylindrical derivatives. Several papers[53], note to CRAS and a book[3] has been published in this period on this subject. The second ingredient is the extension to “parabolic situations” of the Helly compactness theorem. For a moving domain we consider the BV regularity, that is to say that, at each time, the moving domain does have a finite perimeter (it is a Cacciapoli set). Now the only constraint for compactness is that this perimeter remain bounded in the $L^1$ norm (in time), which is much weaker than saying that the non cylindrical evolution associated set has a bounded perimeter in dimension N+1.

Through these new compactness results we derive existence for set transport (in the sense of mass transport for probability functions) associated with non smooth vector fields which are just square integrable (together with there divergence fields). Indeed the classical optimal control theory is 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 the classical setting of the heat or wave equations or fluid motion, 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 . So the breakthrough is that now the optimal control is part of the equation (state equation) itself. In this direction we have two new families of existence results associate with optimality: for moving boundaries in waves equation with Neumann-like boundary conditions (extending the previous works with Dirichlet condition) and solution to incompressible Euler fluid. We also develop a new modeling for the viscous incompressible solutions which are variational and having some stability virtues.

Shape Optimization theory The ongoing collaborations with the CRM in Montreal (mainly with professor Michel Delfour) led to several extensions to the theory contained in the book Shape and Geometry (SIAM 2001). In that direction 2 more papers have been published[26, 23]. The emphasis is made 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, flat conditions and uniform non differentiability of the oriented distance function are studied. Several new compactness results are derived [20, 21, 24]. Also the fine study of Sobolev domains leads to several properties concerning boundaries convergences and boundaries integral convergence under some weak global curvature boundedness.

The extension to hyperbolic problems with Neumann condition and to Maxwell system of the so-called extractor technique (introduced in 1995 by Delfour and Zolesio) permitted us to improve some Sharp regularity results b I. Lasiecka-R. Triggiani but also (and mainly) it provides constructive estimates which enable the previous shape analysis for Maxwell system. This new technique, we call it the pseudodifferential extractor is based on pseudo differential technique associated with the classical extractor which consists in a shape derivative of a transported norm of the solution.

Concerning the stabilization of the wave equation, we have extended in a non obvious way the former “cubic derivative“ by C. Trucchi (1988) to Neumann like condition, and we derived a new geometrical-boundary smart motion for the energy decay.

Control of Coupling Fluid-structure devices 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 yielded to the publication of a note at the Comptes Rendus of Academy of Sciences (presented by Roland Glowinski), and a book [5], as well as a conference papers at the TC7 IFIP conference. 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 [58].

Shape Gradient in Maxwell Equations It is well known that in 3-D 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 [35, 34] and implemented numerically in the 3D code of France Telecom. This work with P. Dubois is potentially applicable to more general singularities.

Frequency Derivative (Harmonic regimes) This work extends the ongoing collaboration with France Telecom (Claude Dedeban) and UNSA (J.P. Damiano, electronic lab.) and the results have been presented in two international conferences [127, 88].

e-lab OpRaTel The collaboration with France Telecom and Thales led to the creation of an e-lab. Our activity is divided in two main themes:

- development of models of array antennas for telecom purposes; a patent will shortly be deposited;

- frequency allocation (M. Moubachir), a difficult modeling topic of major importance for our industrial partners.

2.5.4 Collaborations

The ongoing collaboration with CRM in Montreal and newly begun with PIM in Vancouver, and the collaboration with several members of CNRS-INLN, in particular C. Toniolo. The on going collaboration with Tunis University (Math Dept.) and with Monastir Math Dept. Also the collaboration with LEAT lab in Sophia Antipolis and the CREMENT lab, and the Thales collaborators in Limours and in Palaiseau.
2.5.5 External support

We mainly used industrial support by France Telecom and Thales.

2.5.6 Self assessment

The weak point is that France Telecom closed the research center in La turbie and that Pierre Dubois didn’t stay with us but joint the Issy-les-Moulineaux France Telecom R&D center. Nevertheless the collaboration is extended through the new association of a part of this center this the CNRS and the lab and a personal collaboration with the Prof. C. Pichot, we will present extensions of the Pierre Dubois works in a joint work in Florida at an international IEEE for electromagnetics. The strong point concerns the geometrical analysis through the breakthrough in the extension of the Courant Shape metrics into the Morphic metrics which extends to metrics betwen shapes having different topologies and no smoothness (fractal are possible) and being shape differentiable. A second edition of the book “Shape and Geometry” with M. Delfour is finished and will soon appear.

