REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 18, 1995

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Performance and Robustness of Self-Tuning and Adaptive Algorithms for Identification, Filtering and Control

5. FUNDING NUMBERS

6. AUTHOR(S)
P. R. Kumar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Illinois at Urbana-Champaign
Coordinated Science Laboratory
1308 W. Main Street
Urbana, IL 61801-2307

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

We present the main results obtained by us on the topics of

(i) design of adaptive systems
(ii) analysis of identification, adaptive filtering and adaptive control algorithms
(iii) design and analysis of robustness modifications for adaptive algorithms
(iv) development of simulation software
(v) analysis of simulated annealing
(vi) design and analysis of learning algorithms
(vii) design and analysis of queueing networks and scheduling polices

14. SUBJECT TERMS
Adaptive systems, Learning, Simulated Annealing, Queueing networks, Scheduling

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

PERFORMANCE AND ROBUSTNESS OF SELF-TUNING AND ADAPTATION ALGORITHMS FOR IDENTIFICATION, FILTERING AND CONTROL

FINAL REPORT

P. R. KUMAR

JANUARY 18, 1995

U. S. ARMY RESEARCH OFFICE

DAAL03-91-G-0182

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

4A. Statement of Problem Studied

The main problems studied were the following:

(i) Design of adaptation algorithms for identification, adaptive filtering and control.

(ii) Analysis of the stability, self-optimality, self-tuning, convergence and robustness of adaptation algorithms.

(iii) How to automate the simulation of complex systems such as adaptive control systems.

(iv) Develop a theory of and procedures for learning of functions under noisy observations.

(v) Study the performance of simulated annealing algorithms for optimization.

(vi) Study the problem of designing scheduling policies for queueing networks, which are central in the modeling of communication, computer and manufacturing systems.

(vii) Design of scheduling algorithms.

4B. Summary of the Most Important Results

In [3] we have shown that just parameter projection alone is sufficient to render an adaptive control algorithm robust.

In [4] we have designed algorithms for adaptive active noise cancellation and adaptive feedforward control. We have also established the stability and optimality of these algorithms, which include the long-standing open problem of the output error identification algorithm and adaptive IIR filtering.

In [6] we have developed robust adaptive controllers for time varying plants, and established their performance.

In [9] we have presented the theory of self-tuning and convergence for linear stochastic systems.

In [14,15] we have developed a new approach to learning functions under noisy data. We have developed and analyzed canonical smooth estimators and learning procedures. These methods provide a new approach to selecting a model of appropriate complexity.

In [1] we have analyzed a new adaptive controller inspired by some recent results in learning from experts. The method of analysis is quite different from available techniques in adaptive control.

In [5] we have developed a new approach to automating the simulation of complex discrete-time systems. The motivation here is that currently many sophisticated and complex control algorithms are being proposed, and it would considerably enable the movement of these algorithms into practice if one could easily test out such algorithms simply by typing in the equations as typically provided in a technical paper. We have developed a software package ISIM which achieves this purpose.

In [22] we have shown that the new class of fluctuation smoothing algorithms developed by us for the efficient scheduling of large re-entrant lines can be regarded as simply trying to alleviated total downstream shortfalls.

In [24] we have proved that these algorithms are stable for reentrant lines in random environments.

In [2] we present our new approach to the stability analysis, performance analysis, and design of queueing networks and scheduling polices. We believe that these results represent a quantum jump in the evolution of the field.

4C. List of All Publications and Technical Reports

1. P. R. Kumar, "An Adaptive Controller Based on Learning form Experts," in *Adaptive Control, Filtering, and Signal Processing*, vol. 74, IMA Volumes in Mathematics and its Applications, K. J. Astrom, G. C. Goodwin, and P. R. Kumar, Editors, Springer-Verlag, New York, 1995, to appear.

2. P. R. Kumar, "Scheduling Queueing Networks: Stability, Performance Analysis and Design," *Stochastic Networks*, IMA Volumes in Mathematics and its Applications, vol. 71, F. P. Kelly and R. William, Editors, Springer-Verlag, New York, 1995, to appear.

3. S. M. Naik, P. R. Kumar, and B. E. Ydstie, "Robust Continuous Time Adaptive Control by Parameter Projection," *IEEE Transactions on Automatic Control*, vol. 37, no. 2, pp. 182-197, February 1992.

4. W. Ren and P. R. Kumar, "Stochastic Parallel Model Adaptation: Theory and Applications to Active Noise Cancellation, Feedforward Control, IIR Filtering and Identification," *IEEE Transactions on Automatic Control*, vol. 37, no. 5, pp. 566-578, May 1992.

5. R. D. Ellis, R. Ravikanth, and P. R. Kumar, "Automating the Simulation of Complex Discrete Time Control Systems: A Mathematical Framework, Algorithms, and a Software Package," *IEEE Transactions on Automatic Control*, vol. 39, no. 9, pp. 1795-1801, September 1994.

6. S. M. Naik and P. R. Kumar, "Robust Indirect Adaptive Control of Time-Varying Plants with Unmodeled Dynamics and Disturbances," *SIAM Journal on Control and Optimization*, vol. 32, no. 5, pp. 1696-1725, November 1994.

