
Contents

Preface	xiii
List of abbreviations	xix
Symbols	xxi
Typographical conventions	xxv
Acknowledgements	xxvii
1 Introduction	1
1.1 The intelligent motion measuring sensor	2
1.1.1 Inputs and outputs	2
1.1.2 Real-time motion estimation	3
1.1.3 The motion estimation algorithm	5
1.1.4 The prototype sensor	7
PART 1 – BACKGROUND	9
2 Mathematical preliminaries	11
2.1 Basic concepts in probability	11
2.1.1 Experiments and trials	12
2.1.2 Sample space and outcome	12
2.1.3 Event	12
2.1.4 Computation of probability	13
2.1.5 Conditional probability	13
2.1.6 Total probability	14
2.1.7 Complement	14
2.1.8 OR	14
2.1.9 AND	15
2.1.10 Independent events	16

2.1.11	Bayes theorem	16
2.1.12	Order statistics	16
2.1.13	Random variable	16
2.1.14	Probability Density Function (PDF)	17
2.1.15	Cumulative Distribution Function (CDF)	17
2.1.16	Joint distribution functions	18
2.1.17	Marginal distribution function	19
2.1.18	Independent, identically distributed (iid)	19
2.1.19	Gaussian distribution and the central limit theorem	19
2.1.20	Random or stochastic processes	19
2.1.21	Stationary processes	20
2.1.22	Average	21
2.1.23	Variance	21
2.1.24	Expectation	22
2.1.25	Likelihood	22
2.2	Simple estimation problems	23
2.2.1	Linear regression	23
2.2.2	Solving linear regression problems	26
2.2.3	The Hough transform	27
2.2.4	Solving Hough transform problems	28
2.2.5	Multiple linear regression and regularisation	29
2.2.6	Solving the membrane model	33
2.2.7	Location estimates	39
2.2.8	Solving location estimation problems	40
2.2.9	Properties of simple estimators	42
2.3	Robust estimation	43
2.3.1	Outliers and leverage points	43
2.3.2	Properties of robust estimators	47
2.3.3	Some robust estimators	50
3	Motion estimation	63
3.1	The motion estimation problem	64
3.2	Visual motion estimation	65
3.2.1	Brightness constancy	66
3.2.2	Background subtraction and surveillance	69
3.2.3	Gradient based motion estimation	69
3.2.4	Displaced frame difference	76
3.2.5	Variations of the OFCE	79
3.2.6	Token based motion estimation	81
3.2.7	Frequency domain motion estimation	85
3.2.8	Multiple motions	87
3.3	Temporal integration	95
3.4	Alternate motion estimation techniques	96
3.5	Motion estimation hardware	98
3.6	Proposed motion sensor	100

PART 2 – ALGORITHM DEVELOPMENT	101
4 Real-time motion processing	103
4.1 Frequency domain analysis of image motion	103
4.2 Rigid body motion and the pinhole camera model	106
4.3 Linking temporal aliasing to the safety margin	109
4.4 Scale space	111
4.5 Dynamic scale space	113
4.6 Issues surrounding a dynamic scale space	114
5 Motion estimation for autonomous navigation	117
5.1 Assumptions, requirements and principles	117
5.1.1 Application	118
5.1.2 Data sources	118
5.1.3 Motion	121
5.1.4 Environment	123
5.2 The motion estimation algorithm	124
5.2.1 Inputs and outputs	124
5.2.2 Constraint equation	125
5.2.3 Derivative estimation – practicalities	126
5.2.4 Effect of illumination change	131
5.2.5 Robust average	132
5.2.6 Comparing our robust average to other techniques	137
5.2.7 Monte Carlo study of the LTSV estimator	146
5.2.8 Computational complexity	153
5.2.9 Dynamic scale space implementation	153
5.2.10 Temporal integration implementation	154
5.2.11 The motion estimation algorithm	156
5.2.12 Simulation results	156
5.3 Navigation using the motion estimate	164
PART 3 – HARDWARE	171
6 Digital design	173
6.1 What is an FPGA?	174
6.2 How do I specify what my FPGA does?	174
6.3 The FPGA design process in a nutshell	175
6.4 Time	177
6.5 Our design approach	178
6.6 Introducing VHDL	178
6.6.1 VHDL entities and architectures	179
6.6.2 VHDL types and libraries	182
6.6.3 Concurrent and sequential statements	190
6.6.4 Inference	199
6.7 Timing constraints	201

6.8	General design tips	204
6.8.1	Synchronisation and metastability	204
6.8.2	Limit nesting of <code>if</code> statements	206
6.8.3	Tristate buffers for large multiplexers	206
6.8.4	Tristate buffers	206
6.8.5	Don't gate clocks	207
6.8.6	Register outputs for all blocks	208
6.8.7	Counters	208
6.8.8	Special features	208
6.8.9	Sequential pipelining	208
6.8.10	Use of hierarchy	208
6.8.11	Parentheses	210
6.8.12	Bit width	210
6.8.13	Initialisation	211
6.8.14	Propagation delay	211
6.9	Graphical design entry	211
6.9.1	State machines	212
6.9.2	A more complex design	221
6.10	Applying our design method	230
7	Sensor implementation	231
7.1	Components	232
7.1.1	Image sensor	232
7.1.2	Range sensor	234
7.1.3	Processing platform	236
7.1.4	PC	236
7.2	FPGA system design	237
7.2.1	Boot process	238
7.2.2	Order of operations	239
7.2.3	Memory management	240
7.2.4	RAMIC	244
7.2.5	Buffers	250
7.2.6	Data paths	253
7.3	Experimental results	270
7.3.1	Experimental setup	270
7.3.2	Aligning the camera and range sensors	270
7.3.3	Stationary camera	273
7.3.4	Moving camera – effect of barrel distortion	273
7.3.5	Moving camera – elimination of barrel distortion	276
7.3.6	Moving camera – image noise	276
7.3.7	Moving camera – noise motion and high velocities	277
7.4	Implementation statistics	277
7.5	Where to from here?	278
7.5.1	Dynamic scale space	278
7.5.2	Extending the LTSV estimator	280

7.5.3	Temporal integration	280
7.5.4	Trimming versus Winsorising	281
7.5.5	Rough ground	281
7.5.6	Extending the hardware	281
PART 4 – APPENDICES		283
A	System timing	285
A.1	Timing for a 512×32 pixel image	286
A.2	Control flow for a 512×32 pixel image	287
A.3	Timing for a 32×32 pixel image	288
A.4	Control flow for a 32×32 pixel image	289
A.5	Legend for timing diagrams	290
A.5.1	Note 1: image data clobbering	294
A.5.2	Note 2: the use of n in the timing diagram	295
A.5.3	Note 3: scale space change over process	295
A.5.4	Note 4: the first frame	295
B	SDRAM timing	297
B.1	Powerup sequence	297
B.2	Read cycle	298
B.3	Write cycle	298
C	FPGA design	301
C.1	Summary of design components	301
C.2	Top level schematic	306
C.3	RAMIC	307
C.4	Buffers	318
	C.4.1 Camera data path	333
C.5	Laser and PC data paths	340
C.6	Processing	344
C.7	Miscellaneous components	360
C.8	User constraints file	368
D	Simulation of range data	377
Bibliography		395
Index		417