2.6 Computing environment: Executive summary

2.6.1 Personnel

- Permanent staff: T. Nguyen
- PhD students: L. Wang

2.6.2 Project-team positioning

The team was involved in the grid computing arena including cooperation with teams inside and outside INRIA, in France (Grid5000) and abroad, in particular in Finland (CSC) and China. Concerning virtual collaborative environments and high-performance distributed computing, the Opale project-team focused on parallel and distributed computing on grid infrastructures. The goal was to design and implement virtual computing environments providing seamless user interfaces, e.g., the CAST workflow prototype. Interfacing CAST with Web Services, CORBA and Java was part of the work of Lizhe Wang during his PhD.

The goal was also to extend workflow management systems and assess their adequacy to deploy large-scale optimization applications on heterogeneous networks of computing resources connected by grid middleware. This was also the focus of Lizhe Wang’s PhD.

Collaboration with CNES (French Space Agency) allowed for a cross-fertilizing specification of such environments in the HEAVEN working group. This laid the ground for the e-CORCE project at CNES which aim is to provide a permanent satellite constellation for high-resolution earth imaging.

2.6.3 Scientific achievements

The main contribution concerning virtual computing environments was to confirm the adequacy of distributed workflow management systems for e-science applications. In particular, their seamless user interfaces make them well suited for engineers and experts in numeric fields to avoid the intricate technicalities of parallel and distributed computing. Indeed, many international conferences and research projects have since incorporated workflow systems in their programs (Grid@Asia and CCGrid Conferences, for example) and they are gaining wide acceptance in the scientific community, e.g., genomic, bioinformatics, etc, because of their powerful support for up-to-date technology in demanding
applications areas, e.g., Web Services and interfaces with peta-scale database systems, while being based on strong formal semantics and providing seamless user interfaces.

The Opale project-team is currently experimenting with the YAWL workflow management system, developed by the Dept of Mathematics and Computer Science at the University of Technology in Eindhoven, in the Netherlands, and by the Queensland University of Technology in Brisbane, Australia (http://www.yawl-system.com).

2.6.4 Collaborations

J. Périaux and T. Nguyen have launched the project DESIGN on multidisciplinary optimization at the University of Jyvasjyla. The project implies industry and academic partners and is supported by the Finnish National Research Agency VTT/TKK.

As mentioned above, the team is also deeply involved in the AEROCHINA projects of the EC, where it works in close cooperation with the CIMNE (Universitat Polytechnica de Catalunya, Barcelona, Spain), coordinator, as a member the Managing Board for the projects.

These projects lay the ground for long-term cooperation with academic and industry partners in Europe and China, particularly in the aeronautics sector (ACTRI, AVIC1 and 2, Nanjing University of Aeronautics and Astronautics, etc).

2.6.5 External support

The project Opale was supported during this evaluation period by the European projects AEROCHINA (FP6) and AEROCHINA2 (FP7), by Agence Nationale de la Recherche (OMD and OMD2 projects, the latter starting mid-2009).

2.6.6 Self assessment

Developing virtual computing environments requires long-term investments from both human and financial perspectives, in order to design, develop, test, distributed and support sophisticated software.

The large efforts that are required suggested that the team should concentrate on collaboration with other groups in order to avoid the development and support of software with an insufficient number of persons. Strong emphasis is therefore put today on reusing a proven technical basis to develop specific items necessary to support large-scale multidiscipline optimization applications.

This is why the team has adopted the YAWL workflow system which is a proven open-source software that is fully supported by two internationally recognized teams in the Netherlands and Australia. This allows the Opale team to concentrate on the adaptation of the YAWL system to support large-scale optimization applications, including the support for distributed and high-performance computations, fault-tolerance, large databases and user-interactions for parametrization purposes in the optimization processes. This is ongoing work for which a PhD student will be recruited in 2009 and funded by the OMD2 project.

This will be implemented in the OMD2 project starting mid-2009, and will be detailed in the forthcoming proposal answering to the upcoming 2009-2010 Call of the "Transport including Aeronautics" of the European FP7.

2.7 Modeling biological structures and functions: Executive summary

The main objective of the present theme is to model selected biological phenomena with mathematical tools in narrow relation to optimization theory. The idea is to investigate
possible relations between the shape and the function of biological structures.

