INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Sydoco

SYstèmes Dynamiques, Optimisation et Commande Optimale

Rocquencourt

THEME NUM

Activity Report

2004

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1. Team

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Mikhail Solodov [IMPA - Rio de Janeiro, 3 semaines]

2. Overall Objectives

To develop new algorithms in deterministic and stochastic optimal control, and deal with associated applications, especially for aerospace trajectories and management for the power industries (hydroelectric resources, storage of gas and petroleum).

In the field of deterministic optimal control, our objective is to develop algorithms combining iterative fast resolution of optimality conditions (of the discretized problem) and refinement of discretization, through the use of interior point algorithms. At the same time we wish to study multiarcs problems (separations, rendez-vous, formation flights) which necessitates the use of decomposition ideas.

In the field of stochastic optimal control, our first objective is to develop fast algorithms for problems of dimension two and three, based on fast computation of consistent approximations as well as splitting methods. The second objective is to link these methods to the stochastic programming approach, in order to deal with problems of dimensions greater than three.

3. Scientific Foundations

For deterministic optimal control problems there are basically three approaches. The so-called direct method consists in an optimization of the trajectory, after having discretized time, by a nonlinear programming solver that possibly takes into account the dynamic structure; see Betts [25]. The indirect approach eliminates control variables using Pontryagin's maximum principle, and solves the resulting two-points boundary value problem by a multiple shooting method. Finally the dynamic programming approach solves the associated Hamilton-Jacobi-Bellman (HJB) equation, which is a partial differential equation of dimension equal to the number n of state variables. This allows to find the global minimum, whereas the two other approaches are local; however, it suffers from the curse of dimensionality (complexity is exponential with respect to n).

There are various additional issues: decomposition of large scale problems, simplification of models (leading to singular perturbation problems), computation of feedback solutions.

For stochastic optimal control problems there are essentially two approaches. The one based on the (stochastic) HJB equation has the same advantages and disadvantages as its deterministic counterpart. The stochastic programming approach is based on a finite approximation of uncertain events called a scenario tree (for problems with no decision this boils down to the Monte Carlo method). Their complexity is polynomial with respect to the number of state variables but exponential with respect to the number of time steps. In addition, various heuristics are proposed for dealing with the case (uncovered by the two other approaches) when both the number of state variables and time steps is large.

4. Application Domains

Aerospace trajectories (rockets, planes), automotive industry (car design), chemical engineering (optimization of transient phases, batch processes).

Storage and management, especially of natural and power resources, portfolio optimization.

5. Software

We have presently two research softwares. The first is an implementation of interior point algorithms for trajectory optimization, and the second is an implementation of fast algorithms for bidimensional HJB equations of stochastic control.

6. New Results

6.1. Trajectory optimization

Participants: F. Bonnans, M. Haddou, S. Avril, J. Laurent-Varin.

En collaboration with N. Bérend (DPRS, ONERA) and Ch. Talbot (CNES Evry).

6.1.1. Order conditions for Runge-Kutta schemes

Participants: F. Bonnans, J. Laurent-Varin.

We have clarified the analysis of discretization errors for an unconstrained optimal control problem with strongly convex Hamiltonian and smooth data. The discretization procedure of W. Hager [26] is reinterpreted as a symplectic discretization scheme for the optimality system. In addition we show how to generate short expressions for the order conditions on the Runge-Kutta coefficients, based on a certain splitting operator for directed graphs. These conditions are generated up to order 7 and displayed up to order 6. For order up to 4 we recover the results of Hager. These results are published in the INRIA Research Report [20].

We note that there are still many open results in this field, especially in the case of non strongly convex Hamiltonian (e.g. linearity with respect to the control, singular arcs), locally strongly convex Hamiltonian with multiple minima, and of course constrained problems.

6.1.2. Error analysis of logarithmic penalty for optimal control problems

Participants: F. Bonnans, J. Laurent-Varin, F. Alvarez [CMM, Universidad de Chile].

