

---

## Contents

<b>List of Contributors.....</b>	xv
<b>1 Trends in Nanohandling.....</b>	1
1.1 Introduction.....	1
1.2 Trends in Nanohandling.....	3
1.2.1 Self-assembly .....	3
1.2.2 SPM as a Nanohandling Robot.....	5
1.3 Automated Microrobot-based Nanohandling.....	8
1.4 Structure of the Book .....	11
1.5 References.....	13
<b>2 Robot-based Automated Nanohandling.....</b>	23
2.1 Introduction.....	23
2.2 Vision Sensors for Nanohandling Automation .....	25
2.2.1 Comparison of Vision Sensors for Nanohandling Automation ...	26
2.2.2 Zoom Steps and Finding of Objects .....	29
2.2.3 SEM-related Issues .....	31
2.2.3.1 Sensor Resolution and Object Recognition.....	31
2.2.3.2 Noise .....	33
2.2.3.3 Velocity and Image Acquisition Time .....	33
2.3 Automated Nanohandling: Problems and Challenges.....	34
2.3.1 Parasitic Forces.....	34
2.3.2 Contact Detection .....	36
2.4 General Description of Assembly Processes.....	37
2.4.1 Description of the Single Tasks.....	38
2.4.2 General Flowchart of Handling Tasks .....	40
2.5 Approaches for Improving Reliability and Throughput.....	40
2.5.1 Improving Reliability .....	40
2.5.2 Improving Throughput .....	41
2.6 Automated Microrobot-based Nanohandling Station .....	42
2.6.1 AMNS Components .....	43
2.6.1.1 Setup .....	43

2.6.1.2	Actuators.....	44
2.6.1.3	Mobile Microrobots .....	45
2.6.1.4	Sensors.....	46
2.6.1.5	Control Architecture .....	47
2.6.1.6	User Interface.....	48
2.6.2	Experimental Setup: Handling of TEM Lamellae .....	49
2.7	Conclusions.....	52
2.8	References.....	54
<b>3</b>	<b>Learning Controller for Microrobots .....</b>	<b>57</b>
3.1	Introduction.....	57
3.1.1	Control of Mobile Microrobots .....	57
3.1.2	Self-organizing Map as Inverse Model Controller .....	58
3.2	Closed-loop Pose Control .....	62
3.2.1	Pose and Velocity .....	62
3.2.2	Trajectory Controller .....	63
3.2.3	Motion Controller.....	64
3.2.4	Actuator Controller.....	65
3.2.5	Flexible Timing During Pose Control .....	65
3.3	The SOLIM Approach .....	66
3.3.1	Structure and Principle .....	66
3.3.2	Mapping .....	68
3.3.2.1	Interpolation.....	69
3.3.2.2	Influence Limits .....	72
3.3.2.3	Extrapolation.....	74
3.3.3	Learning .....	76
3.3.3.1	Approximation .....	76
3.3.3.2	Self-organization in Output Space .....	78
3.3.3.3	Self-organization in Input Space.....	82
3.3.4	Conclusions .....	83
3.4	SOLIM in Simulations.....	83
3.4.1	Mapping .....	83
3.4.2	Learning .....	85
3.4.2.1	Procedure .....	85
3.4.2.2	Inverse Kinematics.....	87
3.5	SOLIM as Actuator Controller .....	89
3.5.1	Actuation Control .....	89
3.5.2	Manual Training .....	91
3.5.3	Automatic Training .....	93
3.6	Conclusions.....	96
3.6.1	Summary .....	96
3.6.2	Outlook.....	97
3.6.2.1	Extrapolation.....	97
3.6.2.2	Computational Load.....	97
3.6.2.3	Predefined Network Size .....	98
3.6.2.4	Applications for SOLIM .....	98
3.7	References.....	99

