
Contents

List of Contributors..... xvii

1 Appropriate Design of Parallel Manipulators 1

J.-P. Merlet, D. Daney

1.1 Introduction 1

1.2 Understanding End-user Wishes and Performance Indices 2

 1.2.1 Establishing the Required Performances 2

 1.2.2 Performance Indices 4

 1.2.3 Indices Calculation 6

1.3 Structural Synthesis 7

1.4 Dimensional Synthesis 8

 1.4.1 Choosing Design Parameters 8

 1.4.2 Design Methods 8

 1.4.3 The Atlas Approach 9

 1.4.4 Cost Function Approach 9

 1.4.5 Other Design Methodologies Based on Optimisation 10

 1.4.6 Exact Design Methodologies 10

1.5 The Parameter Space Approach 12

 1.5.1 Parameter Space 12

 1.5.2 Principle of the Method 12

 1.5.3 Finding Allowed Regions 13

 1.5.4 Finding Allowed Regions with Interval Analysis 14

 1.5.5 Search for Appropriate Robots 19

 1.5.6 Design Examples 19

1.6 Other Design Approaches 20

 1.6.1 Design for Reliability 20

 1.6.2 Design for Control 21

1.7 Conclusions 21

References 21

2 Gravity Compensation, Static Balancing and Dynamic Balancing of Parallel Mechanisms 27

Clément Gosselin

2.1 Introduction and Definitions 27

2.2 Mathematical Conditions for Balancing 28

| | | |
|----------|---|-----------|
| 2.3 | Static Balancing..... | 30 |
| 2.3.1 | Static Balancing of a Planar Four-bar Linkage..... | 30 |
| 2.3.2 | Spatial 6-dof Parallel Mechanism..... | 31 |
| 2.4 | Gravity Compensation..... | 36 |
| 2.5 | Dynamic Balancing..... | 40 |
| 2.5.1 | Dynamic Balancing of Planar Four-bar Linkages..... | 40 |
| 2.5.2 | Synthesis of Reactionless Multi-dof Mechanisms..... | 44 |
| 2.5.3 | Synthesis of Reactionless Parallel 3-dof Mechanisms..... | 44 |
| 2.5.4 | Synthesis of Reactionless Parallel 6-dof Mechanisms..... | 47 |
| 2.6 | Conclusions..... | 47 |
| | References..... | 47 |
| 3 | A Unified Methodology for Mobility Analysis Based on Screw Theory..... | 49 |
| | <i>Zhen Huang, Jingfang Liu, Qinchuan Li</i> | |
| 3.1 | Introduction..... | 49 |
| 3.2 | Basic Screw Theory and Mobility Methodology..... | 51 |
| 3.2.1 | Dependency and Reciprocity of Screws..... | 51 |
| 3.2.2 | Modified Grübler-Kutzbach Criterion..... | 54 |
| 3.2.3 | Four Key Techniques..... | 55 |
| 3.3 | Mobility Analysis of Single-loop Mechanisms..... | 57 |
| 3.3.1 | The Bennett Mechanism..... | 57 |
| 3.3.2 | The Goldberg Mechanism..... | 60 |
| 3.3.3 | The Bricard Mechanism with a Symmetric Plane..... | 61 |
| 3.4 | Mobility Analysis of Parallel Mechanisms..... | 63 |
| 3.4.1 | 4-DOF 4-URU Mechanism..... | 63 |
| 3.4.2 | The CPM Mechanism..... | 65 |
| 3.4.3 | The 4-DOF 1-CRR+3-CRRR Parallel Mechanism..... | 66 |
| 3.4.4 | DELTA Robot..... | 68 |
| 3.4.5 | H4 Manipulator..... | 70 |
| 3.5 | Discussions..... | 73 |
| 3.6 | Conclusions..... | 75 |
| | References..... | 76 |
| 4 | The Tau PKM Structures..... | 79 |
| | <i>Torgny Brogårdh, Geir Hovland</i> | |
| 4.1 | Introduction..... | 79 |
| 4.2 | Non-symmetrical PKM Structures..... | 81 |
| 4.3 | The SCARA Tau PKM..... | 84 |
| 4.4 | The Gantry Tau PKM..... | 87 |
| 4.5 | The Reconfigurable Gantry Tau PKM..... | 90 |
| 4.5.1 | Kinematics and Workspace..... | 92 |
| 4.5.2 | Calibration..... | 98 |
| 4.5.3 | Stiffness..... | 101 |
| 4.5.4 | Mechanical Bandwidth..... | 102 |

