Final Technical report

Project Title: University of Nevada Las Vegas LED Display Engineering

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Recipient: Department of Electrical and Computer Engineering
University of Nevada, Las Vegas

Award Number: **DE-FG26-08NT01933**

Cost-Sharing Partners: UNLV, Tecnovision, Milan, Italy

Project Objective:

The primary objective of this part of the project is to develop and implement a method that compensates for the inefficiency of the green LED. The proposed engineering solution which will be the backbone of this project will be to use RGBW combination in every pixel to save energy. Two different RGBW geometrical pixel configurations will be implemented and compared against traditional LED configurations. These configurations will be analyzed for energy efficiency while keeping the quality of the display the same. Cost of the addition of white LEDs to displays along with energy cost savings will be presented and analyzed.

Task 1.0 Develop Photometer System

We have successfully developed and implemented the photometer system. Our new and improved tri-color sensor allows for full and complete testing of LED test bricks.

Even though the system developed was functional, it was of limited use for the heart of project which is presented under Task 3.5 and 4.

Task 2.0: Develop Self-Diagnostic Reconfigurable System

Even though this task was considered important at the start of the project, as the project evolved, it was realized that the project could be done with the proposed system and hence was not pursued.

Task 3.0: Brightness and Grayscale Linearity

Subtask 3.1 & 3.2 & 3.3: LED Display Configuration and Building of the Display Board, hardware and software

We built a 32” x 16” display with pixel spacing of 1” which is usually used for outdoor applications. The pixel consisted of 4 LEDs, red, green, blue and white, placed in a square configuration as shown in Figure 1.

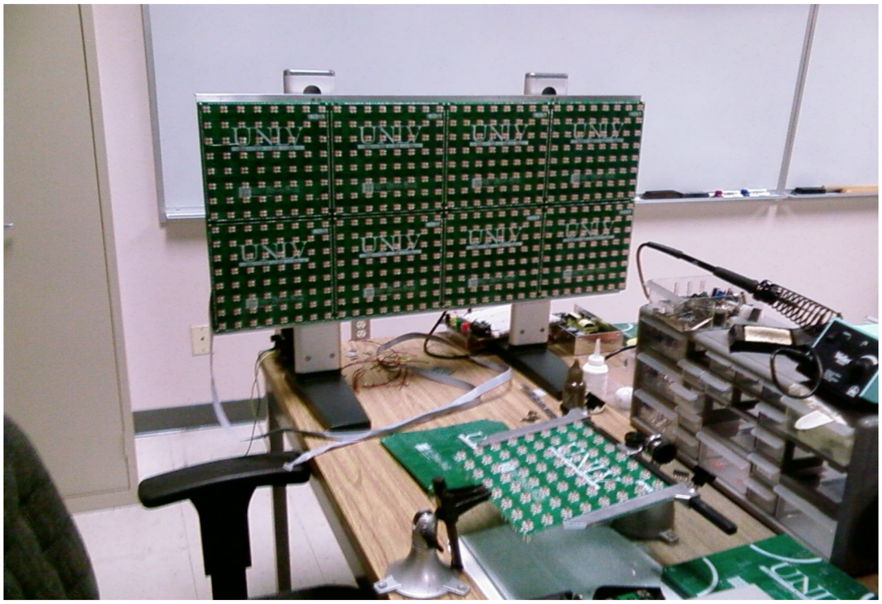

Figure 1 A 32” x 16” display board with RGBW pixels in square configuration

Hardware

To drive the LED display panel, Altera ® DE2 development and education board that is shown in the Figure 2 is used. The DE2 Kit provides several features that need to develop many advanced digital designs using Altera Cyclone Device. The features of DE2 are given in the following:

DE2 Board Information

FPGA

- Cyclone II EP2C35F672C6 with EPCS16 16-Mbit serial configuration device

I/O Interfaces

- Built-in USB-Blaster for FPGA configuration
- Line In/Out, Microphone In (24-bit Audio CODEC)
- Video Out (VGA 10-bit DAC)
- Video In (NTSC/PAL/Multi-format)