Here we try to estimate the difference between a solution of an optimal control problem and the one of the associated problem with logarithmic penalty of constraints. Our premilinary results deal with the special case of a linear quadratic convex problem with nonnegativity constraints on the control, and without distributed cost on the state.

We are able to give an expansion of the optimal triple (state, control and adjoint state), the first term having coefficient $\varepsilon \log \varepsilon$, where ε is the penalty parameter. This result will be published in the proceedings of the Moscow conference in honor of Tihomirov.

Graph	Condition	Graph	Condition
	$\sum \frac{1}{b_k} a_{lk} d_k d_l = \frac{1}{8}$		$\sum a_{jk} d_j c_k = \frac{1}{24}$
	$\sum \frac{b_i}{b_k} a_{ik} c_i d_k = \frac{5}{24}$		$\sum b_i a_{ij} c_i c_j = \frac{1}{8}$
	$\sum c_j^2 d_j = \frac{1}{12}$		$\sum b_i c_i^3 = \frac{1}{4}$
	$\sum \frac{1}{b_k} c_k d_k^2 = \frac{1}{12}$		$\sum \frac{1}{b_l^2} d_l^3 = \frac{1}{4}$

Figure 1. Ordre 4

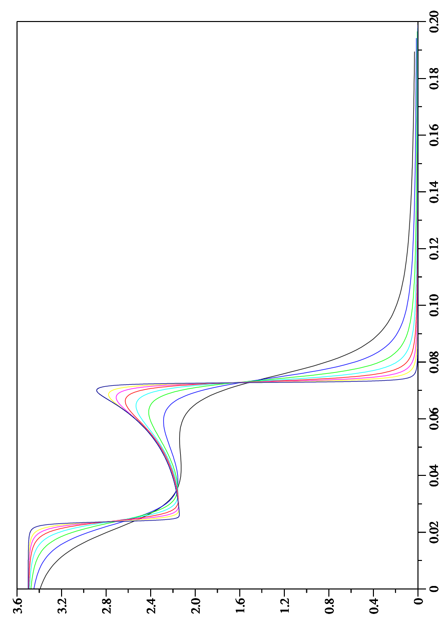

Figure 2. This image displays the optimal control computed for several values of the penalty parameter on the interior point algorithm for Goddard's problem, which is the optimal ascent for a rocket with vertical trajectory and variable mass. The optimal strategy consists in an arc of maximum thrust, followed by a singular arc (with a moderate speed that limitates losses of energy due to aerodynamic forces) and then a zero thrust arc when the minimum mass is attained.

6.1.3. Analysis of multiarc optimization

Participants: F. Bonnans, J. Laurent-Varin, M. Haddou, N. Bérend, C. Talbot.

We have completed a theoretical study of the sparse factorization of the Jacobian occuring when solving an optimal control problem, with multiple arcs. The basic idea is to eliminate, by successive QR factorizations, starting from the leaves of the graph representing the connection between arcs. The main result is that the cost of factorization is proportional to the number of arcs plus nodes. For each arc the cost is proportional to the number of time steps, multiplied by the square of number of state variables. For each node the cost is proportional to the cube of the number of variables at this node.

The results will be published in the proceedings of the Internation School of Mathematics "G. Stampacchia" Workshop on "Large Scale Nonlinear Optimization". June 22th - July 1st, 2004 - Erice - Sicile.

6.1.4. Software enhancements

Participant: J. Laurent-Varin.

A main change in the code was to avoid to compute the discretization estimate inside the Jacobian factorization. This discretization estimate is now a separate module that can be called for a given time step, adding more flexibility to the code and allowing a significant decrease on the number of operations (since the number of internal states is divided by more than two, and the number of operations is roughly speaking proportional to the square of this number).

The linear algebra kernel has been rewritten in order to allow to take into account a nested structure. This is used presently for successive elimination of slack variables and distributed in time variables, and will be applied to the case to multiarc optimization.