We concentrate our attention on two applications:

- anti-angiogenesis
- wound healing

In order to set appropriate optimization related problems, namely which criteria are to be optimized, using which variables, it is required that the governing equations are well established, a requirement that is not always fulfilled: for the wound healing application, our main past and present effort is put on the building and validation of acceptable PDE models.

2.7.1 Personnel

- Permanent staff: A. Habbal
- Intern: O. Duhamel (4 months)

2.7.2 Project-team positioning

At present, mathematical modeling of cancer and wound healing is a very active area, and the contributors are too numerous to be exhaustively cited here. Let us only cite the worldwide known seminal work and book (Mathematical Biology) by James D. Murray.

There are many INRIA project teams involved in computational life science: seemingly, project-teams like Anubis or Galen do intend to apply control and identification theory to biomathematics. As image processing is a central issue in validating biomathematical models, we have initiated a long term collaboration with the project-team Asclepios.

To our knowledge, there is no research team in the field of application of mathematics which focuses its attention on investigating the relationship between topology, shape and function of biological structures using optimization and game theory.

2.7.3 Scientific achievements

**MDCK cell sheet dynamics (Barelli, Habbal, Malandain)** More than 90% of malignant tumors in adult mammalians occur in epithelial tissues. It is then of highest importance to understand the dynamic regulations of focal adhesions involved during the cell migration in epithelial lines. To this end, mathematical and computational modeling is more and more considered as a helpful tool to shed light on non-easily accessible qualitative or quantitative characteristics of the cell line dynamics.

Nevertheless, as anywhere else where a mathematical model is used, the latter has to be confronted to the biological experience.

As an illustration, it is a common belief among biologists that epithelial cells have a constant speed during the wound closure, probably to avoid concentration of mechanical stresses which would lead to degraded neoplastic mechanical properties.

The present work focuses on the validation of the above constant speed hypothesis, using a simple partial differential equation, the Fisher-KPP equation. This mathematical model is used to describe the closure behavior from a kinematic point of view of a particular cell sheet, the Madin-Darby canine kidney (MDCK) monolayer cell sheet.
MDCK cells are used worldwide as a general model to study the migration of epithelial cells. These cells exhibit a migratory response to the Hepatocyte Growth factor (HGF) or to the Scatter Factor (SF).

Combining the activation role of HGF to selected inhibitors leads to a variety of the MDCK sheet closure scenarios but to our knowledge, only one relatively recent article by Maini in 2004\(^2\) was devoted to a biological validation of the constant speed hypothesis, using a one dimensional Fisher-KPP model. Our work contributes to corroborate the constant speed hypothesis, and the relevance of the Fisher-KPP model as a satisfactory first approximation to describe the wound closure of the MDCK cell-sheet, in the absence of inhibitors.

**Embryonic epidermal wound healing** (Almeida, Bagnerini, Habbal, Noselli, Sarman) Tissue repair is an essential mechanism for assuring an organism’s integrity and protection from external aggressions and it is active all through its life (from embryonic to adult stages). In embryos, this process is achieved through mechanisms that recall strongly those used for building the original tissue and yield perfect repair (regenerative repair in the sense of Gurtner\(^3\)). However, in many species (in particular for humans) adult wound healing generally involves different mechanisms and ends up generating a mass of fibrotic tissue commonly known as a scar. This fibrosis is not only aesthetically undesirable but has also serious clinical consequences, specially if we consider that fibrotic healing is at the origin of many tissue malfunctions following a wide class of injuries from heart attacks to burns and cirrhosis (see Gurtner\(^3\) for a description of the biological and clinical issues related to wound healing and regeneration). A good understanding of regenerative healing mechanisms (such as embryonic wound healing and the closely related morphogenetic events like Dorsal Closure) and of how we can re-activate or reproduce them in adult setting is an important public health issue for the future. In this work we have studied embryonic epidermal wound healing taking as biological model the fruit fly Drosophila Melanogaster. We introduced a simple mathematical model for epithelial sweeping in wild type fly embryos, and performed a preliminary validation of this model using movies of laser wound healing of stage 14/15 fly embryos and of Dorsal Closure of the fly embryos. See the paper by Almeida and al [13].

**Anti-angiogenesis for Solid Tumors** (Habbal) An original approach based on game theory framework was proposed to model anti-angiogenesis. It relies on a competition between two density functions which are intended to represent respectively activators and inhibitors of angiogenesis.

