INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Opale

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

Sophia Antipolis - Rhône-Alpes

THEME NUM

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2. Overall Objectives

2.1. Research fields

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

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

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

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

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

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 [74]. Our evolution field approaches permit to extend this viewpoint to the topological shape optimization ([77]).

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: $< \mathcal{A}\varphi, \varphi > \geq |\varphi|^2_H$ where H denotes a root space. We consider the following problem: given Ω_0, find a non autonomous vector field $V \in C^0([0, \infty[, H^r(D,\mathbb{R}^N)) \cap C([0, , \infty[, L^\infty(D,\mathbb{R}^N))$ such that, $T_t(V)$ being the flow mapping of V,

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

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

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

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

The intrinsic geometry is the main ingredient to treat convection by a vector field V. Such a non autonomous vector field builds up a tube. The use of BV topology permits these concepts to be extended to non smooth vector fields V, thus modeling the possible topological changes. The *transverse field* concept Z has been developed in that direction and is now being applied to fluid-structure coupled problems. The most recent results have been published in three books [2], [11], [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 [76]. 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. [78].

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. An international collaborative project has been set up in 2003 on this subject involving the OPALE project at INRIA in cooperation with CNES. 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 2007 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. CAST

The main contributions concerning the software platform CAST are twofold :

- first, a technical collaboration within the project has been set up for the development of a distributed computing environment for the deployment of parallel applications concerning the modelling of airfoil optimization techniques on distributed PC-clusters and the parallelization of the corresponding algorithms;
- second, a cooperation has been set up with CNES for the design, implementation and deployment of Grid-based Virtual Computing Environments.

The first aspect implies the parallelisation of the Simplex and 3D multi-level parameterization algorithms and the use of the PC-clusters and other various Linux workstations at INRIA Sophia-Antipolis and Grenoble. This will use the CAST distributed software platform on this environment.

The second aspect concerning Virtual Computing Environments resulted in the setup of an industrial collaboration with CNES for the design of seamless application design interfaces on the Grid. Based on current Grid technology and Web Services, a specific doctoral thesis is devoted to this aspect. The goal is to design and implement an "upperware" software that is extending the functionalities of current middleware platform to simplify the deployment of complex applications on heterogeneous Grids.

Further, strong implication in European Networks, e.g., AEROCHINA, led us to specify with European aircraft manufacturers and research centers the characteristics of a software integration platform for multidisciplinary code validation and verification in aeronautics. A demonstator of this platform is currently being designed in cooperation with CIMNE (Spain).

5.2. FAMOSA package for Optimum-Shape Design in Aerodynamics

We are developing the FAMOSA code (Full Adaptive Multi-level Optimum Shape Algorithms), designed for shape optimization of 3D aerodynamic bodies, based on the former OBEZ package. It integrates the following toolboxes:

- a flow-solver based on the NS3D code (legacy of the SINUS project);
- a module F-MANAGER managing the communications between the flow solver and the optimizer, by calculating an objective function (based on the results of the flow-simulation), by building metamodels and estimating statistical quantities for robust design;
- a parameterization module BZPARAM implementing a 3D multi-level and adaptive Bézier parameterization (Free-Form Deformation) and 3D mesh-update routines;
- an optimization module OPTIM containing general optimization routines using deterministic as well as semi-stochastic algorithms;
- a module PAROPTI allowing the use of a parallel architectures to instantiate the cost function evaluations.

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.

Moreover, a graphical interface has been developed in order to facilitate the use of the software and allow an easy integration of temporary users and developers.

5.2.1. NS3D (updates of the flow solver code):

Keywords: *compressible inviscid or viscous flow*, *finite volumes*, *implicit pseudo-time-marching methods*, *upwind schemes*.

Participants: Michele Andreoli [former trainee], Aleš Janka [former Post Doctoral Student, presently at Fribourg Univ., Switzerland].

The NS3D flow code solves the 3D Euler and Navier-Stokes equations, on general unstructured tetrahedra meshes. The steady flow solution is found as the asymptotic limit of a pseudo-time-dependent process. The code combines the following ingredients:

