Contents

1. Introduction 13
1.1. Definition of Sound Synthesis 13
1.2. Taxonomy of Synthesis Methods 15
1.3. The Purpose and Scope of the Monograph 18

2. Direct Methods 20
2.1. Spectral Methods 20
2.1.1. Modular View on Elements of a Synthesizer 20
2.1.1.1. Voltage Controlled Oscillator 21
2.1.1.2. Voltage Controlled Amplifier 25
2.1.1.3. Voltage Controlled Filter 25
2.1.1.4. Low Frequency Oscillator 25
2.1.1.5. Envelope Generator 26
2.1.2. Additive Synthesis 30
2.1.2.1. Evolution of Spectrum 31
2.1.2.2. Control Data 32
2.1.2.3. Resynthesis 35
2.1.2.4. Control of Pitch, Duration, and Timbre 37
2.1.2.5. Variants of Additive Synthesis 42
2.1.2.6. Implementation Remarks 43
2.1.3. Subtractive Synthesis 45
2.1.3.1. Source-Modifier Principle 46
2.1.3.2. Synthesizer Designs 49
2.1.3.3. Resynthesis 52
2.1.3.4. Control of Pitch, Duration, and Timbre 57
2.1.3.5. Descendants of Subtractive Synthesis 60
2.2. Waveform-Based Methods 61
2.2.1. Wavetable Synthesis 61
2.2.1.1. Single-Cycle and Multi-Cycle Wavetable 63
2.2.1.2. Signal Modification and Evolution 65
2.2.1.3. Resynthesis 68
2.2.1.4. Control of Pitch, Duration, and Timbre 69
2.2.1.5. Multiple Wavetable Synthesis 70

2.2.1.6. Wave Terrain Synthesis . . . 72
2.2.1.7. Progress of Wavetable . . . 77
2.2.2. Sampling . . . 78
2.2.2.1. Digital Sampling Synthesis Principle . . . 81
2.2.2.2. Control of Pitch . . . 83
2.2.2.3. Control of Timbre . . . 88
2.2.2.4. Control of Duration . . . 89
2.2.2.5. Application of Envelopes and Filters . . . 92
2.2.2.6. Sampler Features and Implementation Remarks . . . 94
2.2.3. Granular Synthesis . . . 97
2.2.3.1. Grains . . . 99
2.2.3.2. Time-Frequency Plane Matrices and Screens . . . 102
2.2.3.3. Pitch-Synchronous Granular Synthesis . . . 103
2.2.3.4. Synchronous and Quasi-Synchronous Granular Synthesis . . . 103
2.2.3.5. Asynchronous Granular Synthesis . . . 105
2.2.3.6. Physical and Algorithmic Models . . . 108
2.2.3.7. Granulation of Sampled Sounds . . . 109
2.2.3.8. Particle Synthesis . . . 110
2.2.4. Concatenative Synthesis . . . 117
2.2.4.1. Segmentation . . . 120
2.2.4.2. Analysis and Descriptors . . . 126
2.2.4.3. Target . . . 126
2.2.4.4. Database . . . 127
2.2.4.5. Selection . . . 128
2.2.4.6. Synthesis . . . 131
2.2.4.7. High Level Instrument Synthesis . . . 132
2.2.4.8. Real-Time Concatenative Synthesis . . . 133
2.2.4.9. Expressive Concatenative Synthesis . . . 135
2.2.4.10. Other Variants of Concatenative Synthesis . . . 141

3. Indirect Methods . . . 147
3.1. Abstract Methods . . . 147
3.1.1. Frequency Modulation . . . 147
3.1.1.1. Frequency and Pitch . . . 149
3.1.1.2. Modulation Index . . . 151
3.1.1.3. Multiple Carriers and Modulators . . . 157
3.1.1.4. Feedback . . . 161
3.1.1.5. Operators and Algorithms . . . 163
3.1.1.6. Simulation of Instruments and Resynthesis . . . 165
3.1.1.7. Variants and Derivatives of FM Synthesis . . . 166
3.1.2. Waveshaping . . . 172
3.1.2.1. Shaping functions . . . 173
3.1.2.2. Amplitude Control . . . 175
3.1.2.3. Variants of Waveshaping . . . 176

