OFFICE OF NAVAL RESEARCH
FINAL PROJECT REPORT

CONTRACT: **N00014-96-1-0241**

TITLE: High Speed, Numerically Superior Signal Processing Algorithms Using QRD & Delta Operator

PI: Dr. H. (Howard) Fan, University of Cincinnati

PERIOD: 1 October 1995 through 30 September 1999

This project was aimed at developing high speed signal processing algorithms using the delta operator. High speed implies fast sampling, in which case most signals and systems become ill-conditioned. Thus many conventional signal processing methods and algorithms have serious numerical problems. Using the delta operator and QR decomposition, we developed methods and algorithms that overcome these numerical problems. Our work during the three funded years and one year of no-cost extension contain many aspects in the general direction. They are described briefly as follows. For more detailed work, please refer to the publications that result from this project in the attached publications list.

1. Stability Tests: We continue to study the δ-operator based stability test algorithms developed by the PI under the previous grant (N00014-90-J-1017) due to the importance of this subject. We have performed a sensitivity analysis, and have shown the advantages of the δ-operator based stability tests. Specifically, we have defined a new kind of sensitivity matrices and have shown that the δ-operator based tests have sensitivity matrices that approach those of the continuous-time tests as the sampling interval vanishes, whereas those of the traditional shift-

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1. Stability Tests: We continue to study the δ-operator based stability test algorithms developed by the PI under the previous grant (N00014-90-J-1017) due to the importance of this subject. We have performed a sensitivity analysis, and have shown the advantages of the δ-operator based stability tests. Specifically, we have defined a new kind of sensitivity matrices and have shown that the δ-operator based tests have sensitivity matrices that approach those of the continuous-time tests as the sampling interval vanishes, whereas those of the traditional shift-

operator based tests grow without bound under the same condition. This establishes the numerical superiority of the δ-operator based stability tests analytically. Another aspect is the singular case of the δ-operator bases stability tests. Similar to the shift-operator based stability tests, the δ-operator tests developed so far are only for the regular case. They will fail in the singular case. Therefore, we have developed a stability test for the singular type I δ-Schur-Cohn test. We have also shown that the limit of this test as the sampling interval vanishes is a corresponding singular test in the continuous-time. Further, we have reconciled two seemingly different approaches in dealing with singularity type II, one in the shift-operator discrete-time and the other in the continuous-time, through the δ-operator test for singularity type II. See papers B4, B8, B9, B13, B15 for more details. The PI also organized an invited session on the delta operator in systems, control and signal processing for IEEE Conference in Decision and Control, San Diego, December 1997.

2. Signal Processing Algorithms: We have studied the normalized lattice structure and its continuous-time limit. It turns out that, unlike any other filter structure, the normalized lattice has a continuous-time limit as the sampling interval vanishes. This explains the well-known good numerical properties of the normalized lattice. However, this limit does not realize an arbitrary stable transfer function in the continuous-time. We thus modified the normalized lattice so its limit can now realize an arbitrary stable transfer function in the continuous-time. Various aspects of stability of the newly modified normalized lattice are studied. The results are summarized in Publication B14.

We have also developed a delta operator based least squares lattice algorithm. This algorithm uses both the forward and the backward delta operators. A continuous-time limit can be achieved with this algorithm. This is quite different from an existing delta operator based least squares lattice algorithm, which only uses the forward delta operator. In fact, this existing algorithm does not have a continuous-time limit. Our simulations show that our new algorithm outperforms both the traditional shift operator based least squares lattice and the existing delta operator based algorithm in terms of numerical properties under finite precision implementations. This work has been published in B16.

We have also published a tutorial paper on high speed signal processing using the delta operator in B18.

3. Generalized Delta Operator: The cooperative research on the "generalized delta operator" with the Swedish researchers led by Prof. Söderström turns out to be very successful. We concentrate our study on identification of continuous-time ARX model parameters using discrete-time data and either the delta operator or the generalized delta operators. We showed that the traditional least squares method will result in a bias for this problem. Ways to deal with this bias include a modified least squares method (B5), bias compensation, and a "no shift" method (B12). We have also investigated integrated sampling. Its use in the noisy situation was studied in B17. Related works include discrete-time noisy AR process parameter identification (B2) and continuous-time AR process parameter identification (B3).

