

# Contents

**About the Authors** *xi*

**Preface** *xv*

**List of Abbreviations** *xvii*

## **1 Introduction** *1*

- 1.1 Motivation and Introduction *1*
- 1.2 History of Automated Driving *3*
- 1.3 ADAS to Autonomous Driving *11*
- 1.4 Autonomous Driving Architectures *13*
- 1.5 Cybersecurity Considerations *13*
- 1.6 Organization and Scope of the Book *14*
- 1.7 Chapter Summary and Concluding Remarks *14*
- References *15*

## **2 Vehicle, Path, and Path Tracking Models** *19*

- 2.1 Tire Force Model *19*
  - 2.1.1 Introduction *19*
  - 2.1.2 Tire Forces/Moments and Slip *20*
  - 2.1.3 Longitudinal Tire Force Modeling *23*
  - 2.1.4 Lateral Tire Force Modeling *24*
  - 2.1.5 Self-aligning Moment Model *28*
  - 2.1.6 Coupling of Tire Forces *29*
- 2.2 Vehicle Longitudinal Dynamics Model *33*
- 2.3 Vehicle Lateral Dynamics Model *36*
  - 2.3.1 Geometry of Cornering *36*
  - 2.3.2 Single-Track Lateral Vehicle Model *38*
  - 2.3.3 Augmented Single-Track Lateral Vehicle Model *42*
  - 2.3.4 Linearized Single Track Lateral Vehicle Model *42*
- 2.4 Path Model *45*
- 2.5 Pure Pursuit: Geometry-Based Low-Speed Path Tracking *51*
- 2.6 Stanley Method for Path Tracking *52*
- 2.7 Path Tracking in Reverse Driving and Parking *54*
- 2.8 Chapter Summary and Concluding Remarks *56*
- References *56*



<b>3</b>	<b>Simulation, Experimentation, and Estimation Overview</b>	<b>57</b>
3.1	Introduction to the Simulation-Based Development and Evaluation Process	57
3.2	Model-in-the-Loop Simulation	60
3.2.1	Linear and Nonlinear Vehicle Simulation Models	60
3.2.2	Higher Fidelity Vehicle Simulation Models	61
3.3	Virtual Environments Used in Simulation	62
3.3.1	Road Network Creation	63
3.3.2	Driving Environment Construction	65
3.3.3	Capabilities	68
3.4	Hardware-in-the-Loop Simulation	72
3.5	Experimental Vehicle Testbeds	74
3.5.1	Unified Approach	75
3.5.2	Unified AV Functions and Sensors Library	76
3.6	Estimation	78
3.6.1	Estimation of the Effective Tire Radius	78
3.6.2	Slip Slope Method for Road Friction Coefficient Estimation	79
3.6.3	Results and Discussion	82
3.7	Chapter Summary and Concluding Remarks	87
	References	87
<b>4</b>	<b>Path Description and Generation</b>	<b>91</b>
4.1	Introduction	91
4.2	Discrete Waypoint Representation	91
4.3	Parametric Path Description	94
4.3.1	Clothoids	95
4.3.2	Bezier Curves	97
4.3.3	Polynomial Spline Description	99
4.4	Tracking Error Calculation	103
4.4.1	Tracking Error Computation for a Discrete Waypoint Path Representation	103
4.4.2	Tracking Error Computation for a Spline Path Representation	104
4.5	Chapter Summary and Concluding Remarks	104
	References	105
<b>5</b>	<b>Collision Free Path Planning</b>	<b>107</b>
5.1	Introduction	107
5.2	Elastic Band Method	111
5.2.1	Path Structure	111
5.2.2	Calculation of Forces	111
5.2.3	Reaching Equilibrium Point	114
5.2.4	Selected Scenarios	115
5.2.5	Results	116
5.3	Path Planning with Minimum Curvature Variation	123
5.3.1	Optimization Based on $G^2$ -Quintic Splines Path Description	123
5.3.2	Reduction of Computation Cost Using Lookup Tables	125
5.3.3	Geometry-Based Collision-Free Target Points Generation	128
5.3.4	Simulation Results	132
5.4	Model-Based Trajectory Planning	134



5.4.1	Problem Formulation	134
5.4.2	Parameterized Vehicle Control	136
5.4.3	Constrained Optimization on Curvature Control	137
5.4.4	Sampling of the Longitudinal Movements	141
5.4.5	Trajectory Evaluation and Selection	143
5.4.6	Integration of Road Friction Coefficient Estimation for Safety Enhancement	145
5.4.7	Simulation Results in Complex Scenarios	148
5.5	Chapter Summary and Concluding Remarks	154
	References	154
<b>6</b>	<b>Path-Tracking Model Regulation</b>	<b>159</b>
6.1	Introduction	159
6.2	DOB Design and Frequency Response Analysis	160
6.2.1	DOB Derivation and Loop Structure	160
6.2.2	Application Examples	162
6.2.3	Disturbance Rejection Comparison	171
6.3	Q Filter Design	171
6.4	Time Delay Performance	172
6.5	Chapter Summary and Concluding Remarks	175
	References	175
<b>7</b>	<b>Robust Path Tracking Control</b>	<b>177</b>
7.1	Introduction	177
7.2	Model Predictive Control for Path Following	178
7.2.1	Formulation of Linear Adaptive MPC Problem	178
7.2.2	Estimation of Lateral Velocity	180
7.2.3	Experimental Results	182
7.3	Design Methodology for Robust Gain-Scheduling Law	185
7.3.1	Problem Formulation	185
7.3.2	Design via Optimization in Linear Matrix Inequalities Form	186
7.3.3	Parameter-Space Gain-Scheduling Methodology	188
7.4	Robust Gain-Scheduling Application to Path-Tracking Control	193
7.4.1	Car Steering Model and Parameter Uncertainty	193
7.4.2	Controller Structure and Design Parameters	195
7.4.3	Application of Parameter-Space Gain-Scheduling	197
7.4.4	Comparative Study of LMI Design	200
7.4.5	Experimental Results and Discussions	202
7.5	Add-on Vehicle Stability Control for Autonomous Driving	206
7.5.1	Direct Yaw Moment Control Strategies	207
7.5.2	Direct Yaw Moment Distribution via Differential Braking	211
7.5.3	Simulation Results and Discussion	213
7.6	Chapter Summary and Concluding Remarks	216
	References	216



**8      Summary and Conclusions    221**

8.1      Summary    221

8.2      Conclusions    223

**Index    225**