

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Design of an FPGA-Based Smart Camera and its Application Towards Object Tracking

A thesis presented in partial fulfilment of the requirements for the degree of

**Master of Engineering
in
Electronics and Computer Engineering**

at Massey University, Manawatu, New Zealand

Miguel Contreras

2016

Abstract

Smart cameras and hardware image processing are not new concepts, yet despite the fact both have existed several decades, not much literature has been presented on the design and development process of hardware based smart cameras. This thesis will examine and demonstrate the principles needed to develop a smart camera on hardware, based on the experiences from developing an FPGA-based smart camera. The smart camera is applied on a Terasic DE0 FPGA development board, using Terasic's 5 megapixel GPIO camera. The algorithm operates at 120 frames per second at a resolution of 640x480 by utilising a modular streaming approach. Two case studies will be explored in order to demonstrate the development techniques established in this thesis.

The first case study will develop the global vision system for a robot soccer implementation. The algorithm will identify and calculate the positions and orientations of each robot and the ball. Like many robot soccer implementations each robot has colour patches on top to identify each robot and aid finding its orientation. The ball is comprised of a single solid colour that is completely distinct from the colour patches. Due to the presence of uneven light levels a YUV-like colour space labelled YC_1C_2 is used in order to make the colour values more light invariant. The colours are then classified using a connected components algorithm to segment the colour patches. The shapes of the classified patches are then used to identify the individual robots, and a CORDIC function is used to calculate the orientation.

The second case study will investigate an improved colour segmentation design. A new HSY colour space is developed by remapping the Cartesian coordinate system from the YC_1C_2 to a polar coordinate system. This provides improved colour segmentation results by allowing for variations in colour value caused by uneven light patterns and changing light levels.

Acknowledgments

I would like to thank my supervisors, Donald Bailey and Gourab Sen Gupta, for all their support throughout this thesis. I am grateful to Donald, for being the driving force that always pushed me to go the extra mile and achieve more. I am thankful to Sen for always being a friendly person to talk to and for his helpful advice.

I would like to thank my mum Lindy Lockett, my dad Raul Contreras, my stepdad Maurice Sackett, and my brother Ben Contreras, for their unconditional love and support throughout this thesis. As teachers, Mum and Dad always put an emphasis on education and our happiness, and worked tirelessly to ensure we had both. I am eternally grateful for my Mum, Dad, stepdad, and brother, for keeping me grounded through the good times and focused through the rest. Thank you Dad and Pop (my grandfather, Alan Lockett) for being the beacons that guided me towards, and inspired, my love of engineering.

I would also like to thank all the friends and neighbours who have supported me from the start with their time, advice, proof reading and listening ears. Special thanks to Sam Corpe, for his support and company through the many long days and late nights at Massey.

Publications

- 1) D. Bailey, G. Sen Gupta, and M. Contreras, "Intelligent Camera for Object Identification and Tracking," in *Robot Intelligence Technology and Applications 2012*. vol. 208, ed: Springer International Publishing, 2012, pp. 1003-1013.
- 2) M. Contreras, D. Bailey, and G. Sen Gupta, "FPGA Implementation of Global Vision for Robot Soccer as a Smart Camera," in *Robot Intelligence Technology and Applications 2013*. vol. 274, ed: Springer International Publishing, 2013, pp. 657-665.
- 3) M. Contreras, D. Bailey, and G. Sen Gupta, "Techniques for Designing an FPGA-Based Intelligent Camera for Robots," in *Robot Intelligence Technology and Applications 2014*. vol. 345, ed: Springer International Publishing, 2014, pp. 633-646.
- 4) M. Contreras, D. Bailey, and G. Sen Gupta, "Robot Identification using Shape Features on an FPGA-Based Smart Camera," in *29th International Conference on Image and Vision Computing New Zealand (IVCNZ '14)*, Hamilton, New Zealand, 2014, pp. 282-287.
- 5) D. Bailey, M. Contreras, and G. Sen Gupta, "Towards automatic colour segmentation for robot soccer," in *6th International Conference on Automation, Robotics and Applications (ICARA '15)*, Queenstown, New Zealand, 2015, pp. 478-483.
- 6) D. Bailey, M. Contreras, and G. Sen Gupta, "Bayer interpolation with skip mode," in *Irish Machine Vision and Image Processing (IMVIP '15)*, Dublin, Ireland, 2015, pp. 67-74.