4. Blind Equalization: This work is a continuation of our previous work which was jointly supported by the AASERT program under Grant N00014-93-1-1032 (expired). We have constructed a family of new cost functions which work at least as well as the well known constant modulus algorithm (CMA), also known as the Godard-2 algorithm, but may even

potentially be better than the CMA. This work is published in B10. We have also filed a provisional patent application on this technique (F1). Recently, we have developed a stochastic Newton-like algorithm for blind equalization. The new algorithm applies to many cost functions including the CMA and our own, and converges much faster than the existing algorithms. The computational complexity is $O(N^2)$. See B19 for details. We have further developed its "fast" version using least squares lattice and QRD least squares lattice (A2). The computational complexity is O(N). We have filed another provisional patent application on this result (F2). In addition, we have developed another QRD based blind equalization algorithms which is not lattice but is subspace based (B20). Both these QRD based algorithms have much better numerical properties than existing ones.

5. Other Topics: We also completed our work on wavelets in system modeling (B1 and B11), convergence speed study (B6), and analyzed properties of certain information matrices (B7). The PI also wrote a book review (B21).

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
for
1 October 1995 through 30 Sept. 1999

Contract/Grant Number: N00014-96-1-0241

Contract/Grant Title: High Speed, Numerically Superior Signal Processing Algorithms Using QRD and Delta Operator

Principal Investigator: Dr. H. (Howard) Fan

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a. Number of Papers Submitted to Refereed Journals but not yet published: 2
b. Number of Papers Published in Refereed Journals: 21
c. Number of Books or Chapters Submitted but not yet Published: 0
d. Number of Books or Chapters Published: 1
e. Number of Printed Technical Reports & Non-Refereed Papers: 2
f. Number of Patents Filed: 2
g. Number of Patents Granted: 0
h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 5
i. Number of Presentations at Workshops or Prof. Society Meetings: 11
j. Honors/Awards/Prizes for Contract/Grant Employees: 1
k. Total number of Graduate Students and Post-Docs Supported at least 25%, on this contract/grant:

Grad Students 5 and Post Docs 0

How many of each are females or minorities? (These 6 numbers are for ONR's EEO/Minority Reports: minorities include Blacks, Aleuts Amindians, etc. and those of Hispanic or Asian extraction/ nationality. These Asians are singled out to facilitate meeting the varying report semantics re "under-represented").

Grad Student Female	____
Grad Student Minority	____
Grad Student Asian e/n	4
Post-Doc Female	____
Post-Doc Minority	____
Post-Doc Asian e/n	____

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
FOR
1 October 1995 through 30 September 1999

A. PAPERS SUBMITTED TO REFEREED JOURNALS

1. V. Shtrom and H. Fan, "Analysis of the effects of additive white Gaussian noise on two blind equalization algorithms," IEEE Trans. on Signal Processing, in review.

2. G. Yan and H. Fan, "Fast algorithms for blind equalization," IEEE Trans. on Signal Processing, in review.

B. PAPERS PUBLISHED IN REFEREED JOURNALS

1. M. Doroslovacki and H. Fan, "Wavelet-based linear system modeling and adaptive filtering," IEEE Trans. Signal Processing, vol. 44, no. 5, pp. 1156-1167, May 1996.

2. Q. Li, H. Fan, and E. Karlsson, "A delta MYWE algorithm for parameter estimation of noisy AR processes," IEEE Trans. Signal Processing, vol. 44, no. 5, pp. 1300-1303, May 1996.

3. H. Fan, "An efficient order recursive algorithm with a lattice structure for estimating continuous-time AR process parameters," Automatica, vol. 33, no. 3, pp. 305-317, March 1997.

4. H. Fan, "Efficient zero location tests for delta-operator based polynomials," IEEE Trans. on Automatic Control, vol. 42, no. 5, pp. 722-727, May 1997.

5. T. Söderström, H. Fan, B. Carlsson, and S. Bigi, "Least-squares parameter estimation of continuous-time ARX models from discrete-time data," IEEE Trans. on Automatic Control, vol. 42, no. 5, pp. 659-673, May 1997.

6. H. Fan, "A structural view of asymptotic convergence speed of adaptive IIR filtering algorithms – Part II: Finite precision implementation," IEEE Trans. Signal Processing, vol. 45, no. 6, pp. 1458-1472, June 1997.

7. Q. Li and H. Fan, "On properties of information matrices of delta-operator based adaptive signal processing algorithms," IEEE Trans. Signal Processing, Vol. 45, No. 10, pp. 2454-2467, Oct. 1997.

8. H. Fan, "A normalized Schur-Cohn stability test for the delta-operator based polynomials," IEEE Trans. Autom. Contrl., Vol. 42, No. 11, pp. 1606-1612, November 1997.