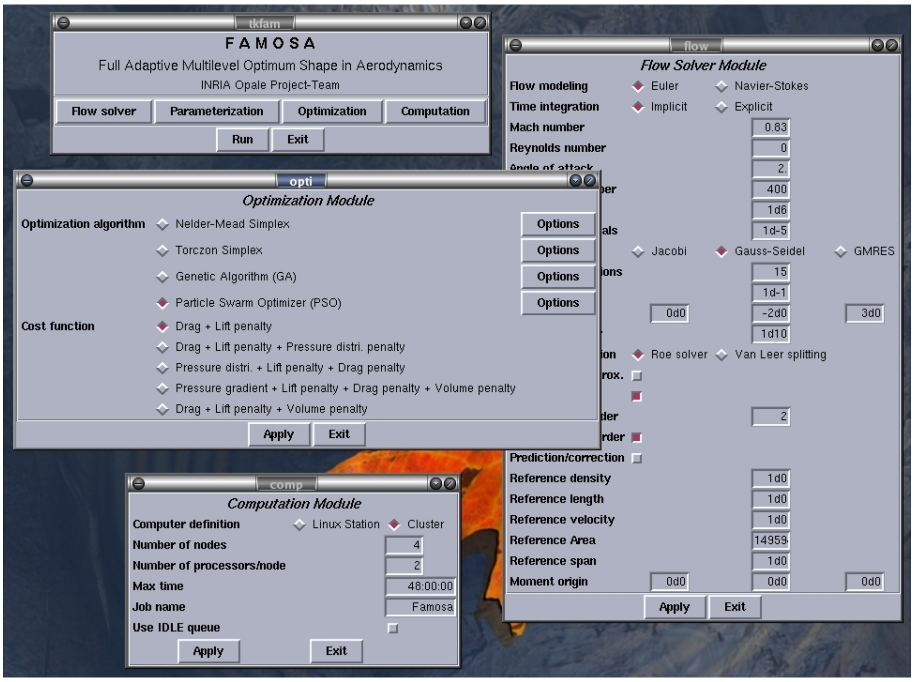
- a finite volume spatial discretization with an upwind scheme for the discretization of the convective fluxes by the Roe or van Leer splittings;
- an extension to second-order spatial accuracy based on the MUSCL (Monotonic Upwind Scheme for Conservative Laws) approach with flux limiters;
- implicit time-stepping by a simple one-step first-order formula.

The code has been revised and modified, its efficiency and memory requirements improved by changing the sparse-matrix representation scheme. The modifications permit to run flow-simulations past complete aircraft.

5.2.2. F-MANAGER (communication between solver and optimizer):

Keywords: *cost function*, *meta-models*, *penalization*, *statistics*.

Participant: Régis Duvigneau.



FAMOSA
Full Adaptive Multilevel Optimum Shape in Aerodynamics
INRIA Opale Project-Team

Optimization Module

Optimization algorithm ○ Nelder-Mead Simplex
○ Torczon Simplex
○ Genetic Algorithm (GA)
● Particle Swarm Optimizer (PSO)

Cost function ● Drag + Lift penalty
○ Drag + Lift penalty + Pressure distri. penalty
○ Pressure distri. + Lift penalty + Drag penalty
○ Pressure gradient + Lift penalty + Drag penalty + Volume penalty
○ Drag + Lift penalty + Volume penalty

Computation Module

Computer definition ○ Linux Station ● Cluster
Number of nodes 4
Number of processors/node 2
Max time 48:00:00
Job name Famosa
Use IDLE queue ☐

Flow Solver Module

Flow modeling ● Euler ○ Navier-Stokes
Time integration ● Implicit ○ Explicit
Mach number 0.83
Reynolds number 0
Angle of attack 2.
ber 400
1d6
als 1d-5
○ Jacobi ● Gauss-Seidel ○ GMRES
ions 15
1d-1
0d0 -2d0 3d0
1d10
ion ● Roe solver ○ Van Leer splitting
rox. ☐
☑
der 2
rder ☑
Prediction/correction ☐
Reference density 1d0
Reference length 1d0
Reference velocity 1d0
Reference Area 14959
Reference span 1d0
Moment origin 0d0 0d0 0d0

Figure 1. Graphical interface for the FAMOSA code

After the flow-simulation for each shape, aerodynamic coefficients are calculated (lift, drag, pressure gradient) and passed to a routine to evaluate the objective function. The objective function is a measure of quality of the shape. It usually combines target values of aerodynamic coefficients together with penalties originating from geometrical constraints (volume, thickness). Several objective functions have been implemented for a lift-drag optimisation in the transonic regime and a sonic-bang minimization in the supersonic regime, with or without geometrical constraints.

The aerodynamic coefficients computed for each shape are then stored in a database, that can be used to buid metamodels (polynomial fitting, neural networks, kriging). These metamodels can then be employed to replace some cost function evaluations or provide additional information (gradient, hessian).

For robust design, statistical quantities, such as mean or variance, of the aerodynamic coefficients are estimated on the basis of the metamodels.

5.2.3. BZPARAM(parameterization):

Keywords: *Free-form deformation*, *elliptic solvers*, *moving mesh*, *multi-level*, *tensorial 3D Bezier*, *torsional springs*.

Participants: Michele Andreoli [former trainee], Régis Duvigneau, Aleš Janka [former Post Doctoral Student].

The parameterization module BZPARAM manages, during the optimization process, the deformations of 3D shapes and of the corresponding tetrahedral computational mesh. It accounts for the possible *a priori* geometrical constraints (fixed parts of the shape, angles, or thicknesses) and uses a represention of the optimized shape by a condensed parametric vector $\mathbf{x} \in \mathbb{R}^N$ (N small) containing just an active set of degrees of freedom of the shape deformation. Such a parametric vector $\mathbf{x}$ can then be passed to a general optimization algorithm operating in $\mathbb{R}^N$.