To illustrate our approach, we defined a porous media versus structural linear elasticity theoretic game. The problem was formulated as a topology design static with complete information game, for which existence of a Nash equilibrium was proved. We assumed that activators would act to provide the tumor with an optimal drainage network, while the inhibitors would try to keep the structural compliance of the extracellular matrix as low as possible (or try to minimize the drainage of the blood vessels network in the case of zero-sum version).


Figure 4: Visual comparison at different times between microscopy snapshots during wound closure of an MDCK cell sheet (up) and computational results of the Fisher-KPP equation (bottom).

A dedicated software was developed, based on proprietary routines, Modulef finite element library, and a third party optimization package. The numerical results clearly characterize the multiplicity of feeding channels as an optimal response of the activators to optimally distributed inhibitors, see the paper [51].

2.7.4 Collaborations

- Hélène Barelli, Institut de Pharmacologie Moléculaire et Cellulaire, CNRS & INSERM, Sophia Antipolis (wound healing, two papers in preparation)
- Grégoire Malandain, Project-team ASCLEPIOS, Sophia Antipolis (wound healing, two papers in preparation)
- Luis Almeida, CNRS, Laboratoire Jean-Alexandre Dieudonné, University of Nice (embryonic wound healing, one paper published)
- Patrizia Bagnerini, University of Genova, Italy (embryonic wound healing, one paper published)
- Stéphane Noselli, Institute of Developmental Biology & Cancer IBDC-Nice (embryonic wound healing, one paper published)
- Fanny Serman, Institute of Developmental Biology & Cancer IBDC-Nice (embryonic wound healing, one paper published)
- Pierre-Emmanuel Jabin, Laboratoire Jean-Alexandre Dieudonné, University of Nice (mathematical modeling of cancer, one paper published[14]).
2.7.5 External support

INRIA COLOR 2005-2006 two-years local collaboration grant (11Keuro).

2.7.6 Self assessment

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(*) HDR Habilitation à diriger des Recherches  
(**) Conference with a program committee

Indicate the major journals in the field and, for each, indicate the number of papers coauthored by members of the project-team that have been accepted during the evaluation period.

Selection of major publications


We have authored 2 books, and edited 4,

We have authored 24 articles in the following 23 different international journals:

European Journal of Computational Mechanics
Revue Africaine de la Recherche en Informatique et Mathématiques Appliquées
Interfaces and Free Boundaries
J. Evol. Equ.
Applied Mathematics and Optimization
Communication in Information and Systems
Control and Cybernetics (2)
Applied Numerical Mathematics
Journal of Computational Physics
European Series in Applied and Industrial Mathematics
Journal of Fluid Engineering
International Journal for Numerical Methods in Fluids
International Journal of Computational Fluid Dynamics
Numerical Heat Transfer
Computers and Fluids
Aerospace Science and Technology
Journal of Computational and Applied Mathematics
Journal of Mathematical Analysis and Applications
Netw. Heterog. Media
Journal of Structural Multidisciplinary Optimization
Revue Européenne de Mécanique Numérique
Computer Methods in Applied Mechanics and Engineering
Journal of Optimization Theory and Applications

We have authored 24 chapters in the following 12 books:

CRM Series, Scuola Normale Superiore, Pisa
Lecture Note in Pure and Applied Math. (6)
Systems, Control and Optimization
Numerical Mathematics and Advanced Applications
Hermes Science Publications-Lavoisier (4)
System Modeling and Optimization (2)
Introduction to Optimization and Multidisciplinary Design (2)
Numerical Analysis and Scientific Computing for Partial Differential Equations and Their Challenging Applications (2)
Contrôle des Décollements : Optimisation des performances et Nouveaux Actionneurs (2)
Control and Boundary Analysis
Indicate the major conferences in the field and, for each, indicate the number of papers coauthored by members of the project-team that have been accepted during the evaluation period.

1. European Congress on Computational Methods in Applied Sciences (7 contributions)
2. IFIP 7 Control and Optimization (2 per year)
3. Conference: World Congress on Structural and Multidisciplinary Optimization (1)
4. AIAA Conferences (5)

2.8 Software

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 collaborative development of the software, 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, the 2D open-source NUWTUN (“Numerical Wind Tunnel Code”), and the incompressible flow solver ISIS-CFD developed at the Ecole Centrale de Nantes.

Flow solver NUM3SIS

Opale has been participating with Smash project-team to the development of the flow solver NUM3SIS for three 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.