9. H. Fan, "On delta-operator Schur-Cohn zero-location tests for fast sampling," IEEE Trans. on Signal Processing, vol. 46, no. 7, pp. 1851-1860, July 1998.

10. V. Shtrom and H. Fan, "A new class of zero forcing cost functions in blind equalization," IEEE Trans. on Signal processing, vol. 66, no. 10, pp. 2674-2683, October 1998.

11. M. Doroslovacki, H. Fan and L. Yao, "Wavelet-based identification of linear discrete-time systems: Robustness issue," Automatica, vol. 34, no. 12, pp. 1637-1640, 1998.

12. H. Fan, T. Söderström, M. Mossberg, B. Carlsson, and Y. Zou, "Estimation of continuous-time AR process parameters from discrete-time data," IEEE Trans. on Signal Processing, vol. 47, no. 5, pp. 1232-1244, May 1999.

13. H. Fan, "Singular root distribution problem for delta-operator based real polynomials," Automatica, vol. 35, pp. 791-807, 1999.

14. P. De and H. Fan, "Stable lattice filters and their continuous-time limits," IEEE Trans. Circuits and Systems, Part II, vol. 46, no. 2, pp. 149-164, Feb. 1999.

15. H. Fan, "Connection between stability tests of Middletown/Goodwin and Lev-Ari/ Bistritz/Kailath," IEEE Trans. on Circuits and Syst., Part I, vol. 46, no. 8, pp. 1031-1033, August 1999.

16. P. De and H. Fan, "A delta least squares lattice algorithm for fast sampling," IEEE Trans. on Signal Processing, vol. 47, no. 9, pp. 2390-2406, Sept. 1999.

17. H. Fan. T. Söderström, and Y. Zou, "Continuous-time AR process parameter estimation in presence of additive white noise," IEEE Trans. on Signal Processing, accepted for publication.

18. H. Fan and P. De, "High speed adaptive signal processing using the delta operator," Digital Signal Processing, accepted for publication.

19. G. yan and H. Fan, "A Newton-like algorithm for complex variables with applications in blind equalization," IEEE Trans. on Signal Processing, accepted for publication.

20. X. Li and H. Fan, "QR factorization based blind channel identification and equalization with second-order statistics," IEEE Trans. Signal Processing, accepted for publication.

21. H. Fan, "Review of Birkäuser book: Sampling in Digital Signal Processing and Control", Automatica, vol. 35, pp. 1338-1341, 1999.

D. BOOKS OR CHAPTERS PUBLISHED

1. H. Fan and X. Liu, "Delta Levinson and Schur type RLS algorithms for adaptive signal processing," IEEE Trans. Signal Processing, vol. 42, no. 7, pp. 1629-1639, July 1994.

   Has been selected to be included in the following edited book:

   High Performance VLSI Signal Processing – Innovative Architectures and Algorithms, K.J.R. Liu and K. Yao, eds.; IEEE Press, 1997.

E. PRINTED TECHNICAL REPORTS

1. T. Söderström, H. Fan, M. Mossberg, and B. Carlsson, "Bias-compensation of least-squares estimates of continuous time AR process parameters," Tech. Report UPTEC 97050R, Inst. of Technology, Uppsala Univ., Sweden,d March 1997.

2. H. Fan, T. Söderström, and Y. Zou, "Continuous-time AR process parameter estimation in presence of additive white noise," Tech. Report TR 233/12/98/ECECS, Dept. of ECECS, Univ. of Cincinnati, December 1998.

F. PATENTS FILED

1. V. Shtrom and H. Fan, "Methods and apparatus useful in blind equalization," Provisional patent application filed by the University of Cincinnati Patent Office, April 1997.

2. G. Yan and H. Fan, "A method and system for fast blind adaptive equalization," Provisional patent application filed by Frost and Jacobs LLp on behalf of University of Cincinnati, Aug. 1998.

H. INVITED PRESENTATIONS AT PROFESSIONAL SOCIETY MEETINGS

1. H. Fan, "Improved delta Levinson and Schur type RLS algorithms," Proc. 34th Allerton Conf. on Communication, Control, and Computing, Monticello, IL, Oct. 1996.

2. M. Doroslovacki and H. Fan, "Wavelet-based identification of linear discrete-time systems," Proc. 11th IFAC Symposium on Syst. Id, vol. 1, pp. 9-14, Kitakyushu, Japan, July 1997.

3. T. Söderström, H. Fan, B. Carlsson, and M. Mossberg, "Some approaches on how to use the Delta operator when identifying continuous-time processes," Proc. 36th IEEE Conf. on Decision & Control, pp. 890-895, San Diego, December 1997.

