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Work by Prof. Oppenheim and his collaborators is summarized here

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Semi-Annual Report

Numerical and Symbolic Algorithms for

Application Specific Signal Processing

October 31, 1993 – April 4, 1994

Research Organization: Digital Signal Processing Group
Research Laboratory of Electronics
Massachusetts Institute of Technology

Principal Investigator: Alan V. Oppenheim
Distinguished Professor oı Electrical Engineering

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Program Manager: Mr. Clifford Lau

94-16226

1 Introduction

During the period of this grant, our detailed technical accomplishments will be reported through journal articles and technical reports. Each of our semi-annual reports will highlight certain technical areas and provide a summary listing of our technical articles related to the project.

2 Overview

In broad terms, we have oriented our efforts to hopefully impact the RASSP program and objectives in two major ways. One is to identify and develop appropriate classes of emerging as well as more classical signal processing algorithms which will exercise and challenge the RASSP tools and process. In this way we would anticipate being able to identify and define in detail signal processing algorithms that are important but that the current tools can't accomodate well. We are currently envisioning doing this with iterative and PDE algorithms, "approximate" algorithms, and algorithms oriented toward fault tolerance. The second is for our research to provide specific input for a real or hypothetical next generation of RASSP tools and process. One phase of this, of course, will follow somewhat from our having indentified weaknesses in the currently available tools. In addition, we are developing specific paradigms for environments that incorporate symbolic design and processing and approximate processing.

There are four major technical themes to our program:

1. Algorithm Based Fault Tolerance: The objective here is the structuring of algorithms so that error correction and/or detection can be accomplished on the output.

2. Symbolic Design Environments and Processing: This area of our research is exploring and developing symbolic rearrangement of algorithms and the coupling of numerical and symbolic processing in signal "understanding" systems.

3. The "New Math" For Signal Processing: There are significant new classes of signal processing algorithms emerging and which we are actively involved in developing, which require non-conventional architectures. These include wavelet-based algorithms, algorithms evolving from nonlinear dynamics, iterative algorithms and algorithms associated with nonlinear partial differential equations. We are actively

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working on the question as to whether some or any of these can be accomodated by the planned RASSP tools.

4. Approximate Processing: In certain cases it is desireable to develop and implement algorithms which have the property that the quality of their outputs evolves in proportion to the amount of computation time. This aspect of our program is directed at designing incremental refinement algorithms and specifying the requirements for design tools for these classes of algorithms.

A significant part of our program involves close coupling with Lockheed Sanders. In relation to the program a member of the Lockheed Sanders technical staff spends approximately two days per week resident in our group. One of the graduate students working as a Research Assistant under the RASSP program spends one day per week resident at Sanders. In addition, during the summer two graduate students will be employed at Sanders. This close interaction between MIT students and Sanders technical staff provides the basis for technology transfer both ways. In addition, the Principal Investigator (Al Oppenheim) for the program at MIT is on the Technical Review Board for the Lockheed Sanders team.

3 Approximate Processing

We have been exploring the design and evaluation of algorithms which may be considered approximations to other algorithms. In any given problem-solving domain, an approximation to a given algorithm may be defined as an algorithm which is computationally more efficient but produces a lower quality answer according to some standard of accuracy, certainty, and/or completeness. The approximate algorithm may be said to carry out *approximate processing* in the problem-solving domain under consideration. Such algorithms have previously been studied in the context of computer science applications, including real-time vehicular tracking and real-time database query processing. Any individual task in such applications must generally be performed within a time interval whose duration may or may not be determined prior to run time. In the case of a predetermined time allocation, an approximate processing algorithm may be used to obtain the requisite computational efficiency by sacrificing the quality of the answer obtained. We refer to this as *deadline-based* approximate processing. In cases where the time allocation is not predetermined, it is desirable to use an approximate processing algorithm which produces an answer of improving quality as a function of time. This allows the algorithm to be terminated whenever desired and the quality of the resulting answer is directly proportional to the actual execution time. These types of approximate processing algorithms are said to carry out *incremental refinement* of their answers. We have developed both deadline-based and incremental refinement algorithms for the short-time Fourier transform (STFT). The results pertaining to the deadline-based algorithms will be published [5] in the proceedings of ICASSP 94. A journal article [6] on deadline-based STFT algorithms has also been submitted to the IEEE Transactions on Signal Processing.