The developed BZPARAM module implements the Free-Form Deformation with a 3D tensorial Bézier parameterization. A multi-level parameterization can be obtained by using the degree elevation property [75].Hence, a set of nested parameterizations can be easily built and used for multi-level optimization strategies.

A routine is being developed, that adapts the initial and perhaps naïve parameterization to the particular problem studied, on the basis of a first approximation of the optimal shape. Basically, it automatically modifies the definition of the deformation basis functions to regularize the deformation field.

Mesh-deformation routines are being developed within this module to update the 3D computational mesh around the deformed objects. The objective is to move rapidly the existing nodes of the mesh to follow (large) mesh deformations, while preserving mesh quality and local mesh metrics (boundary layers). Experiments were performed with torsional-spring pseudo-elasticity model and with elliptic solvers. The FFD technique, which operates a volumic deformation, can also be employed to deform the shape and the mesh simultaneously.

5.2.4. OPTIM (optimizers):

Keywords: *genetic algorithm*, *hybridization*, *particle swarm optimization*, *reduced models*, *simplex method*.

Participants: Michele Andreoli [former trainee, simplex algorithm], Yannick Berard [former trainee, hybridization in PIKAIA], Régis Duvigneau [Multi-directional search algorithm, Particle swarm optimization, parallel implementation], Abderrahmane Habbal [hybridization in PIKAIA], Aleš Janka [former Post Doctoral Student, simplex algorithm], Latifa Oulladji [former trainee, new genetic operators in AG2D].

The optimization module contains some general optimization algorithms which minimize a given objective function in a parametric space $\mathbb{R}^N$. The implemented algorithms are:

- a “binary-coded” genetic algorithm based on AG2D (legacy of the SINUS project), with modified genetic operators;
- a “real-coded” genetic algorithm based on PIKAIA, with a gradient-based hybridization;
- a particle swarm optimization (PSO) algorithm;
- the Nelder-Mead simplex algorithm;
- the Torczon multi-directional search algorithm.

The last two routines implement deterministic descent methods, that do not require gradient information. However, due to the multimodality of aerodynamic cost functions, semi-stochastic optimization strategies, such as genetic algorithms of particle swarm optimization, are mandatory for global optimization. Genetic algorithms mimic the evolution of a population, through genetic operators such as selection, crossover and mutation. Particle swarm optimization 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 most serious disadvantage of semi-stochastic algorithms is the necessity to evaluate fitness (objective) functions for a large number of shapes. Each evaluation of fitness function comprises at least one simulation of the flow problem in 3D. At the same time, most of the evaluations are not usefull for the evolutionary process. Therefore, simplified models for fitness evaluation, such as metamodels, are of interest. A new algorithm has been developed based on the “real-coded” genetic algorithm PIKAIA employing a first-order gradient interpolation of fitness values on subsets (clusters) of the current population. The use of neural networks to replace some evaluations or provide additional informations (gradient, hessian) is also studied.

5.2.5. *PAROPTI (parallelization):*

Keywords: *MPI*, *parallel computing*.

Participant: Régis Duvigneau.

Most of the optimization algorithms implemented employ at each iteration independent and simultaneous cost function evaluations. A parallel implementation has been developed, based on the MPI library, to distribute these evaluations on a given number of processors. It results in a significant reduction (quasi linear) of the computational time.

5.3. Numerical Modules for Gradient Computations in Electromagnetics

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

Shape gradients with respect to 3D geometries in electro-magnetic 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 (6.4.9). This code is to be latter interfaced with the code for array antenna optimization (6.4.8).

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].

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 the long run, the simulation tool will be used in a control loop to prevent flood or reduce the damages it causes.

The proposed numerical approach consists in simulating the flow by solving the shallow-water equations, as it is customary in estuary-flow-type simulations, by a finite-volume method. Exploiting an original idea by Leroux, the system of partial-differential equations with topographic source term is completed by a trivial equation for the bathymetry. By applying a change of variable, the system is given a celerity-speed formulation, and linearized. As a result, an approximate Riemann solver preserving the positivity of the celerity can be constructed, permitting *wet and dry simulations* to be performed. The numerical simultation of test cases has been presented [68]. The next step will be to extend the approach to a realistic numerical terrain model, using topographic data provided by geographs. Special boundary conditions will be implemented to account for the possibility of flood.

6.1.2. Interpolation of Infinite Sequences by Entire Functions

Participant: Jean-Antoine Désidéri.

