INRIA

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 4B

Activity Report

2003

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2. Overall 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, and the geometrical optimization of antennas in partnership with France Télécom and Thalès Air Défense (see Opratel Virtual Lab.).

3. Scientific Foundations

3.1. Numerical Optimization of PDE systems

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

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, 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.

Genetic Algorithms (GAs), and more generally Evolutionary Strategies (ES), are methods based on natural selection. They rely on the analogy with one of the best known Darwinian principles : *survival of the fittest*. GAs operate on a population of individuals that *evolve* in the course of generations, according to pseudo-stochastic operators, towards an optimal individiual, solution to an optimization problem. These individuals are referred to as *chromosomes* and can be coded as binary strings. They evolve selectively according to their *fitness function* value, that is the value of the functional to be optimized.

GAs differ from the more classical deterministic methods (steepest descent, conjugate gradient, one-shot methods) in three principal ways : *(i)* they do not necessitate the explicit calculation of the gradient, or even higher-order derivatives; *(ii)* they operate on a population of individuals instead of a single representative; *(iii)* they involve semi-stochastic operators. As a consequence, they are notably very robust, often successful in optimizing multimodal, non-convex and non-differentiable functions, and better equiped to avoid stagnation in local minima [58].

In this area, the project aims at developing numerical approaches by ES or hybrid methods, for the treatment of more and more general optimization problems, but also, at enhancing the computational cost-efficiency of these methods by various techniques of numerical analysis (model reduction, e.g. by POD; convergence acceleration, in particular by multi-level methods; best approximation and shape-parameterization; hybridization of optimizers; 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 view point 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. While obviously in any finite dimensional approach we are back in the Hilbert framework, and dual spaces are identified implicitly to the shape parameter spaces. Ignoring this question leads to well-known instabilities which necessitate some smoothing procedure in order to stabilize the shape large evolution. This point is sharp in the "narrow band" techniques where the lack of stability implies 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 rises 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 are back 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 a "had 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 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([5]). Our evolution field approaches permit to extend this view point to the topological shape optimization ([17]).

3.2.1. *Shape differential equation*

We denote $G(\Omega)$ the shape gradient of a functional J at Ω. There exists $s \in R^+$ such that $G(\Omega) \in H^{-s}(D, R^N)$, where D is the universe (or "hold all") for the analysis. For example $D = R^N$. 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 to be the basic tool for intrinsic geometry. The limit case $b_\Omega \in C^{1,1}(\mathcal{U})$ (where $\mathcal{U}$ is a tubular neighborhood of the boundary Γ) is the important case.

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

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

The existence of such bound has been proved first 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 completely analysed in 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 charts, and to work at *minimal* regularity for the geometries.

The intrinsic geometry is the main ingredient to treat convection by a vector fields 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 [5]. The most recent results are in three books [3] [9] [1].

3.3. Integration platforms

Grids for complex problem solving 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 require powerful computing infrastructures and particular software coupling techniques. Simultaneousl, advances in computer technology advocates 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 numeric technology and computer science. New approaches including evolutionary algorithms, parametrisation, multi-hierarchical decomposition lend themselves seamlessly to parallel implementations in such computing infrastructures. This opportunity is being dealt by project OPALE since its very beginning. A software integration platform has been designed by project OPALE for the definition, configuration and deployment of multidisciplinary applications on distributed heterogeneous infrastructure [15]. 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 hierarchic algorithms with game theory [60].

The main drawback 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. Still however, it 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

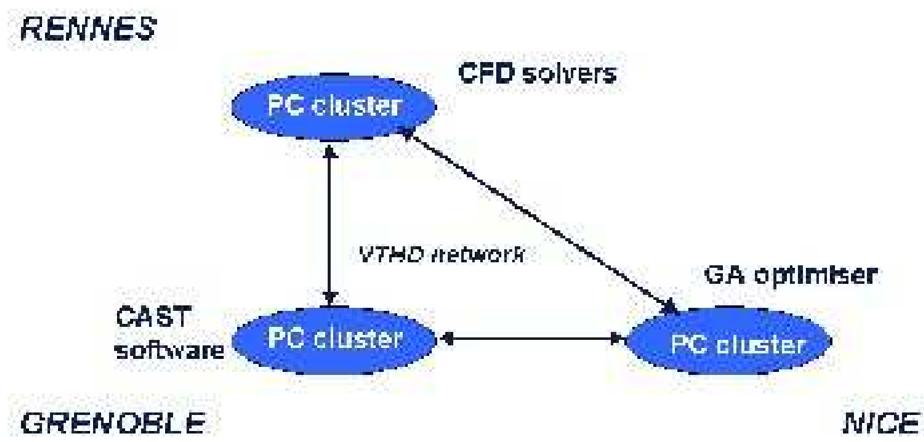


Figure 1. Mise en réseau VTHD des grappes de PCs.

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.

4. Application Domains

4.1. Scope

Key words: *transportation systems*, *telecommunications*, *environment*, *biology*.

Focused on the development of numerical methods for the optimization of PDE systems and related numerical analysis, mathematical or software issues, the project conducts studies in optimum shape design in aerodynamics (drag, external noise or sonic bang reduction, high-lift configurations, etc.) and electromagnetics (optimal positioning and motion of sensors) in the framework of engineering problems in transport demanding new technologies.

The Rhône-Alpes project component develops software platforms for the treatment of these multi-disciplinary applications by code coupling and distributed computing (*grid computing*).

4.2. Aeronautics and Space

The demand of the aeronautical industry remains very strong in aerodynamics, as much for conventional aircraft, whose performance need 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.

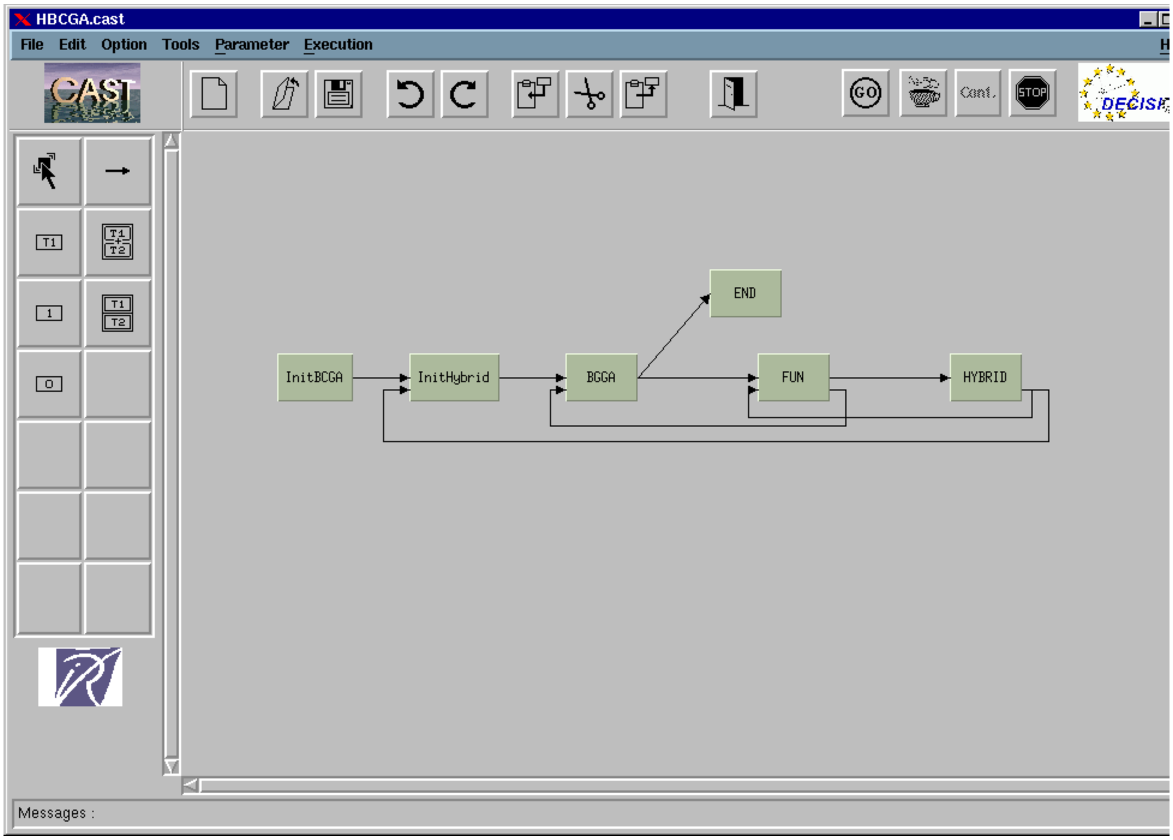
Our current involvement with Space applications relate to software platforms for code coupling.

