

MICROROBOTICS

Methods
and
Applications

Yves Bellouard



CRC Press
Taylor & Francis Group

Contents

Preface.....	xvii
Author.....	xix

1. Introduction.....	1
1.1 What Is Microrobotics?.....	1
1.2 The Microworld.....	3
1.3 Microrobots for What?	5
1.3.1 Microrobots in Medicine: Exploring the Human Body	6
1.3.2 Assembling Heterogeneous Components.....	6
1.3.3 Materials Sciences—Exploring New Frontiers in Research.....	7
1.3.4 Mobile Microrobots	8
1.4 What Are the Science and Technology behind Microrobotics?	10
1.4.1 Structure of the Book.....	11
1.4.2 Overview of Chapters	11

Part I Prerequisites

2. Fundamental Concepts of Linear Elasticity.....	15
2.1 Mechanics of Materials in the Context of Microrobotics	15
2.1.1 Introduction.....	15
2.1.2 Typical Material Behavior Response to a Load	15
2.1.3 Material Structures across Scales	17
2.1.4 Strength of Materials for Microrobotics	19
2.2 Concept of Stress.....	19
2.3 Concept of Deformation: Strain	21
2.3.1 Single-Axis Tensile and Shear Strain.....	21
2.3.2 Plane Strain.....	22
2.3.3 Three-Dimensional Case and Strain Tensor	24
2.3.4 Practical Implementation.....	24
2.4 Elasticity: Hooke's Law	25
2.4.1 Linear Elastic Model.....	25
2.4.2 Generalization of Hooke's Law	27
2.4.3 Effect of Temperature: Illustration for the Two-Dimensional Case.....	28
2.5 Properties of Plane Area: Second Moment of Inertia	29

2.6	Element of Beam Theory.....	30
2.6.1	Elastica.....	30
2.6.2	Stress State in a Beam during Bending.....	31
2.6.3	Fundamental Equations for Bending: Simple Beam Theory.....	33
2.7	Torsion	35
2.7.1	Loading Case Description	35
2.8	Yield Criteria.....	37
2.8.1	Tresca and von Mises Criteria.....	37
2.8.1.1	Tresca Criteria	37
2.8.1.2	von Mises Criteria	38
2.8.2	Ductile versus Brittle Materials	38
	References and Further Readings	39
	Exercises	40
3.	Fundamental Concepts of Kinematics	43
3.1	Problem Definition.....	43
3.2	Basics Tools for Kinematic Analysis.....	46
3.2.1	Introduction: Notations Used in This Book.....	46
3.2.1.1	Vectors.....	46
3.2.1.2	Coordinate Frame.....	46
3.2.1.3	Rigid Body.....	46
3.2.1.4	Velocity Vector	47
3.2.1.5	Angular Velocities (Noted ω)	47
3.2.1.6	Force Vectors	47
3.2.2	Rigid Body	48
3.2.3	Spatial Orientation of a Solid Body Relative to a Coordinate Frame.....	48
3.2.4	Rotation Matrices	49
3.2.5	Euler Angles	50
3.2.6	Essential Properties of Rotation Matrices	52
3.3	Kinematics.....	52
3.3.1	Definition	52
3.3.2	Spatial Vectors Using Wrenches and Screw Notations	53
3.3.3	Spatial Velocity (Called Twist)	56
3.4	Kinetics	58
3.4.1	Force Spatial Vector Representation (Wrench)	58
3.5	Kinetics and Dynamics	59
3.5.1	Introduction.....	59
3.5.2	Moment of Inertia	59
3.6	Linear and Angular Momentum.....	61
3.6.1	Kinetic Energy.....	62
3.7	Equations of Motion	63

