Design, Analysis, and Control of Parallel Robots with Different Applications

by

Xu Qing Song

Doctor of Philosophy in Electromechanical Engineering

July 2008

Faculty of Science and Technology
University of Macau

TABLE OF CONTENTS

LIST OF FIGURES xi

LIST OF TABLES xiv

LIST OF ABBREVIATIONS xvi

CHAPTER 1: INTRODUCTION 1

1.1 Research Background 1

1.2 Objectives and Contribution 7

1.3 Structure of the Dissertation 8

CHAPTER 2: NOVEL DESIGN AND ANALYSIS OF TRANSLATIONAL PARALLEL KINEMATIC MACHINES 11

2.1 Review of Screw Theory and Optimization Algorithms 11

2.1.1 Overview of Screw and Reciprocal Screw Systems 11

2.1.2 Survey on Optimization Methods 13

2.2 A 3-PRC Parallel Manipulator with Intersecting Guideways 15

2.2.1 Architecture Description 15

2.2.2 Mobility Analysis of the Manipulator 16

2.2.3 Kinematic Modeling 18

2.2.4 Singularity and Isotropy Analysis 21

2.2.5 Workspace Analysis 25

2.2.6 Overconstraint, Accuracy, and Optimization 28

2.2.7 Dexterity Analysis 45

2.2.8 Stiffness Analysis 48

2.2.9 Dynamic Modeling and Validation 60

2.2.10 Robust Control 66

2.2.11 Conclusion 80

2.3 A 3-PRC Parallel Manipulator with Orthogonal Guideways 82

2.3.1 Architecture Description and Mobility Analysis 82

2.3.2 Kinematic Modeling 83

2.3.3 Singularity-Free Manipulator Design 87

2.3.4 Isotropic Configurations 90
2.3.5 Workspace Determination 91
2.3.6 Case Studies 92
2.3.7 Conclusion 95
2.4 A Class of 3-PCR Translational Parallel Manipulators 96
2.4.1 Architecture Description and Mobility Analysis 97
2.4.2 Kinematic Modeling 100
2.4.3 An Orthogonal 3-PCR TPM 101
2.4.4 Conclusion 102
2.5 Conclusion 102

CHAPTER 3: NOVEL DESIGN AND ANALYSIS OF CPM FOR MICRO/-NANO SCALE MANIPULATION 103
3.1 Design Considerations for a CPM 103
3.1.1 Compliant Joints 103
3.1.2 Actuators, Sensors, Materials and Fabrication 105
3.2 A 2-DOF Compliant Parallel Micromanipulator 107
3.2.1 Architecture Description 107
3.2.2 PRB Modeling of the CPM 109
3.2.3 Workspace Determination 112
3.2.4 Optimal Kinematic Design 114
3.2.5 Structure Improvement and Kinematics Analysis 116
3.2.6 Statics and Dynamics Analysis 123
3.2.7 Dimension Optimization 130
3.2.8 Prototype Development and Experimental Setup 133
3.2.9 Kinematic Calibration 134
3.2.10 Trajectory Planning and Visual Servo Control 138
3.2.11 Conclusion 145
3.3 A Decoupled 2-DOF Compliant Parallel Micromanipulator 146
3.3.1 Design and Enumeration of an XY TDPS 147
3.3.2 Matrix Method-Based Modeling of Flexure Mechanisms 150
3.3.3 Compliance Modeling of the Displacement Amplifier 155
3.3.4 Compliance and Stiffness Modeling of the XY Stage 158
3.3.5 Mobility and Workspace Determination 165

3.3.6 Dynamics and Natural Frequency Analysis 167
3.3.7 Architecture Optimization of the XY Stage 170
3.3.8 Prototype Fabrication and Experimental Setup 172
3.3.9 System Identification and Controller Design 174
3.3.10 Conclusion 185
3.4 A 3-PRC Compliant Parallel Micromanipulator 185
3.4.1 Architecture Description 185
3.4.2 Kinematic Modeling 186
3.4.3 Structure Improvement Procedures 190
3.4.4 Kinematics, Workspace, and Parasitic Motion Assessment . . . 195
3.4.5 Statics and Stiffness Prediction 201
3.4.6 Dynamics and Natural Frequency Evaluation 204
3.4.7 Multi-Objective Dimension Optimization 207
3.4.8 Conclusion 211
3.5 Conclusion 212

CHAPTER 4: EXPLORATION OF NOVEL APPLICATIONS OF PARALLEL ROBOTS 213
4.1 Design and Development of a Medical Parallel Robot for Cardiopulmonary Resuscitation 213
4.1.1 Conceptual Design of a CPR Robot System 214
4.1.2 Kinematic Analysis of the Medical Robot 215
4.1.3 Architecture Optimization for a Large Singularity-Free Usable Workspace 224
4.1.4 Dynamic Modeling and Control 227
4.1.5 Experiments on the Prototype 231
4.1.6 Conclusion 232
4.2 Design and Modeling of a Mobile Parallel Manipulator 234
4.2.1 Architecture Design of a MPM 234
4.2.2 Kinematic Modeling 235
4.2.3 Singularity and Workspace Analysis 241
4.2.4 Dynamic Modeling 243
4.2.5 Model-Based Dynamics Control 247
4.2.6 Conclusion 250

4.3 Conclusion 250

CHAPTER 5: GENERAL CONCLUSION ·····251

5.1 Concluding Remarks 251

5.2 Suggested Future Works 253

APPENDIX A: FORWARD KINEMATIC MODELING OF A 3-PRC TPM ····255

A.1 Forward Kinematics Solutions 255

A.2 A Case Study 256

APPENDIX B: ANALYTICAL METHOD FOR MOBILITY ANALYSIS OF A 3-PRC TPM ·····259

APPENDIX C: FORWARD KINEMATIC MODELING OF AN ORTHOGONAL 3-PRC TPM ·····261

APPENDIX D: STABILITY PROOF OF RIDC CONTROLLER ·····263

APPENDIX E: STABILITY PROOF OF PBRC CONTROLLER ·····265

APPENDIX F: NONLINEAR MODELING OF AN XY CPM ·····267

F.1 Nonlinear Modeling 267

F.1.1 Nonlinear Modeling of Output Motions with Input Variable q_1 . 267

F.1.2 Predication of Output Motions with Input Variables q_1 and q_2 . 280

F.2 Experimental Validation 282

BIBLIOGRAPHY ·····285

CANDIDATE'S PUBLICATIONS ·····297