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Several new optimization techniques suitable for parallel computers have been developed and have been tested on an Intel hypercube. On a number of nonlinear problems, the algorithms tested have demenstrated dramatic speed-ups over their sequential counterparts. The fact that these speedups are better than can be attributed to parallelism done suggest that they may lead to improved sequential methods.

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Stephen G. Nash

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Final Scientific Report

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1. Research Objectives.

The problem of minimizing a real-valued function arises in many contexts. Newton's method is an effective general tool for this problem. However, when the number of variables is large, or when derivative information is difficult to compute, Newton's method must be compromised or adapted. Truncated-Newton methods are one such approach, one designed for large-scale problems.

Because large-scale methods frequently exhibit special structure, it can be useful to examine specific problems in order to gain intuition and motivation for numerical methods for solving general large-scale problems. Here, we consider a set of estimation problems arising in statistics, which also are of independent interest. They give rise to structured large-scale optimization problems, and to nested optimization problems. We propose improved approaches for the statistical problems, and relate these to potential improvements to techniques for the general problem.

2. Summary of the Research.

During the three years of the grant, the following projects were undertaken:

1. Shortly after the beginning of the project, my application for guest worker status at the National Institute of Standards and Technology (formerly National Bureau of Standards) was approved; in addition, a graduate student Michael Clingman was given a student co-op position. Together, we investigated the performance of the Cyber 205 pipelined vector computer. A "vectorized" truncated-Newton method was implemented. In collaboration with Bert Rust of NBS, I studied a family of constrained regression problems [5,6]. A book on numerical methods [7] was prepared with David Kahaner and Cleve Moler. And a study of computational testing [8] was prepared for the Mathematical Programming Society.
2. Ralph Byers, currently of the University of Kansas, acted as a consultant to the project. We worked on problems arising in Control Theory, in particular some applications of optimization methods to stability analysis of control systems. This work appeared as [1,9].
3. From June to August 1986, I was a Resident Associate with the Mathematics and Computer Science Division of the Argonne National Laboratory. The purpose of this visit was to gain practical experience with parallel computers. Five different parallel machines were available. The machines were used to study parallel versions of quadratic programming algorithms.
4. During Summer 1986, a graduate student Yaw Chang investigated some high-order methods for unconstrained optimization. Such methods are practical if the objective function can be represented in "factorable" form; in this case, the methods would be useful on parallel and vector computers. This work was reported in [3].
5. A study was made of compact numerical methods for optimization. Since certain parallel computers have many processors, each of which as a limited memory, it may be necessary to avoid elaborate algorithms to make effective use of these machines. This work was reported in [4].
6. The statistical estimation techniques were extended to a wide range of statistical problems [2]. This paper describes extensions of nonparametric estimators to a wider range

of statistical problems, in particular (a) density estimation for censored data, (b) intensity function estimation for inhomogeneous Poisson processes, (c) estimation of hazard-rate functions.

7. A study was made [4] of compact numerical methods for optimization. This work is applicable to parallel computations where the individual processors have a moderate amount of local memory.
8. The paper [10] developed improved strategies for handling non-convex functions in the context of Newton-like algorithms.
9. I spent the final year of the project at George Mason University, in the Department of Operations Research and Applied Statistics. In collaboration with Ariela Sofer, I investigated optimization techniques suitable for parallel computers. The ideas have been tested on an Intel hypercube parallel computer and are described [11, 13]. This work has been particularly successful. On a number of nonlinear optimization problems, the algorithms tested have demonstrated dramatic speed-ups over their sequential counterparts, better than can be attributable to parallelism alone. This suggests that they are not only good parallel algorithms, but may also lead to improved sequential methods.

3. Publications.

The following reports have been prepared in connection with the project.

[1] R. Byers and S.G. Nash, "On the singular 'vectors' of the Lyapunov operator," *SIAM J. of Algebraic and Discrete Methods* 8 (1987), pp. 59–66.

[2] V.K. Klonias and S.G. Nash, "Numerical techniques in nonparametric estimation," *J. of Statistical Computation and Simulation* 28 (1987), pp. 97–126.

[3] Y. Chang and S.G. Nash, "On high-order methods for unconstrained minimization," Report 480, Mathematical Sciences Dept., The Johns Hopkins University (1986).

[4] J.C. Nash and S.G. Nash, "Compact Algorithms for Function Minimization," *Asia-Pacific J. of Oper. Res.* 5 (1988), pp. 173–192.