Table of Contents

Abstract.....	i
Acknowledgments.....	ii
Publications.....	iii
Table of Contents.....	iv
List of Figures.....	vii
List of Tables.....	x
Chapter 1 Introduction.....	1
1.1. Introduction.....	1
1.2. What is a Smart Camera?.....	2
1.3. Why use an FPGA?.....	3
1.4. Issues with Smart Camera Design.....	4
1.5. Goals.....	7
1.6. Overview.....	7
Chapter 2 Smart Camera Design.....	9
2.1. Introduction.....	9
2.2. Current Research.....	9
2.3. Development and Testing Scheme.....	11
2.4. Hardware Design Principles.....	14
2.4.1. Programming Languages.....	14
2.4.2. Modularity.....	15
2.4.3. Parameterisation.....	16
2.4.4. Stream Processing.....	16
2.4.5. Pipelining.....	17
2.5. Module Design.....	18
2.5.1. Synchronous Design.....	18
2.5.2. Asynchronous Design.....	20
2.6. Summary.....	22
Chapter 3 Case Study 1: Robot Soccer.....	23
3.1. Introduction.....	23
3.2. Context.....	23
3.3. Robot Soccer.....	25

3.3.1. Review of Algorithms.....	26
3.3.2. Review of Smart Camera Architecture	29
3.4. Design Specifications	30
3.5. Hardware	31
3.5.1. FPGA	31
3.5.2. Camera.....	31
3.6. Smart Camera Architecture	36
3.7. Communication	40
3.7.1. RS-232.....	40
3.8. Algorithm Overview.....	42
3.9. Bayer Demosaicing Filter	44
3.10. Edge Enhancement Filter.....	49
3.11. Colour Space Conversion	52
3.12. Colour Thresholding	54
3.13. Noise Suppression Filter	56
3.14. Connected Component Analysis.....	60
3.15. Centre of Gravity	72
3.16. Robot Association.....	73
3.17. Robot Recognition	80
3.18. Orientation and Position	87
3.19. Camera Performance.....	91
3.19.1. Area	93
3.19.2. Centre of Gravity	94
3.19.3. Robot Association and Recognition.....	95
3.19.4. Robot Orientation.....	96
3.19.5. Robot Soccer Algorithm.....	98
3.20. Conclusion	98
Chapter 4 Case Study 2: Improved Colour Segmentation	100
4.1. Introduction.....	100
4.2. Context	100
4.3. Algorithm Overview.....	101
4.4. Colour Correction & Exposure Control	102
4.5. Colour Space	107

4.6. Modified YC_1C_2	110
4.7. Hue Thresholding	112
4.8. Discussion.....	113
4.9. Conclusion.....	118
Chapter 5 Discussion and Conclusion	120
5.1. Discussion.....	120
5.1.1. Development and Testing Scheme	121
5.1.2. Modularity.....	123
5.1.3. Parameterisation.....	125
5.1.4. Stream Processing.....	126
5.1.5. Pipelining.....	126
5.2. Conclusion.....	127
5.3. Future Development	128
5.3.1. Case Study 1: Robot Soccer.....	128
5.3.2. Case Study 2: Improved Colour Segmentation	129
References	131