- RS232
- Infrared port
- PS/2 mouse or keyboard port
- 10/100 Ethernet
- USB 2.0 (type A and type B)
- Expansion headers (two 40-pin headers)

Memory

- 8 MB SDRAM, 512 KB SRAM, 4 MB Flash
- SD memory card slot

Displays

- Eight 7-segment displays
- 16 x 2 LCD display

Switches and LEDs

- 18 toggle switches
- 18 red LEDs
- 9 green LEDs
- Four debounced pushbutton switches

Clocks

- 50 MHz clock
- 27 MHz clock
- External SMA clock input

The following is a list of the DE2 components and features that are used in the project as listed in the user manual of the DE2 board:

- Altera Cyclone® II 2C35 FPGA device
- Altera Serial Configuration device - EPCS16
- USB Blaster (on board) for programming and user API control; both JTAG and Active Serial
- 512-Kbyte SRAM

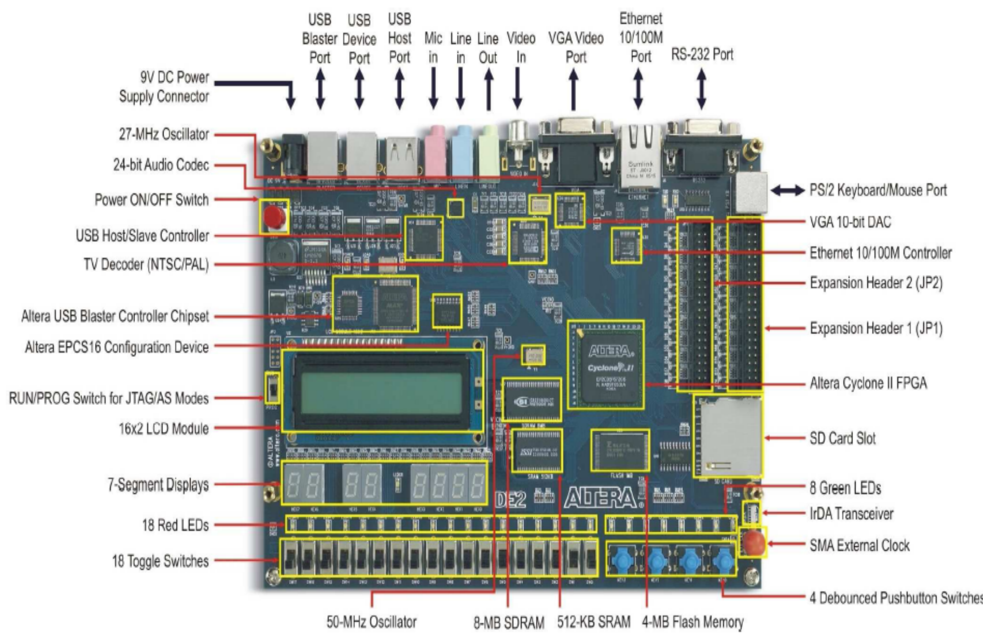

Figure 2 Altera ® DE2 development and education board

- 8-Mbyte SDRAM
- Expansion headers (76 signal pins)
- 4-Mbyte Flash memory
- 18 toggle switches
- 18 red user LEDs
- 50-MHz oscillator and 27-MHz oscillator for clock sources

- VGA DAC (10-bit high-speed triple DACs) with VGA-out connector

The LED Driver

The STP16CP05 is a monolithic, low voltage, low current power 16-bit shift register modeled for LED panel displays. The STP16CP05 contains a 16-bit serial-in, parallel-out shift register that feeds a 16-bit, D-type storage register. Figure 3 shows the pin-out of the chip used. In the output stage, sixteen regulated current sources provide from 5 mA to 100 mA constant current to drive the LEDs. The output current setup time is 40 ns (typical), enhances the system performance. The LED's brightness can be controlled by using an external resistor to adjust the STP16CP05 output current. The STP16CP05 assures a 20 V output driving capability, allowing the users to connect more LEDs in series. The high clock frequency, 30 MHz, makes the device compatible for high data rate transmission. The 3.3 V voltage supply is useful in many applications that interface with a 3.3 V micro controller.

