Table of Contents

Preface ..... **VII**

Table of Contents ..... **XIII**

1 The Motivation for Differential Evolution **1**
1.1 Introduction to Parameter Optimization 1
1.1.1 Overview 1
1.1.2 Single-Point, Derivative-Based Optimization 6
1.1.3 One-Point, Derivative-Free Optimization and the Step Size Problem 11
1.2 Local Versus Global Optimization 16
1.2.1 Simulated Annealing 18
1.2.2 Multi-Point, Derivative-Based Methods 19
1.2.3 Multi-Point, Derivative-Free Methods 20
1.2.4 Differential Evolution – A First Impression 30
References 34

2 The Differential Evolution Algorithm **37**
2.1 Overview 37
2.1.1 Population Structure 37
2.1.2 Initialization 38
2.1.3 Mutation 38
2.1.4 Crossover 39
2.1.5 Selection 40
2.1.6 DE at a Glance 41
2.1.7 Visualizing DE 43
2.1.8 Notation 47
2.2 Parameter Representation 48
2.2.1 Bit Strings 48
2.2.2 Floating-Point 50
2.2.3 Floating-Point Constraints 52
2.3 Initialization 53
2.3.1 Initial Bounds 53

2.3.2 Initial Distributions 56
2.4 Base Vector Selection 61
2.4.1 Choosing the Base Vector Index, *r*0 61
2.4.2 One-to-One Base Vector Selection 63
2.4.3 A Comparison of Random Base Index Selection Methods 64
2.4.4 Degenerate Vector Combinations 65
2.4.5 Implementing Mutually Exclusive Indices 68
2.4.6 Gauging the Effects of Degenerate Combinations: The Sphere 70
2.4.7 Biased Base Vector Selection Schemes 72
2.5 Differential Mutation 74
2.5.1 The Mutation Scale Factor: *F* 75
2.5.2 Randomizing the Scale Factor 79
2.6 Recombination 91
2.6.1 Crossover 92
2.6.2 The Role of *Cr* in Optimization 97
2.6.3 Arithmetic Recombination 104
2.6.4 Phase Portraits 112
2.6.5 The Either/Or Algorithm 117
2.7 Selection 118
2.7.1 Survival Criteria 119
2.7.2 Tournament Selection 121
2.7.3 One-to-One Survivor Selection 122
2.7.4 Local Versus Global Selection 124
2.7.5 Permutation Selection Invariance 124
2.7.6 Crossover-Dependent Selection Pressure 125
2.7.7 Parallel Performance 127
2.7.8 Extensions 128
2.8 Termination Criteria 128
2.8.1 Objective Met 129
2.8.2 Limit the Number of Generations 129
2.8.3 Population Statistics 129
2.8.4 Limited Time 130
2.8.5 Human Monitoring 130
2.8.6 Application Specific 130
References 131

3 Benchmarking Differential Evolution 135
3.1 About Testing 135
3.2 Performance Measures 137
3.3 DE Versus DE 139
3.3.1 The Algorithms 139

3.3.2 The Test Bed 142
3.3.3 Phase Portraits 142
3.3.4 Summary 154
3.4 DE Versus Other Optimizers 156
3.4.1 Comparative Performance: Thirty-Dimensional Functions 157
3.4.2 Comparative Studies: Unconstrained Optimization 167
3.4.3 Performance Comparisons from Other Problem Domains 171
3.4.4 Application-Based Performance Comparisons 175
3.5 Summary 182
References 182

4 Problem Domains 189
4.1 Overview 189
4.2 Function and Parameter Quantization 189
4.2.1 Uniform Quantization 190
4.2.2 Non-Uniform Quantization 191
4.2.3 Objective Function Quantization 192
4.2.4 Parameter Quantization 195
4.2.5 Mixed Variables 201
4.3 Optimization with Constraints 201
4.3.1 Boundary Constraints 202
4.3.2 Inequality Constraints 206
4.3.3 Equality Constraints 220
4.4 Combinatorial Problems 227
4.4.1 The Traveling Salesman Problem 229
4.4.2 The Permutation Matrix Approach 230
4.4.3 Relative Position Indexing 231
4.4.4 Onwubolu's Approach 233
4.4.5 Adjacency Matrix Approach 233
4.4.6 Summary 237
4.5 Design Centering 239
4.5.1 Divergence, Self-Steering and Pooling 239
4.5.2 Computing a Design Center 242
4.6 Multi-Objective Optimization 244
4.6.1 Weighted Sum of Objective Functions 244
4.6.2 Pareto Optimality 246
4.6.3 The Pareto-Front: Two Examples 247
4.6.4 Adapting DE for Multi-Objective Optimization 250
4.7 Dynamic Objective Functions 255
4.7.1 Stationary Optima 256
4.7.2 Non-Stationary Optima 259
References 262

5 Architectural Aspects and Computing Environments 267
5.1 DE on Parallel Processors..... 267
5.1.1 Background..... 267
5.1.2 Related Work..... 267
5.1.3 Drawbacks of the Standard Model 271
5.1.4 Modifying the Standard Model..... 272
5.1.5 The Master Process..... 273
5.2 DE on Limited Resource Devices..... 276
5.2.1 Random Numbers..... 276
5.2.2 Permutation Generators 279
5.2.3 Efficient Sorting 282
5.2.4 Memory-Saving DE Variants 282
References 284

6 Computer Code 287
6.1 DeMat – Differential Evolution for MATLAB® 287
6.1.1 General Structure of DeMat 287
6.1.2 Naming and Coding Conventions..... 288
6.1.3 Data Flow Diagram 291
6.1.4 How to Use the Graphics..... 293
6.2 DeWin – DE for MS Windows®: An Application in C 295
6.2.1 General Structure of DeWin 296
6.2.2 Naming and Coding Conventions..... 300
6.2.3 Data Flow Diagram 300
6.2.4 How To Use the Graphics 304
6.2.5 Functions of graphics.h 305
6.3 Software on the Accompanying CD 307
References 309

