Acoustic Signal Processing

Algorithms for Reverberant Environments

Terence Betlehem

B.Sc. B.E.(Hons) ANU

November 2005

A thesis submitted for the degree of Doctor of Philosophy of The Australian National University

Department of Information Engineering
Research School of Information Sciences and Engineering
The Australian National University
Declaration

The content of this thesis are the result of original research and has not been submitted for a postgraduate degree at any other university or institution. Much of this work has either been published or submitted for publications as journal papers and conference proceedings. Following is a list of these papers.

Journal Publications


Conference Proceedings


The research presented in this thesis has been performed jointly with Dr. Thushara D. Abhayapala and Prof. Robert C. Williamson. Approximately 70% of this work is my own.

______________________________
Terence Betlehem
Australian National University
November 2004
Acknowledgements

Without the support of the many faces in my life, this work would not have been possible. I would like to acknowledge and thank each of the following:

First and foremost, My God, Lord and Saviour Jesus Christ for the faithfulness, grace and mercy shown to me during my studies.

My supervisors Dr. Thushara Abhayapala Prof. Bob Williamson and Prof. Rod Kennedy for their insight, inspiration, feedback and encouragement. Special thanks goes to Thushara for his helpfulness and support, especially over the last ten months, not to mention his sense of humour and optimism. This thesis would certainly not have been possible without his support. Thanks to Bob Williamson for his helpful ideas and general rock-solid reliability as a supervisor.

The Commonwealth Government for an Australian Postgraduate Award. The Research School of Information Sciences and Engineering for additional financial support and the use of their facilities in the production of this thesis.

My family, for providing for me physically, giving me a roof on my head and a meal every dinner time, and emotionally. They have really being there for me during some difficult times.

Lesley Cox for her role as administrator, freeing me from paperwork, and being friendly. My advisor Dr. Darren Ward. My fellow colleagues in the Department of Telecommunications who have kept me company.

Finally, to all my friends and to the people of Crossroads Christian Church who have offered me support during this time.
Abstract

This thesis investigates the design and the analysis of acoustic signal processing algorithms in reverberant rooms. Reverberation poses a major challenge to acoustic signal processing problems. It degrades speech intelligibility and causes many acoustic algorithms that process sound to perform poorly. Current solutions to the reverberation problem frequently only work in lightly reverberant environments. There is need to improve the reverberant performance of acoustic algorithms.

The approach of this thesis is to explore how the intrinsic properties of reverberation can be exploited to improve acoustic signal processing algorithms. A general approach to soundfield modelling using statistical room acoustics is applied to analyze the reverberant performance of several acoustic algorithms. A model of the underlying structure of reverberation is incorporated to create a new method of soundfield reproduction.

Several outcomes resulting from this approach are: (i) a study of how more sound capture with directional microphones and beamformers can improve the robustness of acoustic equalization, (ii) an assessment of the extent to which source tracking can improve accuracy of source localization, (iii) a new method of soundfield reproduction for reverberant rooms, based upon a parametrization of the acoustic transfer function and (iv) a study of beamforming to directional sources, specifically exploiting the directionality of human speech.

The approach to soundfield modelling has permitted a study of algorithm performance on important parameters of the room acoustics and the algorithm design. The performance of acoustic equalization and source tracking have been found to depend not only on the levels of reverberation but also on the correlation of pressure between points in reverberant soundfields. This correlation can be increased by sound capture with directional capture devices. Work on soundfield reproduction has shown that, though reverberation significantly degrades the performance of conventional techniques, by accounting for the reverberation it is possible to design reproduction methods that function well in reverberant environments.
Symbols and Terms

⌈·⌉ ceiling operator
⌊·⌋ floor operator
⌈·⌉* complex conjugate of a matrix
⌈·⌉T transpose of a matrix
⌈·⌉H complex conjugate transpose of a matrix
| · | magnitude of a complex number
∠· phase of a complex number
∥ · ∥ Euclidian norm of a vector
x · y dot product between two vectors
E{·} expectation operator
Pr{·} probability
Var{·} variance operator
Re{·} real part
Im{·} imaginary part
δ(·) Dirac delta function
δnm Kronecker delta function
i \( \sqrt{-1} \)
\( I_n \) \( n \times n \) identity matrix
\( \mathbb{C}^n \) \( n \) dimensional complex number space
\( \mathbb{R}^n \) \( n \) dimensional real number space
\( \mathbb{Z}^* \) set of non-negative integers
CDF cumulative density function
DFT discrete Fourier transform
DRR direct-to-reverberant energy ratio
MTF modulation transfer function
PDF probability density function
SNR signal-to-noise ratio
STI speech transmission index
ULA uniform linear array
WNG white noise gain
3 Robustness of Equalization

3.1 Introduction 51
3.2 Robustness of Equalization 52
  3.2.1 Criterion for Stochastic Soundfields 53
  3.2.2 Criterion for Deterministic Soundfields 54
3.3 Analysis of Robustness Expressions 54
  3.3.1 Preliminaries 55
  3.3.2 Stochastic Criterion in a Diffuse Field 56
  3.3.3 Modal Analysis of Deterministic Criterion 63
3.4 Robustness of Equalization to Movement of Source 67
3.5 Examples 69
  3.5.1 Study of Dependence on Sound Capture Strategy 69
  3.5.2 Study of Dependence on Field Geometry Parameters 74
3.6 Conclusion and Future Research 76
3.7 Summary and Contribution 78
3.8 Appendices 79
  3.8.1 Proof of Theorem 3.3.2 79
  3.8.2 Proof of Theorem 3.3.3 80
  3.8.3 Proof of Lemma 3.3.1 80
  3.8.4 Proof of Theorem 3.3.4 81

4 Performance of Combined Localization and Tracking 83

4.1 Introduction 83
4.2 Overview of Analysis Approach 84
4.3 Signal Model 85
4.4 Generic Algorithm for Steered Beamforming 88
  4.4.1 Description of Steered Beamformer Algorithm 88
  4.4.2 Beamformer Specifications 89
4.5 Algorithm Independent Description of Source Tracking 91
4.6 Probability of Estimation Error 93
  4.6.1 Upper Performance Limit 94