7. S. M. Naik and P. R. Kumar, "Stability of Adaptively Controlled Systems Using Parameter Projection," Invited paper, *Control - Theory and Advanced Technology, Special Issue on "Identification and Adaptive Control - Continuous Time Approaches*, vol. 9, no. 1, pp. 191-201, March 1993.

8. M. Desai, S. Kumar, and P. R. Kumar, "Quasi-Statically Cooled Markov Chains," *Probability in the Engineering and Informational Sciences*, vol., 8 pp. 1-19, 1994.

9. W. Ren and P. R. Kumar, "Stochastic Adaptive Prediction and Model Reference Control," *IEEE Transactions on Automatic Control,* vol. 38, no. 10, pp. 2047-2060, October 1994.

10. P. R. Kumar and S. P. Meyn, "Stability of Queueing Networks and Scheduling Policies," 1993, *IEEE Transactions on Automatic Control,* February 1995, to appear.

11. W. J. Aldrich and P. R. Kumar, "Computation of Uniform Recurrence Equations over Finite Domains," submitted to *IEEE Transactions on Automatic Control,* 1993.

12. S. Kumar and P. R. Kumar, "The Last Buffer First Policy is Stable for Stochastic Re-Entrant Lines," submitted to *Journal of Discrete Event Dynamic Systems: Theory and Applications*, February 1994.

13. J. R. Perkins and P. R. Kumar, "Optimal Control of Pull Manufacturing Systems," submitted to *IEEE Transactions on Automatic Control,* 1994.

14. K. L. Buescher and P. R. Kumar, "Learning by Canonical Smooth Estimation, Part I: Simultaneous Estimation," submitted to *IEEE Transactions on Automatic Control,* 1994.

15. K. L. Buescher and P. R. Kumar, "Learning by Canonical Smooth Estimation, Part II: Learning and Model Complexity," submitted to *IEEE Transactions on Automatic Control,* 1994.

16. H. Jin, J. Ou, and P. R. Kumar, "The Throughput of Closed Queueing Networks: Functional Bounds, Asymptotic Loss, Efficiency, and the Harrison-Wein Conjectures," submitted to *Mathematics of Operations Research*, October 1994.

17. K. L. Buescher and P. R. Kumar, "Relating Simultaneous Learning and Simultaneous Estimation for Classes of Sets over Classes of Probabilities," *Proceedings of the 25th Annual Conference on Information Sciences and Systems*, pp. 108-113, Johns Hopkins University, 1991.

18. S. M. Naik and P. R. Kumar, "Robustness of Extended Least Squares Based Adaptive Control," *Proceedings of the 30th IEEE Conference on Decision and Control*, vol. 1, pp. 754-759, Brighton England, December 1991.

19. S. M. Naik and P. R. Kumar, "Adaptive IIR Filtering and Output Error Identification: Robustness Analysis," *1992 Proceedings of the 1992 American Control Conference*, pp. 1471-1475, June 1992.

20. P. R. Kumar and S. P. Meyn, "Stability of Queueing Networks and Scheduling Policies," *Proceedings of the 32nd IEEE Conference on Decision and Control*, vol. 1, pp. 2730-2735, San Antonio, Texas, December 1993.

21. K. L. Buescher and P. R. Kumar, "Selecting Model Complexity in Learning Problems," invited paper, *Proceedings of the 32nd IEEE Conference on Decision and Control*, vol. 4, pp. 3527-2533, San Antonio, Texas, December 1993.

22. S. C. H. Lu and P. R. Kumar, "Fluctuation Smoothing Scheduling Policies for Queueing Systems," *Computing and Intelligent Systems: Proceedings of the Silver Jubilee Workshop on Computing and Intelligent Systems*, pp. 116-121, Tata McGraw Hill, New Delhi, 1994.

23. J. R. Perkins and P. R. Kumar, "Optimal Control of Pull Manufacturing Systems, *Proceedings of the 1994 American Control Conference*, vol. 3, pp. 3588-3592, 1994.

24. S. Kumar and P. R. Kumar, "Fluctuation Smoothing Policies are Stable for Stochastic Re-Entrant Lines," *Proceedings of the 33rd IEEE Conference on Decision and Control*, vol. 2, pp. 1476-1480, Orlando, Florida, December 1994.

25. W. Ren, "Stochastic Adaptive Systems Theory for Identification, Filtering and Control," Ph.D. Thesis, 1991.

26. S. M. Naik, "Robust Adaptive Control and Filtering," Ph.D. Thesis, 1992.

27. B. Madan, " Adaptive Active Noise Cancellation," M.S. Thesis, 1993.

28. J. R. Perkins, "Control of Push and Pull Manufacturing Systems," Ph.D. Thesis, 1993.

4D. List of all Participating Scientific Personnel Showing Any Advanced Degrees Earned by Them While Employed on the Project

Prof. P. Kumar
Mr. Qing Xu
Mr. Sunil Kumar
Mr. Haiming Jin
Dr. Kevin Buescher, Ph.D.
Dr. James Perkins, Ph.D.
Mr. William Aldrich, M.S.
Ms. Barkha Madan, M.S.
Dr. Chi Hung Lu, Ph.D.
Dr. Sanjeev Naik, Ph.D.
Dr. Wei Ren, Ph.D.

5. Report of Inventions

(i) An adaptive active noise cancellation algorithm system.

(ii) An automated simulator for complex discrete time systems.

6. Bibliography

See list in 4C.