7 Applications 311
7.1 Genetic Algorithms and Related Techniques for Optimizing Si–H Clusters: A Merit Analysis for Differential Evolution 313
7.1.1 Introduction 313
7.1.2 The System Model..... 315
7.1.3 Computational Details 317
7.1.4 Results and Discussion 318
7.1.5 Concluding Remarks 325
References 325
7.2 Non-Imaging Optical Design Using Differential Evolution..... 327
7.2.1 Introduction 327
7.2.2 Objective Function 328
7.2.3 A Reverse Engineering Approach to Testing 331

7.2.4 A More Difficult Problem: An Extended Source 334
7.2.5 Conclusion 337
References 337
7.3 Optimization of an Industrial Compressor Supply System 339
7.3.1 Introduction 339
7.3.2 Background Information on the Test Problem 340
7.3.3 System Optimization 340
7.3.4 Demand Profiles 341
7.3.5 Modified Differential Evolution; Extending the Generality of DE 342
7.3.6 Component Selection from the Database 343
7.3.7 Crossover Approaches 343
7.3.8 Testing Procedures 348
7.3.9 Obtaining 100% Certainty of the Results 348
7.3.10 Results 349
7.3.11 Summary 350
References 351
7.4 Minimal Representation Multi-Sensor Fusion Using Differential Evolution 353
7.4.1 Introduction 353
7.4.2 Minimal Representation Multi-Sensor Fusion 357
7.4.3 Differential Evolution for Multi-Sensor Fusion 361
7.4.4 Experimental Results 364
7.4.5 Comparison with a Binary Genetic Algorithm 372
7.4.6 Conclusion 374
References 375
7.5 Determination of the Earthquake Hypocenter: A Challenge for the Differential Evolution Algorithm 379
7.5.1 Introduction 379
7.5.2 Brief Outline of Direct Problem Solution 382
7.5.3 Synthetic Location Test 384
7.5.4 Convergence Properties 385
7.5.5 Conclusions 389
References 389
7.6 Parallel Differential Evolution: Application to 3-D Medical Image Registration 393
7.6.1 Introduction 393
7.6.2 Medical Image Registration Using Similarity Measures 395
7.6.3 Optimization by Differential Evolution 398
7.6.4 Parallelization of Differential Evolution 401
7.6.5 Experimental Results 404
7.6.6 Conclusions 408

Acknowledgments 408
References 408
7.7 Design of Efficient Erasure Codes with Differential Evolution ... 413
7.7.1 Introduction 413
7.7.2 Codes from Bipartite Graphs 414
7.7.3 Code Design 418
7.7.4 Differential Evolution 421
7.7.5 Results 423
Acknowledgments 426
References 426
7.8 FIWIZ – A Versatile Program for the Design of Digital Filters Using Differential Evolution 429
7.8.1 Introduction 429
7.8.2 Unconventional Design Tasks 432
7.8.3 Approach 435
7.8.4 Examples 444
7.8.5 Conclusion 445
References 445
7.9 Optimization of Radial Active Magnetic Bearings by Using Differential Evolution and the Finite Element Method 447
7.9.1 Introduction 447
7.9.2 Radial Active Magnetic Bearings 448
7.9.3 Magnetic Field Distribution and Force Computed by the Two-Dimensional FEM 454
7.9.4 RAMB Design Optimized by DE and the FEM 455
7.9.5 Conclusion 461
Acknowledgments 461
References 462
7.10 Application of Differential Evolution to the Analysis of X-Ray Reflectivity Data 463
7.10.1 Introduction 463
7.10.2 The Data-Fitting Procedure 466
7.10.3 The Model and Simulation 469
7.10.4 Examples 471
7.10.5 Conclusions 477
References 477
7.11 Inverse Fractal Problem 479
7.11.1 General Introduction 479
7.11.2 Conclusion 495
References 497
7.12 Active Compensation in RF-Driven Plasmas by Means of Differential Evolution 499

7.12.1 Introduction 499
7.12.2 RF-Driven Plasmas 500
7.12.3 Langmuir Probes 501
7.12.4 Active Compensation in RF-Driven Plasmas 501
7.12.5 Automated Control System Structure and Fitness Function 502
7.12.6 Experimental Setup 504
7.12.7 Parameters and Experimental Design 505
7.12.8 Results 509
7.12.9 Conclusion 509
Acknowledgments 510
References 510

Appendix 513
A.1 Unconstrained Uni-Modal Test Functions 514
A.1.1 Sphere 514
A.1.2 Hyper-Ellipsoid 515
A.1.3 Generalized Rosenbrock 515
A.1.4 Schwefel's Ridge 516
A.1.5 Neumaier #3 517
A.2 Unconstrained Multi-Modal Test Functions 518
A.2.1 Ackley 518
A.2.2 Griewangk 519
A.2.3 Rastrigin 520
A.2.4 Salomon 521
A.2.5 Whitley 522
A.2.6 Storn's Chebyshev 523
A.2.7 Lennard-Jones 525
A.2.8 Hilbert 526
A.2.9 Modified Langerman 526
A.2.10 Shekel's Foxholes 528
A.2.11 Odd Square 529
A.2.12 Katsuura 530
A.3 Bound-Constrained Test Functions 531
A.3.1 Schwefel 531
A.3.2 Epistatic Michalewicz 531
A.3.3 Rana 532
References 533

Index 535