4. H. Fan, "Efficient stability tests: Unifying theory and further results using the Delta operator," Proc. 36th IEEE Conf. on Decision & Control, pp. 896-901, San Diego, December 1997.

5. X. Li and H. Fan, "QR decomposition based blind channel identification and equalization," Proc. 32nd Asilomar Conference on Signals, Systems, and Computers, October 1998.

I. PRESENTATIONS AT PROFESSIONAL SOCIETY MEETINGS

1. T. Söderström, H. Fan, S. Bigi, and B. Carlsson, "Can a least-squares fit be feasible for modelling continuous-time auto-regressive processes from discrete-time data?" Proc. 34th IEEE Conf. on Decision and Control, vol. 2, pp. 1795-1800, New Orleans, Dec. 1995.

2. V. Shtrom and H. Fan, "Blind equalization: A new convex cost function," Proc. 1996 Intl. Conf. on Acoust., Speech, Signal Processing, vol. 3, pp. 1779-1782, Atlanta, GA, May 1996.

3. P. De and H. Fan, "A modified normalized lattice adaptive filter for fast sampling," Proc. Intl. Conf. on Acoust., Speech, Signal Processing, Vol. 3, pp. 1941-1944, Munich, Germany, April 1997.

4. V. Shtrom and H. Fan, "A refined class of cost functions in blind equalization," Proc. Intl. Conf. on Acoust., Speech, Signal Processing, Vol. 3, pp. 2273-2276, Munich, Germany, April 1997.

5. H. Fan, "Delta-operator based efficient stability tests," Proc. 1997 American Control Conference, Vol. 4, pp. 2508-2512, Albuquerque, NM, June 1997.

6. T. Söderström, H. Fan, M. Mossberg, and B. Carlsson,"A bias-compensation scheme for estimating continuous-time AR process parameters," Proc. 11th IFAC Symposium on Syst. Id., Vol. 3, pp. 1337-1342, Kitakyushu, Japan, July 1997.

7. H. Fan and T. Söderström, "Parameter estimation of continuout-time AR processes using integrated sampling," Proc. 36th IEEE Conf. on Decision & Control, pp. 3474-3475, San Diego, December 1997.

8. H. Fan, T. Söderström, M. Mossberg, B. Carlsson, and Y. Zou, "Continuous-time AR process parameter estimation from discrete-time data," Proc. Intl. conf. on Acoust., Speech, Signal Processing, vol. 4, pp. 2333-2336, Seattle, Washington, May 1998.

9. P. De and H. Fan, "A delta least squares lattice algorithm for fast sampling," Proc. Intl. Conf. on Acoust., Speech, Signal Processing, vol. 3, pp. 1373-1376, Seattle, Washington, May 1998.

10. G. Yan and H. Fan, "Fast algorithms for blind adaptive equalizers," Proc. 8th IEEE Digital Signal Processing Workshop, Bryce, Utah, August 1998.

11. X. Li and H. Fan, "Recursive blind channel identification and equalization by ULV decomposition," Proc. Intl. Conf. on Acoustics, Speech, Signal Processing, vol. 5, pp. 2639-2642, Phoenix, AZ, March 1999.

J. HONORS/AWARDS/PRIZES FOR CONTRACT/GRANT EMPLOYEES

1. H. Fan, promoted to professor by the University of Cincinnati, effective Sept. 1, 1996.

K. GRADUATE STUDENTS SUPPORTED ON THIS CONTRACT/GRANT

1. V. Shtrom, Ph.D., completed November 1996
2. P. De, Ph.D., completed June 1998
3. G. Yan, Ph.D., completed February 1999
4. Y. Zou, M.S., completed March 1998
5. X. Li, Ph.D., near completion

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13. ABSTRACT (Maximum 200 words)
Several research topics ralated to the delta-operator have been studied. First, we continued research on the delta-operator based efficient stability tests. We defined new sensitivity matrices and studied their properties. We also developed tests for singular cases, and studied a few other related aspects. Second, we studied the normalized lattice filter structure and analyzed its connection with the delta operator. We also developed a delta-operator based least squares lattice algorithm, which is computationally efficient and numerically robust. Third, we continued to work on the "generalized delta operator" in the identification of continuous-time ARX process parameters. We developed de-biasing methods in conjunction with using the computationally efficient least squares method. We also studied the use of the generalized delta operator in a noisy environment, and investigated integrated sampling and its effectiveness in coping with noise. Other topics such as blind equalization and wavelet based time-varying system modelling were also studied.

14. SUBJECT TERMS
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