Key features as listed in the data sheet of the LED driver chip are:

- Low voltage power supply down to 3 V
- 16 constant current output channels
- Adjustable output current through external resistor
- Serial data IN/parallel data OUT
- Can be driven by a 3.3 V microcontroller
- Output current: 5-100 mA
- Max clock frequency 30 MHz
- Electro Static Discharge (ESD) protection 2 kV HBM, 200 V MM

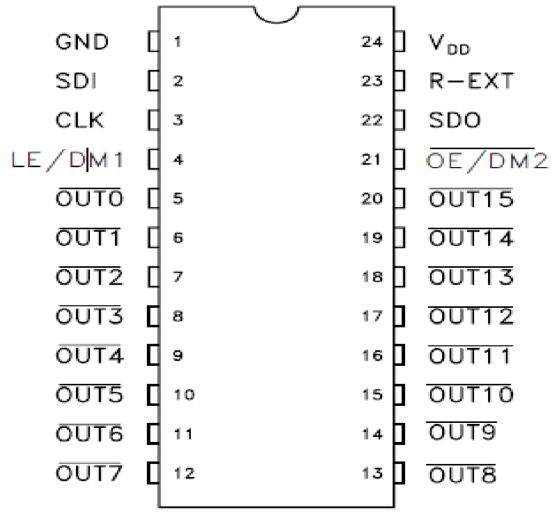

Figure 3 A schematic diagram showing Low voltage 16-bit constant current LED sink driver (STP16CP05)

The timing diagram provided in the data-sheet needs to be considered in the software design and is shown in Figure 4. Latch and Output Enable are level sensitive and are not synchronized with rising-or falling edge of CLK signal. When LE/DM1 terminal is low, the latch circuit holds the previous set of data. When LE/DM1 terminal is high level, the latch circuits refresh new set of data from SDI chain. When OE/DM2 terminal is low level, the output terminals - Out0 to Out15 respond to data in the latch circuits, either '1' for ON or '0' for OFF. When OE/DM2 terminal is at high level, all output terminals will be switched OFF.

Quartus II Software

Quartus II is a software tool designed by Altera for analysis and synthesis of hardware description language (HDL) designs, which enables the developer to compile the designs, perform timing analysis, examine RTL diagrams, simulate a design's reaction to different stimuli, and configure the target device with the programmer. Design entries can be done using several methods like altera- HDL (AHDL), electronic design interchange format (EDIF), block diagram/schematic, state machine file, system verilog, TCL script file, Verilog HDL and VHDL. The Quartus II software has unique features in field programmable gate array (FPGA) design flow methodology; system design, timing-closure methodology, in-system verification technology, and third-party electronic design automation (EDA) support. Figure 5 shows a high-level example of some of the Quartus II software FPGA design flow options.