4.3. Electromagnetics

In the context of antenna shape optimization, we can split the existing results in two folds: 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 class and makes intensive use of the 2-D solvers based on the specific 2-D Green kernels. The 2-D approach for

(a) Serveur CAST



(b) Champs initial et optimisé de nombre de Mach

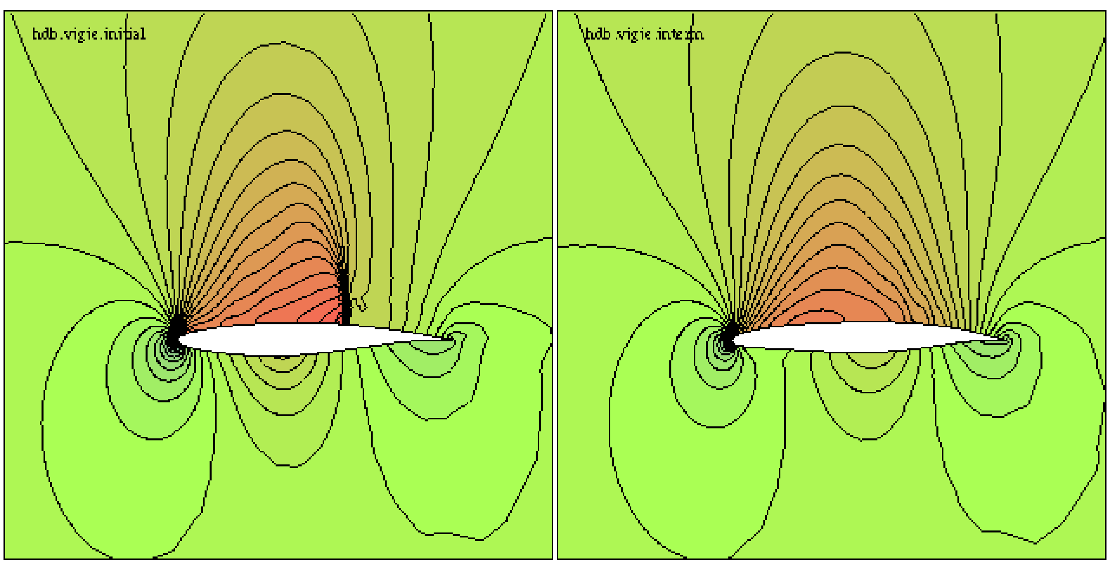


Figure 2. Algorithme d'optimisation hybride gradient-génétique en démonstration sur la plateforme du projet européen DECISION; noter que la diminution de traînée résulte de la quasi-disparition du choc sur l'extrados du profil d'aile.

the optimization of *directivity* led recently to historical 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. Making use of the derivative with respect to the frequency, we derive the derivative of the shape gradient with respect to the frequency (it is a kind of second order derivative). 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, as in several devices such as radar, tomography, 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.

4.4. 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, etc., in collaboration with specialists of these fields.

5. Software

5.1. CAST

As part of the development of software infrastructures for the support of demanding applications in optimisation and simulation, extensions to the CAST platform are currently underway for the control of distributed applications and the co-allocation of distributed resources. This is part of the PhD of M. Kamal Beydoun. The goal is to explore facilities to dynamically allocate remote resources based on performance sensors. In a first step, the CAST software will be interfaced with the resource allocation manager available in the Globus environment.

In a further approach, extensions to the design of virtual computing environments are being explored. As such, the goal is to provide the end-users with features that support the dynamic definition of ad-hoc computing infrastructures, masking the specifics of the underlying grid environments at hand.

5.2. Numerical Modules for Optimum-Shape Design in Aerodynamics

We are developing an optimization package OBEZ (Optimization with BEZier parameterization) designed for shape-optimization of 3D aerodynamic bodies. It has been applied mostly to a lift-drag minimization in the transonic regime and sonic-bang reduction in supersonics. It integrates the following toolboxes:

- a flow-solver based on the NS3D code (legacy of the SINUS project), together with a calculation of an objective function based on the results of the flow-simulation (pressure field around the aircraft, gradient of pressure, lift and drag coefficient);
- a new parametrization module BZPARAM implementing a black-box 3D Bézier parameterization and 3D mesh-update routines;
- an optimization module containing general optimization routines by a genetic-algorithm and a Nelder-Mead simplex method.

5.2.1. NS3D:

Participants: Michele Andreoli [updates of the code], Aleš Janka.

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

The NS3D flow code solves the 3D Euler and Navier-Stokes equations, on general unstructured tetrahedric 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 (Monotone 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 around complete aircraft.

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 the 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.

5.2.2. BZPARAM:

Participants: Michele Andreoli, Aleš Janka.

Key words: *Free-form deformation*, *tensorial 3D Bezier*, *moving mesh*, *elliptic solvers*, *torsional springs*.

The parametrization module BZPARAM manages, during the optimization process, the deformations of 3D shapes and of the corresponding tetrahedric computational mesh. It accounts for the possible *a priori* geometric 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 algorithms working in $\mathbb{R}^N$.

The developed BZPARAM module implements the Free-Form Deformation with a 3D tensorial Bezier parametrization. It can perform the degree elevation while recalculating the new parametric vector $\mathbf{x}' \in \mathbb{R}^{N'}$ corresponding to shapes before the degree elevation.

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.

5.2.3. Optimization module:

Participants: Michele Andreoli [simplex algorithm and validation], Yannick Berard [hybridization in PIKAIA], Abderrahmane Habbal [hybridization in PIKAIA], Aleš Janka [simplex algorithm and validation], Latifa Oulladji [new genetic operators in AG2D].

Key words: *genetic algorithm*, *hybridization*, *reduced models*, *simplex method*.

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 Nelder-Mead simplex algorithm.

The Genetic algorithms operate on a set (population) of shapes (individuals) to produce an artificial evolution. Their task is to modify (evolve) shapes towards the optimal shape by using three main genetic operators: *selection* (of best-fitted individuals), *cross-over* (recombination of the selected individuals to obtain new shapes), and *mutation* (random changes in shapes). The shape parametric vector $\mathbf{x}$ is coded either in a fixed precision scheme (binary-coded) or in a floating point scheme (real-coded). Accordingly, the genetic operators operate either on a set of bits (0/1's) or on a set of real numbers.

The most serious disadvantage of an ordinary genetic algorithm 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 shapes are rejected during the evolutionary process. Therefore, simplified models for fitness evaluation, permitting to reject unsatisfactory shapes without necessitating the 3D flow simulation, are of interest. A new algorithm has been developed based on the genetic algorithm with real coding PIKAIA (public domain software) employing a first-order gradient interpolation of fitness values on subsets (clusters) of the current population.

5.2.4. NS3D-VSAERO:

Participants: Aleš Janka, Dario Pinelli.

Key words: *hierarchy of flow solvers*, *panel method*, *multi-point optimization*.

A coupling of two different flow solvers for two flow regimes is currently under development in collaboration with PIAGGIO Aero (Italy).

For CPU-time reasons, we have been using within NS3D only the cheapest Euler flow model for compressible inviscid flows. A shape optimization using this simplified model neglecting viscous effects is known, however, to give super-critical optimal shapes which are not optimal with respect to the non-simplified physical laws (viscous, turbulent, with a boundary-layer model).

One standard approach to avoid erroneous optimal shapes is to increase the complexity of the mathematical flow model in NS3D, and this leads to a substancial increase of computational effort in the flow solution phase. As an alternative, we are currently integrating to the optimization loop a commercial 3D panel method solver VSAERO with an enhanced boundary layer model (courtesy of PIAGGIO Aero), which accounts for the viscosity and turbulence effects, but whose validity is limited to subsonic regimes.