The study was originally motivated by a theoretical question raised by Warming and Hyett in a famous publication on the *Modified Equation Approach* [79]. Their classical accuracy analysis of a finite-difference method applied to a time-dependent problem implicitly relies on the assumption that a function interpolating the numerical values can be expanded, over an indefinite domain, in Taylor's series of the independent variables x and t. We have established [39] constructively that the problem of interpolation of an arbitrary infinite sequence of real numbers by an *entire* function of x (and possibly t) admits uncountably many solutions. In the case of a single variable, if the values are bounded, the interpolant can be made bounded, and all its derivatives bounded. Besides, the construction is generalized to the interpolation of the values of the function and its derivatives up to an arbitrarily prescribed order (*Hermitian interpolation*). The proposed interpolant depends on a free parameter λ, and its behavior as λ varies is illustrated by a numerical example.

6.1.3. Periodic solutions to the Maxwell equations

Participants: H.Q. Chen [Nanjing University of Aeronautics and Astronautics], R. Glowinski [University of Houston], P.M. Jacquart [Dassault Aviation, DTIAE], S. Lapin [Univ. of Houston, Dept. of Mathematics], J. Périaux.

An asymptotic domain–decomposition method using Lagrange multipliers and the conjugate–gradient algorithm has been devised to capture periodic solutions to the Maxwell equations in heterogeneous media. This method will be replaced subsequently by the so-called *HUM (Hilbert Uniqueness Method)* more robust for optimization problems with evolutionary algorithms [58].

6.1.4. Domain decomposition methods in fluid dynamics

Participants: H.Q. Chen [Nanjing University of Aeronautics and Astronautics], R. Glowinski [University of Houston], Jacques Périaux.

A domain decomposition/Nash equilibrium methodology for the solution of direct and inverse problems has been devised and tested in relevant problems of fluid dynamics [54].

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" (see paragraph 8.1.1).

6.2.1. Hierarchical (multilevel) and adaptive shape parameterization

Participants: Badr Abou El Majd, Praveen Chandrashekarappa, Jean-Antoine Désidéri, Régis Duvigneau, Abderrahmane Habbal, Jichao Zhao.

6.2.1.1. Algebraic theory of multilevel parametric optimization

With the purpose of developing a basic conceptual model for shape optimization, we have considered the minimization of the quadratic form measuring the square of the distance between a candidate shape and a given target geometry. When solving this problem by a steepest-descent-type optimizer (without special preconditioning), the iteration becomes similar to the classical point–Jacobi iteration applied to a specific linear system, whose matrix reflects the choice of parameterization. This model has been used to support a spectral analysis of the algebraic system under consideration, permitting us to establish a parallel between the present approach and standard geometrical multigrid concepts, identifying in particular the notion of modes and frequency. Thirdly, the analysis suggests us an alternate definition of the *two-level ideal algorithm*, which is classically the theoretical building block of a more general multilevel strategy [40].

6.2.1.2. Multilevel shape optimization algorithms, FAMOSA

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 multilevel strategy and a technique for parameterization self-adaptivity have been assessed by numerical experiments on an inverse shape model problem, confirming both are very effective [41].

6.2.1.3. Application of FAMOSA to 3D Aerodynamic Problems

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 [61].

6.2.1.4. Parameterization adaption

Parameterization techniques commonly used in aerodynamic shape optimization are essentially general and multi-purpose approaches. As a consequence, they cannot be well suited to a particular shape optimization problem. A new method has been developed that adapts an initial and perhaps naïve parameterization of an aerodynamic shape by the Free-Form Deformation (FFD) technique, to the particular optimization problem to solve, according to a first approximation of the solution. It is based on the optimization of the mapping that defines the FFD coordinates from the lattice coordinates, in order to regularize the displacement of the control points.

This approach was tested on the optimization of the wing shape of a business aircraft. It was shown that parameterization adaption permits to reach shapes of better fitness and also to accelerate the convergence. Especially, it was found that the use of an adapted parameterization of lower degree yields better results than the use of a naïve parameterization of higher degree [57], [70], [61].

6.2.1.5. Combining multilevel algorithms with evolutionary computing

The use of multilevel parameterization strategies in conjunction with evolutionary algorithms is not straightforward, since these methods do not rely on an optimization path that could be split into several parts to solve the problem in different design spaces. Particularly, we have shown in the past that genetic algorithms are not well suited to these strategies.

Therefore a new approach has been developed using Particle Swarm Optimization (PSO) algorithms. Particle swarm optimization 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 [69].

6.2.2. Multidisciplinary Optimization

Participants: Badr Abou El Majd, Praveen Chandrashekarappa, Jean-Antoine Désidéri, Régis Duvigneau, Abderrahmane Habbal, Jichao Zhao.

6.2.2.1. 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. 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 [71].

6.2.2.2. Coupled fluid-structure optimization

In his thesis, B. Abou El Majd is treating a particular case of concurrent shape–optimization by coupling the drag minimization of a transonic aircraft wing with the reduction of a criterion related to structural design under surface and volume constraints. The structural criterion attempts to equalize over the geometry the stress due to the aerodynamic load. Again, a game strategy is elaborated in which the primitive shape control variables are split in two packets, each packet corresponding to the *strategy* of a player in a simulated Nash game. The experiments succeed but indicate that a delicate choice of numerical parameters is necessary to achieve the equilibrium.