We have reorganized the input-output operations, taking advantage of the Scilab software for scientific computation. A tcl-tk interface based on Scilab allows to modify a number of data, and the graphic part was improved.

6.1.5. Atmospheric reentry

Participant: J. Laurent-Varin.

Our code now runs for several atmospheric reentry trajectory optimization problems for a space shuttle. We have used the data of Betts [25] for the shuttle itself and the atmosphere and gravity model, and have recovered his results (for the maximization of cross range, i.e. of final latitude, with or without a bound on the instantaneous heating). We have tested also a number of other criteria such as the final longitude, and other constraints such as a nonpositive path angle. These results will be published in an INRIA report to appear.

6.1.6. Optimal transfer of satellites

Participants: F. Bonnans, S. Avril, N. Bérend [DPRS-ONERA].

An optimization tool based on an indirect shooting method has been encoded in C++. This tool deals with an tranfer problem with free final time and maximal final mass. The trajectory is decomposed in a fixed number of balistic and propelled arcs, the switching times being unknown of the problem. The algorithm includes a Newton step with linesearch, and an initialization procedure based on the resolution of a simplified model. The sofware has been validated on some simple transfer problems, with final constraints on two orbital parameters.

6.2. Numerical methods for HJB equation

Participants: F. Bonnans, H. Zidani, S. Maroso, E. Ottenwaelter.

This section presents our research for the numerical approximation of the HJB (Hamilton-Jacobi-Bellman) equation of stochastic control. The latter is of the following type

$$(HJB) \quad \begin{aligned} -v_t(t,x) = &\ \inf_{u \in U} \{\ell(t,x,u) + f(t,x,u)\cdot v_x(t,x) + a(t,x,u)\circ v_{xx}(t,x)\}, \\ &\quad \text{for all} \quad t,x \in [0,T]\times\mathbb{R}^n. \\ v(T,x) = &\ \ell_F(x), \ \text{ for all } \ x\in\mathbb{R}^n. \end{aligned}$$

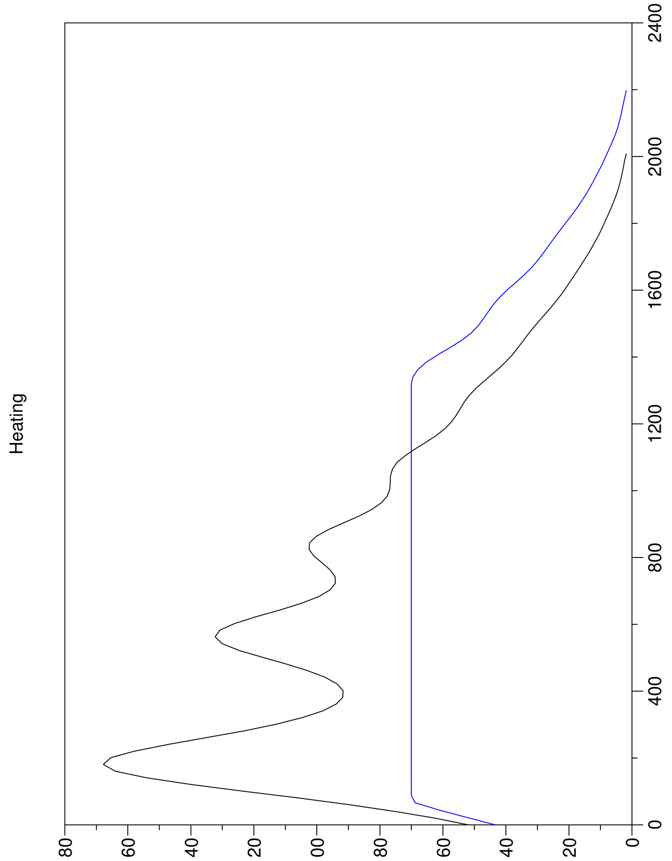

Figure 3. This figure displays the instantaneous heating flux with respect to time, for the problem of reentry of an American space shuttle, maximizing the final latitude. The gray plot shows, as expected, oscillations due to several rebounds. The blue plot takes into account an additional constraint on the maximum instantaneous heating flux (rebounds are essentially eliminated). The results are in accordance with those of the literature [25].