By coupling the inviscid transonic Euler code (NS3D) with the subsonic panel code including a boundary layer model, in the framework of a multi-criteria optimization, we would like to filter-out the non-physical optimal shapes while maintaining the CPU-cost at a reasonable level.

5.3. Numerical Modules for Gradient Computations in Electromagnetics

Participants: Claude Dedeban [France Télécom, La Turbie], Pierre Dubois, 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, allow to compute the derivative w.r.t. the frequency.

6. New Results

6.1. Computational methods, numerical analysis and validation

6.1.1. Multigrid methods for compressible flow

Participants: Jean-Antoine Désidéri, Aleš Janka, Xuejun Xu [CAS, Beijing, Dept. of Numerical Mathematics].

The cascadic multigrid in which only prolongation transfers onto finer grids are performed was previously studied for an advection-diffusion problem. This technique remains the topic of collaboration with the Liama French-Chinese Institute in Beijing.

More classically, a finite-volume based linear multigrid algorithm has been proposed and used within an implicit linearized scheme to solve the Navier-Stokes equations for compressible laminar flows. Coarse level problems are constructed algebraically based on convective and diffusive fluxes, without the knowedge of coarse geometry. Numerical results for complex 2D geometries such as airfoils, including stretched meshes, show mesh size independent convergence and efficiency of the method compared to other finite-volume based multigrid method [28].

6.1.2. Multidisciplinary code validation

Participants: Simon Baudot-Roux, Jean-Antoine Désidéri, William E. Fitzgibbon [University of Houston], Toan Nguyen, Jacques Périaux.

Code validation is an essential activity in pre-industrial applications of scientific computing, particularly those integrating several disciplines. Initiated within International cooperations [40] and the European Thematic Network FLOWnet (Flow Library Over the Web) [35], we edited and disseminated in Europe a CD-Rom « State of the Art in CFD validation for Aeronautics: the FLOWnet experience » [19] [51] of the project database main results in the following areas:

- Aeronautics
- Propulsion and Turbo-Machinery
- Wind Energy
- Multi Physics
- Unsteady Flows.

This activity is now being developed within a European Project Promuval (Prospective Tools for Multidisciplinary Validation) aiming at identifying the models, numerical methods and software environments that will be necessary to carry on tommorrow's ambitious multi-disciplinary simulations. (See International Networks.)

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) and software aspects.

6.2.1. Shape parameterization, hierarchical (multilevel) algorithms, adaptivity, artificial neural networks.

Participants: Michele Andreoli, Farid Belahcene, Alberto Clarich [Doctoral student, University of Trieste, I], Jean-Antoine Désidéri, Badr Abou El Majd, Aleš Janka, Marios Karakasis [Doctoral student, University of Athens], Dario Pinelli.

We are concerned with the general problem consisting of minimizing a functional constrained by a PDE state equation subject to a shape-dependent boundary condition. The prototype 2D test problem is the optimization of an airfoil shape immersed in a two-dimensionnal flow (of Eulerian type in the simplest case) to reduce drag; the shape is then subject to certain geometrical constraints (specified endpoints, vertical tangent at leading edge, given area, etc). In general applications, the field, or distributed state, is computed by some standard PDE approximation method (e.g. of finite-volume type) over a mesh, one boundary of which is optimized in shape, via *design parameters* in number much less than the boundary gridpoints. The shape is thus formally represented, prior to mesh-discretization, by a *parameterization* here specifically chosen to be of Bézier type, based on *control points* whose abscissas are prescribed, and ordinates optimized according to some physical criterion.

6.2.1.1. Hierarchical (multilevel) algorithms.

We exploit the classical *degree-elevation process* [57] 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 *Full Multi-Grid* concept, and referred to as the *Full and Adaptive Multi-Level Optimum-Shape Algorithm* (*FAMOSA*). Our construction yields rigorously-nested optimization search spaces. The framework allows us also to propose ways to employ *reduced models*, as well as to construct *hybrid optimizers* (combining gradient-based with evolutionary algorithms) [31] [54] [33] [32].

6.2.1.2. Aerodynamic optimization of three-dimensional geometries.

A versatile parameterization technique has been developed for 3D shape optimization in aerodynamics. Special attention is paid to construct a hierarchical parameterization by progressive enrichment of the parametric space. After a brief review of possible approaches, the free-form deformation framework was elected for a 3D tensorial Bézier parameterization. The classical degree-elevation algorithm applicable to Bézier curves is still valid for tensor products, and its application yields a hierarchy of embedded parameterizations. A drag-reduction optimization of a 3D wing in transonic regime has been carried out by applying the Nelder-Mead simplex algorithm and a genetic algorithm. The new parameterization including degree-elevation is validated by numerical experimentation and its performance assessed [33] [32] [49].

6.2.1.3. Adaptivity.

A shape optimization in aerodynamics can benefit greatly in conditioning by adaption, at regular intervals, of the parameterization supporting the shape representation. From the knowledge of an approximate optimal shape, one considers the set of all Bézier parameterizations of same degree that approximate the shape in the sense of least squares. One elects the parameterization associated with the most regular control polygon (least total variation). We have provided all the details of the formulation, that is very close to our initial works but relies on a lesser number of numerical quadratures most of which are realized by fourth-order formulas. We have proposed a shape-optimization test-case originating from calculus of variations. This surrogate “physical optimization” has allowed us, at moderate cost, to demonstrate the convergence of the algorithm coupling the pseudo-physical optimization with the Bézier parameterization adaption, and to assess its merit [50].

6.2.1.4. Model reduction, artificial neural networks.

We had proposed a method to reduce the dimension of the design parameter set consisting in first constructing an artificial neural network (ANN), and second identifying the subspace spanned by those eigenvectors of the Hessian matrix that, according to this ANN, have the greatest influence on the cost functional reduction. Actual substancial gains in efficiency were measured when reducing the search to one such subspace [8].

Alternately, the Proper Orthogonal Decomposition (POD) model-reduction technique has been successfully incorporated in various computations as a preconditioner of the optimization algorithm. This method was presented at a MACSInet event [56]; see also: [52] and [34].

Both techniques are promising and their development will be continued in the thesis of B. Abou El Majd to identify optimal geometrical territories in a multi-disciplinary shape optimization.

6.2.2. Hybrid minimization with GAs/gradients

Participants: Yannick Bérard, Alain Dervieux, Jean-Antoine Désidéri, Abderrahmane Habbal, Aleš Janka, Latifa Oulladji.