<b>4 Real-time Object Tracking Inside an SEM .....</b>	103
4.1 Introduction.....	103
4.2 The SEM as Sensor.....	104
4.3 Integration of the SEM .....	106
4.4 Cross-correlation-based Tracking.....	107
4.5 Region-based Object Tracking .....	111
4.5.1 The Energy Functions.....	111
4.5.2 Fast Implementation .....	114
4.5.3 Minimization .....	116
4.5.4 Evaluation and Results .....	119
4.5.4.1 Performance .....	119
4.5.4.2 Robustness Against Additive Noise.....	120
4.5.4.3 Robustness Against Clutter.....	121
4.5.4.4 Robustness Against Gray-level Fluctuations .....	123
4.6 Conclusions.....	124
4.6.1 Summary .....	124
4.6.2 Outlook .....	126
4.7 References .....	126
<b>5 3D Imaging System for SEM .....</b>	129
5.1 Introduction.....	129
5.2 Basic Concepts.....	130
5.2.1 General Stereoscopic Image Approach.....	130
5.2.1.1 The Cyclopean View.....	131
5.2.1.2 Disparity Space .....	131
5.2.1.3 Vergence and Version.....	132
5.2.1.4 Vergence System .....	134
5.2.2 Principle of Stereoscopic Image Approaches in the SEM .....	135
5.2.2.1 Structure of the SEM .....	135
5.2.2.2 Generation of Stereoscopic Images in the SEM.....	136
5.2.2.3 Influences on the Disparity Space.....	138
5.2.3 Mathematical Basics.....	139
5.2.3.1 Convolution .....	139
5.2.3.2 Frequency Analysis.....	139
5.2.3.3 Gabor Function .....	141
5.2.4 Biological Vision Systems.....	143
5.2.4.1 Neuron Models .....	143
5.2.4.2 Depth Perception in Biological Vision Systems .....	144
5.2.4.3 Energy Models .....	144
5.3 Systems for Depth Detection in the SEM .....	145
5.3.1 Non-stereoscopic Image Approaches .....	146
5.3.2 Stereoscopic Image Approaches.....	147
5.4 3D Imaging System for Nanohandling in an SEM .....	148
5.4.1 Structure of the 3D Imaging System for SEM.....	148
5.4.2 Image Acquisition and Beam Control .....	149
5.4.3 The 3D Module.....	151

5.4.3.1	Stereo System .....	152
5.4.3.2	Vergence System .....	156
5.5	Application of the 3D Imaging System.....	158
5.5.1	Results of the 3D Imaging System .....	158
5.5.2	Application for the Handling of CNTs .....	160
5.5.3	Application for the Handling of Crystals.....	161
5.6	Conclusions.....	161
5.6.1	Summary.....	161
5.6.2	Outlook .....	163
5.7	References .....	163
<b>6</b>	<b>Force Feedback for Nanohandling.....</b>	<b>167</b>
6.1	Introduction.....	167
6.2	Fundamentals of Micro/Nano Force Measurement.....	168
6.2.1	Principles of Force Measurement .....	168
6.2.2	Types of Forces in Robotics .....	170
6.2.2.1	Gripping Forces .....	170
6.2.2.2	Contact Forces .....	172
6.2.3	Characteristics of the Micro- and Nanoworld.....	172
6.2.4	Requirements on Force Feedback for Nanohandling.....	174
6.2.5	Specific Requirements of Force Feedback for Microrobots .....	177
6.3	State-of-the-art.....	178
6.3.1	Micro Force Sensors.....	178
6.3.1.1	Piezoresistive Micro Force Sensors .....	178
6.3.1.2	Piezoelectric Micro Force Sensors.....	180
6.3.1.3	Capacitive Micro Force Sensors .....	180
6.3.1.4	Optical Methods for Micro Force Measurement.....	181
6.3.1.5	Commercial Micro Force Sensors.....	183
6.3.2	Microgrippers with Integrated Micro Force Sensors .....	183
6.3.3	Robot-based Nanohandling Systems with Force Feedback.....	184
6.3.3.1	Industrial Microhandling Robots .....	185
6.3.3.2	Microrobots Outside the Scanning Electron Microscope.....	188
6.3.3.3	Microrobots Inside the Scanning Electron Microscope.....	192
6.3.3.4	Mobile Microrobots .....	193
6.3.4	AFM-based Nanohandling Systems .....	195
6.3.4.1	Commercial and Custom-made AFMs for Nanohandling .....	195
6.3.4.2	AFMs combined with Haptic Devices and Virtual Reality.....	196
6.3.4.3	AFMs integrated into Scanning Electron Microscopes .....	196
6.4	Conclusions.....	197
6.5	References .....	197