| | | |
|----------|---|------------|
| 4.6 | Industrial Potential of PKMs based on Tau Structures | 105 |
| 4.6.1 | Performance Advantages | 105 |
| 4.6.2 | Life-cycle Cost Advantages..... | 106 |
| 4.6.3 | Relieving People from Bad Working Conditions | 107 |
| 4.7 | Conclusions | 108 |
| | References..... | 109 |
| 5 | Layout and Force Optimisation in Cable-driven Parallel Manipulators..... | 111 |
| | <i>Mahir Hassan, Amir Khajepour</i> | |
| 5.1 | Introduction | 111 |
| 5.2 | Static Force Analysis..... | 112 |
| 5.3 | Optimum Layout for the Redundant Limb | 115 |
| 5.3.1 | Background on Convex Optimisation..... | 117 |
| 5.3.2 | Optimum Direction of the Redundant Limb..... | 121 |
| 5.3.3 | Multiple Poses | 124 |
| 5.3.4 | Multiple Redundant Limbs | 125 |
| 5.3.5 | Case Study | 126 |
| 5.4 | Minimising Cable Tensions..... | 130 |
| 5.4.1 | Case Study | 132 |
| 5.5 | Conclusions | 133 |
| | References..... | 134 |
| 6 | A Tripod-based Polishing/Deburring Machine | 137 |
| | <i>Fengfeng (Jeff) Xi, Liang Liao, Richard Mohamed, Kefu Liu</i> | |
| 6.1 | Introduction | 137 |
| 6.2 | Hybrid Machine Design..... | 139 |
| 6.2.1 | Description of the Machine..... | 139 |
| 6.2.2 | ParaWrist Design..... | 141 |
| 6.3 | Motion Planning | 142 |
| 6.3.1 | Tripod Constraints | 143 |
| 6.3.2 | Inverse Kinematics | 145 |
| 6.3.3 | Motion Planning | 145 |
| 6.4 | Motion Simulation, Part Localisation and Measurement | 146 |
| 6.4.1 | Forward Kinematics for Motion Simulation and Part Measurement..... | 146 |
| 6.4.2 | Three-point Method for Part Localisation | 148 |
| 6.5 | Tripod Stiffening | 150 |
| 6.5.1 | Compliance Modelling | 151 |
| 6.5.2 | Tripod Stiffening | 152 |
| 6.6 | Compliant Toolhead Design..... | 153 |
| 6.6.1 | Axial Compliance Design..... | 153 |
| 6.6.2 | Radial Compliance Design | 154 |
| 6.7 | Tool Control | 157 |
| 6.7.1 | Parameter Planning Based on Contact Model..... | 157 |

| | | |
|----------|--|------------|
| 6.7.2 | Control Methods | 159 |
| 6.7.3 | Model-based Control | 160 |
| 6.8 | Test Examples | 163 |
| 6.9 | Conclusions | 164 |
| | References..... | 165 |
| 7 | Design and Analysis of a Modular Hybrid Parallel-Serial Manipulator for Robotised Deburring Applications..... | 167 |
| | <i>Guilin Yang, I-Ming Chen, Song Huat Yeo, Wei Lin</i> | |
| 7.1 | Introduction | 167 |
| 7.2 | Design Considerations..... | 169 |
| 7.2.1 | Robot Modules | 169 |
| 7.2.2 | 6-DOF Hybrid Parallel-Serial Manipulator | 170 |
| 7.3 | Forward Displacement Analysis..... | 172 |
| 7.3.1 | 3RRR Planar Parallel Platform..... | 173 |
| 7.3.2 | PRR Serial Robot Arm | 176 |
| 7.3.3 | Entire Hybrid Manipulator..... | 178 |
| 7.4 | Inverse Displacement Analysis..... | 179 |
| 7.4.1 | Orientation Analysis | 179 |
| 7.4.2 | Position Analysis | 180 |
| 7.4.3 | Parallel Platform Analysis | 180 |
| 7.5 | Instantaneous Kinematics | 181 |
| 7.5.1 | 3RRR Planar Parallel Platform..... | 181 |
| 7.5.2 | Entire Hybrid Manipulator..... | 182 |
| 7.6 | Computation Examples..... | 183 |
| 7.7 | Application Studies | 184 |
| 7.8 | Conclusions | 186 |
| | References..... | 187 |
| 8 | Design of a Reconfigurable Tripod Machine System and Its Application in Web-based Machining..... | 189 |
| | <i>Z. M. Bi, Lihui Wang</i> | |
| 8.1 | Introduction | 189 |
| 8.2 | Related Work..... | 190 |
| 8.3 | Design of Reconfigurable Tripod Machine Tools | 191 |
| 8.4 | Kinematics, Dynamics and Optimisation | 193 |
| 8.4.1 | Inverse Kinematics | 194 |
| 8.4.2 | Direct Kinematics | 195 |
| 8.4.3 | Stiffness Model..... | 196 |
| 8.4.4 | Dynamic Model | 202 |
| 8.4.5 | New Criterion in Optimisation | 205 |
| 8.5 | Integrated Design Tools..... | 206 |
| 8.5.1 | Modelling Tool..... | 207 |
| 8.5.2 | Analysis Tool..... | 209 |
| 8.5.3 | Simulation Tool | 211 |