Its solution is the value function of the following problem

$$(P_{\tau,x}) \quad \begin{array}{l} Min \quad \mathbb{E}\displaystyle\int_\tau^T \ell(t,y(t),u(t)) \ \mathrm{d}\ t + \ell_F(y(T)); \\ \begin{cases} \mathrm{d}\ y(t) = f(t,y(t),u(t)) \ \mathrm{d}\ t + \sigma(t,y(t),u(t)) \ \mathrm{d}\ w(t), \\ y(\tau) = x; \qquad u(t) \in U, \ \ t \in [\tau,T], \ \ \tau \in [0,T]. \end{cases} \end{array}$$

We had previously introduced the generalized finite differences approximation scheme [4] and obtained a fast implementation of this algorithm when the state space dimension n is two, in [7].

6.2.1. Antidiffusive schemes for first order HJB equations

Participants: N. Megdiche, H. Zidani.

The first order HJB equations allow to compute the value function of a deterministic optimal control problem. Our interest comes from with control problems with state constraints (Rendez-vous problem, target problem, minimal time). When some strong controlability assumptions are not satisfied, the solution of the HJB equation is discontinuous and the classical discretization schemes (such as finite differences or semi-lagrangian) provide poor quality approximation because of numerical diffusion.

In collaboration with O. Bokanowski (Univ. Paris 7), we have proposed in [17] two new anti-diffusive schemes for advection (or linear transport),and have shown how to apply these schemes to the resolution of the time-dependant first order HJB equations with discontinuous initial data, possibly infinitely-valued.

The numerical experiments tested on several benchmark problems and compared to other algorithms are very encouraging, in term of the approximation error.

In [16], we have investigated the use of an antidiffusive scheme to treat some viability problems. Numerical experiments, compared with the viability algoritm [27], show the relevance of our scheme for computing viability kernels.

Within the framework of the thesis of N. Megdiche, we have studied the implementation of an antidiffusive scheme on an adaptive grid. The use of the adaptive grid enables us to have a better approximation precision, in particular around the discontinuities, while optimizing the number of meshs in the grid of calculation. A corresponding preprint is in preparation.

6.2.2. Splitting decomposition for generalized finite differences

Participants: F. Bonnans, E. Ottenwaelter, H. Zidani.

This study exploits the expression of the generalized finite difference approximation scheme, as a sum of finite differences operators, in order to derive a splitting decomposition algorithm. At each inner step of the splitting scheme, one has to solve several one dimensional diffusions along parallel directions. Each time step needs as many inner steps as elements of the stencil. We had shown previously that in general, the computation of an accurate approximation necessitates a large stencil; however, in many cases a small stencil will be enough. We show that splitting combined with implicit time discretization allows large time steps (of order of space step rather than the square of it).

6.2.3. Error analysis for HJB equations

Participants: F. Bonnans, S. Maroso, H. Zidani.

This work deals with a zero-sum game problem where the first player minimizes the expectation of an integral cost, whereas the second player takes the decision to stop the game. We extend to this situation some techniques of Krylov and Barles and Jakobsen. These references obtain error estimates for a stochastic optimal control problem, by combining a certain regularization procedure due to Krylov with the idea of penalizing changes of the control. We show that a certain adaptation of these techniques allows to obtain similar error estimates. This study is published in an INRIA report [18].

