## Contents

List of Contributors xiii

Foreword xv

Series Preface xvii

Acknowledgments xix

1 Introduction 1

John Valasek

1.1 Introduction 1

1.2 The Early Years: Bio-Inspiration 2

1.3 The Middle Years: Variable Geometry 5

1.4 The Later Years: A Return to Bio-Inspiration 9

1.5 Conclusion 10

References 10

Part I BIO-INSPIRATION

2 Wing Morphing in Insects, Birds and Bats: Mechanism and Function 13


2.1 Introduction 13

2.2 Insects 14

2.2.1 Wing Structure and Mechanism 15

2.2.2 Gross Wing Morphing 18

2.3 Birds 25

2.3.1 Wing Structure and Mechanism 25

2.3.2 Gross Wing Morphing 28

2.3.3 Local Feather Deflections 30

2.4 Bats 32

2.4.1 Wing Structure and Mechanism 33

2.4.2 Gross Wing Morphing 35

2.5 Conclusion 37

Acknowledgements 37

References 38
3 Bio-Inspiration of Morphing for Micro Air Vehicles 41
Gregg Abate and Wei Shyy
3.1 Micro Air Vehicles 41
3.2 MAV Design Concepts 43
3.3 Technical Challenges for MAVs 46
3.4 Flight Characteristics of MAVs and NAVs 47
3.5 Bio-Inspired Morphing Concepts for MAVs 48
  3.5.1 Wing Planform 50
  3.5.2 Airfoil Shape 50
  3.5.3 Tail Modulation 50
  3.5.4 CG Shifting 50
  3.5.5 Flapping Modulation 51
3.6 Outlook for Morphing at the MAV/NAV scale 51
3.7 Future Challenges 51
3.8 Conclusion 53
References 53

Part II CONTROL AND DYNAMICS

4 Morphing Unmanned Air Vehicle Intelligent Shape and Flight Control 57
John Valasek, Kenton Kirkpatrick, and Amanda Lampton
4.1 Introduction 57
4.2 A-RLC Architecture Functionality 58
4.3 Learning Air Vehicle Shape Changes 59
  4.3.1 Overview of Reinforcement Learning 59
  4.3.2 Implementation of Shape Change Learning Agent 62
4.4 Mathematical Modeling of Morphing Air Vehicle 63
  4.4.1 Aerodynamic Modeling 63
  4.4.2 Constitutive Equations 64
  4.4.3 Model Grid 64
  4.4.4 Dynamical Modeling 68
  4.4.5 Reference Trajectory 71
  4.4.6 Shape Memory Alloy Actuator Dynamics 71
  4.4.7 Control Effectors on Morphing Wing 73
4.5 Morphing Control Law 73
  4.5.1 Structured Adaptive Model Inversion (SAMI) Control for Attitude Control 73
  4.5.2 Update Laws 76
  4.5.3 Stability Analysis 77
4.6 Numerical Examples 77
  4.6.1 Purpose and Scope 77
  4.6.2 Example 1: Learning New Major Goals 77
  4.6.3 Example 2: Learning New Intermediate Goals 80
4.7 Conclusions 84
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Modeling and Simulation of Morphing Wing Aircraft</td>
<td>87</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>87</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Gull-Wing Aircraft</td>
<td>87</td>
</tr>
<tr>
<td>5.2</td>
<td>Modeling of Aerodynamics with Morphing</td>
<td>88</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Vortex-Lattice Aerodynamics for Morphing</td>
<td>90</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Calculation of Forces and Moments</td>
<td>92</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Effect of Gull-Wing Morphing on Aerodynamics</td>
<td>92</td>
</tr>
<tr>
<td>5.3</td>
<td>Modeling of Flight Dynamics with Morphing</td>
<td>93</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Overview of Standard Approaches</td>
<td>93</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Extended Rigid-Body Dynamics</td>
<td>97</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Modeling of Morphing</td>
<td>100</td>
</tr>
<tr>
<td>5.4</td>
<td>Actuator Moments and Power</td>
<td>105</td>
</tr>
<tr>
<td>5.5</td>
<td>Open-Loop Maneuvers and Effects of Morphing</td>
<td>109</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Longitudinal Maneuvers</td>
<td>109</td>
</tr>
<tr>
<td>5.5.2</td>
<td>Turn Maneuvers</td>
<td>114</td>
</tr>
<tr>
<td>5.6</td>
<td>Control of Gull-Wing Aircraft using Morphing</td>
<td>118</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Power-Optimal Stability Augmentation System using Morphing</td>
<td>119</td>
</tr>
<tr>
<td>5.7</td>
<td>Conclusion</td>
<td>123</td>
</tr>
<tr>
<td>6</td>
<td>Flight Dynamics Modeling of Avian-Inspired Aircraft</td>
<td>127</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>127</td>
</tr>
<tr>
<td>6.2</td>
<td>Unique Characteristics of Flapping Flight</td>
<td>129</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Experimental Research Flight Platform</td>
<td>129</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Unsteady Aerodynamics</td>
<td>130</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Configuration-Dependent Mass Distribution</td>
<td>131</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Nonlinear Flight Motions</td>
<td>131</td>
</tr>
<tr>
<td>6.3</td>
<td>Vehicle Equations of Motion</td>
<td>134</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Conventional Models for Aerospace Vehicles</td>
<td>134</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Multibody Model Configuration</td>
<td>136</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Kinematics</td>
<td>138</td>
</tr>
<tr>
<td>6.3.4</td>
<td>Dynamics</td>
<td>138</td>
</tr>
<tr>
<td>6.4</td>
<td>System Identification</td>
<td>140</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Coupled Actuator Models</td>
<td>141</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Tail Aerodynamics</td>
<td>143</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Wing Aerodynamics</td>
<td>143</td>
</tr>
<tr>
<td>6.5</td>
<td>Simulation and Feedback Control</td>
<td>144</td>
</tr>
<tr>
<td>6.6</td>
<td>Conclusion</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>148</td>
</tr>
</tbody>
</table>
# Contents

