

# Contents

<b>List of figures</b>	<b>iv</b>
<b>List of tables</b>	<b>vii</b>
<b>Agraiments</b>	<b>1</b>
<b>Resum</b>	<b>5</b>
<b>Abstract</b>	<b>6</b>
<b>1 Introduction</b>	<b>7</b>
1.1 Introduction to 3D metrology . . . . .	7
1.2 Context and motivation . . . . .	14
1.3 Objectives . . . . .	14
1.4 Thesis outline . . . . .	16
<b>2 Triangulation 3D laser scanners</b>	<b>19</b>
2.1 Introduction . . . . .	19
2.2 The principle of triangulation . . . . .	20
2.3 Proposed classification . . . . .	23
2.4 Systems and methods for shape acquisition . . . . .	31
2.4.1 Pose measurement . . . . .	32
2.4.2 Projective approach . . . . .	34
2.4.3 Euclidean approach . . . . .	38
2.4.4 Time multiplexing. Switching the laser slit . . . . .	43
2.4.5 Lookup Table generation . . . . .	46
<b>3 Laser peak detection</b>	<b>49</b>
3.1 Introduction . . . . .	49
3.2 Scanning different surfaces . . . . .	50
3.3 Noise sources . . . . .	50
3.4 A new method for peak detection . . . . .	53

3.5	Summary . . . . .	54
<b>4</b>	<b>Calibration with the Complete Quadrangle</b>	<b>57</b>
4.1	Introduction . . . . .	57
4.2	Projective geometry . . . . .	58
4.2.1	Homogeneous coordinates . . . . .	59
4.2.2	The cross-ratio . . . . .	61
4.2.3	The complete quadrangle . . . . .	61
4.3	Parameter estimation . . . . .	62
4.4	Previous work . . . . .	66
4.5	A new method for obtaining point correspondences . . . . .	68
4.5.1	Points on the upper and lower edges . . . . .	68
4.5.2	Points on the laser stripe . . . . .	70
4.5.3	Validation . . . . .	70
4.6	Calibration . . . . .	72
4.7	Summary . . . . .	75
<b>5</b>	<b>Experimental results</b>	<b>77</b>
5.1	Test bench . . . . .	77
5.2	Experiments with the peak detector . . . . .	78
5.3	Experiments with the scanner calibration . . . . .	85
5.4	Qualitative results . . . . .	85
5.5	Summary . . . . .	88
<b>6</b>	<b>Conclusion</b>	<b>97</b>
6.1	Contributions . . . . .	97
6.2	Conclusions . . . . .	98
6.2.1	Survey of triangulation laser devices . . . . .	98
6.2.2	Applications . . . . .	99
6.2.3	Peak detector . . . . .	99
6.2.4	Calibration method . . . . .	100
6.3	Future work . . . . .	100
6.3.1	Peak optimisation . . . . .	101
6.3.2	Improvement of parameter estimation . . . . .	101
6.3.3	kaka . . . . .	102
6.4	Related publications . . . . .	102
6.4.1	Journals . . . . .	102
6.4.2	Conferences . . . . .	103

<b>A Applications</b>	<b>105</b>
A.1 The Chen & Kak system . . . . .	105
A.2 Smart sensors. Yet another approach . . . . .	110
A.2.1 Slit detection . . . . .	110
A.2.2 Calibration procedure . . . . .	110
A.2.3 Noise evaluation . . . . .	119
A.2.4 Simulation results . . . . .	122
A.3 An attempt to Underwater Range Sensing . . . . .	122
A.3.1 Introduction . . . . .	122
A.3.2 The Underwater Robot . . . . .	125
A.3.3 The use of light underwater: Scattering and Absorption	126
A.3.4 The Range Imaging System . . . . .	126
A.3.5 Experimental Results . . . . .	131
<b>B Notation</b>	<b>133</b>
B.1 Mathematics Convention . . . . .	133
<b>References</b>	<b>135</b>



# List of Figures

1.1	Concentration of light transducers on the retina. . . . .	9
1.2	Cones and Rods present on the retina. . . . .	10
1.3	Side section of a human eye. . . . .	11
1.4	Interconnections in the vision system. Sub-cortical areas: LGN, Lateral Geniculate Nucleus; SupCol, Superior Colliculus; Pulv, Pulvinar nucleus. Cortical areas: MT, Middle Temporal; MST, Middle Superior Temporal; PO, Parieto-occipital; VIP, LIP, MIP, AIP, Ventral, Lateral, Medial and Anterior intraparietal respectively; STS, Superior Temporal Sulcus. . . . .	12
1.5	A text as seen with a foveal vision sensor. . . . .	12
1.6	The basic 3D laser scanner. . . . .	13
2.1	Triangulation principle using 2 cameras. . . . .	21
2.2	Laser scanner system with scanning light source. . . . .	22
2.3	3D reconstruction by triangulation using a laser plane and a camera. . . . .	23
2.4	A stereo rig with only one camera and a laser stripe. . . . .	33
2.5	Centroid Computation Strategy in Oike et.al. . . . .	34
2.6	The system arrangement of Chen & Kak. . . . .	36
2.7	Elements of two dimensional projectivity. . . . .	37
2.8	Oxford/NEL range-finder scheme. . . . .	38
2.9	Low cost <i>wand</i> scanner. . . . .	41
2.10	Low cost <i>wand</i> slit scanner. . . . .	42
2.11	Calibration-free 3D laser scanner. . . . .	43
2.12	Space-encoding method. . . . .	44
2.13	Yu et al. digitiser geometric parameters. . . . .	45
2.14	Change on the slit ray projection axis. . . . .	47
2.15	Line of sight computation in Gruss et al. . . . .	48
2.16	Calibration target used in Gruss et al. . . . .	48