[5] S.G. Nash and B. Rust, "Regression problems with bounded residuals," submitted to the *J. of Opt. Th. Appl.*

[6] B. Rust, B. Geldzahler, and S.G. Nash, "The Proper Motion vs. Redshift Relation for Superluminal Radio Sources," *Astro. Phys. and Space Sci.* 152 (1989), pp. 141–170.

[7] D. Kahaner, C. Moler, and S.G. Nash, *Numerical Methods and Software*, Prentice-Hall, 1988.

[8] P.T. Boggs, R.H. Jackson, S.G. Nash, and S. Powell, "Guidelines for the Reporting of Computational Experiments," (1988).

[9] R. Byers and S.G. Nash, "Approaches to Robust Pole Assignment," *International Journal of Control* 49 (1989), pp. 97–117.

[10] S.G. Nash, "Avoiding Modified Matrix Factorizations in Newton-like Methods," *J. Inf. Opt. Sci.* 9 (1988), pp. 159–182.

[11] S.G. Nash and A. Sofer, "Block Truncated-Newton Methods for Parallel Optimization," submitted to *Math. Prog.*

[12] S.G. Nash, "The Mathematical Tables Project," Report 88–103, ORAS Dept., George Mason University (1988).

[13] S.G. Nash and A. Sofer, "Parallel Optimization via the Block Lanczos Method," in *Computer Science and Statistics: Proceedings of the 20th Symposium on the Interface*, (E. Wegman, D. Gantz, and J. Miller, editors) ASA (1989, to appear).

4. Personnel.

The following people have been associated with the project.

1. Ralph Byers (Mathematics Department, University of Kansas) was a consultant to the project.
2. Yaw Chang (Ph.D. student, Mathematical Sciences Department, The Johns Hopkins University) assisted the project in Summer 1986.
3. Michael Clingman (graduate student, Mathematical Sciences Department, The Johns Hopkins University) completed a variety of tasks in connection with the project. He left the university in Spring 1986, graduating with a Master's degree.
4. Elena Piatnicia (Ph.D. student, Mathematical Sciences Department, The Johns Hopkins University) assisted with the work of the project during Summer 1987.

5. Interactions.

Here is a summary of travel and consulting made in association with the project:

1. The results in [3] were presented as a contributed paper at the SIAM Annual Meeting, Boston MA, July 1986.
2. A poster session based on [4] was also presented at the SIAM Annual Meeting, Boston MA, July 1986.
3. A seminar based on [1] was presented to the Mathematical Sciences Department, The Johns Hopkins University, Baltimore MD, in April 1986.
4. A seminar based on [2] was presented to the Mathematics and Computer Science Division, Argonne National Laboratory, Argonne IL, in June 1986.
5. I was a guest worker with the Scientific Computing Division, National Institute of Standards and Technology, Gaithersburg MD. My supervisor was Paul Boggs. The work there supported several areas of the project, through contacts with other employees and visitors of the division, as well as access to the Cyber 205 supercomputer.
6. I was a Resident Associate with the Mathematics and Computer Science Division at the Argonne National Laboratory, Argonne IL, from June to August 1986. My supervisor was Paul Messina. The purpose of the visit was to gain experience with parallel computers.
7. The results in [2] were presented as a contributed paper at the SIAM Conference on Optimization, Houston TX, May 1986, and at the International Conference on Industrial and Applied Mathematics, Paris France, July 1987.
8. Seminars based on [2,6] were presented to: Mathematical Sciences Department, The Johns Hopkins University, Baltimore MD; Department of Operations Research and Applied Statistics, George Mason University, Fairfax VA; Faculty of Administration, University of Ottawa, Ottawa Canada.
9. The results in [5] were presented as an invited talk at the WORMSC Symposium, Washington DC, October 1987.
10. The work in [11] was presented as a poster session, SIAM Conference on Parallel Processing, Los Angeles, December 1987.
11. The work in [11] was presented as the Department Seminar, Mathematics Dept., The University of Kansas, April 1988.
12. The work in [13] was presented as an invited paper, Interface 88 Meeting, Reston VA, April 1988.

13. The work in [12] was presented as a seminar, Supercomputer Research Center, Institute for Defense Analyses, June 1988.
14. The work in [13] was presented as a contributed paper, SIAM Annual meeting, Minneapolis, July 1988.
15. The work in [11] was presented as a seminar, Omega Rho Society, September 1988.