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6. AUTHOR(S)
John E. Dennis, Jr. and Richard A. Tapia

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
William Marsh Rice University
P.O. Box 1892
Houston, Texas 77251-1892

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"Parallel Structured Optimization Algorithms for Inverse Problems"

Final Report

John E. Dennis, Jr. and Richard A. Tapia

Period Covered: 15 April 1990 - 14 August 1993

U.S. Army Research Office

Contract/Grant #: DAAL03-90-G-0093

Rice University

Scientific Personnel

Scientific Personnel Supported by this project and degrees awarded during this reporting period:

- Professor J.E. Dennis
- Professor R.A. Tapia
- Professor Yin Zhang (now at Univ. of Maryland - Baltimore County)
- Graduate student Debora Cores
- Catherine Samuelsen - Ph.D. May 1992

Manuscripts

List of manuscripts submitted or published under ARO sponsorship during this reporting period, including journal references:

- On the Convergence of the Multi-Directional Search Algorithm, *SIOPT (SIAM Journal on Optimization)* 1, (1991) pps. 123 - 145 by Virginia Torczon.

- A View of Unconstrained Minimization, in Optimization, Handbooks in O.R. and M.S. 1, (1989) pps. 1-72, ed by Nemhauser, Kan, and Todd, by J.E. Dennis and R.B. Schnabel.

- A Curvilinear Search Using Tridiagonal Secant Updates for Unconstrained Optimization, *SIOPT (SIAM Journal on Optimization)* 1, (1991) pps. 333-357, by J.E. Dennis, N. Echebest, M.T. Guardarucci, J.M. Martinez, H.D. Scolnik, and C. Vacchino.

- Direct Search Methods on Parallel Machines, *SIOPT (SIAM Journal on Optimization)* 1, (1991) pps. 448-474, by J.E. Dennis and Virginia Torczon.

- An SQP Augmented Lagrangian BFGS Algorithm for Constrained Optimization, *SIOPT (SIAM Journal on Optimization)* 2, (1992) pps. 210-241, by R.H. Byrd, R.A. Tapia and Y. Zhang.

- Multi-Directional Search: A Direct Search Algorithm for Parallel Machines, by Virginia Torczon.

- On the Superlinear and Quadratic Convergence of Primal-Dual Interior Point Linear Programming Algorithms, *SIOPT (SIAM Journal on Optimization)* 2(2), (1992) pps. 304-324, by R.A. Tapia, Yin Zhang, and J.E. Dennis.

- On the Superlinear Convergence of Interior Point Algorithms for a General Class of Problems. To appear in *SIOPT (SIAM Journal on Optimization)*, by R.A. Tapia, Yin Zhang, and F. Potra.

- The Predictor-Corrector Interior-Point Method as a Composite Newton Method.

To appear in *SIOPT (SIAM Journal on Optimization)*, by R.A. Tapia, Yin Zhang, M.J. Saltzman, and A. Weiser.

- A Study of Indicators for Identifying Zero Variables in Interior - Point Methods. Accepted for Publication in *SIAM Review*, by R.A. Tapia, Amr El-Bakry, and Yin Zhang.

- A Superlinearly Convergent Polynomial Primal-Dual Interior-Point Algorithm for Linear Programming. *SIOPT (SIAM Journal on Optimization)* 3(1), February (1993) pps. 118-133, by R.A. Tapia and Yin Zhang.

- A Superlinearly Convergent $O(\sqrt{n}L)$ Iteration Algorithm for Linear Programming, by Y. Ye, R.A. Tapia, and Y. Zhang.

- An Interior-Point Method with Polynomial Complexity and Superlinear Convergence for Linear Complementarity Problems. Submitted for Publication in *Annals of Operations Research*, by J. Ji, F. Potra, R.A. Tapia, and Y. Zhang.

- On the Convergence of the Iteration Sequence in Primal-Dual Interior-Point Methods. Submitted for Publication in *Mathematical Programming*, by Y. Zhang, R.A. Tapia, and Y. Ye.

- A Quadratically Convergent $O(\sqrt{n}L)$ Iteration Algorithm for Linear Programming. *Mathematical Programming* 59 (2), April (1993) pps. 151-162, by Y. Ye, O. Güler, R.A. Tapia, and Y. Zhang.