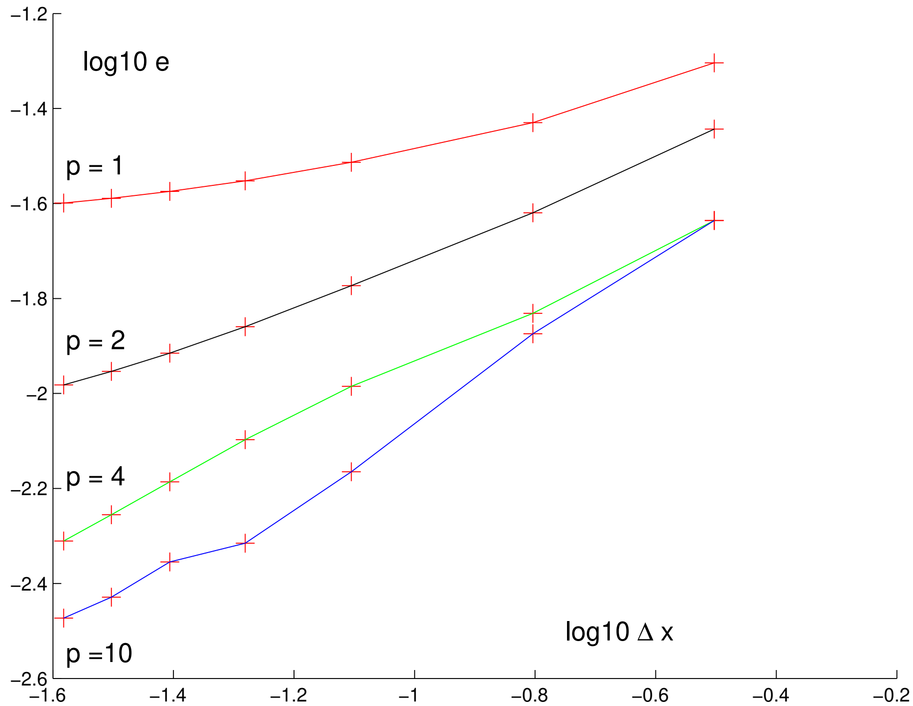

Figure 4. This figure illustrates the precision of the geenralized finite difference approximation (the exact solution of the continuous problem is known) with respect to the space step, for various values of the size p of the stencil. As expected, the larger the stencil, the more accurate is the solution. See details in [19].

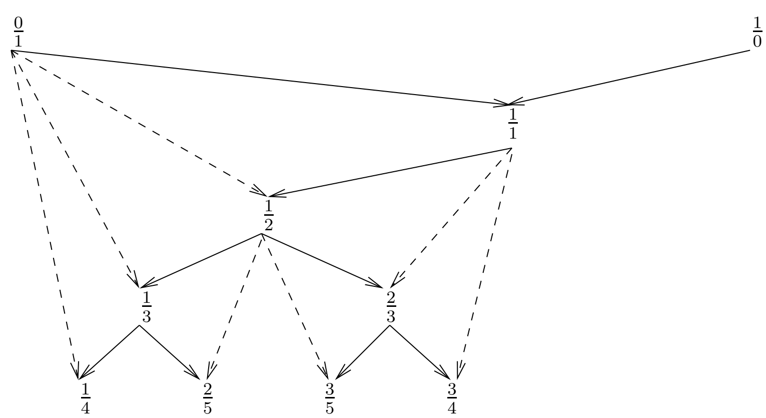

Figure 5. This figure illustrates the Stern Brocot tree that generates in a natural way all irreducible fractions. This tree is used in an essential way in the design of a fast algorithm for the HJB equation of stochastic control, when there are two state variables.

6.3. Nonlinear optimization

6.3.1. Positive semidefinite optimization

Participants: F. Bonnans, H. Ramirez-Cabrera.

In collaboration with Rafael Correa (CMM, Universidad de Chile)

A general problem in sensitivity theory for optimization problems is to characterize "strong regularity" in the sense of Robinson. One looks for a characterization in terms of first and second order derivatives of data at the current point, that one can check easily. Such characterizations are known presently in a limited number of situations, see chapter 5 of [3].

In our work we have analysed first and second order optimality conditions for nonlinear second-order cone programming problems, and their relation with semidefinite programming problems. For doing this we extend in an abstract setting the notion of optimal partition. Then we state a characterization of strong regularity in terms of second order optimality conditions. The results are published in the INRIA Research Report [21].