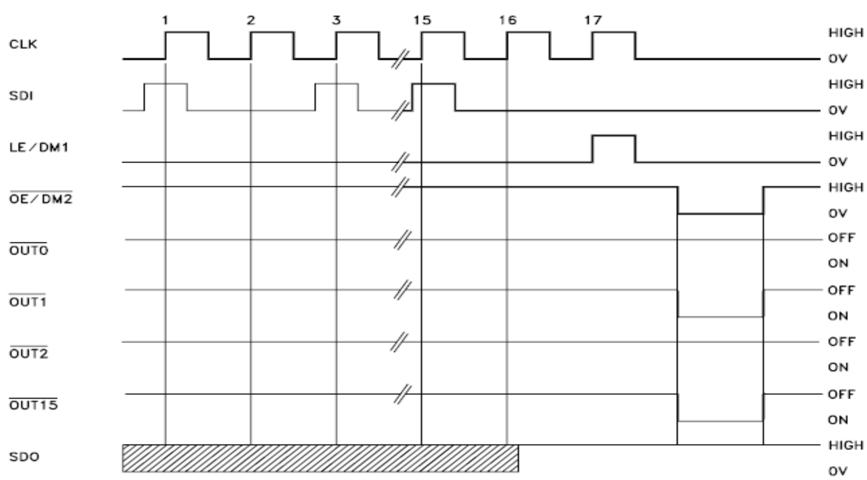

Figure 4 A timing diagram showing the pin’s statuses of the LED driver chip

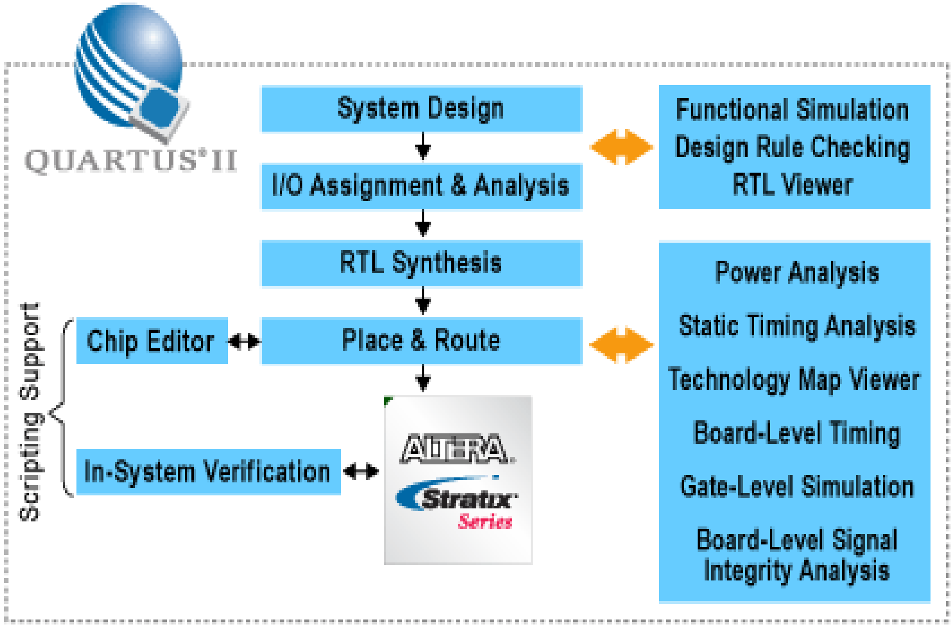

Figure 5 FPGA design flow

Video Processing

The DE2 board provides a variety of resources, including the FPGA Cyclone® II EP2C35672C6 device (consists of 105 M4K RAM blocks), SDRAM (8 Mbytes), flash (4 Mbytes), SRAM (512 Kbytes), a VGA digital-to-analog converter (DAC), TV decoder ADV7181B, infrared data association (IrDA) transceiver, an SD card interface etc. This FPGA based set up box (STB) design is used to implement real-time processing, display, and playback of audio/video as well as e-photo album and music playback functions. The system uses system-on-a-programmable-chip (SOPC) technology with a Nios® II processor embedded in an FPGA. Using the software tools and SOPC concepts, we implemented an FPGA-based STB demonstration system that is capable of performing embedded real-time video processing. The video source is input through the video in port. It passes through the TV decoder chip (ADV7181) on the DE2 board. The analog video signals input through the video in port are converted to NTSC-format system digital video signals that comply with the ITU-R656 standard. Then, the signals are sent to the FPGA internal video decoding module, which converts the YCbCr (luminance and chroma) color difference signals into RGB signals. Next, the signals go through the video processing module, which performs 16:9 resolution processing, 4:3 resolution processing, or cutting. The system stores the processed video signals in the video buffer module. It reads the data in the buffer module, conducts analog-to-digital (ADC) conversion with the XSGA 10-bit DAC chip (ADV7123), and outputs the signals through the VGA interface [44]. Figure 6 shows the block diagram of the design.