Our deadline-based algorithms for the STFT have the property that they dynamically alter the quality of the answer in order to meet a specified bound, B, on the number of arithmetic operations allowed per STFT frame. The quality of the answer is measured in terms of three quality factors: frequency resolution, frequency coverage and SNR. The primary means of approximation involves the application of severe quantization and backward differencing to the short-time frames of the input signal. Experimental results have been obtained involving real and synthetic signals to demonstrate the preservation of important time-frequency features in results produced using several times fewer arithmetic operations than are required by FFT-based algorithms for the exact evaluation of the STFT.

In some applications, bounds on the maximum allowable number of arithmetic operations may not be available *a priori* or may change after execution has begun. We have identified alternative algorithmic structures which allow solutions of reduced quality to be produced in a more general manner, which we refer to as *incremental refinement.* Such algorithms can be conceptualized as consisting of successive approximation stages, each of which improves upon the quality of the output resulting from the previous stages. One such algorithm, which we have recently developed, incrementally improves upon the frequency resolution of an STFT frame. In particular, the i-th stage of approximation produces STFT frames whose frequency resolution is given by:

$$\Delta f = 2\pi \left(1 - \frac{i-1}{N_w}\right) \text{ rad/sample} \tag{1}$$

The algorithm consists of a total of N_w stages, where N_w is the length of the STFT analysis window. We have also derived expressions for the average cost per approximation stage for this agorithm.

Another incremental-refinement algorithm we have developed for the STFT improves incrementally upon the frequency coverage of each frame. The frequency coverage of the analysis at stage i is

$$\Delta F = \frac{4\pi i}{N} \text{ rad/sample} \tag{2}$$

where N is the DFT length for each STFT frame. After $N/2$ stages, all frequency bins have been calculated, and the complete frequency coverage of 2π rad/sample is attained. We have also derived expressions for the average cost per approximation stage for this algorithm.

The above two incremental refinement algorithms exploit the notion of successive approximation, but each is suitable to a different kind of analysis task. While the first maintains complete frequency coverage and improves incrementally in frequency resolution, the second does just the opposite. We have also formultaed a more general successive approximation technique where instead of improving only in frequency coverage or only in frequency resolution at each stage, output quality is improved in one, the other, or both in a stage-dependent manner.

Of primary importance to the informed use of approximate methods in signal processing systems is the assessment of quality. For discrete Fourier analysis, we have used the measures of frequency coverage, frequency resolution, and SNR to characterize the results generated using a variety of methods. In general, we may characterize the quality of an approximation using an appropriately selected ensemble of numeric *quality measures*, which we represent mathematically as functional mappings into $\mathbb{R}$. We may completely characterize an approximation by applying all quality measures simultaneously, defining a mapping into $\mathbb{R}^n$ where n is the number of quality measures in the ensemble, and each dimension of quality is mapped into an orthogonal dimension of n-space. This ensemble mapping, which we call a *quality function*, provides a convenient way of assessing solution quality, particularly when approximations are used that affect the signal in more than one dimension of quality.

In addition to structures for quality assessment, we have also been considering methods for assessing the costs of producing solutions of a given quality. One promising approach we have investigated for the STFT is to define a *cost function* which describes the computational cost of producing a solution of some quality *given* a solution of lower quality. In particular, we have been successful in deriving such expressions for the various approximation stages of the incremental refinement algorithms for the STFT.

We have also been considering how the structures for quality and cost assessment may be used as the basis of control strategies for successive approximation algorithms. A cost function on the quality space of a successive approximation may be viewed mathematically as a weighted directed graph with the points of the quality space corresponding to nodes, potential paths of improvement represented as arcs, and the cost functions assigning the arc weights. Such graphs, which we call *quality/cost (QC) graphs*, offer promise for the control of successive approximation algorithms due to the existence of powerful **graph traversal methods**. Candidate graph-traversal algorithms include Dijkstra's algorithm [1], Moore's algorithm [2], the Bellman-Ford algorithm [3], Floyd's algorithm [4], and the A^* algorithm [5]. The use of quality and cost functions for the formulation of QC graphs offers the important advantage of hiding the underlying algorithmic structure by which solutions are obtained. When a variety of different algorithms are available for approximating a result, an appropriately chosen quality space may incorporate the quality assessments of each algorithm. A QC graph may be formulated incorporating all available methods of obtaining solutions, and graph traversals may be derived which incorporate stages from each method so that overall computation is minimized.

4 Algorithm Development

One component of our research within the RASSP program involves the investigation of some important classes of algorithms for signal processing applications with particular regard to how they are accomodated within the framework of current and potential RASSP tools. A key aspect involves assessing the degree to which these algorithms are well-matched to current signal processing architectures and computational platforms, and exploring what the implications are for the next generation of signal processors and for processor design tools.