- Superlinear and Quadratic Convergence of Primal-Dual Interior-Point Methods for Linear Programming Revisited, *JOTA (Journal of Optimization Theory and Applications)* 73(2), (1992) pps. 229-242, by R.A. Tapia and Y. Zhang.

- On the Convergence of Interior-Point Methods to the Center of the Solution Set in Linear Programming. Submitted for Publication in *Mathematics of Operations Research*, by Y. Zhang and R.A. Tapia.

- The Dikin-Karmarkar Principle for Steepest Descent, by Catherine M. Samuelsen.

- On the Convergence of the Mizuno-Todd-Ye Algorithm to the Analytic Center of the Solution Set. Submitted for publication in *SIOPT (SIAM Journal on Optimization)*, by C. Gonzaga and R.A. Tapia.

- On the Quadratic Convergence of the Simplified Mizuno-Todd-Ye Algorithm for Linear Programming. Submitted for publication in *SIOPT (SIAM Journal on Optimization)*, by C. Gonzaga and R.A. Tapia.

- Sizing the BFGS and DFP Updates: A Numerical Study. To appear in *JOTA (Journal of Optimization Theory and Applications)*, by M. Contreras and R.A. Tapia.

- Extending the Farkas Lemma Approach to Necessity Conditions to Infinite Programming. To appear in *Math Review*, by R.A. Tapia and M. Trosset.

- On Alternative Problem Formulations for Multidisciplinary Design Optimization, appeared in Proceedings of the AIAA Conference on Multidisciplinary Design Optimization, Cleveland, Sept. 1992, by E.J. Cramer, P.D. Frank, G.R. Shubin, J.E. Dennis, and R.M. Lewis. Submitted for publication.

- A Unified Approach to Global Convergence of Trust-Region Methods for Nonsmooth Optimization, by J.E. Dennis, Shou Bai Li, and R.A. Tapia. To appear in *Mathematical Programming*.

- Least-Change Secant Methods, Sizing, and Shifting, by J.E. Dennis and H. Wolkowicz. To appear in *SIAM Journal on Numerical Analysis*.

- Triangular Decomposition Methods for Solving Reducible Nonlinear Systems of Equations, by J.E. Dennis, J.M. Martinez, and X. Zhang. To appear in *SIOPT (SIAM Journal on Optimization)*.

- A Global Convergence Theory for Trust-Region-Based Algorithms for Equality Constrained Optimization, by J.E. Dennis, M. El-Alem, and M.C. Maciel. Submitted for publication.

- A Trust-Region Algorithm for Least-Squares Solutions of Nonlinear Systems of Equalities and Inequalities by J.E. Dennis, M. El-Alem, and Karen Williamson. In preparation.

Research Findings

In this report, we will organize the reports on the accomplishments as:

- Results for Interior Point Methods.
- Results for Optimization with Simulation Constraints
- Results for Large Scale Nonlinear Methods
- Results for Parallel Direct Search Methods

Research on Interior Point Methods

Dennis, Tapia, and Zhang have made progress in fast primal-dual interior-point methods for linear programming. The work done under this contract has helped explain the role of phaseout of the centering step in the speed of convergence of these promising methods.

During the period since our last report, we have made progress on two fronts. Tapia has been working with visitors to the NSF Center for Research on Parallel Computation on interior-point methods for linear programming. They have found a method with the best known iteration complexity as well as the best known asymptotic rate of convergence. There are several other reports in preparation on interior-point methods as well.

Tapia and visitor Gonzaga from Brazil successfully completed two manuscripts. The first paper demonstrates the quadratic convergence of a primal-dual algorithm for linear programming. The existence of such an algorithm and the corresponding proof of quadratic convergence has been an important open question that has received attention in the last few years. The second manuscript is concerned with demonstrating that a particularly well-known primal-dual algorithm converges to the analytic center of the solution set. Again, this issue had been an open question for several years. The solution of these two open questions has been particularly satisfying. Both papers have been accepted for publication in the SIAM Journal on Optimization.

Tapia together with Rice researchers Sorensen, and El-Bakry and visitor Zhang have made excellent initial progress in the construction of a parallel primal-dual interior-point algorithm for linear programming.