6.2.2.3. Metamodels

Multidisciplinary optimization is particularly time consuming, since several disciplines and simulation tools are involved in the design procedure. Moreover, communication between the different displines may be tedious in practice, because of the use of different shape representations, meshes, length scales, objective functions, etc.

Therefore, we are currently developing approaches that rely on *metamodels*, i.e. models of models, to accelerate the optimization procedure and facilitate communication among disciplines. Metamodels can be used to replace some expensive simultations by cheap estimations or provide information about the gradient or hessian of the objective function, that can be employed by the optimizer or for the splitting of territories in concurrent optimization.

Different techniques of metamodeling (polynomial fitting, radial basis functions, kriging functions) have been validated on academic problems. Strategies to implement them in practical multidisciplinary optimization procedures are currently in study. These developements are mainly supported by the OMD project granted by ANR/RNTL.

6.2.2.4. Hybrid algorithms

Derivative-free optimization algorithms are appealing, since they give sense to the expression ‘‘one solver = one optimizer”.

These algorithms are essentially divided in two families. The first family contains *P*owell-like algorithms developed in the 60s. These methods cannot pretend to perform global optimization. The second family contains evolutionary algorithms, particularly genetic algorithms and evolution strategies. These probabilistic algorithms are designed *t*o perform global optimization. John Holland defined their fundamental principles in 1962 and David Goldberg contributed in popularizing them for practical problems in 1989.

Comparing evolutionary algorithms to classical descent methods using gradient information raises pros and cons, wich are accepted or not depending on the nature of the optimization problem. Evolutionary algorithms are not trapped in local-minimum regions, but require a large number of cost function evaluations. On the contrary, classical descent methods are characterized by a high convergence rate, but they have no way to escape from local-minimum regions. Moreover, gradient computations may yield theorical or computational difficulties.

In 2003, we have implemented a hybridization approach using a local discontinuous approximation based on a classification algorithm, without memory effects from one generation to the next. In the present work, we develop a new variant using a local continuous approximation, so-called “Liszka-Orkisz approximation”, including memory effects. This approach has been applied to a difficult industrial problem concerning preform forming [44].

6.2.3. Robust design

Participant: Régis Duvigneau.

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, that includes uncertainty effects in the design procedure, by maximizing the statistical mean of the objective function while minimizing its variance.

First results, based on the linearization of the system [33] to estimate statistical quantities, have shown that first-order statistics can be too limited for complex applications. Then, a more straightforward and *non-linear* approach is now under study. This methodology is based on the use of metamodels to estimate the uncertainties of the objective function from the uncertainties of the input parameters of the simulation tool. During the optimization procedure, a few expensive simulations are performed for each design variables set, for different values of the uncertain parameter in order to build the database used for metamodels training. Then, metamodels are used to estimate some statistical quantities (probalistic mean and variance) of the objective function and constraints. Finally, a robust optimization problem is solved by maximizing the mean of the objective function while minimizing its variance.

This strategy is currently tested for the aerodynamic optimization of the wing shape of a business aircraft. The robust design of the wing is performed by reducing the drag mean and the drag variance, under a probabilistic constraint on the lift, for uncertainties on the Mach number.

6.2.4. Application of sensitivity analysis and optimization algorithms in CFD

Participants: Régis Duvigneau, Michel Visonneau [Laboratoire de Mécanique des Fluides CNRS UMR6598, Nantes], Dominique Pelletier [Ecole Polytechnique de Montréal].

Recent developments concerning shape optimization in fluid mechanics have been applied to flow control, in order to optimize actuator parameters (e.g. oscillatory jet frequency and position). Promising results have been obtained by optimizing the characteristics of oscillatory/steady jets for stall control for an airfoil [36], [35], [56].

Some improvements have also been reported in sensitivity analysis (Continuous Sensitivity Equation Method) by increasing the accuracy of the functional gradient for shape parameters when complex problems are considered [34]. This methodology has been applied to shape optimization problems [32], fast estimation of nearby solutions [60] and uncertainty analysis [33]

6.2.5. Numerical Shape Optimization of Axisymmetric Radiating Structures

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

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

To initiate these developments, we have first considered the simplified approximation known as “Physical Optics” for which the fields are known explicitly for a given geometry. This approximation has been validated by comparison with the result of SRSR, a 3D solver of the Maxwell equations provided by France Télécom R & D, in terms of radiating diagrams.

A typical optimization problem consists in finding the shape whose radiation fits a target radiation. A parametrical shape optimization based on *Free-Form deformation* (FFD) has been considered. The analytical gradient w.r.t. the FFD parameters has been derived and validated by finite differences. Gradient-based strategies showed efficiency for small shape perturbations. A new multilevel semi-stochastic algorithm based on Particle Swarm Optimization (PSO) methods showed robustness for global optimization [69]. In a next step the field will be computed using SRSR.

