## Contents

1 Introduction .......................................................... 1
  1.1 Feedback in Engineering and Living Systems ................. 1
  1.2 Benefits of Feedback Control .................................. 3
  1.3 Challenges of Feedback Control ................................. 6
  1.4 Feedback Turbulence Control is a Grand Challenge Problem .... 7
  1.5 Nature Teaches Us the Control Design ......................... 8
  1.6 Outline of the Book ............................................ 9
  1.7 Exercises ....................................................... 9

2 Machine Learning Control (MLC) .................................... 11
  2.1 Methods of Machine Learning ................................ 12
    2.1.1 System Identification as Machine Learning ............. 13
    2.1.2 Genetic Algorithms ...................................... 14
    2.1.3 Genetic Programming ..................................... 16
    2.1.4 Additional Machine Learning Methods .................. 18
  2.2 MLC with Genetic Programming ................................ 19
    2.2.1 Control Problem .......................................... 19
    2.2.2 Parameterization of the Control Law .................... 20
    2.2.3 Genetic Programming as a Search Algorithm ............ 21
    2.2.4 Initializing a Generation ................................ 23
    2.2.5 Evaluating a Generation ................................ 24
    2.2.6 Selecting Individuals for Genetic Operations .......... 26
    2.2.7 Selecting Genetic Operations ............................. 27
    2.2.8 Advancing Generations and Stopping Criteria .......... 30
  2.3 Examples ....................................................... 33
    2.3.1 Fitting a Function Through Data Points ................. 33
    2.3.2 MLC Applied to Control a Dynamical System .......... 36
  2.4 Exercises ....................................................... 44
  2.5 Suggested Reading .............................................. 45
  2.6 Interview with Professor Marc Schoenauer .................... 46
# Contents

3 Methods of Linear Control Theory ........................................ 49
  3.1 Linear Systems .................................................. 50
  3.2 Full-State Feedback ............................................. 51
  3.3 Sensor-Based State Estimation ................................. 53
  3.4 Sensor-Based Feedback .......................................... 56
  3.5 System Identification and Model Reduction .................... 58
    3.5.1 System Identification ..................................... 59
    3.5.2 Eigensystem Realization Algorithm (ERA) ............... 59
    3.5.3 Observer Kalman Filter Identification (OKID) ........... 62
  3.6 Exercises ....................................................... 65
  3.7 Suggested Reading .............................................. 67

4 Benchmarking MLC Against Linear Control .......................... 69
  4.1 Comparison of MLC with LQR on a Linear Oscillator .......... 70
  4.2 Comparison of MLC with Kalman Filter on a Noisy Linear Oscillator .................................................. 73
  4.3 Comparison of MLC with LQG for Sensor-Based Feedback .... 80
  4.4 Modifications for Small Nonlinearity ........................ 84
  4.5 Exercises ....................................................... 86
  4.6 Interview with Professor Shervin Bagheri .................... 89

5 Taming Nonlinear Dynamics with MLC ............................... 93
  5.1 Generalized Mean-Field System .................................. 94
  5.2 Machine Learning Control ....................................... 98
    5.2.1 Formulation of the Control Problem ....................... 98
    5.2.2 MLC Parameters ........................................... 99
    5.2.3 MLC Results .............................................. 99
  5.3 Derivation Outline for the Generalized Mean-Field Model ... 105
  5.4 Alternative Control Approaches ................................. 109
    5.4.1 Open-Loop Forcing ....................................... 109
    5.4.2 Closed-Loop Forcing .................................... 111
    5.4.3 Short-Term Forcing ...................................... 113
  5.5 Exercises ....................................................... 115
  5.6 Suggested Reading .............................................. 116
  5.7 Interview with Professor Mark N. Glauser .................... 117

6 Taming Real World Flow Control Experiments with MLC .......... 121
  6.1 Separation Control Over a Backward-Facing Step ............. 122
    6.1.1 Flow Over a Backward-Facing Step ....................... 122
    6.1.2 Experimental Setup at PMMH ............................. 123
    6.1.3 Results .................................................. 127
  6.2 Separation Control of Turbulent Boundary Layers .......... 128
    6.2.1 Separating Boundary Layers ............................. 128
    6.2.2 Experimental Setups at LML and PRISME ................. 129
    6.2.3 Results .................................................. 132
6.3 Control of Mixing Layer Growth
   6.3.1 Mixing Layer Flows
   6.3.2 Experimental Setup of the TUCOROM Wind Tunnel
   6.3.3 Results
6.4 Alternative Model-Based Control Approaches
6.5 Implementation of MLC in Experiments
   6.5.1 Real-Time Control Loop—from Sensors to Actuators
   6.5.2 MLC Implementation in the PMMH Flow Over a Backward-Facing Step
   6.5.3 MLC Implementation in the LML and PRISME Experiments
   6.5.4 MLC Implementation in the TUCOROM Experiment
6.6 Suggested Reading
6.7 Interview with Professor David Williams

7 MLC Tactics and Strategy
   7.1 The Ideal Flow Control Experiment
   7.2 Desiderata of the Control Problem—From the Definition to Hardware Choices
   7.2.1 Cost Function
   7.2.2 Actuators
   7.2.3 Sensors
   7.2.4 Search Space for Control Laws
   7.3 Time Scales of MLC
   7.3.1 Controller
   7.3.2 Response Time of the Plant
   7.3.3 Learning Time for MLC
   7.4 MLC Parameters and Convergence
   7.4.1 Convergence Process and Its Diagnostics
   7.4.2 Parameters
   7.4.3 Pre-evaluation
   7.5 The Imperfect Experiment
   7.5.1 Noise
   7.5.2 Drift
   7.5.3 Monitoring

8 Future Developments
   8.1 Methodological Advances of MLC
   8.2 System-Reduction Techniques for MLC—Coping with High-Dimensional Input and Output
   8.3 Future Applications of MLC
8.4 Exercises .................................................. 182
8.5 Interview with Professor Belinda Batten ................. 184

Glossary ............................................................. 189

Matlab® Code: OpenMLC .................................. 195

References ......................................................... 197

Index ................................................................. 209
Machine Learning Control – Taming Nonlinear Dynamics and Turbulence
Duriez, Th.; Brunton, S.; Noack, B.R.
2017, XX, 211 p. 73 illus., 58 illus. in color., Hardcover
ISBN: 978-3-319-40623-7