6.3.2. $\mathcal{V}U$-algorithms and theory

Participant: C. Sagastizábal.

Joint work with Robert Mifflin (Washington State University - EUA).

In [23] we introduce an algorithm for convex minimization based on $\mathcal{V}U$-space decomposition, see Report 2003. The method uses a bundle subroutine to generate a sequence of approximate proximal points. When a primal-dual track leading to a solution and zero subgradient pair exists these points approximate the primal track points and give the algorithm's $\mathcal{V}$ or corrector steps. The subroutine also approximates dual track points that are $\mathcal{U}$-gradients needed for the method's $\mathcal{U}$-Newton predictor steps. With the inclusion of a simple line search the resulting algorithm is proved to be globally convergent. The convergence is superlinear if the primal-dual track points and the objective's $\mathcal{U}$-Hessian are approximated well enough.

This work is a follow-up of our more theoretical research on nonsmooth functions with `pdg` structure. In [9] we show that when strong transversality is satisfied, there exists a C^2 trajectory leading to $\overline{x}$ and an associated subdifferential that is C^1. As a result, there exists a space decomposition mapping that is C^1 and a second order expansion of f on the trajectory. For $\overline{x}$ a minimizer, we give conditions on f to ensure that for any point near $\overline{x}$ its corresponding proximal point is on the trajectory. This purely theoretical result is fundamental for minimization algorithms and their implementations, since it is known that, at least in the convex case, a sequence of null steps from a bundle mechanism can approximate proximal points with any desired accuracy.

Suppose the function is not `pdg` structured, but has additional properties of prox-regularity and prox-boundedness. In [10] we make use of $\mathcal{V}U$-space decomposition theory to connect three minimization-oriented objects. These objects are $\mathcal{U}$-Lagrangians obtained from minimizing a function over $\mathcal{V}$-space, proximal points depending on minimization over $\mathbb{R}^n = \mathcal{U} \oplus \mathcal{V}$, and epi-derivatives determined by lower limits associated with epigraphs. We relate second-order epi-derivatives of a function to the Hessian of its associated $\mathcal{U}$-Lagrangian. We also show that the function's proximal points are on a trajectory determined by certain $\mathcal{V}$-space minimizers.

6.3.3. Bundle methods for constrained optimization problems

Participant: C. Sagastizábal.

Global convergence in constrained optimization algorithms has traditionally been enforced by the use of parametrized penalty functions. Recently, the filter strategy has been introduced as an alternative. At least part of the motivation for filter methods consists in avoiding the need for estimating a suitable penalty parameter, which is often a delicate task. In [11] we demonstrate that the use of a parametrized penalty function in nonsmooth convex optimization can be avoided without using the relatively complex filter methods. We propose an approach which appears to be more direct and easier to implement, in the sense that it is closer in spirit and structure to the well-developed unconstrained bundle methods. Preliminary computational results are also reported.

Joint work with M. Solodov (IMPA).

For comparison purposes, we are currently working on a filter-based variant [22], which combines the ideas of the proximal bundle methods with the filter strategy for evaluating candidate points. The resulting algorithm inherits some attractive features from both approaches. On the one hand, it allows an effective control of the size of quadratic programming subproblems via the compression and aggregation techniques of the proximal bundle methods. On the other hand, the filter criterion for accepting a candidate point as the new iterate is expected to be easier to satisfy than the usual descent (serious step) condition in bundle methods.

Joint work with E. Karas, A. Ribeiro (UFPR), and M. Solodov (IMPA).

6.4. Industrial applications

Participant: C. Sagastizàbal.

In [8], [12], [14] we consider the inclusion of hydro-thermal unit-commitment in the optimal management of the Brazilian power system, as well as a long term generation and interconnection expansion planning problem.

In [6] we consider the problem of optimal design of hybrid car engines which combine thermic and electric power.