3.1.3. Non-Standard Methods . . . 177
3.1.3.1. Waveform Segment . . . 177
3.1.3.2. Graphics Synthesis . . . 178
3.1.3.3. Motion-Driven Synthesis . . . 180
3.1.3.4. Noise Modulation . . . 182
3.1.3.5. Stochastic Waveform Synthesis . . . 185
3.1.3.6. Cellular Automata Synthesis . . . 186
3.1.3.7. Waveset Distortion . . . 192
3.1.3.8. Sequential Waveform Composition . . . 192
3.1.3.9. Neural Audio Synthesis . . . 194
3.2. Physical Modelling Methods . . . 196
3.2.1. Finite Difference Approximation . . . 198
3.2.1.1. Temporal Operators . . . 199
3.2.1.2. Spatial Operators . . . 200
3.2.1.3. Input and Output Operators . . . 207
3.2.1.4. Simplified Ideal String . . . 211
3.2.1.5. Damped Stiff String . . . 218
3.2.1.6. String Excitation . . . 222
3.2.1.7. String Model Refinements . . . 226
3.2.1.8. Bar . . . 234
3.2.1.9. Acoustic Tube . . . 237
3.2.1.10. Reed Excitation Mechanism . . . 239
3.2.1.11. Toneholes in Acoustic Tube . . . 242
3.2.1.12. Other Wind Instruments . . . 245
3.2.1.13. Membrane . . . 245
3.2.1.14. Plate . . . 248
3.2.2. Networks of Lumped Elements . . . 253
3.2.2.1. Lumped Elements . . . 253
3.2.2.2. Operation . . . 254
3.2.3. Modal Synthesis . . . 254
3.2.3.1. Model Data . . . 255
3.2.3.2. Synthesis Process . . . 255
3.2.3.3. Output . . . 256
3.2.4. Karplus–Strong Synthesis . . . 256
3.2.4.1. Basic Control . . . 257
3.2.4.2. Plucked Strings and Drums . . . 257
3.2.4.3. Decay Stretching . . . 258
3.2.5. Waveguide Synthesis . . . 258
3.2.5.1. Digital Waveguide . . . 258
3.2.5.2. Dispersion, Damping, and Other Effects . . . 260
3.2.5.3. Scattering Junction . . . 260
3.2.5.4. Examples of Waveguide Configurations . . . 261
3.2.5.5. Applications . . . 263
3.2.6. Other Physical Modelling Methods . . . 263

4. Phrase Assembling Synthesis:
a New Approach to Music Reproduction 265
4.1. Sound Synthesis in Music Reproduction 265
4.1.1. Shortcomings of Sample-Based Methods 266
4.1.2. Issues of Concatenative Method 268
4.2. The Concept 271
4.2.1. Motivation 271
4.2.2. Key Ideas 272
4.2.3. Method Outline 274
4.2.4. Phrase 275
4.2.5. Signal Processing of Samples 276
4.2.6. Musical Expression 277
4.3. The Design 278
4.3.1. Input and Output 278
4.3.2. Samples and Descriptions 279
4.3.3. The Principle of Operation 281
4.4. The Corpus 283
4.4.1. Instruments 283
4.4.2. Structure 284
4.4.3. Contents 286
4.4.3.1. Units 286
4.4.3.2. Multisampling 289
4.4.4. Recordings 289
4.4.5. Analysis and Preparation of Samples 290
4.5. Applied Techniques 294
4.5.1. Musical Score Analysis 295
4.5.1.1. Score Segmentation Algorithm 295
4.5.1.2. Phrase Matching Algorithm 295
4.5.2. Sound Samples Processing 300
4.5.2.1. Concatenation 300
4.5.2.2. Control of Duration 302
4.5.2.3. Tempo and Rhythm 304
4.5.3. Performance Rules 305
4.5.4. Phrase Envelopes 308
4.5.4.1. Dynamics Envelope 308
4.5.4.2. Tempo Envelope 310
4.6. Implementation 311
4.6.1. Overall Program Design 312
4.6.2. Modules 313
4.6.2.1. Score Analysis Module 313
4.6.2.2. Figure Matching Module 314
4.6.2.3. Waveform Generator Module 315
4.6.2.4. Management Module 316