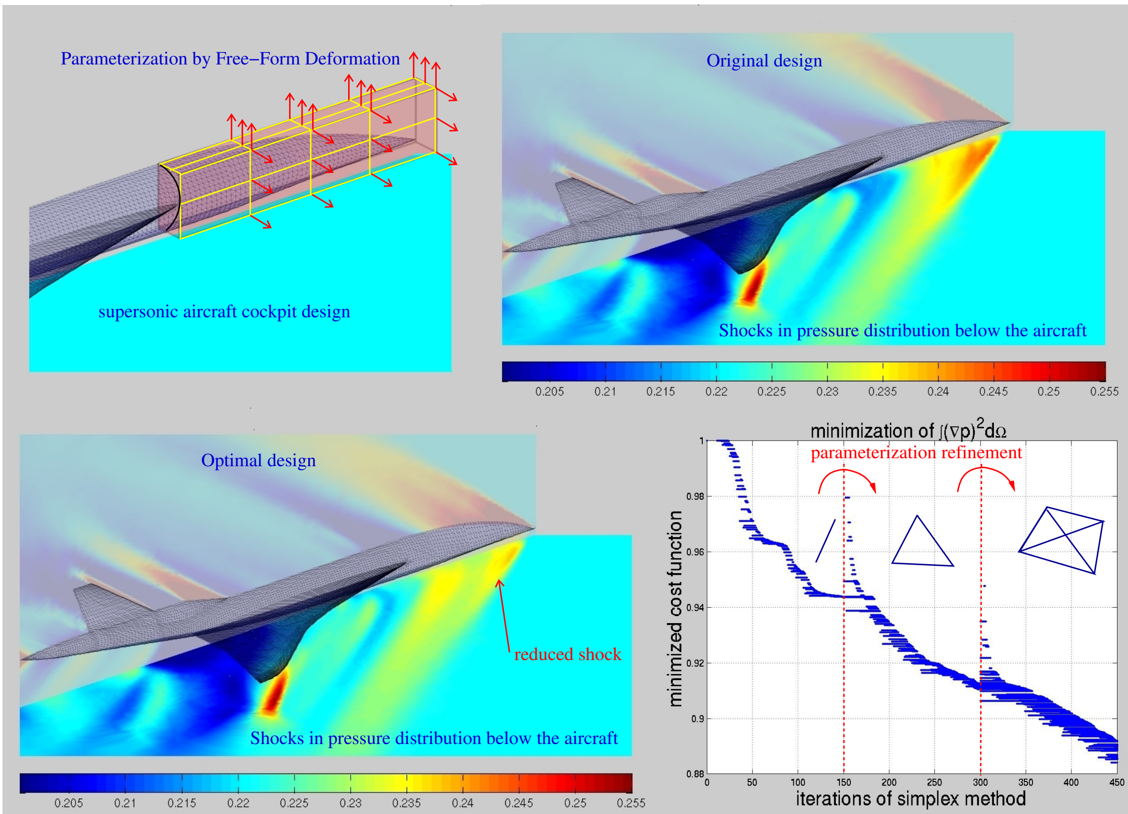


Figure 3. Shape optimization of a supersonic business-jet geometry for external noise reduction; « Free-Form Deformation » parameterization in the nose region of a generic geometry (courtesy of Dassault Aviation); initial supersonic flow (pressure field); optimized flow demonstrating reduced shock attached to the nose; convergence history of a multilevel simplex method using successive degree elevations. Technical elements: mesh: 173526 nodes, 981822 tetrahedras (for the half-geometry); flow solver: NS3D solver, inviscid option, Roe FDS; flow conditions: $M_\infty = 1.8$, $\alpha = 1^o$; parameterization and optimizer: free-form deformation of cockpit region in tensor form (length $\times$ height $\times$ span), Nelder-Mead simplex method, degree elevation every 150 iterations applied 3 times: 2-1-1 for 6 active d.o.f., 3-1-1 for 12 active d.o.f., 3-2-2 for 30 active d.o.f. of shape deformation.

Genetic algorithms (GAs) have been introduced to deal with global optimization. They have been successfully used in a very large broadband of scientific applications, including structural mechanics and aerodynamics. One important keypoint for their success is that evolutionary algorithms ideally fit to the concept "solver-optimizer".

Nevertheless, the use of such -evolutionary- methods in large scale industrial applications is still often prohibitively costly, due to the need for too many expensive evaluations of the objective functional.

This is why gradient-based methods have gained a large audience in these application areas. These descent methods use first and sometimes second-order derivatives as fundamental information to progress at reduced cost towards the optimum. Unfortunately, the iterates could be trapped by local minima with no possibility to escape (due to the local character of these methods).

Since in many industrial problems, like e.g. in shape optimization for aerodynamics, several local optima of poor interest for engineers may be present, it has become mandatory to make use of global minimizers such as the GAs.

6.2.2.1. Standard hybridization in a sonic-bang reduction problem

Trying to take advantage from the benefits of each of these approaches, a first natural idea which turned out to be efficient has been to use GAs in order to identify a close neighborhood of the global minimum, then run a gradient method to converge to it accurately [52].

6.2.2.2. Cluster-based hybridation

In the present work, we introduced another kind of hybridation which consists in using the first order derivatives in order to perform a local and cheap evaluation of the objective functionals, while the GAs leads the minimization process. The local evaluation is done by means of a first order Taylor expansion. When a global minimum has been closely detected, a few steps of some gradient-based method may be performed. Numerical experiments have been performed which illustrate the efficiency of the method [29].

6.2.3. Multidisciplinary topology optimization solved as a Nash game

Participants: Abderrahmane Habbal, Mikael Thellner [Linköping University, Sweden].

In the present work, multidisciplinary optimization is formulated in the game theory framework. We choose a coupled heat transfer - thermoelastic system as case study for which a topology design approach is developed. The multidisciplinary optimization problem is solved as a noncooperative game and we determine a Nash equilibrium. The game has two players and the parameterization of the design domain is such that the design variables describes the material density and a parameter which influences the heat flow by convection to the surrounding fluid. The first player controls the structure and the second player controls the temperature distribution in the structure. For the second player we present mathematical proof of existence of a discrete valued optimal solution and it is concluded that no regularization of the suboptimization problem is needed. We present two numerical examples to illustrate the proposed methodology. One of the examples is also solved by weighting the objectives to a scalar valued objective function and the result is compared with the Nash game solution [42] [41].

6.2.4. Hierarchical Parallel Evolutionary Algorithms, Game strategies and Variability of Boundary conditions in Optimization

Participants: Jean-Antoine Désidéri, Toan Nguyen, Jacques Périaux, Mourad Sefrioui [Dassault-Aviation/UPMC Scientific Pole], Zhi Li Tang [former Opale Post. Doct. fellow, currently at Dassault-Aviation/UPMC Scientific Pole], Eric Whitney [Dassault-Aviation/UPMC Scientific Pole].

6.2.4.1. Hierarchical Parallel Evolutionary Algorithms.

The approach of Hierarchical EAs on asynchronous environment has been tested on the 20 processors of the Scientific Pole in order to speed up the convergence of the evolutionary algorithm named HAPEA developed by E. Whitney.

Focusing on the multi-point UAV (Unmanned Aerodynamic Vehicle) shape optimisation, two test cases have been considered for drag reduction at subsonic speeds; T1: transit and loiter, and T2: transit and take off. The flow analysis solver, the DRELA code from MIT, is based on the panel method coupled with a treatment of the boundary layers. The different layers contain different discretizations of the airfoils. The results obtained for T1 are satisfactory, but for T2, the full Navier Stokes equations with turbulent K-epsilon model are necessary because of local flow separation [34] [48].

6.2.4.2. Game strategies and variability of Boundary Conditions.

We have tested a number of "splits of territory", identified as portions of an airfoil shape, allocated to virtual players competing in a Nash game, each one optimizing a different criterion in a multi-point aerodynamic optimization and until an equilibrium is reached. The technique is effective, and very cost-efficient compared to the construction of a complete Pareto equilibrium, but obviously less general, but in a design loop it realizes feasible trade-offs between criteria [47].

Current aspects of this research includes the following two topics:

1. comparing the 2-D and 3-D results obtained by the capture of non dominated airfoil shape solutions of the Pareto front of a multi objective design optimization of subsonic-transonic flow using a Navier-Stokes code and structured meshes; Dr. Tang (Nanjing University of Aeronautics and Astronautics and Dassault Aviation) visited INRIA Sophia Antipolis during the European MACSInet/AFFRST seminar on Optimization and presented the status of his research at this occasion including the comparisons of Pareto fronts with deterministic and stochastic optimizers and different parameterizations (Bézier spline vs Hick Henne representations).
2. increasing the stability of the solution under uncertainty of boundary and environment conditions via robust design using a Navier Stokes solver.

After realizing a significant progress in both topics, the software will be installed in Grenoble to achieve substantial speed up on a grid computing environment.

6.3. Geometrical Boundary Evolution

6.3.1. Shape Optimization theory

Participants: Michel Delfour [CRM, Montréal], Jean-Paul Zolésio.

The ongoing collaboration with the CRM Montréal has led to several extensions to the theory contained in the book *Shape and Geometry* (SIAM 2001). 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 » and « fat conditions » are studied and compactness is derived [24], [37], [38], [39]. Also the fine study of *Sobolev domains* leads to several properties concerning the convergence of boundaries and boundary integral convergence under some weak global curvature boundedness assumption [23]. The classical topologies on domains (for example the Hausdorf topology, etc.) does not permit to control boundary convergence in order to derive continuities of boundary integrals and such phenomena. The straightforward idea is then to impose pointwise constraints at the boundaries, such as uniform cone condition or uniform cusp condition or uniformely-bounded curvatures. These conditions determine constraint subsets (or families) of domains for which we have no characterisation of tangential space and then no idea of admissible deformation. The concepts of uniform positive reach, density perimeter, bounded total mass D^2b (b is the oriented distance function and bounded refer to the Banach linear space $M1(D)$ of bounded measures) developed with D. Bucur and M. Delfour led to « extended » measure term of the boundary whose boundedness implies the « correct » convergence of boundaries. For example: assume that

$$||D^2 b_{\Omega_n}||_M(\mathcal{U}_h)(\partial\Omega_n) \leq M$$

where $U_h(K)$ is the tubular neighborhood of the closed set K with « size » h, then (for a subsequence) we derive the convergence of the boundary integrals.

