

Table of Contents

Foreword	xvii
Introduction	xxi
Chapter 1. The Physics of the Microworld	1
Michaël GAUTHIER, Pierre LAMBERT and Stéphane RÉGNIER	
1.1. Introduction	1
1.1.1. Scale effect	1
1.1.2. Illustration of the scale effect	2
1.1.3. Microworlds	3
1.2. Details of the microworld	4
1.2.1. Perception	5
1.2.1.1. Position-sensing	5
1.2.1.2. Force-sensing	6
1.2.2. Design of microactuators and fabrication technology	7
1.2.3. Micro-object behavior	7
1.2.4. Environmental control	8
1.2.5. Repeatability and dexterity of microrobots	8
1.2.6. Summary	8
1.3. Surface forces	8
1.3.1. Van der Waals forces	9
1.3.1.1. Origins	10
1.3.1.2. Intermolecular van der Waals potential	11
1.3.1.3. Integration of the intermolecular potential	12
1.3.1.4. Hamaker constant	14
1.3.1.5. Lifshitz theory	14
1.3.1.6. Combination equations	16
1.3.1.7. Retardation effects in van der Waals forces	16

1.3.1.8. Simplified Derjaguin model	17
1.3.1.9. Numerical approach	19
1.3.2. Surface tension effects: capillary forces	22
1.3.3. Electrostatic forces	35
1.3.3.1. Plane-plane and plane-sphere models	36
1.3.3.2. Conical model	38
1.3.3.3. Asymptotic model	38
1.3.3.4. Inclined conical model	39
1.3.3.5. Hyperboloid model	40
1.4. Contact forces	40
1.4.1. Introduction to the thermodynamics of surfaces	40
1.4.2. Various models	42
1.4.2.1. Hertz model	42
1.4.2.2. JKR model	44
1.4.2.3. DMT model	45
1.4.2.4. Dugdale model	45
1.4.3. Transition between surface energy and the Hamaker constant	46
1.5. Experimental analysis of forces for micromanipulation	48
1.5.1. The atomic force microscope	48
1.5.1.1. Description of an atomic force microscope	48
1.5.1.2. Method of measurement	50
1.5.1.3. Pull-off forces and van der Waals forces	52
1.5.1.4. Electrostatic forces	54
1.5.2. Measurement of capillary forces	56
1.5.2.1. Description of the force measurement system	56
1.5.2.2. Analysis of the measurement of force-distance characteristics	57
1.6. Forces in liquid media	60
1.6.1. Impact of the liquid medium on surface forces and adhesive forces	60
1.6.1.1. Impact of the liquid medium on capillary forces	60
1.6.1.2. Impact of liquids on the electrostatic force	60
1.6.1.3. Impact of liquid on the pull-off force	61
1.6.1.4. Impact of liquid on van der Waals forces	61
1.6.1.5. Some measurements in water	62
1.6.2. Electric double-layer models	62
1.6.2.1. Surface charges in liquid media	63
1.6.2.2. Qualitative models of the electric double layer	64
1.6.2.3. Stern model	64
1.6.2.4. Zeta potential	65
1.6.2.5. Poisson-Boltzmann equation	66
1.6.3. Sphere-sphere and sphere-plane interactions	67
1.6.3.1. LSA method	67