3.7.1	Newton's and Euler's Laws.....	63
3.7.2	Newton's Third Axiom	64
3.8	Lagrange Formalism.....	64
3.8.1	Virtual Work Principle and the d'Alembert Principle.....	64
3.8.2	Lagrange Equations.....	65
3.9	Illustrative Example: The Double Pendulum	65
3.9.1	Description.....	65
3.9.2	Lagrangian of the System	68
3.9.3	Equation of Motion Using Newton–Euler.....	71
3.10	Analysis of Multibody Systems	74
3.10.1	Introduction.....	74
3.10.2	Parametric Representation of a Mechanism	76
3.10.3	Joints	77
3.10.4	Graphical Representation of a Mechanism.....	77
3.10.5	Mobility of a Mechanism.....	80
3.10.6	The Chebyshev–Grübler–Kutzbach Formula	81
3.10.7	Mobility Analysis: Illustrative Examples	82
3.11	Forward Kinematics (Geometrical Model).....	86
3.11.1	Methods Based on 3×3 Matrices.....	86
3.11.2	Methods Based on 4×4 Matrices (Homogeneous Matrices).....	87
3.11.3	Discussion about Forward Kinematics.....	89
3.12	Direct Kinematics: Jacobian of a Robot.....	89
3.12.1	Definition	89
3.12.2	Practical Implementation.....	90
3.12.3	Mechanism with Loops: Parallel Mechanism	95
3.13	Inverse Kinematics.....	97
	References	100
	Further Readings.....	100
	Exercises	101

Part II Core Technology

4.	Applied Physics for Microrobotics	113
4.1	Scaling Effects.....	113
4.1.1	Introduction.....	113
4.1.2	Scaling Laws	114
4.1.3	Scaling Effect on Surface and Volume	114
4.1.4	Effects on Various Physical Properties	115
4.1.4.1	Mass	115
4.1.4.2	Moment of Inertia.....	115
4.1.4.3	Spring Force and Oscillating Frequency	116

4.1.5	Illustration of Scaling Effects on Electrical Properties	116
4.1.5.1	Electrical Properties	116
4.1.5.2	Inductance	117
4.1.6	Scaling Effect on Fluids	117
4.1.7	Scaling Effect on Physical Forces	118
4.1.7.1	Gravitational Forces	118
4.1.7.2	Electromagnetic Forces	119
4.2	An Introduction to the Physics of Adhesion	121
4.2.1	Types of Contact	121
4.2.2	Illustration of Adhesion Force Measurements Using Atomic Force Microscopy	122
4.2.3	Modeling of the Contact Regions	126
4.2.3.1	Hertz Model	126
4.2.3.2	Sneddon Model	127
4.2.4	Modeling of the Contact Regions Taking into Account Surface Forces	128
4.2.4.1	Bradley Model	128
4.2.4.2	Derjaguin–Müller–Toporov (DMT) Theory	128
4.2.4.3	Johnson–Kendall–Roberts Theory	129
4.2.4.4	Maugis Theory	129
4.2.5	Comparison/Domain of Validity	130
4.2.6	Nature of Adhesion Forces	131
4.2.6.1	Capillary Forces	131
4.2.6.2	Electrostatic Forces	133
4.2.6.3	Van der Waals Forces	134
4.2.7	Comparison between Adhesion Forces	135
4.3	Material Structure and Properties: Crystal and Symmetry	136
4.3.1	Introduction: Rationale for This Section in a Microrobotics Book	136
4.3.2	Materials Come in Different Structures	137
4.3.2.1	Amorphous	137
4.3.2.2	Crystalline	137
4.3.2.3	Polycrystalline	138
4.3.2.4	Glass Materials	138
4.3.2.5	The Concept of Phase in Materials Science	138
4.3.2.6	Nanoscale Structures as Forms of Atomic Layers	138
4.3.3	An Introduction to the Concept of Tensors in Physics	139
4.3.3.1	The Dummy Suffix Notation	140
4.3.3.2	Transformations	141

4.3.4	Matrix Notation.....	143
4.3.4.1	Strain, Stress, and Stiffness Tensors in Matrix Notations.....	143
4.3.4.2	Change of Coordinate Frame	144
4.3.5	Miller Indices and Their Use to Describe Geometrical Entities Related to Crystals.....	145
4.3.6	Illustration of the Use of Miller Indices: The Crystal Structure of Silicon	147
4.3.7	The Effect of Crystal Symmetry on Physical Properties of Crystals.....	150
4.3.8	Illustration: Magnitude of a Physical Property in a Given Direction	150
	References	153
	Exercises	155
5.	Flexures	159
5.1	Introduction	160
5.1.1	Scaling Effect	160
5.1.2	Definition of a Flexure	160
5.1.3	Why Use Flexures?	162
5.1.4	Examples of Flexures.....	163
5.1.4.1	Early Example of Flexures	163
5.1.4.2	The CD/DVD Player Flexure (Low-Cost Flexure)	163
5.1.4.3	Illustration of Flexures Used in MEMS Devices.....	163
5.2	Historical Perspective.....	166
5.3	Mathematical Formalism: Generalized Stiffness Matrix	166
5.3.1	Problem Definition	166
5.3.2	Deformation Twist	167
5.3.3	Generalized Stiffness Matrix	168
5.3.4	Coordinates Transform to Express the Stiffness Matrix at Any Arbitrary Point	169
5.3.5	Overall Mechanism of Stiffness: Stiffness at the End-Effector	170
5.3.6	Methodology to Analyze Flexure Stiffness	173
5.4	Elemental Flexures (Building Blocks): Design Methodology.....	173
5.4.1	Introduction	173
5.4.2	Bending Mode	173
5.4.3	Torsion Mode	174
5.5	Elemental Flexures: Cantilever Beam	174
5.5.1	Stiffness Matrix for the Cantilever Beam.....	176
5.5.1.1	Principal Stiffness	176
5.5.1.2	Kinematics Model	179

