

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.

⊗○○○

# INVESTIGATIVE DEVELOPMENT OF AN ACCESSIBLE LED MATRIX DISPLAY

○○⊗○

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

Master of Engineering in

Mechatronics

○○⊗○

Scott de Jong

2014

○○○⊗

**MASSEY UNIVERSITY**  
**TE KUNENGA KI PŪREHUROA**  

---

**UNIVERSITY OF NEW ZEALAND**



# ABSTRACT

---

Display technology stands central to today's society, with many routine tasks involving at least one type of display. As LCDs replaced CRT monitors, LED-based displays are on course to replace LCDs as the main display technology. LED technology offers advantages across the board: Aside from their inherently greater efficiency, LED technology also brings gains in lifetime, colour gamut, and relatively environmentally friendly manufacturing processes.

While the technology still requires some development before it is to replace LCDs, widespread adoption in applications such as live displays and performances has already begun. This dissertation aims to investigate the foundations the development of LED displays through the development of a prototype implementation. A strong focus is placed on flexibility and accessibility of the design.

The prototype system utilises a simple PC software based video controller, which processes and distributes raw image data to a network of microcontrollers via a USB connection. Each microcontroller module contains circuitry to drive a 16x16 array of SMD RGB LEDs, and is addressable over the integrated I<sup>2</sup>C bus.

This thesis describes the work completed towards the development of this prototype and steps taken to maintain alignment with outlined objectives. Development is broken down into the PC software development, electronics development, and embedded software development of the prototype.



# ACKNOWLEDGEMENTS

---

Johan Potgieter played a large role in ensuring that the project was eventually finished. Without his in-depth understanding of the university's internal systems, I would not have had sufficient time to complete my work. There have been many points at which he could have effortlessly let the project lapse, yet his constant use of hands-off reverse-psychology led me to ultimately complete the project. In the final fragments, Frazer Noble's attention to detail and concision motivated me to trim and tweak the presentation of the content.

Regardless of their limited technical understanding, my parents continually offer support by periodically providing an environment in which the work could be more easily completed. In much the same sense, my girlfriend Chantel Daniels helped me stay task, as well as take time off, where appropriate.

-Scott de Jong



# CONTENTS

---

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Objectives	1
1.2	Thesis overview	2
<b>2</b>	<b>LED Displays</b>	<b>3</b>
2.1	Key Characteristics of Human Vision	3
2.1.1	Structure	3
2.1.2	Colour Perception	4
2.1.3	Effective Resolution	5
2.1.4	Apparent Motion	7
2.1.5	Summary	9
2.2	LED Design Considerations	9
2.2.1	Operation	9
2.2.2	Behaviour	12
2.2.3	Relative Efficiency	14
2.2.4	Driving Circuitry	16
2.2.5	Pulse Width Modulation	17
2.3	LED Display Systems	18
2.3.1	System Layout	19
2.3.2	Control System	22
2.3.3	Panel design	22
2.4	Summary	26
<b>3</b>	<b>Implementation</b>	<b>29</b>
3.1	System overview	29
3.2	PC Application Development	31
3.2.1	Software Design	31
3.2.2	Software implementation	33
3.3	Module Electronics Design	38
3.3.1	LED matrices	38
3.3.2	LED Driving Circuitry	40
3.3.3	Multiplexing Signal	46
3.3.4	Control System	52
3.3.5	Power Requirements	53
3.3.6	Circuit and PCB design	54
3.4	Embedded System Development	72
3.4.1	Development Environment and Licenses	72
3.4.2	Program Layout	75
3.4.3	PC-Controller Communication	77
3.4.4	Controller-Controller Communication	78
3.4.5	LED Driver Control	82
3.4.6	Digital Input/Output Control	86
3.4.7	SRAM Considerations	89
3.4.8	Code Dynamics	91
3.4.9	Gamma Correction	92
3.5	Application Demonstrations	95
3.5.1	Fading Colours	95
3.5.2	Graphic Equaliser Visualisation	98
3.5.3	Optimal Light Output	102



3.6	Summary.....	105
<b>4</b>	<b>Discussion.....</b>	<b>107</b>
4.1	Prototype Evaluation .....	107
4.1.1	Resolution and Frame Rate.....	107
4.1.2	Driving Efficiency .....	108
4.1.3	Communication Reliability and Error Detection.....	108
4.2	Proposed Follow-up Prototype.....	109
<b>5</b>	<b>Conclusion .....</b>	<b>112</b>
<b>6</b>	<b>Works Cited .....</b>	<b>113</b>
<b>Appendix A</b>	<b>TLC5940 Programming.....</b>	<b>115</b>
<b>Appendix B</b>	<b>DIP Prototype Schematic .....</b>	<b>117</b>
<b>Appendix C</b>	<b>Fading Colour Code.....</b>	<b>118</b>
<b>Appendix D</b>	<b>Visual Equaliser Code .....</b>	<b>121</b>