1.6.3.2. Derjaguin method	68
1.6.3.3. Enhanced formulae	69
1.6.3.4. DLVO theory	71
1.6.3.5. XDLVO model	72
1.6.4. Impact of hydrodynamic effects on immersed manipulation	74
1.6.4.1. Fluid regime relevant to microrobotics	74
1.6.4.2. Flow laws	75
1.6.4.3. Applied forces	77
1.6.4.4. Impact on the behavior of micro-objects	77
1.7. Friction and roughness	78
1.7.1. Simplified description of microscopic friction	78
1.7.1.1. Admonton's laws	78
1.7.1.2. The Bowden and Tabor adhesion model	78
1.7.1.3. Single asperity approach	80
1.7.1.4. Microscopic approach	80
1.7.2. Roughness	80
1.7.2.1. Surface profiles: a multiscale problem	81
1.7.2.2. Surface profile measurement	82
1.7.2.3. Roughness models	82
1.7.2.4. Roughness models and fabrication processes	84
1.8. Relevant parameters and indicators	85
1.8.1. Relevant parameters	85
1.8.2. List of constants	86
1.8.2.1. Hamaker constants	86
1.8.2.2. Surface energy	87
1.8.2.3. Contact angle and surface tension	87
1.9. Exercises	88
1.9.1. Impact of viscous effects on the behavior of micro-objects	88
1.9.2. Illustration of the impact of capillary forces during micromanipulation in an immersed medium	89
1.9.3. Estimating the van der Waals force for an interaction between a cone and a plane using the Derjaguin method	90
1.9.4. Analysis of the experimental force curve	90
1.9.5. Numerical calculation of the capillary force between two parallel plates	91
1.9.6. Calculation of the capillary force by derivation of the interfacial energy	92
1.9.6.1. Useful information	92
1.9.6.2. Force between a sphere and a plane	93
1.9.7. Choice of probe for force measurement	94
1.10. List of symbols	95

Chapter 2. Actuators for Microrobotics	99
Nicolas CHAILLET, Moustapha HAFEZ and Pierre LAMBERT	
2.1. Introduction	99
2.2. Principles of motion and guiding	100
2.2.1. Motion generation	100
2.2.2. From sliding guidance to compliant guidance	104
2.3. Classification of actuators	111
2.4. Piezoelectric actuators	113
2.4.1. Introduction to piezoelectricity	113
2.4.2. Principles of piezoelectric materials	115
2.4.3. Ferroelectricity in piezoelectric ceramics	116
2.4.4. Properties of piezoelectric ceramics	117
2.4.4.1. Mechanical deformations	117
2.4.4.2. Electrical displacement	117
2.4.4.3. Generalization to 3D space	118
2.4.5. Multilayer (stack) actuators	121
2.4.6. Bimorph (bender) actuators	122
2.4.7. Stick-slip actuators	125
2.5. Electrostatic actuators	126
2.5.1. Principles	129
2.5.2. Elementary electrostatic actuator	130
2.5.2.1. Vertical actuator with parallel plates	130
2.5.2.2. Lateral actuator using parallel plates	133
2.5.2.3. Scale effect	135
2.5.3. Comb drive	137
2.5.4. Scratch-drive actuator	138
2.5.5. Conclusion	141
2.6. Thermal actuators	141
2.6.1. Scale effect	141
2.6.2. Actuators based on thermal expansion	143
2.6.2.1. Thermal bilayer	144
2.6.2.2. Thermal gradient microactuators	148
2.6.3. Shape memory alloys	151
2.6.3.1. Preamble	151
2.6.3.2. Principle	151
2.6.3.3. One-way memory effect	155
2.6.3.4. Two-way memory effect	155
2.6.3.5. Applications in micromanipulation	156
2.6.3.6. Other materials	159
2.7. Electro-active polymers	160
2.7.1. Ionic polymers	160
2.7.1.1. IPMC polymers (<i>ionic polymer metal composites</i>)	160
2.7.1.2. Conductive polymers	161