6.3.2. Control of Coupling fluid-strucure devices

Participants: John Cagnol, Raja Dziri, Marwan Moubachir [LCPC], Jean-Paul Zolésio.

The ongoing collaboration with LCPC and Tunis University resulted in the publication of a note at the Comptes Rendus of Académie des Sciences, [25] and a forecoming book [20], as well as a conference paper at the TC7 IFIP conference in July 2003 [43]. Also the ongoing collaboration with P.U.L.V. (J. Cagnol) and U.V.A. (I. Lasiecka and R. Triggiani) on stabilization for coupled acoustic-shell modeling, [22].

6.3.3. Shape Gradient in Maxwell Equations

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

That activity has two main focuses:

6.3.3.1. The analysis of the Shape Sensitivity in presence of Singular Geometry.

It is well known that in 3-D scattering the geometrical singularities play a special role. The work with Pierre Dubois achieved the characterization of shape derivative of a functional governed by the 3-D Maxwell equations in presence of singular geometries. A communication to the forecoming conference ECCOMAS 2004 has been submitted. Concerning evolutions of cracks, we develop a technique which operates in intrinsic geometry framework and applies to cracked manifolds; a paper in the journal of differential equation is accepted for publication [26].

6.3.3.2. Frequency Derivative (Harmonic regimes).

These works extend the ongoing collaboration with France Télécom (Claude Dedeban) and UNSA (J.P. Damiano, electronics lab.) and we present the results at an international conference [36].

6.3.4. Weak Shape Evolution

Participant: Jean-Paul Zolésio.

The large Shape Evolution of a domain or a Manifold was solved in 1976 through the so-called *Velocity Method* and the *Shape Differential Equation* associated with a (Shape functional) flow gradient. The main results (existence and stability of solutions) have been established under the *a priori* boundedness of the Shape Gradient. This approach is now referred to as the *Strong-Shape Evolution*. Besides this strong theory, we considered the weak formulation for the large evolution problem of convection by non smooth vector fields. We revisited the theory with a special focus on pairs of elements $(V,\chi) \in L^1(0,\infty,L^2(D,R^N)) \times L^1(0,\infty,BV(D))$ with $\chi^2=\chi$, $\frac{\partial\chi}{\partial t}+V.\nabla\chi=0$.

This setting enables us to revisit the *level set* approach and to furnish a weak solution to some associated Hamiton-Jacobi equation and includes topological evolutions. The first chapter of the book [20] extends some previous results. The new results were presented in several conferences and seminars in 2003 (CRM Montréal, Scuola Normale Superiore di Pisa, IFIP TC7, I.H.P., C.I.M.E., etc.) It also opens a new approach to large deformations in many other fields such as *Optimal Trajectories* and nonlinear shell analysis.

6.3.5. Stabilization and Smart Material

Participants: John Cagnol, Jean-Paul Zolésio.

We have considered the coupling of acoustic and elastic structures, and studied the stabilization of the system by a quasi-periodic motion of a smart actuator device at the boundary. This work extends the ten years old results by J.P. Zolésio, and C. Truchi-J.P. Zolésio concerning the wave equation under moving boundary and Dirichlet conditions. The main new result concerning the wave equation is contained in an INRIA research report to appear in 2003 [53] and a paper at IFIP TC7 [30].

6.4. Virtual computing infrastructures

Participants: Kamal Beydoun, 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 of demanding applications that can now be deployed on thousands of connected processors and they can connect petabytes of data through tens gigabits/sec networks at affordable cost.

So far, however, there seem to be some reluctance from the industry to use these environments because they require expertise in the computer science field which is currently not yet widely available on the job market [59]. Users have become in the last decade experts in the manipulation of Web browsers to access inter-continental mass of data and execute remotely located pieces of code transparently. Unfortunately, grid computing environment are still far from providing these seamless and flexible interfaces. New concepts and interfaces are therefore required to alleviate these shortcomings.

One approach that is currently being 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 middleware services implemented on top of existing grid environments. The goal is to provide standardised services and the corresponding procedures to help the users specify the resources and computing environment they need to run the complex (and soon, multidisciplinary) applications they currently execute. This implies the design of generic graphic problem solving interfaces, of the implementation of enabling middleware and of ad-hoc interfaces on top of existing grid environments. An international consortium has been set up on this subject, including twelve corporate and academic research institutions, as well as industry partners from Italy, Great Britain, Greece, Cyprus and France. The OPALE project is one of the founding members of this consortium.

7. Contracts and Grants with Industry

7.1. Contracts

7.1.1. Optimum-shape design in aerodynamics and multidisciplinary extensions

- *Self-Adaptive Parameterization for multidisciplinary optimum-shape design*, with Dassault Aviation, St Cloud.
- Additionally, a tight cooperation with Piaggio Aero France, Nice, has been reinforced through a Local Cooperative Action (COLORS) on “Hierarchical Parameterizations”, the participation in the project of the ingineer, D. Pinelli, and the set up of Ph.D. program financed by the PACA Region.

7.1.2. Optimization in electromagnetics

- France Télécom (La Turbie): optimization of antennas;
- 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. 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 telecom purposes.

More specifically, the classical problem of frequency allocation is closely examined. This problem results in a very acute technological challenge today due to the numerous concurrently-operational systems (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).

8.1.2. Local Cooperative Action: Hierarchical Shapes for optimization in Aerodynamics

The OPALE project launched jointly with the GALAAD project a Local Cooperative Action (COLORS) “Hierarchical Shapes for optimization in aerodynamics” in order to initiate a cooperation with Piaggio Aero France, Nice (see http://www-sop.inria.fr/opale/). This project has permitted to finance the trainings of M. Andreoli and D. Pinelli (in OPALE) and M. Celikbas (in GALAAD). This initiative also facilitated the financing by the Region of a doctoral thesis on related topics (B. Abou El Majd). This cooperation initially related to aerodynamics and geometrical tools to interface with CAD systems, is meant to be extended to other engineering fields demanding advanced computational tools, such as structural design.

8.2. International Networks and Working Groups

Participants: Simon Baudot-Roux, Jean-Antoine Désidéri, Toan Nguyen, Jacques Périaux.

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. European Thematic Network FLOWnet

The OPALE project has participated in the kernel of the former European Thematic Network FLOWNET (« Flow Library Over the Web Network ») within the Industrial and Material Technologies Programme, BRITE/EURAM III. This network focused on pre-industrial code validation in fluid mechanics, and INRIA has designed and managed its database system of documented computations and experiments of complex flows (http://dataserv.inria.fr/flownet/).

A CD Rom has been edited by OPALE (and disseminated throughout Europe by the University of Barcelona) [19] [51].

8.2.2. European Accompanying Measures Promuval

This European project coordinated by CIMNE, Barcelona, is a follow-up of FLOWnet, with an extended scope. It started in December 2002 at INRIA Sophia Antipolis, and its main objective is to prospect methods and tools for the validation of multi-physics codes. The development of the project consists in collecting available data on a database and prospecting new models, new numerical methods and validation tools which will be necessary for the Verification and Validation (“V and V”) of multi physics codes. Since several disciplines are interfacing numerically a pilot integrated platform is proposed by the Grenoble project’s component (as workpackage leader) to provide a cooperative environment for knowledge sharing. Several new mathematical methods and models have also been suggested by the OPALE project (as another workpackage leader) in order to achieve a good matching of information at interfaces (maintaining numerical accuracy of each discretized discipline, in particular). Several Working Groups focused on multiphysics applications have been set up to discuss these new lines of V and V: aeroelasticity, thermal flows, aeroacoustics and Flight Dynamics couplings.

