

Contents

1	Introduction	1
1.1	3D Acquisition Techniques.....	2
1.1.1	2D Vision.....	3
1.1.2	Stereo Vision.....	4
1.1.3	Time of Flight	5
1.1.4	Laser Triangulation Sensor	6
1.2	Structure of Robot Visual Control System.....	6
1.2.1	Structured-Light Sensor Based Visual Control.....	9
1.2.2	Selection of Industrial Robots.....	9
1.2.3	Applications of Robot Visual Systems	11
1.2.4	Calibration of Robot Visual Systems.....	12
1.2.5	Laser Sensor Based Commercial Robot Visual Systems	14
1.3	Outline of Chapters	15
	References.....	18
2	Characteristics of Laser Structured-Light Sensors.....	21
2.1	Formation of Laser Structured-Light Sensors.....	21
2.1.1	Light Source.....	23
2.1.2	Detector Types.....	26
2.1.3	Triangulation Measurement Principle.....	29
2.2	Accuracy Analysis	31
2.2.1	Effect of Laser Speckle Noise on the Measurement Accuracy	33
2.2.2	Effect of the Environmental Factors on the Measurement Accuracy	35
2.3	Commercial Systems	37
	References.....	39
3	Laser Stripe Sensor Calibration	41
3.1	Modeling of Laser Stripe Sensor and Calibration Strategy.....	41
3.2	Camera Modeling	42
3.2.1	Pinhole Model of the Camera	43

3.2.2	Nonlinear Modeling with Lens Distortion	46
3.3	Calibration of Cameras	47
3.3.1	Calibration with Direct Linear Transform Method	47
3.3.2	Calibration with Tsai's RAC Based Algorithm	51
3.3.3	Calibration with Multiple View Algorithms	54
3.4	Calibration of Laser Stripe Sensor	58
3.4.1	Laser Stripe Plane Calibration with Two Known Planes	62
3.4.2	Laser Stripe Plane Calibration Based on Invariance of Cross Ratios	63
3.4.3	Laser Plane Calibration with a Planar Target	67
3.4.4	Calibration of Dual Laser Stripe Sensor	70
3.4.5	Calibration of the Rotation Table	70
3.4.6	Calibration of the Laser Stripe Sensor with Robot Alignment	72
3.4.7	Laser Scanner Calibration with Direct Coordinate Mapping	74
3.4.8	Calibration of Laser Stripe Sensor with Scheimpflug Configuration	77
3.5	Conclusion and Remarks	89
	References	89
4	Calibration of a Robot Visual System	93
4.1	General Solution of Robot Tool Calibration	94
4.1.1	Calibration Target with Geometry Constraint: Point	100
4.1.2	Calibration Target with Geometry Constraint: Line	102
4.1.3	Calibration Target with Geometry Constraint: Sphere	104
4.1.4	Calibration Target with Geometry Constraint: Plane	105
4.2	TCP Calibration for a Point Laser	109
4.2.1	Algorithms	109
4.2.2	Calibration of Laser Beam Orientation (n_x, n_y, n_z)	110
4.2.3	Calibration of Laser Sensor Position (x_0, y_0, z_0)	111
4.2.4	Experimental Results	112
4.3	TCP Calibration for Cameras	113
4.3.1	Camera Pose Calibration with Linear Equations	114
4.3.2	Camera Pose Calibration with Nonlinear Optimizations	116
4.4	TCP Calibration for 3D Laser Scanner	117
4.4.1	TCP Calibration with a Sphere	117
4.4.2	TCP Calibration with a Plane	121
4.4.3	TCP Calibration with a Structure Pattern	124
4.5	TCP Calibration with Direct Measurement	128
4.5.1	Calibration of Spindle	129
4.5.2	Calibration of Tools with Different Length	130
4.6	Relative Robot Workcell Calibration	130
4.6.1	Robot Workcell Calibration	131
4.6.2	Robot Error Compensation with Relative Measurement	136