5.5.1.3	Illustration of the Use of the Stiffness Matrix Transport Formula	180
5.5.1.4	Position of the Center of Rotation	183
5.5.2	Range Motion	183
5.5.2.1	Effect of Compressive Load: Mechanical Instability.....	184
5.5.2.2	Effect of Combined Loads Applied on a Cantilever.....	184
5.6	Notch Hinge.....	186
5.6.1	Stiffness along the Other Axis	187
5.7	Cross Pivot	187
5.7.1	Cross-Strip Flexure (Assembled Cross Pivot).....	188
5.7.2	Monolithic Cross Pivot.....	191
5.8	System Based on Flexures: Design Methodology	194
5.8.1	From Building Blocks to a System.....	194
5.8.2	Designing Steps.....	195
5.9	Flexure Systems.....	196
5.9.1	Linear Guidance Systems	196
5.9.1.1	Two-Beam Guidance: Leaf-Spring Guidance.....	196
5.9.1.2	Compensated Linear Guidance.....	199
5.9.2	Remote Center of Rotation Device	200
5.9.3	Motion Amplifications: Lever Principles.....	203
5.9.3.1	Upscaling Motions	203
5.9.3.2	Downscaling Motions	204
5.9.4	Flexures Made Out of Unconventional Material.....	205
5.9.4.1	Shape Memory Alloys Flexures	205
5.9.4.2	Flexures Made Out of Fused Silica Glass	206
5.9.4.3	Flexures Made Out of Single Crystals (Silicon)	207
	References	208
	General Books on the Topic That Have Been Published Recently	209
	Exercises	210
	Reference	215
6.	Actuators	217
6.1	Introduction	217
6.2	Design Principles of Actuators.....	218
6.2.1	Introduction.....	218
6.2.2	Amplification of Motion.....	219
6.2.2.1	Bimorph Assembly.....	219
6.2.2.2	In-Plane Motion Amplification.....	220
6.3	Electrostatic Actuators	223
6.4	Thermal-Based Actuators	229
6.4.1	Thermal Expansion as a Means to Produce Motion.....	229

6.4.2	Thermal Bimorph (Bilayer Structures)	230
6.4.2.1	Expression of the Beam Curvature for a Bimorph as a Function of the Temperature Difference	231
6.4.2.2	Maximum Stress Found in the Beam.....	231
6.4.2.3	Stoney Equation: Thin Films/Substrate Bimorph	231
6.4.3	Monolithic Thermal Expansion Actuators.....	232
6.5	Shape Memory Alloys	234
6.5.1	Introduction: Phenomenological Description	234
6.5.2	Phase Transformation: Stress/Temperature Diagram.....	237
6.5.3	Shape Memory Effect	240
6.5.4	SMA Microactuators: Design Principles	241
6.5.4.1	Bias Spring.....	241
6.5.5	Antagonistic Design	244
6.5.6	SMA Bimorphs	245
6.5.7	Monolithic Designs.....	247
6.5.7.1	Two-Way Shape Memory Effect	248
6.5.7.2	Monolithic Actuators through Partial Annealing.....	250
6.5.7.3	Design Principles of SMA Actuators: Summary	253
6.6	Piezoelectric Actuators.....	254
6.6.1	The Direct Piezoelectric Effect.....	254
6.6.2	The Converse Piezoelectric Effect	256
6.6.3	Piezocrystals and Symmetry	257
6.6.4	Constitutive Equations of Piezoelectric Actuators	258
6.6.5	Polling Process	259
6.6.6	Characteristic Behavior of Piezoactuators	260
6.6.6.1	Strain Response as a Function of Applied Voltage: "The Butterfly Curve".....	260
6.6.6.2	Hysteresis and Creeping Behavior	261
6.6.6.3	Energy Conversion (Coupling Efficiency)	262
6.6.6.4	Energy Loss in the Material.....	263
6.6.7	Piezoelectric Actuators/Design Principles	264
6.6.7.1	Concept of Blocking Force	264
6.6.7.2	Effect of a Load	266
6.6.7.3	Amplification Principles Used for Piezoactuator Technology.....	266
6.6.8	Piezoelectric Motors: Various Principles	269
6.6.8.1	Ultrasonic Motors.....	269
6.6.8.2	Stick-and-Slip Piezoactuators	271
6.6.8.3	Impact-Drive Mechanism	272
6.6.8.4	InchWorm® Construction Principle.....	273