4.6.3. Program Parameters Adjustments . . . 317
4.6.3.1. Listening Tests – Phase I . . . 318
4.6.3.2. Listening Tests – Phase II . . . 322
4.6.4. Evaluation . . . 325
4.7. Concluding Remarks . . . 325
4.7.1. Issues and Necessary Improvements . . . 326
4.7.2. Further Development . . . 326

5. Infeasible Instruments:
a Novel Means for Music Performance . . . 329
5.1. Synthesis Methods for Music Performance . . . 329
5.1.1. Control and Timbre Capabilities . . . 330
5.2. Infeasible Quasi-Physical Systems as Musical Instruments . . . 331
5.2.1. Concept of Infeasible Instruments . . . 332
5.2.2. Design Outline . . . 332
5.3. Real-Time FD Simulations Using GPUs . . . 334
5.3.1. GPU Programming Framework . . . 335
5.3.1.1. OpenCL Standard . . . 336
5.3.1.2. Heterogeneous Computing . . . 340
5.3.1.3. OpenCL Framework Contents . . . 340
5.3.2. Single String . . . 342
5.3.2.1. The Model . . . 342
5.3.2.2. Finite Difference Scheme . . . 342
5.3.2.3. Implementation Considerations . . . 344
5.3.2.4. Program Design . . . 345
5.3.2.5. User-Controllable Instrument Parameters . . . 347
5.3.2.6. Host Program . . . 348
5.3.2.7. Kernel . . . 353
5.3.3. Multiple Strings . . . 357
5.3.3.1. Implementation Considerations . . . 358
5.3.3.2. Changes in Program Design . . . 358
5.3.3.3. Control Considerations . . . 359
5.3.3.4. Host Program . . . 359
5.3.3.5. Kernel . . . 363
5.3.4. Real-Time Control . . . 364
5.3.4.1. Control Procedure Design . . . 364
5.3.4.2. Controller Program Implementation . . . 364
5.3.4.3. Handling Control Events . . . 366
5.4. Hyper-Dimensional Objects . . . 368
5.4.1. Hyper-Membrane . . . 369
5.4.1.1. Basic Model . . . 369
5.4.1.2. Excitation . . . 370
5.4.1.3. Finite Difference Scheme . . . 370
5.4.1.4. Stability . . . 371

5.4.2. Model Implementation . . . 372
5.4.2.1. Implementation Considerations . . . 372
5.4.2.2. User-Controllable Instrument Parameters . . . 375
5.4.3. Example Signals . . . 375
5.4.3.1. Brief Evaluation . . . 379
5.4.4. Other Instruments . . . 380
5.5. Impossible Boundaries . . . 381
5.5.1. Looped Boundaries . . . 381
5.5.1.1. Bi-Directional Loop . . . 382
5.5.1.2. One-Dimensional Loop . . . 382
5.5.1.3. Twisted Loop . . . 382
5.5.2. Implementation Details . . . 382
5.5.3. Selected Examples . . . 383
5.5.3.1. Rectangle . . . 383
5.5.3.2. Square . . . 385
5.5.3.3. Rectangular Cuboid . . . 386
5.5.4. Further Study . . . 387
5.6. Evolving Instruments . . . 388
5.6.1. Evolution Parameters . . . 388
5.6.2. Means of Control . . . 389
5.6.3. Implementation Consideration . . . 390
5.6.4. Selected Examples . . . 390
5.6.4.1. Evolving Material Parameter . . . 390
5.6.4.2. Evolving Shape . . . 391
5.6.4.3. Floating Readout . . . 392
5.6.5. Further Study . . . 395
5.7. Concluding Remarks . . . 395

6. Conclusions of the Monograph . . . 397

Index . . . 445