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 [45], [59].

6.4. Mathematical analysis in geometrical optimization

6.4.1. Non cylindrical dynamical system

Participant: Jean-Paul Zolésio.

The 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 [37].

6.4.2. 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 [28]. 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. 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 [23].

An alternate approach to fluid-structure has been developed with P.U.L.V. (J. Cagnol) [24] and the University of Virginia (I. Lasiecka and R. Triggiani, Charlottesville) on stabilization issues for coupled acoustic-shell modeling. [73].

6.4.4. 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 [31].

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

6.4.5. 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 [30], [55].

6.4.6. Shape stabilization of wave equation

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.

6.4.6.1. 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 technic [24].

6.4.6.2. 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 [52], [53].

6.4.7. OpRaTel Electronic-Laboratory

Participants: Marwan Moubachir, Jean-Paul Zolésio.

The collaboration with France Télécom 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 telecommunication purposes; a patent will shortly be deposited;
- frequency allocation, a difficult modeling topic of major importance for our industrial partners.

6.4.8. 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 [25], [26].

6.4.9. 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. Jerome 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 Jerome 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) [25], [26].

6.4.10. 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 apporach in the Euler setting. Let us recall that the Courant metric is roughtly defined as follows: For exemple

$$\mathfrak{F} \;=\; \{F \in C^1(R^N, R^N) : F - I_d \in C^1_0(R^N,\; R^N), F^{-1} \in C^1_0(R^N,\; R^N)\,\}$$

$$\Omega_1,\;\Omega_2 \quad \text{open sets},$$

We consider all functions $F \in \mathfrak{F}$ such that :

$$F(\Omega_1) = \Omega_2,$$

These function will be decomposed as :

$$F = (I_d + f_1)o(I_d + f_2)o(I_d + f_3)o....(I_d + f_M)$$

Where we recall that the *COMPOSITION* is

$$FoG(x) \;=\; F(\;G(x)\;)$$

The Identity mapping I_d being the Neutral element. Then

$$f_i = F_i \,-\, I_d$$

represents the displacement at each "step".

$$d(\Omega_1, \Omega_2) \;=\; INF\;\Sigma_{i=1,\ldots,M}(\;\;||f_i||_E + \;||g_i||_E\quad)$$

The Infimun being on all M, and all families of M smooth mappings

$$F_i = I_d + f_i,\;\; F_i^{-1} = I_d \,+\, g_i \;\;\in E$$

such that the following CONNECTION holds:

$$(I_d + f_1)o(I_d + f_2)o(I_d + f_3)o....(I_d + f_M)(\Omega_1) \;=\Omega_2$$

This metric furnishes a complete metric space on sets.
It is extended to larger class of sets and using the *transverse flow mapping* (see the book [23]) we derive *evolution equation* which caracterises the Geodesic for that differentiable metric [65].

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

6.5. Virtual computing environments

Participant: Toan Nguyen.

The advantages demonstrated by grid-computing infrastructures and complex problem solving environments are fundamental in terms of raw computing power and massive storage media. Indeed, they allow parallel and distributed computing for demanding applications that can now be deployed on thousands of connected processors and they can connect petabytes of data through gigabits/sec networks at affordable cost.

So far, however, there seems to be some reluctance from the industry to use these environments because they require uncommonly available expertise in the computer science field [72]. In the last decade, users have become experts in the manipulation of Web browsers to access inter-continental mass of data and remotely execute pieces of code transparently. Unfortunately, grid computing environments are still far from providing these seamless and flexible interfaces. New concepts and interfaces are therefore required to alleviate these shortcomings.

One approach which is currently marketed by software vendors is "on demand computing" and "Utility computing". Other companies have developed niches where "virtual clusters", "user-centric virtual environments" and "virtual data-centers" can be rented and charged based on hourly and resource fees. These approaches are basically offering distributed and integrated data and compute centers to large customers. Resellers make grid and parallel compute centers available to the application users. This does not however solve two problems:

- the seamless access of large computing power to SMEs
- the easy and affordable design, deployment, execution and monitoring of complex applications to non experts

To solve these two problems, the approach that is currently explored by the OPALE project is the definition of virtual computing infrastructures by which users will be able to define their specific computing environment and use it with their own ad-hoc procedures. This requires the design and implementation of powerful services implemented on top of existing grid middleware environments. The goal is to provide standardised services and the corresponding procedures to help the non-expert application developers specify the resources and computing infrastructure they need to run the complex multidisciplinary applications they want to execute. This implies the design of generic graphic problem solving interfaces, the implementation of enabling "upperware" and ad-hoc interfaces on top of existing grid middleware.

The CAST platform has therefore been interfaced with the UNICORE and GLOBUS middleware (GT3 and GT4, WSRF) , and also with the J2EE and standard Web service (WSDL) environments by Vincent Bel and Lizhe Wang. Ongoing work implies the deployment of this software environment and the implementation of parallel 3D airfoil optimization testcases using hierachical multilevel parameterization on the Grid5000 research network [62], [63], [64], [22].