This 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 (5 and 7 eqs models);
• 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.

Its distribution as open-source software is currently in discussion.

2.8.1 Valorization and technology transfer

A collaboration is currently set up with the company K-Epsilon, located at Sophia-Antipolis, to use the platform FAMOSA for hull shape design. This will give the opportunity to Opale to tackle very complex optimization problems related to the multidisciplinary optimization of racing sailing boats (America’s Cup). Moreover, a discussion has been initiated with the Tata Institute for Fundamental Research (Bangalore, India), concerning the possibility of a common software development for the platform FAMOSA.

A free of charge licence for the flow solver NUM3SIS has been written for the Tata Institute for Fundamental Research (Dept. of Applicable Mathematics, Bangalore, India), for academic studies and common publications purpose.

2.9 Teaching

Opale members teach the following courses:

Introduction to game theory and its application to economy (A. Habbal, University of Nice Sophia-Antipolis, Master 1, 47hrs)

Numerical Engineering methods (A. Habbal, Engineering school Polytech’Nice, first year, 75 hrs)

Programming mathematics (A. Habbal, Engineering school Polytech’Nice, first year, 16 hrs)

Shape optimization (A. Habbal, J.-A. Désidéri, R. Duvigneau, Engineering school Polytech’Nice, third year, 45 hrs)

Numerical Methods in Finance (A. Habbal, Engineering school Polytech’Nice, third year, 18 hrs)

Introduction to biomathematics (A. Habbal, Engineering school Polytech’Nice, second year, 14 hrs)

Project on Partial Differential Equations (R. Duvigneau, Engineering school Polytech’Nice, first year, 24 hrs)
Moreover, Opale members have participated in international courses:


J.-A. Désidéri delivered an invited lecture at the German Aerospace Lab (DLR, Braunschweig, 29-30 November, 2005) within the MEGADESIGN project.

J.-A. Désidéri delivered two invited lectures in the course ”Introduction to Optimization and Multidisciplinary Design” at the Von Karman Institute, Brussels (B), March 2006.


J.-A. Désidéri will deliver one of five plenary lectures at the 24th IFIP TC7 Conference on System Modelling and Optimization, Buenos Aires, Argentina, July 27-31, 2009 on “Hierarchical Optimization”.

R. Duvigneau delivered an invited lecture on ”méthodes sans gradient pour l’optimisation et le controle en mécanique des fluides” (Derivative-free approaches for control and optimization in fluid mechanics) at the spring courses “Control and Optimization of Flows and Transfers” organized by CNRS/LIMSI, 12-17 March 2006, Aussois, France.

J.-P. Zolésio delivered the short-course: “Controle Optimal des systèmes non autonomes” (Optimal Control of Non-Autonomous Systems) at the University of Monastir, Tunisia, 2007.

A. Habbal delivered a lecture at ”UNESCO Modèles mathématiques du cancer” (Mathematical Models of Cancer), Tunis, march 2007.

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.

### 2.10 Visibility

Opale team has organized the following events:

The Opale project-team (with A. Dervieux, TROPICS project-team) organized the French-Indian Workshop on Numerical Simulation and Design for Aeronautical and Space Applications, INRIA Sophia Antipolis, November 29-December 1, 2006.

The Opale project-team (with A. Dervieux, TROPICS project-team) organized the 42nd Applied Aerodynamics Colloquium of A3F (French Aeronautics and Astronautics Association), INRIA Sophia Antipolis, April 19-21, 2007, whose theme has been: Multidisciplinary Couplings and Optimization.
The Opale project-team organized an international seminar in May 2007 in Grenoble, sponsored by the French-Finnish Association for Scientific and Technology Research (AFFRST) as well as several Finnish universities (Helsinki and Jyvaskyla) and scientific bodies (CSC). The title was: "Computational Science: Understanding and Solving Multiphysics Problems for Industry and Society with Large Scale Simulation".

The Opale project-team was also invited to participate in several open workshops on large-scale multidiscipline design, simulation and optimization in the aeronautics sector in China (Beijing, October 2005, Xi’an, April 2006 and Nanjing, April 2008) and Europe (Barcelona, April 2007 and Marseilles, June 2008).

