

# Contents

<b>Introduction</b>	<b>11</b>
Main Contributions . . . . .	11
Dissertation Outline . . . . .	11
<b>I THRUST VECTOR CONTROL OF CONSTRAINED MULTI-BODY SYSTEMS</b>	<b>13</b>
<b>1 Introduction</b>	<b>15</b>
1.1 <i>Problem Motivation</i> . . . . .	15
1.2 <i>Main Contributions</i> . . . . .	23
1.3 <i>Conclusions</i> . . . . .	24
<b>2 Problem Statement</b>	<b>25</b>
2.1 <i>Problem Setup</i> . . . . .	25
2.2 <i>Constraints</i> . . . . .	28
2.2.1 Dynamic Constraints . . . . .	28
2.2.2 Kinematic Constraints . . . . .	29
2.3 <i>Control Objective</i> . . . . .	29
2.4 <i>Equations of Motion</i> . . . . .	30
2.4.1 Kinetic Energy . . . . .	30
2.4.2 Potential Energy . . . . .	31
2.4.3 Equations of Motion . . . . .	32
2.5 <i>Attainable Configurations of Equilibrium</i> . . . . .	39
2.6 <i>Conclusions</i> . . . . .	42
<b>3 Control Scheme</b>	<b>43</b>
3.1 <i>General Control Architecture</i> . . . . .	43
3.2 <i>Inner Loop</i> . . . . .	44
3.2.1 Control Law on $SO(2)$ . . . . .	45
3.2.2 Control Law on $S^2$ . . . . .	46
3.2.3 Control Law on $SO(3)$ . . . . .	48
3.3 <i>Outer Loop</i> . . . . .	50

3.3.1	Outer Loop Design Assuming an Ideal Inner Loop . . . . .	51
3.3.2	Stability Analysis in the Presence of Attitude Dynamics . . . . .	60
3.4	<i>Stability and Convergence Properties of the Interconnected System</i> . . . . .	65
3.5	<i>Conclusions</i> . . . . .	68
<b>4</b>	<b>Constraints Enforcement</b>	<b>69</b>
4.1	<i>Constraints to be Enforced</i> . . . . .	69
4.2	<i>Mapping and Constraints</i> . . . . .	70
4.3	<i>Reference Governor</i> . . . . .	71
4.3.1	Scalar Reference Governor . . . . .	71
4.3.2	Explicit Reference Governor . . . . .	74
4.4	<i>Conclusions</i> . . . . .	77
<b>II</b>	<b>APPLICATION TO AERIAL ROBOTICS</b>	<b>81</b>
<b>5</b>	<b>Control of a UAV Manipulating an Object with a UGV</b>	<b>85</b>
5.1	<i>State of the Art</i> . . . . .	85
5.2	<i>Problem Statement</i> . . . . .	86
5.3	<i>Attainable Configurations of Equilibrium</i> . . . . .	91
5.4	<i>Control Architecture</i> . . . . .	93
5.4.1	UGV Control Law . . . . .	94
5.4.2	UAV Control Law . . . . .	94
5.5	<i>Stability Properties</i> . . . . .	99
5.6	<i>Constraints Enforcement</i> . . . . .	103
5.7	<i>Numerical and Experimental Results</i> . . . . .	104
5.7.1	Simulations . . . . .	104
5.7.2	Experiments . . . . .	108
5.8	<i>Conclusions</i> . . . . .	111
<b>6</b>	<b>Control of Tethered Quadrotors</b>	<b>115</b>
6.1	<i>State of the Art</i> . . . . .	115
6.2	<i>Problem Statement</i> . . . . .	117

6.3	<i>Attainable Configurations of Equilibrium</i>	119
6.4	<i>Control Architecture</i>	121
6.4.1	Inner Loop	122
6.4.2	Outer Loop	122
6.5	<i>Stability Properties</i>	127
6.6	<i>Constraints Enforcement</i>	130
6.7	<i>Simulations</i>	131
6.8	<i>Conclusions</i>	138
<b>7</b>	<b>Other Case Studies</b>	<b>143</b>
7.1	<i>Control of Two UAVs Manipulating an Object with a Crane</i>	143
7.1.1	Equations of Motion	144
7.1.2	Control Scheme and Mapping	145
7.1.3	Stability Properties	146
7.2	<i>Control of a UAV Manipulating an Object in 3D</i>	146
7.2.1	Equations of Motion	147
7.2.2	Control Scheme	148
7.2.3	Stability Properties	149
7.3	<i>Conclusions</i>	150
<b>8</b>	<b>General Conclusions</b>	<b>151</b>
8.1	<i>Future Research Opportunities</i>	152
8.2	<i>Closing Remarks</i>	153
<b>Bibliography</b>		<b>155</b>
<b>Appendices</b>		<b>165</b>