7. Contracts and Grants with Industry

7.1. Optimum-shape design in aerodynamics and multidisciplinary extensions

Aerodynamic Generic-Wing Shape Optimization for a Business Aircraft, with Piaggio Aero France; this contract reinforces a cooperation initiated through a Local Cooperative Action (COLORS) on “Hierarchical Parameterizations”, and complements the set up of B. Abou El Majd Doctoral’s program financed by the PACA Region. Additionally, it is being consolidated by a Cooperation Agreement with CIRA (Centro Italiano per la Ricerche Aerospaziale), Capua, under finalization.

7.2. Optimization in electromagnetics

- France Télécom (La Turbie): optimization of antennas; a new contract supports partially the thesis of B. Chaigne.
- Thalès (Bagneux) : optimization of the most dangerous trajectories in radar applications.

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.

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).

8.1.3. Action COLOR 2005 : Ab in vivo ad in silico

A. Habbal is responsible in the OPALE project for the Action COLOR *Ab in vivo ad in silico*. The other partners are the "Institut de Pharmacologie Moléculaire et Cellulaire" IPMC (CNRS and INSERM) and EPIDAURE project. The grant is 11 Keuros for one year.

8.2. International Networks and Working Groups

The OPALE project is involved in European interest groups on code validation and mathematical modelling, and in international cooperations on optimum-shape design.

8.2.1. The HEAVEN Project

Whereas resource co-allocation and dynamic control of distributed applications remains an important objective, a large effort is also currently dedicated to Virtual Computing Environments which are emerging as a new concept encompassing the grid technologies, distributed and parallel computing, as well as business processes for their widespread use in sophisticated technology areas, such as multidiciplinary design and optimisation.

The vision which underpins this approach is that seamless interfaces to distributed and multidisciplinary design are mandatory for the general use of grid technology in engineering, business and education.

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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))

In much the same way as the Internet is now available everywhere to everyone today through Web browsers, the focus is here to deliver new application design methodologies by making the grid technology transparent through Virtual Computing Environments.

These environments, based on graphic interfaces, will rely on grid technology middleware and presumably require specific functionalities for the advanced definition and control of user applications, in particular in multidisciplinary engineering, based on mixed data and workflow management. This approach is a joint collaboration with CNES (French National Space Research Center).

The goal is here to define and develop software "upperware" concepts, which will build on current middleware technology for the Grid, in order to provide Virtual Computing Environments. They will be able to support seamlessly application definition in various multidisciplinary fields, including engineering, business and education.

For this objective to be reached, high-level functionalities will be defined and developed for the modular and incremental construction of heterogeneous applications. This will rely on software component models and Web Services to provide simple interfaces that will hide the technicalities of current distributed computing technology, e.g., Corba.

The goal is to mask the technicalities of grid middleware, e.g., Globus, to the casual users, and provide a software layer in charge of high-level tasks concerning the control of grid-based applications (remote control of suspended sub-tasks, analysis of performance bottlenecks, advisory input to the users concerning the distribution of sub-tasks, etc). This work is conducted within the New Collaborative Working Environments Unit of the DG INFSO F4 of the EC.

8.2.2. Support Action AEROCHINA

The OPALE project participates in the European project AEROCHINA which started in october 2005 and aims at developing the cooperation between European and Chinese industries and research institutions in multidisciplinary modeling, simulation and design in aeronautics. This is a large network of participants. It involves twelve major European companies and institutes (ONERA, DLR, Airbus, EADS, Dassault-Aviation, ...) and twelve major Chinese partners. The goal is to implement a reference framework for modeling and simulation for research and industry in the domain of multidisciplinary design in aeronautics.

The project's participation is to contribute jointly with CIMNE (Barcelona, Spain) and ACTRI (China) to develop software tools for data collection and cooperative work and to participate in the definition of numerical methods for multiphysics analysis and optimization. Cooperation will be developed particularly with the universities of Nanjing and Tsing-Hua in aerodynamic optimization.

Following a meeting held in Xi'an (China) in October 2006, the next action will be the final project meeting to be held in Barcelona in April 2007.

8.2.3. 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.

8.2.4. Collaboration with India

The French–Indian Workshop in Aeronautics was organized in Sophia Antipolis (November 29-December 1). This workshop is a follow–up of a SAROD workshop held in Bangalore last year, and gathered experts from France (CNES, Dassault Aviation, Esterel Technologies, INRIA, LEA Poitiers, ONERA, Univ. Toulouse) and from INDIA (ADA, NAL, IIS, EMU, JNCASR,Bangalore, DRDL, Hyderabad) on topics related to multidisciplinary optimization and control in aeronautics.

9. Dissemination

9.1. Education

The members of the OPALE project participate in the Educational effort within different areas at the University of Nice (UNSA).