Moreover, Opale members participate to national and international committees:

J.-A. Désidéri has been appointed by the department of simulation in aerodynamics and aeroacoustics (DSNA) of ONERA Châtillon. This appointment includes a monthly visit at ONERA, and the direction of one thesis (M. Bompard) for the first year; a second thesis on aero-structural design is programmed to start in the fall 2009.

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.

2.11 Misc.:

J.-A. Désidéri and A. Habbal audited the GEAR2 research team of the Automotive Center of Arcelor-Mittal (Montataire, France).

R. Duvigneau received the prize of “best communication 2007” by A3F (French Aeronautics and Astronautics Association) at the occasion of the 42nd Applied Aerodynamics Colloquium.
## 3 External Funding

*Indicate the budget allocated to your project-team in keuros.*

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<td>205</td>
</tr>
</tbody>
</table>

† INRIA Cooperative Research Initiatives
‡ Large-scale Initiative Actions
* other than those supported by one of the above projects
+ junior engineer supported by INRIA
# engineer supported by INRIA

**ARCs**

**National initiatives**

Opale participates in the RNTL (National Network for Software Technologies, a program supported by the National Agency for Research (ANR)) Project “OMD” for multi-disciplinary optimization (see http://omd.lri.fr). This project was set-up by
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. Chandrashekappa, J. Zhao and A. Benzaoui.

**E-Lab Opratel**

The collaboration with France Télécom and Thales 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).

**European projects**

**AEROCHINA**: Coordination and support action of the "Aeronautics and Space" program of the FP6 (2005-2006). Included 24 partners (12 from Europe: AIRBUS, EADS, DASSAULT, etc, and 12 from China: AVIC1, ACTRI, ASRI, NUAA, etc).

**AEROCHINA2**: Coordination and support action of the "Transport including Aeronautics" program of the FP7 (2007-2009). The Opale project was and is a member of both the AEROCHINA and AEROCHINA2 coordination and support actions 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 the latter project, formed by five Chinese (ACTRI, NUAA, SADRI, NPU and BUAA) and five European members (AIRBUS, EADS-IW, ALENIA Aeronautica, CIMNE, INRIA). Current discussions for the set-up of a proposal answering to the Call 2009 in the "Transport including Aeronautics" Objective of the FP7 are undertaken concerning Multidiscipline Optimization calling for High-Performance Computing services in cooperation with the AEROCHINA2 partners.

**NODESIM**: Opale and Tropics Project-Teams participate to the European project NODESIM (NOOn 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. It includes 17 partners (Numeca International (Coordinator), AIRBUS-UK, ALENIA, BAE System, CIMNE,
EXCITING: Opale and Galaad Project-Teams participate to the European project EXCITING (EXaCt-geometry sImulTIoN for optimized desiGn of vehicles 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. three partners belong to academic institutions (JKU, NTUA, TUM), two partners are national research labs (INRIA, SINTEF), and four are industrial companies ranging from global players (HYDRO, DNV, SIEMENS) to a small scale enterprise (HRS).

Associated teams and other international projects

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.

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. The project is gathering several teams from France:(INRIA/Opale, University of Nice, “École des Ponts et Chaussées” and Technical University of Compiègne) and Morocco (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.

Industrial contracts

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.

Arcelor Mittal
In 2007, 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 intern from Arcelor, J.-G.
Moineau, was hosted and directed at INRIA for a four-months period. A PhD student will be recruited in September 2009, whose work will be supervised by Opale team.

Other funding,

4 Objectives for the next four years

4.1 Objective 1: Computational methodologies for the simulation and optimization of multidisciplinary PDE systems in applied sciences

We propose to focus our efforts on the following main lines of research particularly, in a coordinated way:

1. Multilevel algorithms in abstract hierarchical basis
2. Iso-geometric approaches
3. General algorithms for multi-disciplinary optimization
4. Uncertainties (estimation and propagation) and robust design
5. Self-adaptive numerical algorithms in all of the above: integration of metamodel-based strategies.

The last item (metamodels) is viewed by us mostly as an all-purpose tool to make algorithms more robust with respect to numerical options, by guiding their adaptation in a more systematic and sensible way: preconditioning in a sequential or parallel environment; sensitivity analysis and hierarchical bases; decision-making in multi-objective problems; semi-stochastic approaches based on a large number of evaluations most of which by low-fidelity models; etc. Additionally, our partnership with Arcelor-Mittal should permit us to develop innovative strategies to couple high and low-fidelity models in structural design.