# FIGURES

---

---

Figure 1 - Anatomy of the Human Eye (Chen, Cranton, & Fihn, 2012) .....	4
Figure 2 - Light Sensitivity of the Human Eye (Chen, Cranton, & Fihn, 2012).....	4
Figure 3 - Photoreceptor Concentration in the Human Eye (Chen, Cranton, & Fihn, 2012) .....	5
Figure 4 - Cone Distribution throughout the Fovea.....	6
Figure 5 - Sensitivity of the Eye (Chen, Cranton, & Fihn, 2012), modified .....	7
Figure 6 - Demonstration of the Phi Phenomenon.....	7
Figure 7 - Critical Flicker Frequency of the Human Eye (Chen, Cranton, & Fihn, 2012).....	8
Figure 8 - Bandgap Energy vs. Lattice Constant for various LED Materials (Chen, Cranton, & Fihn, 2012).....	10
Figure 9 - LED Efficiency (Chen, Cranton, & Fihn, 2012).....	11
Figure 10 - LED Emissive Performance vs. Perceptive Performance of the Human Eye (Chen, Cranton, & Fihn, 2012).....	11
Figure 11 - LED Forward Voltage vs. Forward Current of Cree Xlamp Xm-l LEDs (CREE Inc, 2013).....	12
Figure 12 - Relative Luminous Flux vs. Forward Current of Cree Xlamp Xm-l LEDs (CREE Inc, 2013).....	13
Figure 13 - Simplified Representation of the Emission Cone of a LED .....	13
Figure 14 - Relative LED Light Output vs. Junction Temperature (CREE Inc, 2013) .....	14
Figure 15 - Luminous Efficacy of LEDs throughout History (Chen, Cranton, & Fihn, 2012), modified.....	15
Figure 16 - LED Driven Using Current Limiting Resistor.....	16
Figure 17 - Constant Current Source (Day, 2004).....	17
Figure 18 - Effect of Pulse Width Modulation.....	18
Figure 19 - Conventional LED display system.....	19
Figure 20 - LED Display Modularisation .....	19
Figure 21 - LED Display Modularisation .....	20
Figure 22 - Daisy Chaining of LED Panels .....	21
Figure 23 - Parallel Daisy Chains of LED Panels.....	21
Figure 24 - Multiplexing on a 16x16 LED Matrix .....	23
Figure 25 - 4x4 LED matrix .....	24
Figure 26 - Timing diagram for 4x4 monochrome LED matrix.....	24
Figure 27 - Virtual Pixels in LED Displays.....	25
Figure 28 - LED Matrix in Honeycomb Configuration .....	26
Figure 29 - Use of a White Supplementary Emitter (Shlayan, Venkat, Ginobbi, & Mercier, 2008) .....	26
Figure 30 - Simplified LED display system .....	30
Figure 31 - Hardware networking .....	30
Figure 32 - PC software functions .....	31
Figure 33 - Software processing steps.....	32
Figure 34 - Packet layout.....	32
Figure 35 - Application GUI control (left) and preview (right) window .....	36
Figure 36 - Application example.....	38
Figure 37 - LED matrix module dimensions .....	39
Figure 38 - 8x8 common anode RGB LED module layout .....	40
Figure 39 - NI TLC5940 Pin Layout.....	42
Figure 40 - TI TLC5940 Block Diagram.....	43
Figure 41 - Daisy Chaining Two TLC5940 Chips.....	43
Figure 42 - TLC5940 simplified block diagram .....	44
Figure 43 - TLC5940 Current Output Setting .....	45
Figure 44 - TLC5940 Circuit .....	45
Figure 45 - Multiplexing Signal Function.....	46
Figure 46 - CD74ACT164 layout.....	47
Figure 47 - SN74LS138N Functional Diagram .....	47
Figure 48 - Transistors in Darlington Configuration .....	48
Figure 49 - Darlington Array (Texas Instruments, 2006) .....	48
Figure 50 - Propagation Delay.....	49
Figure 51 - TI TLC59213 Darlington Source Driver (Texas Instruments, 2009-2010).....	50
Figure 52 - TLC59213 Source Driver Schematic (Texas Instruments, 2009-2010).....	50
Figure 53 - TLC59213 MAX DIP Current Output (Texas Instruments, 2009-2010) .....	51
Figure 54 - Multiplexing routine.....	51
Figure 55 - Arduino Nano .....	52