<b>7 Characterization and Handling of Carbon Nanotubes.....</b>	203
7.1 Introduction.....	203
7.2 Basics of Carbon Nanotubes.....	204
7.2.1 Structure and Architecture.....	204
7.2.2 Electronic Properties.....	205
7.2.3 Mechanical Properties .....	207
7.2.4 Fabrication Techniques.....	208
7.2.4.1 Production by Arc Discharge.....	208
7.2.4.2 Production by Laser Ablation .....	209
7.2.4.3 Production by Chemical Vapor Deposition (CVD) ....	209
7.2.5 Applications.....	210
7.2.5.1 Composites.....	211
7.2.5.2 Field Emission .....	211
7.2.5.3 Electronics .....	212
7.2.5.4 AFM Cantilever Tips .....	212
7.3 Characterization of CNTs .....	213
7.3.1 Characterization Techniques and Tools.....	213
7.3.1.1 Microscopic Characterization Methods .....	213
7.3.1.2 Spectroscopic Characterization Methods .....	214
7.3.1.3 Diffractioal Characterization Methods.....	215
7.3.2 Advantages of SEM-based Characterization of CNTs .....	215
7.4 Characterization and Handling of CNTs in an SEM.....	216
7.5 AMNS for CNT Handling .....	218
7.5.1 Experimental Setup .....	218
7.5.2 Gripping and Handling of CNTs .....	220
7.5.3 Mechanical Characterization of CNTs .....	221
7.6 Towards Automated Nanohandling of CNTs .....	224
7.6.1 Levels of Automation .....	224
7.6.2 Restrictions on Automated Handling Inside an SEM .....	225
7.6.3 Control System Architecture .....	226
7.6.4 First Implementation Steps .....	230
7.7 Conclusions.....	231
7.8 References .....	232
<b>8 Characterization and Handling of Biological Cells.....</b>	237
8.1 Introduction.....	237
8.2 AFM Basics .....	239
8.2.1 Cantilever Position Measurement.....	239
8.2.1.1 Optical: Laser Beam Deflection.....	240
8.2.1.2 Self-sensing: Piezoelectric and Piezoresistive .....	240
8.2.2 AFM Modes .....	240
8.2.2.1 Contact Mode.....	240
8.2.2.2 Dynamic Mode .....	241
8.2.2.3 Lateral Force Mode.....	242
8.2.2.4 Jumping Mode / Force Volume Mode and Force Distance Curves .....	242
8.2.3 Measurements of Different Characteristics .....	243

8.2.3.1	Mechanical Characterization.....	243
8.2.3.2	Magnetic Force Measurements .....	245
8.2.3.3	Conductivity Measurements .....	245
8.2.3.4	Molecular Recognition Force Measurements .....	246
8.2.4	Sample Preparation.....	247
8.2.5	Cantilevers.....	247
8.2.6	Video Rate AFMs.....	248
8.2.7	Advantages and Disadvantages of AFM for Biohandling .....	248
8.3	Biological Background .....	249
8.3.1	Characteristics of Cells.....	249
8.3.1.1	Mechanical Characteristics .....	249
8.3.1.2	Electrical Characteristics.....	250
8.3.1.3	Chemical Characteristics.....	251
8.3.2	<i>Escherichia Coli</i> Bacterium.....	251
8.3.3	Ion Channels.....	252
8.3.4	Intermolecular Binding Forces .....	253
8.4	AFM in Biology – State-of-the-art .....	254
8.4.1	Imaging.....	254
8.4.2	Physical, Electrical, and Chemical Properties .....	255
8.4.2.1	Elasticity and Stiffness Measurements.....	255
8.4.2.2	Intermolecular Binding Forces.....	256
8.4.2.3	Adhesion Forces .....	256
8.4.2.4	Cell Pressure .....	257
8.4.2.5	Virus Shell Stability .....	257
8.4.2.6	Electrical Properties of DNA .....	257
8.4.3	Cooperation and Manipulation with an AFM .....	258
8.4.3.1	Stimulation and Recording of Mechanosensitive Ion Channels .....	258
8.4.3.2	Cutting and Extraction Processes on Chromosomes ...	258
8.4.4	Additional Cantilever .....	259
8.5	AMNS for Cell Handling.....	259
8.5.1	Experimental Setup .....	259
8.5.2	Control System .....	260
8.5.3	Calculation of the Young's Modulus.....	261
8.5.4	Experimental Results.....	262
8.6	Conclusions.....	263
8.6.1	Summary .....	263
8.6.2	Outlook.....	263
8.7	References.....	264
<b>9</b>	<b>Material Nanotesting .....</b>	<b>267</b>
9.1	Instrumented Indentation .....	267
9.1.1	Sharp Indentation.....	267
9.1.1.1	Introduction.....	267
9.1.1.2	Basic Concepts of Materials Mechanics .....	270
9.1.1.3	Similarity Between Sharp Indenters of Different Shape.....	270