3.1	Behaviour of light reflected on a specular surface (a), and a lambertian surface (b). . . . .	51
3.2	Behaviour of light reflected on a lambertian surface. . . . .	52
3.3	A laser stripe on a translucent (left) and a lambertian (right) surface. . . . .	53
3.4	Laser peak and first derivative. . . . .	55
4.1	The Last Supper, by Leonardo da Vinci . . . . .	60
4.2	Cross-ratio of a pencil of lines . . . . .	62
4.3	The complete quadrangle . . . . .	63
4.4	Total Least Squares and Algebraic Least Squares examples . .	64
4.5	Geometric scheme of Chen & Kak's method. . . . .	67
4.6	The cross-ratio and the complete quadrangle. . . . .	69
4.7	The laser plane defined by upper and lower points (a) and Point generation (b). . . . .	71
4.8	Plots of the values of ${}^W T_I$ and the lines fitted. . . . .	74
5.1	A picture of the test bench (a) and the lab scanner. . . . .	79
5.2	Peak estimation with the 6 methods, SN=0.92dB. . . . .	82
5.3	Effect of peak detection on a lambertian (up) and translucent (down) surface. Using <b>PM</b> . . . . .	83
5.4	Effect of peak detection on a lambertian (up) and translucent (down) surface. Using <b>BR</b> . . . . .	84
5.5	Effect of peak detection on a lambertian (up) and translucent (down) surface. Using <b>CM</b> . . . . .	84
5.6	Errors in the reconstruction of the calibration planes using (a) TLS and (b) FNS methods. . . . .	86
5.7	Reconstruction of a cylinder (a). . . . .	87
5.8	A dense cloud of points of a bust of Wagner. . . . .	89
5.9	The bust of Wagner: interpolated surface (a), the extracted profile (b) and its picture (c). . . . .	90
5.10	A laughing sun: interpolated surface (a), the extracted profile (b) and its picture (c). . . . .	91
5.11	A meditative samurai: interpolated surface (a), the extracted profile (b) and (c) its picture. . . . .	92
5.12	The bust of a horse: Interpolated surface (a) and its picture (b). . . . .	93
5.13	Reconstruction of a translucent surface with letters carved on it (a) and its picture (b). . . . .	94
5.14	Reconstruction of a portion of human tissue. . . . .	95
A.1	Co-ordinate frames for Chen & Kak system simulation. . . . .	106

A.2 Reconstruction errors as a function of range. . . . . 107  
A.3 Reconstruction of a plane at  $W_z=0$ . . . . . 108  
A.4 Reconstruction of a plane at  $W_z=110$ . . . . . 109  
A.5 Co-ordinate frames for Smart Sensor-based system simulation. 111  
A.6 Detection of laser slit by voltage comparison. . . . . 111  
A.7 One row in common cathode. . . . . 112  
A.8 Detection circuit. . . . . 112  
A.9 Intersection between a line-of-sight and the laser plane. . . . . 118  
A.10 The underwater robot GARBÍ. . . . . 125  
A.11 Laser system with the 8 parameters describing its model. . . . . 129





# List of Tables

2.1	Classification of three-dimensional digitiser systems. . . . .	24
4.1	Fit of a plane equation to each of the laser plane positions. . .	72
5.1	Estimator formulae. The $\hat{\delta}$ stand for the subpixel offset. The a,b and c stand for the 3 consecutive pixels of the peak, where b is the maximum in intensity value. The $x_o, y_0, x_1, y_1$ of <i>PM</i> are the coordinates of two points to which a line is fitted, as explained in chapter 3. . . . .	81
5.2	Values of $\sigma$ estimating the peak using the 6 methods with 4 S/N levels. . . . .	81
5.3	Mean value and $\sigma$ , estimating the peak on two types of material under different light power conditions (S/N values in dB). . . . .	83
5.4	Reconstructed diameter of the fitted cylinder with different noise levels. . . . .	87
A.1	Performance of the Chen and Kak scanner. . . . .	108
A.2	The three main electrical noise sources under consideration. .	120
A.3	Performance evaluation in terms of the S/N. . . . .	121
A.4	Metric errors due to electric noise. . . . .	122
A.5	Metric errors due to quantisation. . . . .	123
A.6	Metric errors due to both quantisation and electric noise. . . .	123