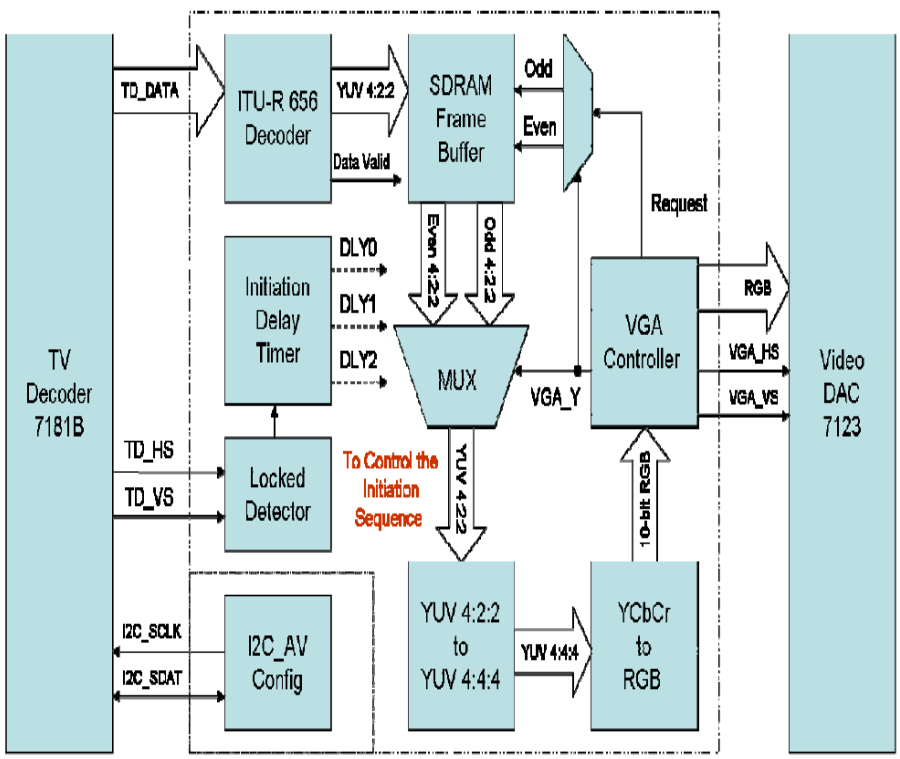

Figure 6 Video Processing Algorithm

There are 2 main blocks in the design circuit: TV_to_VGA and I2C_AV_Config. The TV_to_VGA block consists of decoder, SDRAM frame buffer, YUV422 to YUV444 converter, YCrCb to RGB, and video graphics array (VGA) controller. When the bit stream is programmed into the FPGA, the register values of the TV decoder chip are used to set the TV decoder via the I2C_AV_Config block. It uses the I2C protocol to communicate with ADV7181B decoder. The ITU-R 656 decoder block extracts YCrCb 4:2:2 video signals from the ITU-R 656 data coming from the TV decoder ADV7181B. It also generates a data valid control signals. As the video signal from the TV decoder is interlaced, it is required to perform de-interlacing on the input data. Interlacing is a method to improving the picture quality of a video signal without consuming extra bandwidth. SDRAM frame buffer and a multiplexer (MUX) to select the field which is controlled by the VGA controller are used to perform the de-interlacing. The YUV422 to YUV444 block converts the YCrCb 4:2:2 video data to the YCrCb 4:4:4 (YUV 4:4:4) video data format. Finally, the YCrCb_to_RGB block converts the YCrCb data into RGB to send the data to VGA. The VGA Controller block generates standard VGA horizontal (VGA_HS) and vertical sync signals (VGA_VS) in order to display on a VGA monitor. A timing diagram of horizontal and vertical synchronization signals for a 25MHz clock is shown in the Figure 7.

The monitor screen for a standard VGA format contains 640 columns by 480 rows of picture elements called pixels as shown in Figure 8. An image is displayed on the screen by switching on or off individual pixels. The monitor continuously scans through the entire screen turning on or off one pixel at a time at a very fast speed. The process of scanning starts from row 0, column 0 at the top left corner, and moves to the right until it reaches the last column in the row. When the scan reaches the end of a row, it continues at the beginning of the next row. When the scan reaches the last pixel at the bottom right corner of the screen, it goes back to the top left corner of the screen, and repeats the scanning process again. To minimize flickering on the screen, the entire screen must be scanned 60 times per second or higher. During the horizontal and the vertical retraces, all the pixels are turned off.