Concerning multilevel algorithms, one objective is to treat optimization problems that are not strictly shape optimization in nature but can involve a more general set of design variables. Our preliminary experience in this area is related to an optimization problem of flight mechanics for a generic supersonic aircraft, for which the different criteria to be optimized or treated as constraints are given by functions known explicitly (not functionals). Our implication in the OMD National Network has given us access to a library in Scilab in which these functions have been programmed (by Dassault Aviation), and can be computed very economically by simple routine calls. Thus, relevant testcases of flight mechanics have been defined as a preliminary step before treating PDE-constrained problems. As a result, it was confirmed that when relying on well-calibrated metamodels, a sensitivity analysis by diagonalization of appropriate reduced Hessians can be very effective by providing a relevant orthogonal basis, particularly suitable to conduct a multilevel approach. This approach will be more thoroughly investigated and extended to PDE problems, such as the optimization of an automobile engine, in partnership with Renault, within the OMD-Phase 2 Project. This will possibly be combined with the usage of the hierarchy of representation, longly purely geometrical, and from here on, more abstract (that is, algebraic), to construct algorithms that are also hybridized, in the sense of mixed deterministic/semi-stochastic, to cope with the multimodality of many relevant difficult engineering problems such as drag-minimization problems in compressible aerodynamics.
Iso-geometric approaches are formulations in which the boundaries are represented “exactly” in the sense that their piecewise-polynomial representation (e.g. NURBS) also serves as an exact support for the mesh generation, and the related construction of the approximation scheme. Consequently, certain forms of error related to the usually necessary projections from one geometrical basis of representation to another are avoided. This rather novel approach has been mostly developed for purpose of pure “analysis” (simulation of PDE’s, not optimization), and mostly in structural mechanics. We are referring here in particular to the work of Prof. Thomas J.R. Hughes and collaborators\(^4\), who showed these schemes had superior order of convergence than usual finite elements. Jointly with the Project-team Galaad and within the European project EXCITING (Exact geometry simulation for optimized design of vehicles and Vessels, http://exciting-project.eu/), we will develop “optimization algorithms” within the framework of iso-geometric approaches. This framework is anticipated to be ideal for generalizing our multilevel geometrical algorithm based on degree-elevation, making thus a link with the previous topic. Besides, the multilevel geometrical representation will also serve as the natural support for high and low-fidelity model coupling. Additionally, this activity should also foster the cooperation with R. Abgrall (Project-team Scalapplix) who is independently currently initiating developments of finite-element schemes of this type for fluids.

Concerning multi-disciplinary optimization, the successful treatment of a mixed aerodynamic/structural design optimization via a split of variables according to an appropriate eigenvalue problem encourages us to persist in this direction by searching for more general, and perhaps generalized eigenvalue problem formulations to be defined according to particular multi-disciplinary situations. Here, we will try also to elaborate an actual software to implement a rigorous decision tree for a self-adaptive optimization procedure, and test the approach in simplified but relevant engineering optimization cases.

We also ambition to provide documented case studies of complex multi-disciplinary optimizations. As mentioned above, numerous examples are inspired by aeronautical problematics (flight mechanics, compressible aerodynamics coupled with structural design and/or acoustic criteria), but not only (computational electromagnetics with France Telecom R and D, design optimization of steel elements with Arcelor-Mittal, optimization of an automobile engine with Renault within the OMD-2). Besides, we expect that our cooperation with ONERA will allows us to treat more profoundly the prototypical aero-structural optimization problem: coupled aero-structural gradients; mixed aerodynamic and structural objectives. A second thesis at ONERA directed by J.-A. Desideri is programmed to start next fall on this topic. Lastly, our Associated Team with the Mathematical Information Technology Department of the University of Jyvaskyla (Prof. P. Neittaanmäki) is very promising to help us develop alternate approaches in the three sectors of algorithms, software and application areas (e.g. Economy). Also, we have been recently approached by M. Pajot, president of the French Spirit Team that will compete in the 2012 America’s Cup. A doctoral thesis directed by us is being set up to develop numerical approaches to certain related concurrent engineering questions (fluid-structure optimization for racing sailing boats).

Last, but certainly not least, the increasing interest of the computational community in the treatment of uncertainties, their quantification, and their propagation encourages us to concentrate a real effort to develop methodologies in this area. Current methods (Monte-Carlo using metamodels, chaos polynomials, method of moments using derivatives by automatic differentiation tools) are very limited in the number of uncertain variables

\(^4\)ONR - Geometrically Exact Structural Analysis and Determination of Hydrodynamic Noise Sources (from http://users.ices.utexas.edu/~hughes/).
that can be taken into account. This line of cooperation with ONERA deserves the development of some basic research.