4.7	Summary	139
	References	139
5	Image Processing of Laser Structured-Light Based Vision System	143
5.1	Control Point Extraction from Pattern Images	143
5.1.1	Feature Extraction from Squared Control Points	144
5.1.2	Feature Extraction from Circle Control Points	147
5.2	Laser Stripe Sub-Pixel Positioning	152
5.2.1	Thinning and Pruning Algorithm	152
5.2.2	Gray Scale Gravity Center Algorithm	156
5.3	Range Image Registration with the ICP Algorithm	158
5.3.1	Determination of Corresponding Points	159
5.3.2	Calculation of Transformation Matrix	160
	References	163
6	Robot Kinematic Calibration	165
6.1	Background	165
6.2	Model Function of Robots	167
6.3	Determination of Independent Error Parameters Using SVD Method	169
6.4	Error Budget Analysis	170
6.5	Solving the Error Parameters	171
6.6	Circle Fitting Based Calibration	171
6.7	TAU Parallel Robot Calibration	174
6.7.1	Kinematic Modeling	175
6.7.2	Jacobian Matrix of TAU Robot with All Error Parameters ...	178
6.7.3	Kinematic Modeling with all Error Parameters	184
6.7.4	Determination of Independent Design Variables	185
6.7.5	Error Budget Analysis	186
6.7.6	Simulation Results	188
6.7.7	Experimental Results	188
	References	190
7	Visual Sensing and Control-Laser Sensor Based Robot Applications ...	193
7.1	Automatic Inspection of Holes in 3D Space	194
7.1.1	Introduction	194
7.1.2	System Overview	195
7.1.3	System Calibrations	196
7.1.4	Inspection Procedure	200
7.1.5	Experimental Results and Conclusion	202
7.2	Robotic Grinding System of Free-Form Workpieces	203
7.2.1	Introduction	204
7.2.2	Offline Programming	205
7.2.3	Workpiece Calibration	206
7.2.4	Robotic System Error Compensation	207

7.2.5	Experimental System	210
7.2.6	Conclusion and Remarks	212
7.3	Robot Remanufacturing of Blade Tip Refurbishment	212
7.3.1	Introduction.....	212
7.3.2	Profile Modeling Based Grinding.....	214
7.3.3	Experimental Setup.....	216
7.3.4	Conclusion and Future Work	218
7.4	Robotic Materials Handling System for Complex Parts	218
7.4.1	System Overview.....	218
7.4.2	Approximately Locating Workpieces	219
7.4.3	Precisely Locating Workpieces.....	220
7.4.4	Another Example	222
7.4.5	Summary and Remarks	223
7.5	Robot Machining System with Visual Feedback	223
7.5.1	Introduction.....	223
7.5.2	System Overview.....	224
7.5.3	Scanning and Edge Detection	225
7.5.4	Path Smoothing Based on the B-Spline	226
7.5.5	Other Examples.....	227
7.5.6	Summary and Remarks	229
7.6	Robotic Measurement and Inspection System for Quality Control.....	229
7.6.1	System Overview.....	229
7.6.2	Pick-up Error Compensation.....	230
7.6.3	Feature Based Workpiece Locationing	232
7.6.4	Point Cloud Comparison.....	232
7.6.5	Summary and Remarks	233
7.7	Robot Weld System with Seam Tracking Sensors.....	233
7.7.1	System Overview.....	234
7.7.2	Welding Joint Detection	234
7.7.3	Path Generation.....	235
7.7.4	Computer-Robot Communication.....	236
7.7.5	A Robotic Tube Panel Weld System.....	237
7.7.6	Summary and Remarks	239
7.8	Robotic Pick and Place System with Point Lasers.....	239
7.8.1	Robot Logs Pick and Center System.....	239
7.8.2	Robot Solar Panel Installation System.....	243
7.8.3	Summary and Remarks	245
	References.....	246
	Appendix	249
	Index	255