6.7	Actuators: Other Principles	274
6.7.1	Magnetostrictive	274
6.7.2	Magnetic Shape Memory Alloys	274
	References	275
	Further Readings	276
	Exercises	280
7.	Sensors	283
7.1	Sensors in Microrobotics	283
7.1.1	Introduction	283
7.1.2	Sensors Terminology	284
7.1.2.1	Noise	284
7.1.2.2	Accuracy	284
7.1.2.3	Precision	284
7.1.2.4	Standard Sample Deviation of a Random Variable	285
7.1.2.5	Standard Errors	286
7.1.2.6	Resolution	286
7.1.2.7	Hysteresis	286
7.1.2.8	Nonlinearity	287
7.1.2.9	Bandwidth	287
7.2	Sensing Technologies for Displacements	287
7.2.1	Introduction	287
7.3	Electromagnetic Sensors	288
7.3.1	Inductive Sensors	288
7.3.1.1	LVDT: Working Principle	288
7.3.1.2	Eddy Current-Based Sensor	289
7.3.2	Capacitive Sensors	290
7.3.3	Resistive Elements	291
7.4	Optical-Based Displacement Sensors	293
7.4.1	Beam-Tracking Methods: Position Sensing Devices	294
7.4.1.1	Four-Quadrant Detectors (Discrete PSDs)	294
7.4.1.2	Continuous PSDs	295
7.4.1.3	Laser Triangulation Setup	296
7.4.2	Sensors Based on Light Intensity Modulation: Shadow-Projection Sensors	297
7.4.3	Displacement Sensors Based on Optical Phase Difference: Interferometers	298
7.4.4	Waveguides Coupling	301
7.5	Motion Tracking with Microscopes	304
7.5.1	Pattern Recognition Techniques	305
7.5.2	Optical Microscope	307
7.5.2.1	Working Principle of a Microscope: A Simplified Description	307
7.5.2.2	Description That Incorporates the Waviness of Light	309

7.5.2.3	Field of View of a Microscope	311
7.5.2.4	Depth of Field	312
7.5.3	Scanning Electron Microscope	313
References		318

Part III Implementation, Applications, and Future Prospects

8.	Implementation: Integration and Fabrication Aspects	321
8.1	Introduction	321
8.1.1	Scope of This Chapter	321
8.1.2	Manufacturing Requirements for Microrobots.....	321
8.2	An Overview of Microfabrication Principles.....	324
8.2.1	Introduction.....	324
8.2.2	Surface Micromachining and Lithography-Based Processes	324
8.2.3	High-Aspect Ratio Micromachining (Electro-Discharge Machining, Laser, DRIE, etc.).....	326
8.2.3.1	Deep-Reactive Ion Etching.....	327
8.2.3.2	LIGA and UV-LIGA (SU-8)	327
8.2.3.3	Electro-Discharge Machining	329
8.2.3.4	Laser Micromachining	331
8.2.3.5	Photoetchable Glass	337
8.2.3.6	Other Processes for Micropart: Water-Jet Machining, Ultrasonic Machining, Fine Stamping, and Sandblasting	337
8.3	Design Selection Criteria	339
8.3.1	A Qualitative Comparison of Micromachining Processes	340
8.3.2	Actuators and Micromachining Processes	341
8.3.3	Flexures Micromachining	342
8.3.4	Packaging/Integration Aspects.....	342
References		343
9.	State of the Art and Future Directions in Microrobotics	345
9.1	Introduction	345
9.2	Applications in Medicine.....	346
9.2.1	Mini-Invasive Surgery.....	346
9.2.2	Surgical Tools: Active Endoscopes	346
9.2.3	Smart Pills.....	348
9.2.4	Microrobotics for Cell Biology	350
9.2.5	Other Illustrations on the Use of Microrobotic Tools in Biology	351