7. Contracts and Grants with Industry

7.1. Trajectory optimization

We have agreements of cooperation with Onera and CNRS concerning the studies on transfer or orbits for low-thrust satellites, and optimal trajectories for future launchers.

8. Other Grants and Activities

8.1. International collaborations

- With Felipe Alvarez, from CMM and Universidad de Chile, Santiago de Chile, F. Bonnans and J. Laurent-Varin have worked on the analysis of logarithmic penalty for optimal control problems.
- With Rafael Correa from CMM and Universidad de Chile, Santiago de Chile : codirection of the thesis of H. Ramirez. F. Bonnans and H. Ramirez have published the INRIA Research report 5293.
- With Claudia Sagastizábal, IMPA, Rio de Janeiro : we are currently analysing some approaches for stochasting programming, with application to the production of electricity.

8.2. Scientific responsabilities outside Inria

F. Bonnans was untill june 2004, Vice President for Publications of SMAI, the French Applied Mathematics Society. This means supervising three scientific journals, one proceedings series, and a series of books. The main event this year was the editorial responsability of SMAI, jointly with ROADEF, of the journal RAIRO-RO.

8.3. Visiting Scientists

C. Sagastizábal and Mikhail Solodov (IMPA - Brazil), F. Alvarez and Hector Ramirez-Cabrera (DIM - Chile), R. Bessi Fourati (ENIT - Tunisie).

9. Dissemination

9.1. Teaching

F. Bonnans- Professeur chargé de cours, Ecole polytechnique and Course on Continuous Optimization, Mastere de Math. et Applications, Filière "OJME" Optimisation, Jeux et Modélisation en Economie, Université Paris VI.

9.2. Conference and workshop committees, invited conferences

- CIMPA School on Control, Optimization and Variational Problems, Lima (Pérou). C. Sagastizábal. Minicourse on *Algorithms for nonsmooth optimization. Application to energy problems*, [24], February 2004.
- V Brazilian Workshop on Continuous Optimization, Florianópolis (Brésil), March 2004. C. Sagastizábal.
- 5th Working Group Meeting "APOMAT". May 13-14 - Angers - France. Expert : F. Bonnans.
- 16ème IFAC SYMPOSIUM "Automatic Control in Aerospace". June 14-18 - St. Petersburg - Russia. Talk : J. Laurent-Varin.
- International School of Mathematics "G. Stampacchia". Workshop on "Large Scale Nonlinear Optimization". June 22 - July 1 - Erice - Sicile. Invited talk : F. Bonnans
- Premier Congrès Canada-France des Sciences Mathématiques. July 12-15 - Toulouse - France. Invited talk : F. Bonnans.
- Journées MAS. September 6-8 - Nancy - France. Invited talk : F. Bonnans.
- EDF's meeting on Energy Optimization, Clamart (France), September 2004. C. Sagastizábal.
- XII French German Spanish Conference on Optimization, Avignon (France), September 2004. Member of program commitee : F. Bonnans. Talk : J. Laurent-Varin.
- Workshop *Matematicas en Accín - Optimización en la Industria*, University of Cantabria, Santander (Spain), September 2004. C. Sagastizábal.
- Numerical Methods for Viscosity Solutions and Applications. September 6-8 - Rome - Italie. Invited talk : H. Zidani. Talks : S. Maroso, E. Ottenwaelter.
- FGS2004. September 20-24 - Avignon - France. Member of program commitee : F. Bonnans. Talks : J. Laurent-Varin, H. Ramirez-Cabrera.
- Atelier CNES "Commande Optimale et boucle fermée". October 4-5 - Toulouse - France. Invited talk : F. Bonnans.
- Workshop on Mathematical Methods in Energy Problems, Curitiba (Brésil), November 2004. C. Sagastizábal.