In this project, we are exploring a class of iterative and approximate processing algorithms that are useful in a number of applications. The particular application area that we are addressing is wireless communication systems. Over the last several years, there has been a dramatic growth in the demand for a broad range of wireless communication services both in the commercial and military sectors. However, this rapidly escalating demand for both wider availability of such services and increasingly sophisticated capabilities has put great pressure on the limited available bandwidth within the radio spectrum. Given such constraints, the use of increasingly sophisticated signal processing algorithms in wireless modems will be critical to accommodating large numbers of services and users within the available spectrum. Furthermore, future generations of wireless systems will benefit enormously from the kinds of tools and architectures being developed within the RASSP program.

The algorithms that we are exploring and using to exercise the RASSP design tools are directed at increasing bandwidth efficiency. In wireless systems involving multiple users, the signal processing invariably required at the receiver involves channel estimation and compensation (equalization), suppression of co-channel interference (i.e., interference from other users), and data detection and decoding. In typical bandwidth-efficient systems, this decoding generally involves some form of sequential processing based upon a Viterbi decoder. Many of the algorithms we are currently developing to perform this signal processing are iterative in nature in order to cope with complexity issues. As examples, we have recently developed a class of efficient iterative receivers for minimum probability-of-error data recovery in unknown Rayleigh fading channels without a feedback path. We have carried out a number of simulations of our algorithms, exploring their performance as a function of iteration, the number of users, signal-to-noise ratio, and carrier-to-interference ratio. These preliminary but ongoing simulations suggest that iterative and adaptive algorithms of this type can lead to dramatically better system performance than is obtained with conventional receiver processing and consequently will quite likely become an important part of the future of bandwidth efficient wireless systems. As we continue to develop and identify the key ingredients of these computations, we are exploring ways in which signal processors can be designed to more efficiently execute them.

5 Publications of Work Supported

[1] K.M. Cuomo, "Synthesizing Self-Synchronizing Chaotic Systems," *International Journal of Bifurcation and Chaos*, Vol. 3, No. 5, October 1993, pp. 1327-1337.

[2] K.M. Cuomo, "Synthesizing Self-Synchronizing Chaotic Arrays," submitted to *International Journal of Bifurcation and Chaos.*

[3] K.M. Cuomo, "Analysis and Synthesis of Self-Synchronizing Chaotic

Systems," M.I.T. Research Laboratory of Electronics Technical Report 582, Cambridge, Massachusetts 02139.

[4] K.M. Cuomo, A.V. Oppenheim and S.H. Strogatz, "Robustness and Signal Recovery in a Synchronized Chaotic System," to appear *International Journal of Bifurcation and Chaos*, December 1993.

[5] E. Dorken, S.H. Nawab, Frame-Adaptive Techniques for Quality Versus Efficiency Tradeoffs in STFT Analysis, IEEE International Conference on Acoustic, Speech and Signal Processing, ICASSP-94, Adelaide, April 1994.

[6] S.H. Nawab and E. Dorken, "A Framework for Quality Versus Efficiency Tradeoffs in STFT Analysis," submitted to *IEEE Trans. on Signal Processing*, Oct. 1993.

[7] A.V. Oppenheim, E. Weinstein, K. Zangi, M. Feder and D. Gauger, "Single-Sensor Active Noise Cancellation," *IEEE Transactions of Speech and Audio Processing*, Vol. 2, No. 4, April 1994, pp. 285-290.

[8] M.D. Richard, "Estimation and Detection with Chaotic Systems," M.I.T. Research Laboratory of Electronics Technical Report 581, Cambridge, Massachusetts 02139.

[9] E. Weinstein, A.V. Oppenheim, M. Feder and J. Buck, "Iterative and Sequential Algorithms for Multisensor Signal Enhancement" *IEEE Transactions on Signal Processing*, Vol. 42, No. 4, April 1994, pp. 846-859.

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[1] E.W. Dijkstra, "A Note on Two Problems in Connection with Graphs," *Numetrische Mathematik*, 1:269:291, 1959.

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[3] L.J. Ford Jr., *Network Flow Theory*, Rand Corporation Rept. P-293, 1956.

[4] R.W. Floyd, "Algorithm 97: Shortest Path," *Commun. of ACM*, vol. 5, June 1962.

[5] P.E. Hart, N.J. Nilsson, and B. Raphael, "A Formal Basis for the Heuristic Determination of Minimum Cost Paths," *IEEE Trans. on SSC*, vol. SSC-4, pp. 100-107, 1968.

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