9.3	Microrobotics/Nanorobotics for Materials Science Study	352
9.4	Tools for Microassembly: Microgripper Technologies	
	Overview	354
9.4.1	Introduction: From Gripper to Microgripper	356
9.4.2	Grippers with Moving Parts Using New Actuator Technologies	358
9.4.2.1	Piezoelectric Microgrippers.....	358
9.4.2.2	Electrostatic-Actuated Microgrippers.....	359
9.4.2.3	Bimorph	361
9.4.2.4	Thermal Expansion.....	362
9.4.2.5	Asymmetrical Thermal Microgrippers.....	363
9.4.2.6	Shape Memory Alloys	364
9.4.2.7	Electropneumatic- and Electrohydraulic-Actuating Grippers: FMA Microgrippers.....	367
9.4.3	Fluidic Grippers Vacuum Technologies	369
9.4.3.1	Water Drop Gripper: Gripping with Capillary Forces.....	370
9.4.3.2	Ice Gripper: Eureka MICROGRIP Project.....	372
9.4.4	Manipulation by Modulating Contact Adhesions	373
9.4.5	Noncontact Grippers and Transportation Systems: Laser Trap Gripper	375
9.4.5.1	Dielectrophoretic and Electrostatic Transportation Systems	377
9.4.5.2	Ultrasonic Standing Wave Field Transportation System.....	378
9.4.6	Microassembly Platforms and Manipulators	379
9.4.7	Microassembly Case Study	385
9.4.7.1	Illustration 1: Fiber-Endoscopes Assembly	385
9.4.7.2	Illustration 2: Leica Assembly of TRIMO-SMD: Illustration of the Concept of Task-Oriented Assembly.....	387
9.4.8	Toward Self-Assembly.....	389
9.5	Autonomous or Semiautonomous Microrobots	391
9.5.1	Miniature Robots for Collaborative Robotics Studies....	391
9.5.2	Remote Actuation Microrobotics (Untether Robot).....	393
	References.....	394

Appendix A: Illustration of Student Projects

A.1	Topics	401
A.1.1	Topic 1: Microgripper for Vertically Mounted Pins.....	401
A.1.1.1	Description.....	401
A.1.1.2	Questions.....	401
A.1.2	Topic 2: Monolithic Slit Mechanism.....	401
A.1.2.1	Description.....	401
A.1.2.2	Questions.....	402

A.1.3	Topic 3: X-Y- θ Planar Robot	402
A.1.3.1	Description	402
A.1.3.2	Questions	402
A.1.4	Topic 4: Gripper with Self-Aligning Compliant Mechanism	402
A.1.4.1	Description	402
A.1.4.2	Task	402
A.1.4.3	Questions	403
A.1.5	Topic 5: θ - ϕ -Z Robot for Positioning	403
A.1.5.1	Description	403
A.1.5.2	Questions	403
A.2	Project Rules and Assessment Method	403
Appendix B:	Types of Joints in Mechanism	405
B.1	Free and Fully Constrained Object	405
B.2	Five Degrees-of-Freedom Joints	405
B.3	Four Degrees-of-Freedom Joints	406
B.4	Three Degrees-of-Freedom Joints	407
B.5	Two Degrees-of-Freedom Joints	408
B.6	One Degree-of-Freedom Joints	409
Appendix C:	Elementary Flexure Joints: Stiffness Matrix	411
C.1	Cantilever Beams	411
C.1.1	Parameterization	411
C.1.2	Stiffness Matrix at the Center of Symmetry	411
C.1.3	Loading Case	411
C.2	Notch Hinge (with Circular Profile)	411
C.2.1	Parameterization	411
C.2.2	Stiffness Matrix	413
C.2.3	Loading Case	413
C.3	Cross Pivot	413
C.4	The Cartwheel Hinge	415
C.5	Double Beam	416
C.6	Linear Guidance	418
C.6.1	Leaf Spring	418
C.6.2	Linear Guidance with Four Elemental Hinges: General Case	418
Appendix D:	Material Properties Tables	421
D.1	Properties of Materials	421
D.2	Actuating Materials	422
	References	424
Index		425