9.3. Conferences, meetings and tutorial organization

- Ecole CIMPA-UNESCO-PAYS ANDINS "Analyse, Optimisation, Commande Optimale". February 9-27 - IMCA - Lima - Pérou. Lecture by F. Bonnans.
- Journées MODE 2004. February 25-27 - Le Havre - France. Talk by J. Laurent-Varin

10. Bibliography

Major publications by the team in recent years

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[2] J.F. BONNANS, M. HADDOU. *Asymptotic analysis of congested communication networks*, in "Mathematics of Operations Research", Rapport de Recherche Inria 3133, 1997, n° 25-3, 2000, p. 409-426.

[3] J.F. BONNANS, A. SHAPIRO. *Perturbation analysis of optimization problems*, Springer-Verlag, 2000.

[4] J.F. BONNANS, H. ZIDANI. *Consistency of Generalized Finite Difference Schemes for the Stochastic HJB Equation*, in "SIAM J. Numerical Analysis", vol. 41, n° 3, 2003, p. 1008-1021.

[5] R. BESSI FOURATI, J.F. BONNANS, H. SMAOUI. *The obstacle problem for water tanks*, in "J. Mathématiques Pures et Appliquées", Rapport de Recherche Inria 4811, n° 82-11, 2003, p. 1527-155, http://www.inria.fr/rrrt/rr-4811.html.

Articles in referred journals and book chapters

[6] J.F. BONNANS, T. GUILBAUD, A. KEFTFI-CHERIF, C. SAGASTIZÁBAL, D. VON WILLSEL, H. ZIDANI. *Parametric optimization of hybrid car engines*, in "Optimization and Engineering", vol. 5, n° 4, 2004, p. 395-415, http://dx.doi.org/10.1023/B:OPTE.0000042032.47856.e5.

[7] J.F. BONNANS, E. OTTENWAELTER, H. ZIDANI. *A fast algorithm for the 2D HJB equation of stochastic control*, in "ESAIM:M2AN", vol. 38, n° 4, 2004, p. 723-735.

[8] E. FINARDI, E. DE SILVA, C. SAGASTIZÁBAL. *Solving the Unit Commitment Problem of Hydropower Plants via Lagrangian Relaxation and Sequential Quadratic Programming*, in "Computational and Applied Mathematics", Accepted for publication, 2004.

[9] R. MIFFLIN, C. SAGASTIZÁBAL. *$\mathcal{VU}$-Smoothness and proximal point results for some nonconvex functions*, in "Optmization Method and Software", vol. 19, n° 5, 2004, p. 463-478.

[10] C. SAGASTIZÁBAL, R. MIFFLIN. *Relating $\mathcal{U}$-Lagrangians to Second Order Epiderivatives and Proximal Tracks*, in "Journal of Convex Analysis", vol. 12, n° 1, 2004, http://www.heldermann.de/JCA/JCA12/jca12.htm.

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Publications in Conferences and Workshops

[12] DINIZ, L.A., T. F.S. COSTA, M.E. MACEIRA, C. SAGASTIZÁBAL, L.C. SOUZA, E.C. FINARDI. *Hydro unit-commitment via Lagrangian relaxation - dessem*, in "Annals of IX SEPOPE", electronic distribution (CD), 2004.

[13] J. LAURENT-VARIN, N. BÉREND, J.F. BONNANS, M. HADDOU, C. TALBOT. *On the refinement of discretization for optimal control problems*, in "16th IFAC SYMPOSIUM Automatic Control in Aerospace, St. Petersburg - Russia", 14-18 june 2004.

[14] C.H. SABOIA, A.C. MELO, C. SAGASTIZÁBAL, M.E. MACEIRA, M.E. LISBOA, M. DAHER, P.H. SALES, L.A. TERRY. *Application of the melp program to define a long term generation and interconnection expansion plan for the Brazilian system*, in "Annals of IX SEPOPE", electronic distribution (CD), 2004.

Internal Reports

[15] F. ALVAREZ, J. BOLTE, J. MUNIER. *Unifying Local Convergence Result for Newton's Method in Riemannian Manifolds*, Technical report, n° 5381, Inria-Rocquencourt, November 2004, http://www.inria.fr/rrrt/rr-5381.html.

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