Another situation where uncertainties are important is flow control. There, the uncertainty is to be quantified in the whole unsteady flowfield, and this results in a more complex computational challenge, with numerous industrial problems in perspective (cooperation with the Fluid Mechanics Laboratory, UMR 6598, Ecole Centrale de Nantes).

Finally, we intend to study more systematically how should uncertainties and sensitivities be adequately integrated within a general optimization algorithm. For example, multi-objective formulations (e.g. parallel games) could also be used to define algorithms for robust design, in which a sensitivity criterion is treated as an auxiliary objective. This line of research will permit us to continue our strong cooperation with the Tropics Project-team in the area of automatic differentiation, particularly for second derivatives. We view this objective as fundamental in the long term for multi-disciplinary optimization. in general. We envisage to develop this research axis also in cooperation with the University of Jyväskyla.

Lastly, our expertise in finite-volume methods for nonlinear hyperbolic problems of fluid mechanics has led P. Goatin to prepare her Habilitation Thesis on pedestrian traffic models within our project-team. We expect this activity to lead her to particular developments of special numerical methods.

4.2 Objective 2 : Mathematical Analysis of Geometrical Optimization

Objectives in the following four years are in the use of very new algorithms for optimization in 3D radiating electromagnetic solution in near field. Algorithms based on Riccati control synthesis in the usual transient 3D electromagnetic. This will permit us to improve all our previous results in shape and obstacle reconstruction, mainly for realistic non metallic dialectic configurations. Several works in this direction have begun in 08-09 with L. Manca and X. Hachair. This new algorithm will permit to use PDE analysis (rather than integral equation analysis and approximations) and then to explore better the important case of shape and parameters singularities and extrapolate the previous analysis to weaker settings. We also just have begun a Thales-Radar optimization which is classified.

4.3 Objective 3 : Computing environment

Concerning collaborative platforms, the Opale project-team will concentrate during the next four years time frame on high-performance computing environments for large-scale multidiscipline optimization.

To this end, it will focus on the adaptation of distributed e-science workflow engines. This approach is currently a topic drawing much attention in the e-science community, and particularly in the distributed and grid computing communities. Indeed, potential users of sophisticated distributed environments have difficulties taking-up these technologies because of the technology barrier. Teams of computer science experts are required to educate and support user groups in other disciplines, e.g., CFD experts.

Workflow environments appear to have excellent features to both simplify access to these techniques and also provide support for distributed computing, using for example Web Services with which some of them interface seamlessly, e.g., YAWL.

The goal of the Opale project-team is therefore to work on distributed e-science workflow environments to provide seamless and powerful high-performance computing resources
to multidiscipline optimization applications, including fault-tolerance, dynamic user interactions and powerful exception handling mechanisms to be tested against large-scale industrial case-studies.

This is one of the goal of the upcoming OMD2 project, supported by the ANR (Agence Nationale de la Recherche). It will focus on access to high-performance distributed and heterogeneous resources providing fault-tolerance and dynamic adaptability. This requires at least two PhD student and one permanent staff member, full time.

4.4 Objective 4 : Modeling cell and tissue dynamics

**Wound healing and vesicle trafficking** With Barelli H. and Malandain G. we intend to investigate the relationship between growth factors (HGF, EGF) and the characteristics of wound healing (mean speed, spreading and scattering of cells). A first step is to develop and validate a mathematical model which couples the EGF+R-Arf1 cascade (ode’s system relating the concentrations of different factors which intervene in the cascade) to a macro biomechanical pde’s model (Olsen-Murray) which describes the wound dynamics.

**Wound healing and mean field behavior** With Almeida L. we are investigating approaches by which a population of cells is seen as playing a N-person noncooperative game with the aim to optimize stress-based criteria. The objective is to obtain macro (tissue) dynamics as limits of infinite number of cells playing their Nash equilibria.

**Cell motion** Our objective is to study the organisation and reorganisation of F-actin, integrin and related proteins when a cell moves. We expect to identify optimal transport maps arising from the dynamics of the latter factors, possibly in a game framework (F-actin monitors protrusion, controls production of lamellipodia and filopodia, and integrin and other adhesion proteins control the structural integrity of the cell).

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