9.1.1.4	Indentation Ranges: Nano-, Micro-, and Macroindentation .....	271
9.1.1.5	Analysis of Load Depth Curves .....	271
9.1.1.6	Applications of the Sharp Instrumented Indentation....	277
9.1.2	Spherical Indentation.....	279
9.1.2.1	Comparing Spherical and Sharp Instrumented Indentation .....	279
9.1.2.2	Analysis of Load Depth Curves Using Spherical Indenters.....	280
9.1.2.3	Applications of Spherical Instrumented Indentation....	281
9.2	Microrobot-based Nanoindentation of Electrically Conductive Adhesives .....	281
9.2.1	Experiments.....	282
9.2.1.1	Material System .....	282
9.2.1.2	Description of the Experimental Setup .....	283
9.2.1.3	The AFM Cantilever .....	285
9.2.1.4	Description of the NMT Module .....	286
9.2.1.5	Experimental Procedure .....	286
9.2.2	Calibrations .....	287
9.2.2.1	Calibration of the Stiffness .....	287
9.2.2.2	Electrical Calibration .....	288
9.2.3	Preliminary Results .....	288
9.2.3.1	Dependency on the Hardness of the ECA on the Curing Time .....	288
9.2.4	Discussion .....	289
9.2.4.1	Different Tip Shapes .....	289
9.3	Conclusions.....	292
9.4	References.....	293
<b>10</b>	<b>Nanostructuring and Nanobonding by EBiD .....</b>	<b>295</b>
10.1	Introduction to EBiD .....	295
10.1.1	History of EBiD.....	297
10.1.2	Applications of EBiD .....	298
10.2	Theory of Deposition Processes in the SEM .....	299
10.2.1	Scanning Electron Microscopy for EBiD .....	299
10.2.1.1	Generation of the Electron Beam.....	299
10.2.1.2	General SEM Setup.....	301
10.2.1.3	Secondary Electron Detector .....	302
10.2.2	Interactions Between Electron Beam and Substrate .....	303
10.2.2.1	Energy Spectrum of Emerging Electrons .....	303
10.2.2.2	Range of Secondary Electrons .....	305
10.2.2.3	Results.....	309
10.2.3	Modeling the EBiD Process .....	310
10.2.3.1	Rate Equation Model .....	310
10.2.3.2	Parameter Determination for the Rate Equation Model.....	312
10.2.3.3	Influence of the SE.....	314

10.2.3.4 Heat Transfer Calculations.....	315
10.3 Gas Injection Systems (GIS).....	316
10.3.1 Introduction .....	316
10.3.2 The Molecular Beam .....	317
10.3.2.1 Modeling of the Mass Flow Between Reservoir and Substrate.....	317
10.4 Mobile GIS .....	322
10.4.1 General Setup .....	322
10.4.2 Position Control of the GIS .....	323
10.4.3 Pressure Control .....	324
10.4.3.1 Constant Evaporation Systems.....	324
10.4.3.2 Heating/Cooling Stages .....	324
10.4.3.3 Control of the Molecular Flux .....	325
10.4.3.4 Pressure Dependence of the Deposition Rate .....	326
10.4.4 Multimaterial Depositions .....	327
10.5 Process Monitoring and Control .....	329
10.5.1 Time-based Control (Open-loop Control) .....	329
10.5.2 Closed-loop Control of EBiD Deposits .....	330
10.5.2.1 Growth of Pin-like Deposits and SE-signal .....	331
10.5.2.2 Application for 2D Deposits .....	332
10.5.3 Failure Detection .....	334
10.6 Mechanical Properties of EBiD Deposits .....	336
10.7 Conclusions.....	336
10.7.1 Summary.....	336
10.7.2 Outlook.....	337
10.7 References .....	338
<b>Index .....</b>	<b>341</b>