The uncertainties of multiphysics simulations and experimentations need to be addressed systematically and managed. The utility of multi-physics modeling and simulation tools will be critical in the accurate and efficient design of modern multidiscipline aircraft sytems. In order to reduce uncertainties in Multi Physics results the sensitivity of computational data associated to multiphysics uncertainties need to be quantified : it is the road map investigated by PROMUVAL partners to increase the credibility of multidisciplinary design. A State of the Art Short course on multi-physics codes validation is scheduled in 2004 in Barcelona.

8.2.3. The HEAVEN integrated Project

The project participates in the HEAVEN Integrated Project proposal (« Hosting Europe and Applications in a Virtual Environment »), currently submitted to the EC as part of the IST FP6 program, concerning the « Grids for complex problem solving » priority. In this proposal, our project is leader of several workpackages including the definition and implementation of the software supporting the virtual computing infrastructure. It is also leader of a test-case workpackage for airfoil optimisation.

8.2.4. European Network of Excellence MACSInet

The project participates in the European Network of Excellence MACSINET (*Mathematics, Computing and Simulation in Industry Network*) supported by DG XIII et DG XII. This network is a joint initiative by ECCOMAS (*European Community for Computational Methods in Applied Sciences*) and ECMI (*European Community of Mathematics for Industry*). It aims at fostering European initiatives to approach new industrial multi-disciplinary challenges by mathematics and scientific computing. See http://www.macsinet.org.

The project organized MACSInet open industrial days on *Modeling, Analysis and Optimisation for the Design of Coupled Industrial Systems*, in Sophia Antipolis (October 27-29) in association with the Finnish-French Association for Research, Science and Technology (AFFRST) and the GDR CNRS ANOFOR (New Applications in Shape Optimization). (See http://www-sop.inria.fr/opale/MACSI-AFFRST-Seminar.)

8.3. Bilateral international cooperations

Chinese-French Institute LIAMA : joint-coordination of the project « Coordination and Optimisation of Hierarchical Methods for the Distributed Numerical Simulation of Nonlinear P.D.E. Problems » (X. Xu, Institute of Computational Mathematics, CAS, and J.-A. Désidéri) also linked to the University of Nanjing (Dept. of Aeronautics and Astronautics) and the University of Tsinghua (grid computing).

Finnish-French Cooperation As mentioned above, this year, the Finnish-French Seminar was organized jointly witha MACSInet scientific event in association with Center for Scientific Computing (CSC), Helsinki University of Technology (HUT) and the French Ambassy in Helsinki.

Australian-French network on UAV systems As a follow up of a successful workshop on UAV systems: methods and tools which took place in Sydney last July 2003, it was decided by the main actors of this event to set up a French-Australian network on « Innovative technologies for the design of UAV systems ». The three main themes of this project are : *(i)* Multi-Disciplinary Optimization (MDO), *(ii)* Autonomy, control and guidance, and *(iii)* sensors. The OPALE project is interested in the first topic since it requires new methods and tools for multidisciplinary and multicriterion optimization, and in particular Evolutionary Algorithms (EAs). Several test cases have been proposed for testing new adaptive methods like colony ants, Particle Swarm Optimization (PSO), Neural networks and EAs. To this end, regular information sharing sessions, on-line tools, sharing and exchange of research students between labs and institutes are being arranged. An on-line information sharing repository has already been established at : http://www.aeromech.usyd.edu.au/UAVThinkTank.

8.4. Invitations

- Michel Delfour, CRM Montréal, 3 weeks; theory of shape optimization.

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 project OPALE 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 » (40 hrs) which includes lessons in

- Calculus of Variations, optimal control, domain deformation, domain derivatives and applications (A. Habbal), and

- Industrial motivation and examples, hierarchical parameterization, adaptative Optimization (J.-A. Désidéri).

9.1.2. Ecole Supérieure en Sciences Informatiques (ESSI)

ESSI is an engineering school in computer sciences of UNSA on the Sophia Antipolis campus. A. Habbal teaches the following courses:

- Calculus (first year, 120 hrs)
- Programming mathematics (first year, 40 hrs)
- Numerical Methods in Finance (third year, 30 hrs)

9.1.3. Graduate program in Economics, option « Industrial Organization »

– Game Theory and Economic Applications (A. Habbal, 15 hrs)

9.2. 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, Ph.D. student (from November 2003); topic: Hierarchical algorithms and game strategies for the aerodynamic and strauctural shape optimization of a business jet.

Rezki Amedjkouh University Joseph Fourier, Grenoble, Oct. 2002- June 2003; topic: Analysis and Control of Distributed Applications on Grids.

Michele Andreoli in his final year of Aeronautical Engineering curriculum at the University of Pisa, Italy, was a six-months trainee (Sophia Antipolis, April-Sept. 2003); topic: *Hierarchical Parameterization for Multilevel 3D Shape Optimization in Aerodynamics*.

Simon Baudot-Roux University de Montpellier II, defended in June a « Technological Research Degree » (DRT) related to the development of databases within the European Thematic Networks FLOWnet and INGENET [51] after an eighteen-month training (Sophia Antipolis).

Farid Belahcène DESS Evry, four months trainee (Sophia Antipolis); topic: adaptative Bézier parameterizations as part of the “Hierarchical Shapes” Local Cooperative Action.

Yannick Bérard DESS University of Savoie (Chambéry), four months trainee (Sophia Antipolis); topic: Hybridization of genetic algorithms by population clustering.

Kamal Beydoun University Joseph Fourier, Grenoble; topic: Analysis and Control of Distributed Applications on PC Clusters.

Pierre Dubois Ecole des Mines and France Télécom, thesis student (Sophia Antipolis); topic: 3D electromagnetic gradient computations.

Mohammed El Kroni DESS University of Savoie (Chambéry), four months trainee (Sophia Antipolis); topic: Optimal patches in domain decomposition.

Mohammed El-Mahbouby DESS University of Savoie (Chambéry), four months trainee (Sophia Antipolis); topic: Concurrent topological/geometrical optimization of elastic structures.

Latifa Oulladji Magistère Sidi Bel Abbès, Algeria, six months trainee (four months in Sophia Antipolis and two in Grenoble); topic: hybridization of genetic algorithms for drag and sonic bang reduction of a supersonic aircraft.

Dario Pinelli Piaggio Aero, three-month trainee (Oct. 15-Jan. 15); topic: 3D aerodynamic design.

9.3. Organization of Scientific Events

The project organized or co-organized the following scientific events:

- 21st **IFIP TC7** (*System Modelling and Optimization*, Sophia Antipolis 21-25 July 2003 (J. Cagnol, J.-A. Désidéri, J.P. Marmorat and J.P. Zolésio);
- **EUROGEN 2003** (*Evolutionary Methods for Design, Optimisation and Control with Applications to Industrial and Societal Problems*), Barcelona 15-17 Sept., (G. Bugeda, J.-A. Désidéri, J. Périaux, M. Schoenauer and G. Winter);
- **MACSInet** Open Industrial Days on Modelling, Analysis and Optimisation for the Design of Coupled Industrial Systems, Sophia Antipolis 27-29 Oct. (J.-A. Désidéri, T. Nguyen, J. Périaux and O. Pironneau).

9.4. Participation in Scientific Committees

- J.-A. Désidéri is a member of « Comité d'Orientation et du Secrétariat Exécutif (COSE) du Réseau de Recherche et d'Innovation Technologique (RRIT) 'Recherche Aéronautique sur le Supersonique' » (« Steering and Executive Committee (COSE) of the Research and Technology Innovation Network 'Aeronautical research for supersonics' »), and co-animates with C. Michaut, ONERA, the topic on « aerodynamic and optimization ».
- 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.

10. Bibliography

Major publications by the team in recent years

[1] *Shape optimization and optimal design.* J. CAGNOL, M. P. POLIS, J.-P. ZOLÉSIO, editors, series Lecture Notes in Pure and Applied Mathematics, volume 216, Marcel Dekker Inc., New York, 2001, pages ii+442.

[2] J.-A. DÉSIDÉRI. *Modèles discrets et schémas itératifs. Application aux algorithmes multigrilles et multidomaines.* Editions Hermès, Paris, 1998.

[3] M. DELFOUR, J.-P. ZOLÉSIO. *Shapes and geometries.* series Advances in Design and Control, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2001, Analysis, differential calculus, and optimization.