7 | Flight Dynamics of Morphing Aircraft with Time-Varying Inertias | 151  
Daniel T. Grant, Stephen Sorley, Animesh Chakravarthy, and Rick Lind  
7.1 | Introduction | 151  
7.2 | Aircraft | 152  
7.2.1 | Design | 152  
7.2.2 | Modeling | 154  
7.3 | Equations of Motion | 156  
7.3.1 | Body-Axis States | 156  
7.3.2 | Influence of Time-Varying Inertias | 157  
7.3.3 | Nonlinear Equations for Moment | 157  
7.3.4 | Linearized Equations for Moment | 159  
7.3.5 | Flight Dynamics | 161  
7.4 | Time-Varying Poles | 162  
7.4.1 | Definition | 162  
7.4.2 | Discussion | 164  
7.4.3 | Modal Interpretation | 164  
7.5 | Flight Dynamics with Time-Varying Morphing | 166  
7.5.1 | Morphing | 166  
7.5.2 | Model | 166  
7.5.3 | Poles | 168  
7.5.4 | Modal Interpretation | 171  
References | 174  

8 | Optimal Trajectory Control of Morphing Aircraft in Perching Maneuvers | 177  
Adam M. Wickenheiser and Ephrahim Garcia  
8.1 | Introduction | 177  
8.2 | Aircraft Description | 179  
8.3 | Vehicle Equations of Motion | 181  
8.4 | Aerodynamics | 185  
8.5 | Trajectory Optimization for Perching | 191  
8.6 | Optimization Results | 196  
8.7 | Conclusions | 202  
References | 202  

Part III | SMART MATERIALS AND STRUCTURES |  
9 | Morphing Smart Material Actuator Control Using Reinforcement Learning | 207  
Kenton Kirkpatrick and John Valasek  
9.1 | Introduction to Smart Materials | 207  
9.1.1 | Piezoelectrics | 208  
9.1.2 | Shape Memory Alloys | 208  
9.1.3 | Challenges in Controlling Shape Memory Alloys | 209
xii

Contents

12  A Collective Assessment  
   John Valasek  
12.1  Looking Around: State-of-the-Art  
   12.1.1  Bio-Inspiration  
   12.1.2  Aerodynamics  
   12.1.3  Structures  
   12.1.4  Automatic Control  
12.2  Looking Ahead: The Way Forward  
   12.2.1  Materials  
   12.2.2  Propulsion  
12.3  Conclusion  

Index  

281
281
281
281
282
282
283
283
283
285