9.1.1. Master's degree in Mathematics, "Shapes"

The OPALE project has been involved in the definition of this new Master's degree program dedicated to mathematical aspects of general shapes, and to industrial applications. The project is fully in charge the second term course UEf4 : "Shape Optimization" (20 hrs) which includes lessons in

- Calculus of variations, optimal control, domain deformation, domain derivatives and applications (A. Habbal),
- Finite element method (A. Habbal),
- Industrial motivation and examples, hierarchical parameterization, adaptative Optimization (J.-A. Désidéri).

9.1.2. Ecole Polytechnique Universitaire (EPU), Nice

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

- Numerical Engineering methods (first year, 75 hrs)
- Programming mathematics (first year, 16 hrs)
- Numerical Methods in Finance (third year, 18 hrs)

J.-A. Désidéri teaches the following courses ("Applied Mathematics and Modelling"):

- Multiscale methods (36hrs)

R. Duvigneau teaches the following courses ("Applied Mathematics and Modelling" and "Information Systems"):

- Numerical Engineering methods (first year, 24 hrs)

9.2. Participation in International Courses

- J. Périaux organized with Prof. H. Deconinck the course *Introduction to Optimization and Multidisciplinary Design* at the Von Karman Institute, March 2006 [20], and delivered three lectures [46] [47] [48]. J.-A. Désidéri delivered two lectures in this course [38] [29].
- R. Duvigneau delivered a lecture on "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.

9.3. Theses and Educational Trainings

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

Badr Abou El Majd, University of Nice-Sophia Antipolis; doctoral student (PACA Region scholarship); topic: Hierarchical algorithms and game strategies for the aerodynamic and structural shape optimization of a business jet.

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.

Louis Blanchard, University of Savoie, Chambéry; April-Aug. 2004: Optimal weighting for network antenna; doctoral student since October 2004; topic: design of antennas by optimization and numerical active control.

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.

9.4. Organization of Scientific Events

J.-A. Désidéri and P. Rambert co-organized at INRIA Sophia Antipolis, July 6-7, 2006 the kick-off meeting of the "3+3 Mediterranean Program". This program, launched this year as an INRIA initiative, supports a number of scientific cooperation projects between INRIA teams and partners in Maghreb (Algeria, Marocco and Tunisia) as well as in Italy and Spain, with a perspective of forming scientific a network capable of proposing European projects in the area of STIC. (See: http://www-direction.inria.fr/international; item: 3+3 Méditerranée.)

A. Dervieux [Project Teams Smash/Tropics], J.A. Désidéri, M. Masmoudi [University Paul Sabatier, Toulouse], J. Périaux and O. Pironneau [University of Paris 6] coorganized the French–Indian Workshop in Aeronautics in Sophia Antipolis, November 29-December 1. This workshop is a follow–up of a SAROD workshop held in Bangalore last year, and gathered experts from France (CNES, Dassault Aviation, Esterel Technologies, INRIA, LEA Poitiers, ONERA, Univ. Toulouse) and from INDIA (ADA, NAL, IIS, EMU, JNCASR,Bangalore, DRDL, Hyderabad) on topics related to multidisciplinary optimization and control in aeronautics. See http://www-sop.inria.fr/opale; Item: French–Indian Workshop.

9.5. Participation in Scientific Committees

- J.-A. Désidéri is a member of *Comité Scientifique et Technique (CST) auprès du Centre National de Recherche Technologique 'Aéronautique et Espace'* (Scientific and Technical Committee of the National Center for Technological Research 'Aeronautics and Space'), CNRT-AE at Cerfacs, Toulouse.
- J.-A. Désidéri is the Delegate of the Directorate for International Relations in the Sophia Antipolis Unit. This responsability consists in participating in hosting a large number of foreign delegations visiting the unit, participating in the organizational activities of the Directorate including juries (such as the jury for the INRIA Associated Teams Program), and in disseminating information related to cooperation programs within the unit. As part of this responsability, J.-A. Désidéri co-organized the kick-off meeting of the "3+3 Mediterranean Program" (see above).
- A. Habbal is member of the specialists board for sections 25-26-27 in IUFM of Nice.
- T. Nguyen is member of the Advisory Board of the French-Finnish Association for Scientific Research.
- J.P. Zolésio is chairman of Working Group IFIP 7.2 *System Modelling and Optimization*.

9.6. Invited or keynote lectures

- *Aeronautics multidisciplinary applications on grid computing infrastructures*, Second Grid@Asia Workshop Shanghai (CN), February 2006 (T. Nguyen).
- *Shape Tube Metric and Geodesic*, Shape Space,IMA Minneapolis , April 2006 (J.P. Zolésio).
- *Stabilization and Wing Shape Morphing*, ICNPAA-2006 - Mathematical problems in Engineering and Aerospace Sciences, Budapest, Hungary, June 2006 (J.P. Zolésio).
- *Courant Metric in Shape Analysis*, MIA06, Paris, France, April 2006 (J.P. Zolésio).

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