| | | |
|-----------|--|------------|
| 8.5.4 | Optimisation Tool..... | 211 |
| 8.5.5 | Monitoring Tool | 212 |
| 8.6 | Web-based Machining: a Case Study | 213 |
| 8.6.1 | Testing Environment | 213 |
| 8.6.2 | Tripod 3D Model for Monitoring | 214 |
| 8.6.3 | Web-based Machining | 215 |
| 8.7 | Conclusions | 217 |
| | References..... | 217 |
| 9 | Arch-type Reconfigurable Machine Tool..... | 219 |
| | <i>Jaspreet S. Dhupia, A. Galip Ulsoy, Yoram Koren</i> | |
| 9.1 | Introduction | 219 |
| 9.2 | Design and Construction | 221 |
| 9.2.1 | Arch-type RMT Specifications | 224 |
| 9.3 | Dynamic Performance | 225 |
| 9.3.1 | Cutting Process Parameters | 226 |
| 9.3.2 | Frequency Response Functions | 228 |
| 9.3.3 | Stability Lobes | 231 |
| 9.4 | Conclusions | 236 |
| | References..... | 236 |
| 10 | Walking Drive Enabled Ultra-precision Positioners..... | 239 |
| | <i>Eiji Shamoto, Rei Hino</i> | |
| 10.1 | Introduction | 239 |
| 10.2 | One-axis Feed Drive..... | 240 |
| 10.2.1 | Driving Principle and Control Method | 240 |
| 10.2.2 | One-axis Walking Device..... | 241 |
| 10.2.3 | Open Loop Control | 242 |
| 10.2.4 | Laser Feedback Control..... | 243 |
| 10.2.5 | Methods to Overcome Disadvantages | 244 |
| 10.3 | Three-axis Feed Drive | 245 |
| 10.3.1 | Three-axis Walking Device | 245 |
| 10.3.2 | Walking Algorithm for Simultaneous 3-axis Drive | 247 |
| 10.3.3 | Three-axis Positioning System with Laser Feedback Control | 251 |
| 10.3.4 | Results of 3-axis Positioning | 252 |
| 10.4 | Conclusions | 255 |
| | References..... | 255 |
| 11 | An $XY\theta_z$ Planar Motion Stage System Driven by a Surface Motor for Precision Positioning | 257 |
| | <i>Wei Gao</i> | |
| 11.1 | Introduction | 257 |
| 11.2 | The $XY\theta_z$ Surface Motor | 259 |