List of Figures

Figure 1 - Development and testing scheme for an FPGA-based smart camera	11
Figure 2 - Block diagram for a basic image capture architecture on an FPGA	11
Figure 3 - Block diagram demonstrating module connectivity	15
Figure 4 - Basic example of a pipeline algorithm processing a concurrent pixel stream over multiple clock cycles	18
Figure 5 - Black box diagram of a synchronous pipeline design with a 4-stage pipeline	19
Figure 6 - Demonstration of a 3x3 window within a buffered image	19
Figure 7 - Windowed design creating a 3x3 window	20
Figure 8 - Black box diagram of a synchronous window design with a 3x3 window	20
Figure 9 - Black box diagram of an asynchronous FIFO Buffer design	21
Figure 10 - Black box diagram of an asynchronous pipeline design with a 4-stage pipeline	22
Figure 11 - View from the camera in a global vision configuration.....	25
Figure 12 - Quadrilateral robot patch design	25
Figure 13 - Robots with an oblique robot patch design, and the ball	26
Figure 14 - Basic robot soccer image processing algorithm design.....	27
Figure 15 - Terasic DE0 Development Board.....	31
Figure 16 - TRDB-D5M Camera.....	32
Figure 17 - Bayer Pattern.....	33
Figure 18 - Actual physical location of captured pixels	33
Figure 19 - Camera blanking areas (image courtesy of Terasic hardware specifications [42]) ...	34
Figure 20 - Synchronisation signal behaviour (image courtesy of Terasic hardware specifications [42])	34
Figure 21 - Image captured using the TRDB-D5M using the standard lens.....	35
Figure 22 - Raw image captured from camera using DSL213A-670-F2.0 lens and 2x skipping...	36
Figure 23 - Basic smart camera architecture.....	36
Figure 24 - Cross domain architecture using DRAM buffer	38
Figure 25 - Cross domain architecture using FIFO buffer	39
Figure 26 - The architecture for the robot soccer smart camera.....	40
Figure 27 - RS-232 driver black box diagram	41
Figure 28 - Basic module connectivity.....	42
Figure 29 - Overview of the image processing algorithm.....	42
Figure 30 - Notation for pixel channels	44
Figure 31 - Standard 3x3 bilinear interpolation	45
Figure 32 - Closest physical pixels for processing bilinear interpolation, with appropriate weightings by distance	45
Figure 33 - Proposed 4x4 bilinear interpolation using weighted equations to compensate for skipping.....	46
Figure 34 - Pixel weighting based on distance measured (a) pixel centred, (b) block centred, (c) block cornered.....	46
Figure 35 - Proposed bilinear test image with artefact examples.....	47
Figure 36 - Direct implementation block diagram for bilinear Bayer interpolation.....	48
Figure 37 - Optimised design block diagram for bilinear Bayer interpolation	48

Figure 38 - 3x3 edge enhancement filter window	49
Figure 39 - Blurry image from the Bayer Interpolation module	50
Figure 40 - Edge enhancement with a 3x3 window.....	50
Figure 41 - (a) 5x5 filter window, (b) Edge enhancement with a 5x5 window	51
Figure 42 - Block Diagram for Edge Enhancement filter.....	52
Figure 43 - Illustration of the YUV colour space transform (image courtesy of Sen Gupta et al. [36]).....	53
Figure 44 - YC_1C_2 module black box diagram	54
Figure 45 - Block diagram for the YC_1C_2 module.....	54
Figure 46 - Individual colour thresholding logic for YC_1C_2 thresholding	55
Figure 47 - Block diagram of colour thresholding module	55
Figure 48 - (a) 8 bits per pixel labelled image, (b) 12 bits per pixel labelled image	56
Figure 49 - Close up view of noise introduced during labelling	56
Figure 50 - Horizontal and vertical unidirectional filter design for noise suppression.....	57
Figure 51 - 3x3 multidirectional filter design for noise suppression	58
Figure 52 - (left) processed image using unidirectional filters, (right) processed image using multidirectional filter	58
Figure 53 - 5x5 multidirectional filter design for noise suppression	59
Figure 54 - Processed image using 5x5 multidirectional filter.....	59
Figure 55 - (left) Test image, (a) close up of robot from test image, (b) close up of robot after noise filter	60
Figure 56 - Example of a common two-pass connected component labelling algorithm	60
Figure 57 - Block diagram for connected component module	63
Figure 58 - Asynchronous synchronisation signal.....	64
Figure 59 - 2-way and 4-way connectivity windows.....	64
Figure 60 - Diagonal only connections in 4-way window	64
Figure 61 - Connected component analysis window notation	65
Figure 62 - 4-state transition diagram for connectivity logic.....	65
Figure 63 - Simplified 2-state transition diagram for connectivity logic.....	66
Figure 64 - Example of a concave merging error in a single-pass solution.....	66
Figure 65 - Results for statistically gathered label assignment	67
Figure 66 - Dual port read/write data table.....	69
Figure 67 - Dual port RAM data table with dedicated ports.....	69
Figure 68 - Real-time finished component detection example	70
Figure 69 - Small components (noise) within connected component algorithm	70
Figure 70 - Results from the connected component analysis algorithm	71
Figure 71 - Block diagram for centre of gravity module	72
Figure 72 - Robot colour patch layout	73
Figure 73 - Worst-case scenario for robot association	74
Figure 74 - Various scenarios used to test the robot association module. (a, b) Ideal, (c, d) Worst-case	75
Figure 75 - Results of applying the threshold to each image, showing the identified robots within bounding boxes.....	76
Figure 76 - Euclidean distances compared with linear approximations	77

