Table of Contents

Abstract i

List of Abbreviations iii

Nomenclature v

Chapter 1: Introduction 1

1.1. Background and Motivation 1

1.2. Contributions of the Thesis 6

1.3. Organisation of the Thesis 7

Chapter 2: Literature Survey 9

2.1. Introduction 9

2.2. Bond Graph Modelling 9

2.3. Multibody Dynamics 11

2.4. Modelling of Stewart Platform 14

2.5. Bond Graph Modelling of Vehicles 16

2.5.1. Antilock Braking System 18

2.5.2. Regenerative Braking System 19

2.6. Simulation and Control of Stewart Platform 22

2.7. Objectives of the Present Work 25

Chapter 3: Bond Graph Modelling of Multibody Dynamics 27

3.1. Introduction 27

3.2. Planar Multibody Systems 29

3.2.1. Plane Impedance Model 29

3.2.2. Model of Rigid Planar Links 30

3.2.3. Model of Revolute Joints 32

Copyright IIT Kharagpur

3.2.4. Model of the Slider Component 34
3.2.5. Case Study: Rapson Slide 37
3.3. Spatial Multibody Systems 42
3.3.1. Cardan Angles 42
3.3.2. Newton's Equations in Non-inertial Frame 43
3.3.3. Euler's Equations 45
3.3.4. Transformation of Linear and Angular Velocities 46
3.3.5. Determination of Euler Angle Rates 48
3.3.6. Implementation of Constraints 49
3.3.7. Example Application: Model of a Spinning Top 49
3.4. Conclusions 52
Chapter 4: Modelling and Control of Stewart Platform 53
4.1. Introduction 53
4.2. Modelling of Planar Stewart Platform 54
4.2.1. Kinematic Analysis 55
4.2.2. Bond Graph Model of Platform 57
4.3. Modelling of Hydraulic Servo-System 59
4.3.1. Four-way Directional Control Valve Model 59
4.3.2. Modelling of Valve Flow Equation 60
4.3.3. Bond Graph Model of Directional Control Valve 60
4.3.4. Hydraulic Cylinder Model 62
4.3.5. Formulation of the Constitutive Model 62
4.3.6. Bond Graph Model of Hydraulic Cylinder 63
4.3.7. PI Controller 66
4.4. Overwhelming Controller as a System Inversion Tool 67
4.5. Overwhelming Controller for Planar Stewart Platform 72
4.6. Case Study–I: Virtual Reality Application 77
4.6.1. A Planar Vehicle Simulator 78
4.6.2. Simulation Results 80
4.6.3. Noise-Sensitivity Study 82
4.7. Case Study–II: Operation on a Plane Surface 85
4.7.1. Trajectory Tracking Performance 86

Copyright IIT Kharagpur

4.7.2. Effect of Leg Inertia 87
4.8. Modelling of 3-D Stewart Platform 89
4.8.1. 3-D Stewart Platform Model without Leg Inertia 90
4.8.2. 3-D Actuator Model 91
4.8.3. 3-D Stewart Platform Model with Leg Inertia 94
4.9. Inverse Model of 3-D Stewart Platform 97
4.10. Conclusions 98
Chapter 5: Application to Vehicle Simulator 99
5.1. Introduction 99
5.2. Single Wheel Model 100
5.3. Planar Bicycle Model 101
5.3.1. Kinematic Relations 102
5.3.2. Bond Graph Model 102
5.4. Four Wheel Vehicle Model 103
5.4.1. Word Bond Graph Representation 104
5.4.2. Vehicle Body 105
5.4.3. Suspension System and Axle 107
5.4.4. Wheel 108
5.4.5. Steering System 110
5.4.6. Tyre Slip Forces and Moments 112
5.4.7. Braking System 114
5.4.8. Engine 129
5.4.9. Differential 136
5.4.10. Gearbox 136
5.4.11. Integrated Vehicle Model with Transmission System 137
5.5. Vehicle Dynamics Simulation 140
5.5.1. Validation of Four Wheel Model 141
5.5.2. Antilock Braking System in Four Wheel Model 142
5.5.3. Sliding Mode Control in Four Wheel Model 143
5.6. Stewart Platform for Vehicle Simulator 145
5.7. Human-Machine Interface 147
5.8. Graphics Interface 148

Copyright IIT Kharagpur

5.9. Results of Test Drive of Driving Simulator 150
5.10. Conclusions 155
Chapter 6: Impedance Control of Stewart Platform 157
6.1. Introduction 157
6.2. Design of Impedance Controller 158
6.2.1. Concept of Flexible Foundation 158
6.2.2. Concept of Virtual Foundation 161
6.2.3. Alternative Impedance Control Technique 161
6.2.4. Amnesia Removal 163
6.3. Force Controlled Machining with Stewart Platform 164
6.3.1. System Parameters and Initial Conditions 165
6.3.2. Trajectory Tracking Performance 165
6.3.3. Interaction Force Control 166
6.4. Conclusions 170
Chapter 7: Conclusions 171
References 175
Appendices 187
Appendix A Bond Graph Notations Revisited 187
A.1. Introduction 187
A.2. Causality 190
A.3. Activation 191
A.4. Sensors, Actuators and Instrumentation Circuits 191
A.5. Systems with Differential Causality 193
A.6. Field Elements 193
Appendix D List of Files and Programs Given in the Compact Disc 195
Curriculum Vitae 197

Copyright IIT Kharagpur