Tapia together with Rice postdoc El-Bakry and visitors Takashi Tsuchiya and Yin Zhang has initiated research in the area of extending the primal-dual interior-point algorithms from linear programming to general nonlinear programming. Limited experimentation has led us to believe that the formulation is quite promising.

Research on Optimization with Simulation Constraints

Professor Dennis, Research Scientist Michael Lewis, and some colleagues at Rice and at Boeing Corporation have discovered some novel ways to pose important practical problems that lead to very promising algorithmic ideas suitable for parallel architectures. The class of problems being considered is the optimization of a nonlinear objective subject to nonlinear differential equations constraints, especially cases where there are coupled differential equations of different types. For example, the aircraft industry is interested in this problem in the case of optimal airfoil design where one constraint is a system of partial differential equations that determine the pressure pattern on a wing of a certain shape caused by the air flowing across it at a certain speed and angle of attack; another constraint is a system of differential equations whose solution corrects the shape of the airfoil given a pressure pattern.

Traditional 'black-box' methods require the designer to resolve the coupled system consisting of both systems of differential equations before the optimization method is allowed to increment the basic shape parameters of the airfoil to improve the design objective. Furthermore, finite differences are generally used to compute the 'system sensitivities'. These require a complete resolution of the coupled system for each design variable!

Our approach is very different. In this particular instance, we uncouple the two constraints by allowing the nonlinear programming algorithm to control as optimization variables the pressure pattern input to the structural analysis code and the shape input to the cfd code. We resolve this inconsistency only in the limit as optimality is approached by adding to the nonlinear programming formulation of the problem constraints that the structures and cfd codes match input and outputs with each other.

In joint work, we have developed and analyzed a new nonlinear programming algorithm that uses only iterative methods with no matrix factorizations. This is very important for the design and control problems mentioned above because of the size of the nonlinear programming problems that result from realistic discretizations of those problems. Lewis has successfully used this algorithm to solve for 1024 coefficients of hydrolic conductivity for inverse transmissivity on a 32x32x64 grid using a 4x4x4 Glowinski & Wheeler nonoverlapping domain decomposition.

This involved roughly 43,000 variables and 42,000 constraints. The computation was done using 64 nodes of the Intel Touchstone Delta in time roughly equivalent to 250 forward solves of the transmissivity equation. Thus, a traditional technique based on finite difference gradients and a complete forward solution of the differential equation for each parameter set would not even have been 25% of the way through the initial gradient calculation when our method finished the entire problem!

Research on Large Scale Nonlinear Methods

Dennis has been working with a graduate student and researchers in the NSF center on a generalization of the Brown-Brent methods for large-scale problems. These methods can be thought of as between traditional SQP and GRG approaches. Our work is motivated by parameter id and control for systems governed by differential equations. This work has resulted in a thesis written by Natalia Alexandrov (a US citizen despite the name.)

Research on Parallel Direct Search Methods

Research Scientist Virginia Torczon and Dennis have developed an extremely robust direct search method that can be used on any number of processors with any ratio of computation costs to communication costs. This method has been tested on the Sequent Symmetry, the iPSC/860 hypercube, and the iPSC Delta. This work was begun under ARO sponsorship in the PhD thesis of Dr. Virginia Torczon.

There have been some very gratifying industrial applications of this work. At Boeing Aircraft Company, there is a flexible manufacturing facility that receives orders each day to stamp out certain aircraft parts from sheet metal. This stock is very expensive, and so it is important to be able to layout the parts as efficiently as possible in order to minimize the trim loss.

Previously, Boeing leased a computer and commercial software to solve this problem for the day's order. Dr. Thomas Grandine and Dr. Samuel Eldersveld of Boeing Computer Services, implemented the Multidirectional Search Algorithm. inside a "nesting" code. "Nesting" is the Boeing word for this problem. The multidirectional search algorithm is now solving an important two variable subproblem that arises in the inner most loop of their code. Not only do their preliminary tests indicate that they will see significant reductions in time and material, but they have also been able to replace a commercial code running on an expensive leased machine with their new code running on a standard Sparc workstation---at significant savings to the company.

General Electric has also informed us that they have imbedded the algorithm in some of their design software where it is used to solve a low dimensional noisy search.