Figure 77 - Block diagram of robot association module.....	78
Figure 78 - State transition diagram for the image processing logic, within the robot association module.....	78
Figure 79 - Robot team and identity patch	80
Figure 80 - Test images for the recognition module	81
Figure 81 - Ambiguous circles and squares, (left) two circles, (right) two squares.....	84
Figure 82 - Block diagram for the recognition module	86
Figure 83 - (a) orientation baseline, (b) orientation offset	88
Figure 84 - Block diagram for CORDIC function.....	89
Figure 85 - Block diagram for orientation processing algorithm.....	90
Figure 86 - Black box diagram for the orientation and position module	90
Figure 87 - (a, b) images from random interval scenario, (c, d) images from sequential scenario	92
Figure 88 - Measured real-world orientations of robots within test scenarios	97
Figure 89 - The susceptibility of YC_1C_2 to global lighting changes	101
Figure 90 - The susceptibility of YC_1C_2 to uneven lighting patterns	101
Figure 91 - Colour correction and exposure control as a pre-processing filter.....	103
Figure 92 - Colour correction and exposure control in-line with the sensor readout	103
Figure 93 - Block diagram for colour correction logic	106
Figure 94 - (left) Un-optimised frame, (centre) Exposure control, (right) Exposure control and colour correction	106
Figure 95 - Averages of different light intensities for a single colour	107
Figure 96 - RGB colour space geometry	108
Figure 97 - HSV colour space geometry.....	108
Figure 98 - Colour pixel distribution in the HSY colour space	109
Figure 99 - HSY module location in robot soccer algorithm.....	110
Figure 100 - Colour pixel distribution using original YC_1C_2 transform (11)	110
Figure 101 - Colour pixel distribution using equation (44).....	111
Figure 102 - Colour pixel distribution using equation (45).....	112
Figure 103 - Hue thresholding limits	112
Figure 104 - Individual colour thresholding logic for HSY thresholding	113
Figure 105 - HSY global lighting improvement	114
Figure 106 - HSY uneven lighting pattern improvement.....	114
Figure 107 - Shape distortion from colour segmentation (example 1)	115
Figure 108 - Shape distortion from colour segmentation (example 2)	115
Figure 109 - Size reduction in low illumination from colour segmentation.....	115
Figure 110 - Colour bleeding introduced by Bayer interpolation.....	116
Figure 111 - Box thresholding image for centre of gravity comparison.....	117

List of Tables

Table 1 - Distance (measured in pixels) between the team patch and correct orientation patch	75
Table 2 - Distance (measured in pixels) between the team patch and incorrect orientation patch (worst-case)	75
Table 3 - Results for complexity descriptors from the test images in Figure 80	83
Table 4 - Results for moment spread descriptors from the test images in Figure 80	84
Table 5 - Results for area descriptors from the test images in Figure 80	85
Table 6 - Results from testing average area normalised recognition method on the FPGA	87
Table 7 - Results for processing only one orientation patch using the same averaging processing pipeline	87
Table 8 - Results for the detected areas for each robot patch within 4 different lighting scenarios	93
Table 9 - Centre of gravity results for X coordinates	94
Table 10 - Centre of gravity results for Y coordinates	94
Table 11 - Results for the robot recognition test (calculated values and colour coded pass or fail)	96
Table 12 - Orientation results for robots extracted by the smart camera. Converted to degrees from FPGA binary values.....	97
Table 13 - Comparison of shape values between hue and box thresholding methods.....	116
Table 14 - Analysis of the centre of gravity results between the hue and box thresholding methods	118