2.7.2. Electrical polymers	163
2.7.2.1. Dielectric elastomers	163
2.7.2.2. Piezoelectric polymers	165
2.8. Magneto-/electrorheological fluids	165
2.8.1. Physics of MR fluids	166
2.8.2. Example of fluid application: haptic interface for musical keyboards	168
2.9. Summary	170
2.10. Suppliers of active materials	170
2.10.1. Suppliers of piezoelectric materials	170
2.10.2. Suppliers of shape memory alloys	173
2.10.3. Suppliers of electro-active polymers	173
2.10.4. Supplier of MR fluids	173
2.10.5. Supplier of magnetostrictive actuators	173
2.11. Exercises	173
2.11.1. Dimensioning of a four-neck table	173
2.11.2. Case study of a multilayer actuator	174
2.11.3. Case study of a bimorph actuator	175
2.11.4. Motion of a dielectric	175
2.11.5. “ <i>xy</i> ” actuator	176
2.11.6. Analysis of a thermal bilayer actuator	178
2.11.7. Calculation for a simple AMF actuator	178
Chapter 3. Microhandling and Micromanipulation Strategies	179
Michaël GAUTHIER, Pierre LAMBERT and Stéphane RÉGNIER	
3.1. Introduction	179
3.2. Contact-free micromanipulation and positioning	180
3.2.1. Using optical tweezers	180
3.2.2. Using electrostatic forces	183
3.2.2.1. Expression for the electrophoretic force	184
3.2.2.2. Dielectrophoretic torque	185
3.2.2.3. Application of dielectrophoresis in micromanipulation	186
3.2.2.4. Particle positioning using electrophoresis	188
3.2.2.5. Use of a d.c. electric field	188
3.2.3. Using magnetic forces	189
3.2.4. Acoustic levitation	191
3.3. Contact-based micromanipulation and positioning	197
3.3.1. Using grippers with jaws	197
3.3.1.1. Monolithic actuator-based microgrippers	198
3.3.1.2. Multicomponent microgrippers	199
3.3.1.3. Gripper with passive jaws	201
3.3.2. Using phase changes	203
3.3.3. Vacuum gripping	206

3.3.4. Manipulation by adhesion	207
3.3.4.1. Description of a manipulation task	207
3.3.4.2. Discussion of the pick-up and release phases	208
3.3.4.3. Static pick-up and release experiments in dry media	211
3.3.5. Capillary gripping	212
3.4. Release strategies	220
3.4.1. Dynamic release	220
3.4.1.1. Bulk pick-up and selective release	224
3.4.2. Release of micro-objects through dielectrophoresis	226
3.4.3. Rolling	227
3.4.3.1. Experimental release using rolling	228
3.4.3.2. Precise release by rolling	229
3.5. Summary	230
3.6. Conclusion	234
3.7. Exercises	234
3.7.1. Acoustic levitation	234
3.7.2. Numerical study of inertial deposition	234
3.7.3. Numerical study of rolling	236
3.7.4. Establishing a frequency range for the validity of the simplified formula for the dielectrophoretic force	238
3.7.5. Determination of the Bode plot of the Clausius-Mosotti equation	239
3.7.6. Calculation of the dielectrophoretic force applied to a micro-object	239
3.7.7. Behavior of a laser-trapped object	241
3.7.8. Simultaneous manipulation of several micro-objects using a single laser	242
Chapter 4. Architecture of a Micromanipulation Station	243
Joël AGNUS, Mehdi BOUKALLEL, Cédric CLÉVY, Sounkalo DEMBÉLÉ and Stéphane RÉGNIER	
4.1. Introduction	243
4.2. Kinematics	244
4.2.1. Overview	244
4.2.2. Evolution and history	245
4.2.3. Range of available architectures	246
4.2.3.1. Mobile working post robots	247
4.2.3.2. Fixed working post robots	250
4.2.4. Current solutions	253
4.2.4.1. Commercial systems	253
4.2.4.2. Study and development of novel systems	254
4.2.4.3. Integration examples	256
4.2.4.4. Example: the μ MAD system	257