[4] F. DESAINT, J.-P. ZOLÉSIO. *Manifold derivative in the Laplace-Beltrami equation.* in « J. Funct. Anal. », number 1, volume 151, 1997, pages 234–269.

[5] R. DZIRI, J.-P. ZOLÉSIO. *Tube Derivative and Shape-Newton Method.* Rapport de recherche, INRIA, november, 2002.

[6] A. HABBAL. *Boundary layer homogenization for periodic oscillating boundaries.* in « Control and Cybernetics », number 3, volume 30, 2001, pages 279-301.

[7] A. IOLLO, A. DERVIEUX, S. LANTERI, J.-A. DÉSIDÉRI. *Stability Properties of POD-Galerkin Approximations for the Compressible Navier-Stokes Equations.* in « Theoretical and Computational Fluid Dynamics », 2000, 13: 377-396.

[8] M. KARAKASIS, J.-A. DÉSIDÉRI. *Model Reduction and Adaption of Optimum-Shape Design in Aerodynamics by Neural Networks.* Rapport de Recherche, number 4503, INRIA, July, 2002.

[9] B. KAWOHL, O. PIRONNEAU, L. TARTAR, J.-P. ZOLÉSIO. *Optimal shape design.* series Lecture Notes in Mathematics, volume 1740, Springer-Verlag, Berlin, 2000, Lectures given at the Joint C.I.M./C.I.M.E. Summer School held in Tróia, June 1–6, 1998, Edited by A. Cellina and A. Ornelas, Fondazione C.I.M.E.. [C.I.M.E. Foundation].

[10] N. MARCO, S. LANTERI, J.-A. DÉSIDÉRI, B. MANTEL, J. PÉRIAUX. *A parallelized Genetic Algorithm for a 2-D shape optimum design problem.* in « Surveys on Mathematics for Industry », volume 9, 2000, pages 207-221.

[11] G.-T. NGUYEN. *Distributed integration platforms for parallel CFD applications.* in « European Parallel CFD Conference », Amsterdam (NL), 2001.

[12] G.-T. NGUYEN. *Distributed integration platforms for parallel multidiscipline applications.* in « French-Finnish seminar on Innovative methods for advanced technologies », CSC. Helsinki (Finlande), 2001.

[13] G.-T. NGUYEN. *Distributed parallel multidiscipline applications.* in « French-Finnish Seminar on Scientific Computing », number 4, volume II, AFFRST, Jyväskyla, Finlande, 2002, Conférence invitée.

[14] G.-T. NGUYEN. *Integration of multidiscipline applications in GRID-computing environments.* in « 6th International Conference on Applied Parallel Computing », Helsinki-Espoo, Finlande, 2002, Invited Lecture.

[15] G.-T. NGUYEN, C. PLUMEJEAUD. *An integration platform for metacomputing applications.* in « International Conference on Computational Science », Springer, P. SLOOT, J. DONGARRA, editors, Amsterdam, Hollande, 2002.

[16] G.-T. NGUYEN, C. PLUMEJEAUD. *Calcul réparti à grande échelle, F. Baude Ed..* 2002, chapter Intégration d'applications multidisciplines dans les environnements de metacomputing, Hermès Lavoisier Publish..

[17] C. RAMANANJAONA, M. LAMBERT, D. LESSELIER, J.-P. ZOLÉSIO. *Shape reconstruction of buried obstacles by controlled evolution of a level set: from a min-max formulation to numerical experimentation.* in « Inverse Problems », number 4, volume 17, 2002, pages 1087–1111, An International Journal on the Theory and Practice of Inverse Problems, Inverse Methods and Computerized Inversion of Data.

Books and Monographs

[18] *Evolutionary Methods for Design, Optimization and Control with Applications to Industrial and Societal Problems.* G. BUGEDA, J.-A. DÉSIDÉRI, J. PÉRIAUX, M. SCHOENAUER, G. WINTER, editors, International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain, September, 2003, Proc. of EUROGEN 2003, Barcelona, September 15-17, 2003.

[19] J.-A. DÉSIDÉRI, F. GRASSO, R. HOELD, M. MARINI, D. SCHWAMBORN, J. PÉRIAUX, editors, *State of the art in CFD validation for Aeronautics: The FLOWnet experience.* CIMNE, Barcelona, Spain, 2003, CD ROM.

[20] M. MOUBACHIR, J. ZOLÉSIO. *Control of Moving Domains.* Marcel Dekker, 2004, 325 pages, accepted on 04/08/2003.

[21] D. ZEITOUN, J. PÉRIAUX, J.-A. DÉSIDÉRI, M. MARINI, editors, *West East High Speed Flow Fields – Aerospace applications from high subsonic to hypersonic regime.* CIMNE, Barcelona, January, 2003.

Articles in referred journals and book chapters

[22] J. CAGNOL, I. LASIECKA, C. LEBIEDZIK, J. ZOLÉSIO. *Uniform stability in structural acoustic models with flexible curved walls.* in « J. Differential Equation », volume 182, 2003, pages 88-121.

[23] M. DELFOUR, J. ZOLÉSIO. *Oriented distance function and its evolution equation for initial sets with thin boundary.* in « SIAM J. on Control and Optim. », accepted 2003.

[24] M. DELFOUR, J. ZOLÉSIO. *The new family of cracked sets and the image segmentation problem revisited.* in « Communications in Information and Systems », accepted on 10.07.03, to appear.

[25] R. DZIRI, M. MOUBACHIR, J. ZOLÉSIO. *Navier-Stokes dynamical shape control.* in « C.R.Acad.Sc. Paris, A », 2004, to appear.

[26] J. FERCHICHI, J. ZOLÉSIO. *Shape sensitivity Analysis for Laplace Beltrami Operator with Singularities.* in « J. Diff. Equations », 2004, to appear.

[27] A. HABBAL. *An effective model for critically wrinkled arches..* in « Journal of Mathematical Analysis and applications », volume Volume 285, Issue 1, 2003, pages 155-173.

[28] A. JANKA. *A flux correction multigrid for compressible flow.* in « Numerical Algorithms », volume 33, 2003, pages 319-330.

Publications in Conferences and Workshops

[29] Y. BÉRARD, J.-A. DÉSIDÉRI, A. HABBAL, A. JANKA, L. OULLADJI. *Experiments with Hybridized Genetic Algorithms in Aerodynamics.* in « Evolutionary Methods for Design, Optimization and Control with Applications to Industrial and Societal Problems », International Center for Numerical Methods in Engineering (CIMNE), G. BUGEDA, J.-A. DÉSIDÉRI, J. PÉRIAUX, M. SCHOENAUER, G. WINTER, editors, Barcelona, Spain, 2003, Proc. of EUROGEN 2003, Barcelona, September 15-17, 2003.

[30] J. CAGNOL, J. ZOLÉSIO. *Numerical Analysis for the Smart Boundary Stabilization in Acoustics.* in « System Modeling and Optimization », Kluwer, accepted for publication on 15.10.03.

[31] J.-A. DÉSIDÉRI. *Hierarchical optimum-shape algorithms using embedded Bézier parameterizations.* in « Numerical Methods for Scientific Computing, Variational Problems and Applications », CIMNE, Y. KUZNETSOV, P. NEITTANMÄKI, O. PIRONNEAU, editors, Barcelona, 2003.

[32] J.-A. DÉSIDÉRI, A. JANKA, M. ANDREOLI. *Hierarchical Parameterization for Multilevel Evolutionary Shape Optimization with Application to Aerodynamics.* in « Evolutionary Methods for Design, Optimization and Control with Applications to Industrial and Societal Problems », International Center for Numerical Methods in Engineering (CIMNE), G. BUGEDA, J.-A. DÉSIDÉRI, J. PÉRIAUX, M. SCHOENAUER, G. WINTER, editors, Barcelona, Spain, 2003, Proc. of EUROGEN 2003, Barcelona, September 15-17, 2003.

[33] J.-A. DÉSIDÉRI, A. JANKA. *Aerodynamic Wing-Shape Optimization by an Adaptive Multi-Level Algorithm.* in « Fifth European Conference on Numerical Mathematics and Advanced Applications (ENUMATH 2003) », Prague (Czech Republic), August 18-22, 2003.