Figure 56 - LM2596 Step-down Power Supply .....	53
Figure 57 - LM2596 Circuit .....	54
Figure 58 - Prototype 1 .....	54
Figure 59 - First Full-featured Prototype .....	55
Figure 60 - Final Breadboard Prototype .....	55
Figure 61 - Prototype Board Implementation .....	56
Figure 62 - Part of Initial Schematic .....	57
Figure 63 - LED Module Dimensions .....	58
Figure 64 - Prototype PCB .....	59
Figure 65 - Routed prototype PCB .....	60
Figure 66 - Prototype PCB Assembly 1 .....	60
Figure 67 - Prototype PCB Assembly 2 .....	61
Figure 68 - Prototype PCB Assembly 3 .....	61
Figure 69 - Prototype PCB Assembly 4 .....	62
Figure 70 - TLC5947 Dimensions .....	62
Figure 71 - TLC5947 Pin Layout .....	63
Figure 72 - Controller Board Daisy Chaining .....	64
Figure 73 - LED Module Circuit Design .....	65
Figure 74 - Arduino Nano Pin Positioning .....	66
Figure 75 - LM2596 Module PCB Layout .....	66
Figure 76 - PCB Surface Mount Implementation .....	67
Figure 77 - Module Rotation .....	67
Figure 78 - Normal Multiplexing .....	68
Figure 79 - Multiplexing with Rotational Offset .....	68
Figure 80 - Final Assembly .....	69
Figure 81 - Second Iteration PCB Assembly .....	71
Figure 82 - Arduino IDE .....	73
Figure 83 - Arduino Code Structure .....	74
Figure 84 - Controller Communication .....	75
Figure 85 - Program Flow Chart .....	76
Figure 86 - USB to Serial .....	77
Figure 87 - Serial Peripheral Interface .....	83
Figure 88 - DigitalWrite() Execution Steps .....	86
Figure 89 - Pin Class Layout .....	87
Figure 90 - Simulated Comparison of Gamma Corrected (left), and non-Gamma Corrected (right) Images (Chen, Cranton, & Fihn, 2012) .....	92
Figure 91 - Intensity Perception (Chen, Cranton, & Fihn, 2012) .....	93
Figure 92 - 12-bit Gamma Correction .....	94
Figure 93 - Diagonally Moving Gradients .....	95
Figure 94 - Colour Addresses .....	97
Figure 95 - Fading colours .....	98
Figure 96 - First Visual Equaliser Implementation .....	99
Figure 97 - Audio Processing Steps .....	99
Figure 98 - EQ Colours .....	100
Figure 99 - MSGEQ7 Functional Diagram .....	101
Figure 100 - MSGEQ7 Chip Layout .....	102
Figure 101 - Comparison of Apparent Intensity in Operating Modes .....	104
Figure 102 - Proposed System Layout I .....	110
Figure 103 - Proposed System Layout II .....	111

# ABBREVIATIONS

---

ASIC.....	<i>Application Specific Integrated Circuit</i>
CFF .....	<i>Critical Flicker Frequency</i>
CMOS.....	<i>Complementary Metal-oxide Semiconductor</i>
CRT.....	<i>Cathode Ray Tube</i>
DAC.....	<i>Digital-to-Analogue Converter</i>
DIP.....	<i>Dual In-line Package</i>
FPGA.....	<i>Field Programmable Gate Array</i>
GPL.....	<i>General Public License</i>
GPP.....	<i>General Purpose Processor</i>
GUI.....	<i>Graphical User Interface</i>
I <sup>2</sup> C.....	<i>Two-wire Interface</i>
IDE.....	<i>Integrated Development Environment</i>
ISP.....	<i>In-system Programmer</i>
ISR.....	<i>Interrupt Service Routine</i>
LSB.....	<i>Least Significant Bit</i>
PCB.....	<i>Printed Circuit Board</i>
PWM.....	<i>Pulse Width Modulation</i>
RGB.....	<i>Red Green Blue</i>
SMT.....	<i>Surface Mount Technology</i>
TTL.....	<i>Transistor-transistor Logic</i>
USB.....	<i>Univeral Serial Bus</i>
VA.....	<i>Visual Acuity</i>