4.3. Visual perception	261
4.3.1. Importance of the image	261
4.3.2. Imaging	262
4.3.3. Properties	263
4.3.4. Modeling and calibration	269
4.3.5. Improving the field of view	271
4.3.5.1. Physical solutions	271
4.3.5.2. Software-based solutions	272
4.3.6. Increasing the depth of field	276
4.3.7. High-resolution metrology	278
4.3.8. Reference control of the image capture system	279
4.3.8.1. A simple example: 2D visual servoing	281
4.4. Force sensing	283
4.4.1. Architecture of force measurement systems	285
4.4.1.1. Indirect measurement methods	286
4.4.1.2. Direct measurement methods	286
4.4.2. Force measurement using sensors integrated into a microprehensor	287
4.4.2.1. Examples of resistive strain gauges	287
4.4.2.2. Examples of capacitive force sensors	291
4.5. Introduction to sensor-based linear multivariable control	294
4.5.1. Microrobotic servo systems	294
4.5.2. Multivariable systems	295
4.5.2.1. Differential representation	295
4.5.2.2. Transfer matrix representation	296
4.5.2.3. State-space model	296
4.5.3. Concepts of controllability and observability	296
4.5.4. Controllability	297
4.5.5. Observability	297
4.5.6. Control techniques for multivariable systems	297
4.5.6.1. Control decoupling	297
4.5.6.2. Optimal linear quadratic control	299
4.6. Application to automation and remote operation for micromanipulation tasks	300
4.6.1. Force feedback control with one degree of freedom	300
4.6.2. Remote micromanipulation with one degree of freedom	304
4.6.2.1. Master device: “Brigit” haptic interface	304
4.6.2.2. Slave organ: μ MAD micro-manipulator	305
4.6.2.3. Investigation of various couplings	306
4.6.2.4. Homothetic coupling	307
4.6.2.5. Passive coupling	308
4.6.2.6. Relative performance of the two coupling strategies	309
4.6.2.7. Industrial haptic interface	315

4.6.2.8. Control of the nanotranslator	316
4.6.2.9. Experimental results	317
4.7. Environmental control	318
4.7.1. Important environmental parameters	319
4.7.1.1. Temperature	319
4.7.1.2. Humidity level	320
4.7.1.3. Mechanical vibrations	321
4.7.1.4. Particles in suspension	321
4.7.1.5. Other relevant parameters	321
4.7.2. Consequences of changes in environmental parameters	322
4.7.3. Solutions to reduce the effects of environmental parameters	323
4.8. Applications	324
4.8.1. Artificial components	325
4.8.1.1. Industrial applications	325
4.8.1.2. Instrumentation and research	327
4.8.2. Manipulation for biological applications	331
4.8.2.1. Cell sorting and manipulation of individual cells	333
4.9. Conclusion	334
4.10. Exercises	334
4.10.1. Exercise 1	334
4.10.2. Exercise 2	334
4.10.3. Exercise 3	334
Chapter 5. Microtechnologies and Micromanipulation	335
Lionel BUCHAILLOT	
5.1. Silicon surface machining processes	335
5.1.1. Introduction	335
5.1.2. Bulk machining of silicon	336
5.1.3. History of surface micromachining	339
5.1.4. Principle	340
5.1.5. Advantages and drawbacks	342
5.1.6. Organization of this chapter	342
5.2. Early demonstrators	343
5.2.1. Mobile micromechanisms	343
5.3. Standard processes and fabrication examples	346
5.3.1. The SUMMiT™ process	347
5.3.2. The MUMPs® process	348
5.4. Alternative surface machining processes	352
5.4.1. The HexSil process	353
5.4.2. The SCREAM process	355
5.5. Co-integration with electronics	356
5.5.1. Integrated fabrication process	357