[34] J.-A. DÉSIDÉRI, A. JANKA, J. PÉRIAUX, E. WHITNEY. *Hierarchical Evolutionary Algorithms: Theory and Aeronautical Optimisation Applications.* in « Fifth European Conference on Numerical Mathematics and Advanced Applications (ENUMATH 2003) », Prague (Czech Republic), August 18-22, 2003.

[35] J.-A. DÉSIDÉRI, M. MARINI, J. PÉRIAUX. *Validation Databases in Fluid Mechanics: From the European Space Shuttle Program Hermès to the European Thematic Network FLOWnet.* in « Fluid Dynamics and Aeronautics New Challenges », series Handbooks on Theory and Engineering Applications of Computational Methods, CIMNE, Barcelona, J. PÉRIAUX, M. CHAMPION, J.-J. GAGNEPAIN, O. PIRONNEAU, B. STOUFFLET, P. THOMAS, editors, September, 2003.

[36] J. DAMIANO, P. DUBOIS, C. DEDEBAN, J. ZOLÉSIO. *Original and accurate polynimial interpoloation method to detrmine the surface currents with a mimimum of known points in the case of diffraction and radiationg problems.* in « ICEAA », pages 491-494, 2003, Torino.

[37] M. DELFOUR, N. DOYON, J.-P. ZOLÉSIO. *Extension of the uniform cusp property in shape optimization.* in « Control Theory for Partial Differential Equations », Lectures Notes in Pure and Applied Mathematics, Marcel Dekker, G. LEUGERING, O. IMANUVILOV, R. TRIGGIANI, B. ZHANG, editors, accepted for pblication on 05.09.03.

[38] M. DELFOUR, N. DOYON, J.-P. ZOLÉSIO. *The uniform fat segment and cusp properties in shape optimization.* in « System Modeling and Optimization », Kluwer, J. CAGNOL, E. J.-P. ZOLÉSIO, editors, accepted for publication on 15.10.03.

[39] M. DELFOUR, N. DOYON, J.-P. ZOLÉSIO. *The uniform fat segment and cusp properties in shape optimization.* in « System Modeling and Optimization », Kluwer, J. Z. J. CAGNOL, editor, accepted for publication on 15.10.03.

[40] W. FITZGIBBON, J.-A. DÉSIDÉRI. *High Speed Flow Field Databases.* in « Fluid Dynamics and Aeronautics New Challenges », series Handbooks on Theory and Engineering Applications of Computational Methods, CIMNE, Barcelona, J. PÉRIAUX, M. CHAMPION, J.-J. GAGNEPAIN, O. PIRONNEAU, B. STOUFFLET, P. THOMAS, editors, September, 2003.

[41] A. HABBAL. *Jeux de Nash en optimisation de forme.* Congrès National d'Analyse Numérique, La Grande-Motte, France, 2 - 6 juin, 2003.

[42] A. HABBAL, M. THELLNER, J. PETERSSON. *A Nash game approach for multidisciplinary topology design.* in « Fifth World Congress on Structural and Multidisciplinary Optimization », Venice, Italy., 19-23 May, 2003.

[43] M. MOUBACHIR, J. ZOLÉSIO. *The transverse field and Coupled Fluid-Strucure.* in « System Modeling and Optimization », Kluwer, J. Z. J. CAGNOL, editor, accepted for publication on 15.10.03.

[44] T. NGUYEN. *Grid-computing in mutidisciplinary CFD optimization problems.* in « Parallel CFD 2003 Conference », Moscou, Mai, 2003.

[45] T. NGUYEN. *Grids : opportunities and drawbacks.* in « Modeling, Analysis and Optimisation for the Design of Coupled Industrial Systems », I. S. ANTIPOLIS, editor, October, 2003, MACSInet Open Industrial Days and French-Finnish Seminar.

[46] T. NGUYEN. *Virtual organisations and multidisciplinary applications.* in « Grid-based Virtual Organisations & collaborative e-Entreprise applications », D. I.-F. COMMISSION EUROPÉENNE, editor, BAE Systems, Londres, Mai, 2003.

[47] Z. TANG, J.-A. DÉSIDÉRI, J. PÉRIAUX. *Distributed Optimization using Virtual and Real Game Strategies for Aerodynamic Multi-Objective Design.* in « West East High Speed Flow Fields – Aerospace applications from high subsonic to hypersonic regime », series Theory and Engineering Applications of Computational Methods, CIMNE, Barcelona, D. ZEITOUN, J. PÉRIAUX, J.-A. DÉSIDÉRI, M. MARINI, editors, 2003.

[48] E. WHITNEY, L. GONZALEZ, K. SRINIVAS, J. PÉRIAUX. *Adaptive Evolution Design without Problem Specific Knowledge: UAV Applications.* in « Evolutionary Methods for Design, Optimization and Control with Applications to Industrial and Societal Problems », International Center for Numerical Methods in Engineering (CIMNE), G. BUGEDA, J.-A. DÉSIDÉRI, J. PÉRIAUX, M. SCHOENAUER, G. WINTER, editors, Barcelona, Spain, 2003, Proc. of EUROGEN 2003, Barcelona, September 15-17, 2003.

Internal Reports

[49] M. ANDREOLI, A. JANKA, J.-A. DÉSIDÉRI. *Free-form-deformation parameterization for multilevel 3D shape optimization in aerodynamics.* Technical report, number 5019, INRIA, December, 2003, http://www.inria.fr/rrrt/rr-5019.html.

[50] F. BÉLAHCÈNE, J.-A. DÉSIDÉRI. *Paramétrisation de Bézier adaptative pour l'optimisation de forme en Aérodynamique.* Technical report, number 4943, INRIA, September, 2003, http://www.inria.fr/rrrt/rr-4943.html.

[51] S. BAUDOT-ROUX. *Mise en place de bases de données thématiques pour la validation de codes numériques.* Diplôme de Recherche Technologie Informatique, Université de Montpellier II Sciences et Techniques du Languedoc, Juin, 2003.

[52] L. OULLADJI, A. JANKA, J.-A. DÉSIDÉRI, A. DERVIEUX. *Optimisation aérodynamique par algorithmes génétiques hybrides: application à la réduction d'un critère de bang sonique.* Technical report, number 4884, INRIA, July, 2003, http://www.inria.fr/rrrt/rr-4884.html.

[53] J. ZOLÉSIO. *Smart Boundary Stabilization in Wave Equation Under Newman Boundary Conditions.* Technical report, INRIA, 2003.

Miscellaneous

[54] J.-A. DÉSIDÉRI. *Hierarchical optimum-shape algorithms using embedded Bézier parameterizations.* Applied Mathematics and Applications of Mathematics (AMAM) First EMS-SMAI-SMF Joint Conference, February 10-13, 2003, Nice, (France), URL: http://www-sop.inria.fr/opale ; Rubrique: Exposés.

[55] J.-A. DÉSIDÉRI. *Optimisation de formes aérodynamiques pour les voilures d'avions.* Conférence invitée, 10es Rencontres INRIA-Industrie, Applications de l'informatique et de l'automatique aux Transports, Rocquencourt, 16 Jannvier 2003, URL: http://www-sop.inria.fr/opale ; Rubrique: Exposés.

[56] J.-A. DÉSIDÉRI. *Hierarchical CFD Models for Optimum-Shape Design in Aerodynamics.* 2003, Invited Lecture, MACSInet Workshop on Model Reduction, Milano, Italy; URL: http://www-sop.inria.fr/opale ; Rubrique: Exposés.

Bibliography in notes

[57] E. FARIN. *Curves and surfaces for computer aided geometric design : a practical guide.* series Comp. science and sci. computing, Acad. Press, 1990.

[58] D. GOLDBERG. *Genetic Algorithms in Search, Optimization and Machine Learning.* Addison-Wesley, 1989.

[59] *IST Grid projects inventory and roadmap.* Document IR-D2.2.1.2-V1.0, GRIDSTART project, June 2003.

[60] J. F. WANG. *Optimisation Distribuée Multicritère par Algorithmes Génétiques et Théorie des Jeux & Application à la Simulation Numérique de Problèmes d'Hypersustentation en Aérodynamique.* Thèse de doctorat, Université de Paris 6, 2001.