| | | |
|-----------|--|------------|
| 11.3 | The Decoupled Controller | 264 |
| 11.4 | The $XY\theta_z$ Surface Encoder | 271 |
| 11.5 | Precision Positioning by the $XY\theta_z$ Stage System | 277 |
| 11.6 | Conclusions | 279 |
| | References..... | 279 |
| 12 | Design and Analysis of Micro/Meso-scale Machine Tools..... | 283 |
| | <i>K. F. Ehmman, R. E. DeVor, S. G. Kapoor, J. Cao</i> | |
| 12.1 | Introduction | 283 |
| 12.2 | Overview of Worldwide Research on the mMT Paradigm..... | 285 |
| 12.3 | Overview of mMT Developments in USA | 288 |
| 12.4 | Development of a Three-axis mMT | 289 |
| | 12.4.1 Design Considerations for the NU 3-axis mMT | 289 |
| | 12.4.2 Physical Realisation of the NU 3-Axis mMT | 290 |
| | 12.4.3 Performance Evaluations | 292 |
| 12.5 | Development of a Five-axis mMT..... | 294 |
| | 12.5.1 Design Considerations for the UIUC 5-axis mMT | 295 |
| | 12.5.2 Motor and Bearing Placement | 298 |
| | 12.5.3 Summary of 5-axis mMT Design | 301 |
| | 12.5.4 Evaluation of Performance | 301 |
| | 12.5.5 Analysis of 5-axis mMT Motion Parameters..... | 304 |
| | 12.5.6 Examples of Micro-scale Machining on the UIUC 5-axis mMT | 305 |
| 12.6 | A Hybrid Methodology for Kinematic Calibration of mMTs..... | 306 |
| | 12.6.1 Design of the Measurement System | 307 |
| | 12.6.2 A Hybrid Calibration Methodology..... | 308 |
| | 12.6.3 Off-machine Measurements..... | 309 |
| | 12.6.4 On-machine Measurements | 309 |
| | 12.6.5 Kinematic Error Modelling..... | 310 |
| | 12.6.6 Validation of Calibration Methodology..... | 311 |
| 12.7 | Challenges in mMT Development..... | 312 |
| 12.8 | The Status of mMT Commercialisation Worldwide..... | 313 |
| 12.9 | Conclusions | 314 |
| | References..... | 315 |
| 13 | Micro-CMM | 319 |
| | <i>Kuang-Chao Fan, Ye-Tai Fei, Weili Wang, Yejin Chen, Yan-Chan Chen</i> | |
| 13.1 | Introduction | 319 |
| 13.2 | Structure of a Micro-CMM..... | 321 |
| | 13.2.1 Semi-circular Bridge Structure | 321 |
| | 13.2.2 Co-planar XY Stage..... | 322 |
| | 13.2.3 Z-axis Design..... | 323 |
| 13.3 | Probes | 324 |
| | 13.3.1 Focus Probe | 324 |
| | 13.3.2 Contact Probe | 327 |

| | | |
|-----------|--|------------|
| 13.4 | Actuator and Feedback Sensor | 329 |
| 13.5 | System Integration and Motion Control | 332 |
| 13.5.1 | System Assembly..... | 332 |
| 13.5.2 | Motion Control | 332 |
| 13.5.3 | System Errors | 332 |
| 13.6 | Conclusions | 334 |
| | References..... | 334 |
| 14 | Laser-assisted Mechanical Micromachining..... | 337 |
| | <i>Ramesh K. Singh, Shreyes N. Melkote</i> | |
| 14.1 | Introduction | 337 |
| 14.2 | Development of LAMM-based Micro-grooving Process | 339 |
| 14.2.1 | Basic Approach..... | 339 |
| 14.2.2 | LAMM Setup for Micro-grooving..... | 339 |
| 14.3 | Process Characteristics | 341 |
| 14.3.1 | Design of Experiment | 341 |
| 14.3.2 | Results and Discussion | 342 |
| 14.4 | Process Modelling | 347 |
| 14.4.1 | HAZ Characterisation and Thermal Modelling | 347 |
| 14.4.2 | Force Modelling in Laser Assisted Micro-grooving..... | 354 |
| 14.5 | Summary and Future Directions..... | 362 |
| | References..... | 363 |
| 15 | Micro Assembly Technology and System..... | 367 |
| | <i>R. Du, Candy X. Y. Tang, D. L. Zhang</i> | |
| 15.1 | Introduction | 367 |
| 15.2 | Micro Grippers | 368 |
| 15.2.1 | Pneumatic Grippers | 369 |
| 15.2.2 | Capillary Force Grippers | 369 |
| 15.2.3 | Bio-inspired Grippers | 372 |
| 15.2.4 | Force Feedback..... | 374 |
| 15.3 | Precision Positioning | 376 |
| 15.3.1 | Servomotor | 376 |
| 15.3.2 | Linear Motor..... | 377 |
| 15.3.3 | Piezoelectric Motor..... | 379 |
| 15.3.4 | Image Based Feedback | 380 |
| 15.4 | A Sample Micro Assembly System..... | 380 |
| 15.5 | Conclusions | 382 |
| | References..... | 383 |
| | Index | 385 |