5.5.2. Sequential construction: microelectronics followed by microstructures	358
5.5.2.1. Sequential construction: microstructures followed by microelectronic circuits	358
5.5.3. Microstructures formed during CMOS circuit post-fabrication	359
5.6. Consistency of surface micromachining	360
5.6.1. Stiction	361
5.6.1.1. Attraction due to capillary forces	361
5.6.1.2. Adhesion through solid-solid contact forces	362
5.6.1.3. Preventing stiction	363
5.6.2. Fatigue in polycrystalline silicon	366
5.6.2.1. Methodology and implementation of tests	366
5.6.2.2. Damage and fatigue mechanisms	366
5.7. Conclusion	367
Chapter 6. Future Prospects	369
Philippe LUTZ and Stéphane RÉGNIER	
6.1. Micromachining	369
6.1.1. The main characteristics of microfactories	370
6.1.2. The main functions of a microfactory	371
6.1.2.1. Micromanipulation and micropositioning	372
6.1.2.2. Transport, positioning, supply and peripherals	373
6.1.2.3. Perception	375
6.1.2.4. Attachment	375
6.1.3. Main implementations worldwide	377
6.1.3.1. Multi-station microfactories	379
6.1.3.2. Single-station microfactory	382
6.1.3.3. Conclusion	389
6.1.4. Proposed microfactory architecture	389
6.1.4.1. Modular, reconfigurable and reorganizable micromanipulation stations	392
6.2. Nanomanipulation	395
6.2.1. Various microscopy techniques	396
6.2.1.1. Transmission electron microscope	396
6.2.1.2. Scanning electron microscope	398
6.2.1.3. Comparison with optical microscopy	398
6.2.1.4. Local probe microscopes	399
6.2.2. Comparison of available imaging techniques	400
6.2.3. Manipulation methods	401
6.2.3.1. Electrophoresis	401
6.2.3.2. Optical trap	401
6.2.3.3. Local probe manipulation	404
6.2.3.4. Comparison of methods	406

6.2.3.5. Use of an AFM in a scanning electron microscope	406
6.2.3.6. Tele-nanomanipulation	409
6.2.4. The nanomanipulator	410
6.2.5. Telenanoproject	411
6.2.6. Zyvex, Texas	412
6.2.7. Conclusion	413
Chapter 7. Solutions to Exercises	415
7.1. Chapter 1	415
7.1.1. Impact of viscous effects on the behavior of micro-objects	415
7.1.2. Illustration of the impact of capillary forces during micromanipulation in an immersed medium	417
7.1.3. Estimating the van der Waals force for an interaction between a cone and a plane using the Derjaguin method	417
7.1.4. Analysis of the experimental force curve	419
7.1.5. Calculation of the capillary force by derivation of the interfacial energy	420
7.1.6. Numerical calculation of the capillary force between two parallel plates	421
7.1.7. Choice of cantilever for force measurement	423
7.2. Chapter 2	423
7.2.1. Dimensioning of a four-neck table	423
7.2.2. Study of the case of a multiayer actuator	424
7.2.3. Study of the case of a bimorph actuator	425
7.2.4. Motion of a dielectric	426
7.2.5. “ <i>xy</i> ” actuator	427
7.2.6. Calculation for a bilayer thermal actuator	428
7.2.7. Calculation for a simple SMA actuator	428
7.3. Chapter 3	429
7.3.1. Acoustic levitation	429
7.3.2. Numerical study of inertial deposition	429
7.3.3. Numerical investigation of rolling	432
7.3.3.1. Static model	432
7.3.3.2. Sliding condition	432
7.3.3.3. Calculating the parameters of the problem	432
7.3.3.4. Rolling condition	433
7.3.3.5. Rolling and sliding conditions	434
7.3.3.6. Simulation and analysis	434
7.3.3.7. Comments	434
7.3.4. Establishing a frequency range for the validity of the simplified formula for the dielectrophoretic force	436
7.3.5. Determination of the Bode plot for the Clausius-Mosotti equation	437

7.3.6. Calculation of the dielectrophoretic force applied to a micro-object	438
7.3.7. Behavior of a laser-trapped object	439
7.3.8. Simultaneous manipulation of several micro-objects using a single laser	441
7.4. Chapter 4	443
7.4.1. Exercise 1	443
7.4.2. Exercise 2	444
7.4.3. Exercise 3	445
Bibliography	447
List of Authors	481
Index	483