

# Contents

---

<b>Abstract</b>	<b>iii</b>
<b>Resumen</b>	<b>v</b>
<b>Resum</b>	<b>ix</b>
<b>Acknowledgements</b>	<b>xiii</b>
<b>List of symbols</b>	<b>xxv</b>
<b>Abbreviations and Acronyms</b>	<b>xxxii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	3
1.2 Motivation . . . . .	5
1.3 Objectives . . . . .	7
1.4 Organization of the Thesis . . . . .	8
<b>2 Preliminaries and Tools</b>	<b>11</b>
2.1 Introduction . . . . .	13
2.2 Frequency domain . . . . .	15
2.2.1 Discrete Fourier Transform . . . . .	18
2.2.2 Fast Fourier Transform . . . . .	19
2.3 Convolution . . . . .	19
2.3.1 Convolution Theorem . . . . .	20
2.3.2 Convolution in Audio Signals . . . . .	21
2.3.3 Convolution with long sequences . . . . .	22
2.3.4 Overlap-save . . . . .	22
2.3.5 Overlap-add . . . . .	23
2.3.6 Other operations in Digital Signal Processing . . . . .	25
2.3.7 Real-time processing . . . . .	27
2.4 Traditional Hardware for Digital Signal Processing . . . . .	28
2.4.1 Digital Signal Processors . . . . .	28
2.4.2 Field-Programmable Gate Arrays . . . . .	28

2.5	Multi-core Architectures and Graphic Processing Units (GPUs)	29
2.5.1	Multi-core and GPUs Origin . . . . .	30
2.6	GPU and CUDA . . . . .	31
2.6.1	Streams on GPU . . . . .	35
2.6.2	Multi-GPU programming with multicore . . . . .	36
2.7	Tools used for the development of the thesis . . . . .	36
2.7.1	ASIO protocol . . . . .	39
<b>3</b>	<b>State-of-the-Art</b>	<b>41</b>
3.1	Generalized crosstalk cancellation and equalization (GCCE)	43
3.2	Headphone-base spatial audio . . . . .	45
3.3	Wave Field Synthesis . . . . .	46
3.4	Sound source localization . . . . .	47
3.5	GPU computing in other research inside audio field . . . . .	49
3.6	Conclusion . . . . .	49
<b>4</b>	<b>Massive Multichannel Filtering</b>	<b>51</b>
4.1	Convolution . . . . .	53
4.1.1	Pipelined algorithm in a multichannel system . . . . .	56
4.2	Crosstalk Cancellation using a stereo signal . . . . .	60
4.2.1	Definition of the problem . . . . .	60
4.2.2	GPU Implementation . . . . .	63
4.2.3	Test system and Results . . . . .	66
4.3	Multichannel massive audio processing for a GCCE application	67
4.3.1	Definition of the problem . . . . .	68
4.3.2	GPU data structure for efficient convolution . . . . .	70
4.3.3	GPU data structure for GCCE applications . . . . .	72
4.3.4	Performance and Results . . . . .	80
4.3.5	Conclusions . . . . .	82
<b>5</b>	<b>Headphone-based spatial sound system</b>	<b>87</b>
5.1	Introduction . . . . .	90
5.2	Processing Head-Related Transfer functions . . . . .	91
5.3	Switching technique . . . . .	93
5.3.1	Evaluation of the switching technique . . . . .	95
5.4	Interpolation technique . . . . .	98
5.4.1	Evaluation of the interpolation technique . . . . .	101
5.5	GPU-based implementation of a head-phone audio application	105
5.5.1	Emulating a source movement . . . . .	111

---

5.5.2	Interaction with the user . . . . .	114
5.6	Results . . . . .	115
5.7	Conclusions . . . . .	119
<b>6</b>	<b>Wave Field Synthesis system</b>	<b>121</b>
6.1	Theory of a WFS system . . . . .	123
6.1.1	Room Compensation in a WFS system . . . . .	126
6.1.2	Practical Implementation of a WFS system . . . . .	127
6.2	Test system . . . . .	129
6.2.1	System Setup . . . . .	130
6.2.2	Computational kernels implemented on GPU . . . . .	133
6.3	Performance and results . . . . .	140
6.4	Conclusion . . . . .	141
<b>7</b>	<b>Sound Source Localization</b>	<b>143</b>
7.1	Introduction . . . . .	146
7.2	Sound Source Localization using SRP-PHAT Algorithm . . . . .	146
7.2.1	SRP-PHAT Implementation . . . . .	149
7.2.2	Computational Cost . . . . .	149
7.3	Algorithm Parallelization for real-time GPU implementation . . . . .	150
7.3.1	Considerations in code of CUDA kernels 23 and 24 . . . . .	158
7.3.2	Multi-GPU Parallelization . . . . .	159
7.3.3	Basic Implementation using two GPUs . . . . .	160
7.4	Experiments and Performance . . . . .	161
7.4.1	Localization Performance . . . . .	163
7.4.2	Computational Performance . . . . .	166
7.5	Conclusion . . . . .	167
<b>8</b>	<b>Multichannel IIR Filtering</b>	<b>169</b>
8.1	Definition of the problem . . . . .	171
8.1.1	Fixed-pole parallel filters . . . . .	172
8.1.2	Filter design . . . . .	173
8.2	Implementations on Many-core architectures (GPU and multi-cores) . . . . .	174
8.2.1	GPU-based parallel implementation . . . . .	175
8.2.2	Multicore-based parallel implementation . . . . .	175
8.3	Results . . . . .	179
8.4	Conclusion . . . . .	182

---

<b>9</b>	<b>Massive Multiple Allpass filtering</b>	<b>183</b>
9.1	Definition of the problem . . . . .	185
9.2	Test Setup . . . . .	187
9.3	GPU-based Implementation . . . . .	188
9.4	Results . . . . .	192
9.4.1	Computational Performance . . . . .	192
9.5	Conclusion . . . . .	195
<b>10</b>	<b>Conclusion</b>	<b>197</b>
10.1	Main Contributions . . . . .	199
10.2	Further Work . . . . .	201
10.3	List of Publications . . . . .	203
10.4	Institutional Acknowledgements . . . . .	207
	<b>Bibliography</b>	<b>208</b>
<b>A</b>	<b>Appendix</b>	<b>225</b>
A.1	Alternative Multi-GPU Parallelization strategy . . . . .	227
A.1.1	Basic Implementation using two GPUs . . . . .	228
A.1.2	Comparison between strategies . . . . .	228