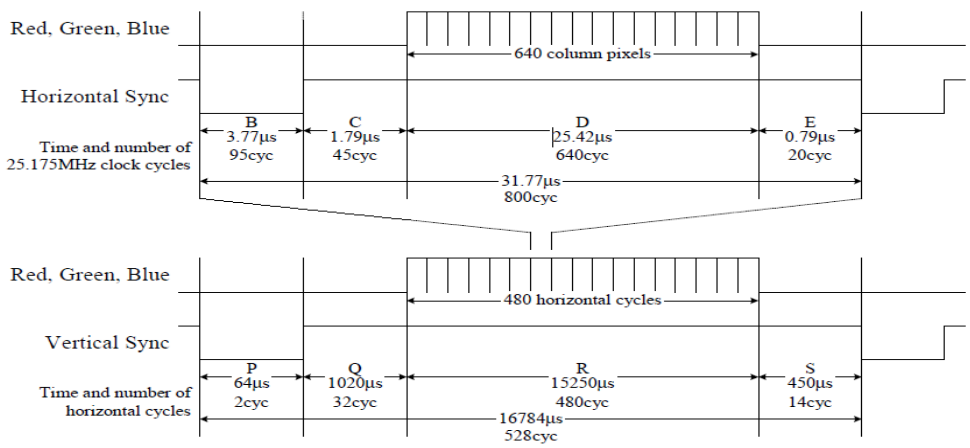

Figure 7 Horizontal and vertical synchronization signals timing diagram

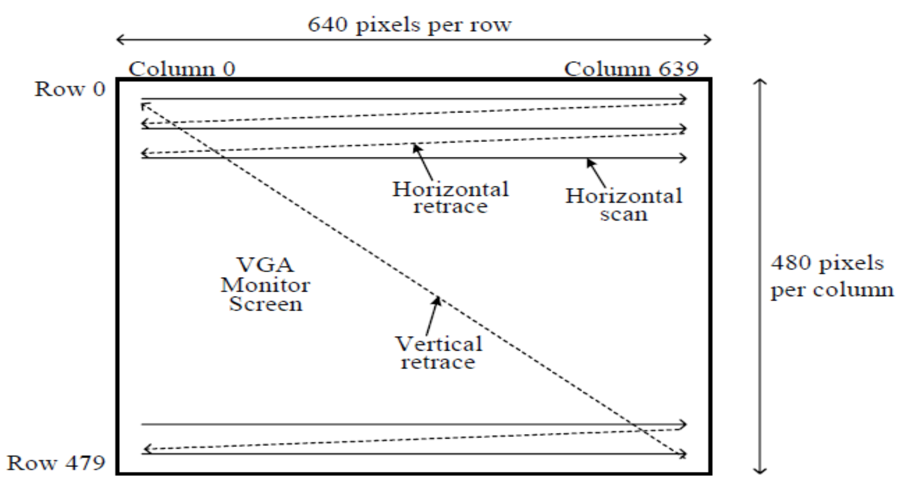

Figure 8 The monitor screen for a standard VGA format

The VGA monitor is regulated by five signals: horizontal synchronization (sync), vertical sync, red, green and blue. The three color signals, together known as the RGB signal, are used to maintain the color of a pixel at any location on the screen. These three RGB color signals are connected such that they can individually turned on or off and hence each pixel can display eight (2^3) colors. The horizontal and vertical sync signals are used to control the timing of the scan rate. The horizontal sync signal determines the time to scan a row, while the vertical sync signal determines the time to scan the entire screen. By controlling these five signals, images are formed on the monitor screen.

The logical implementation of the design is shown in the following schematics Figures 9 (a thru f). The complete schematic file is split into different parts due to its large size. Figure 9.a shows the implementations of I2C where the register values of the TV decoder chip ADV7181B are used to set the TV decoder.

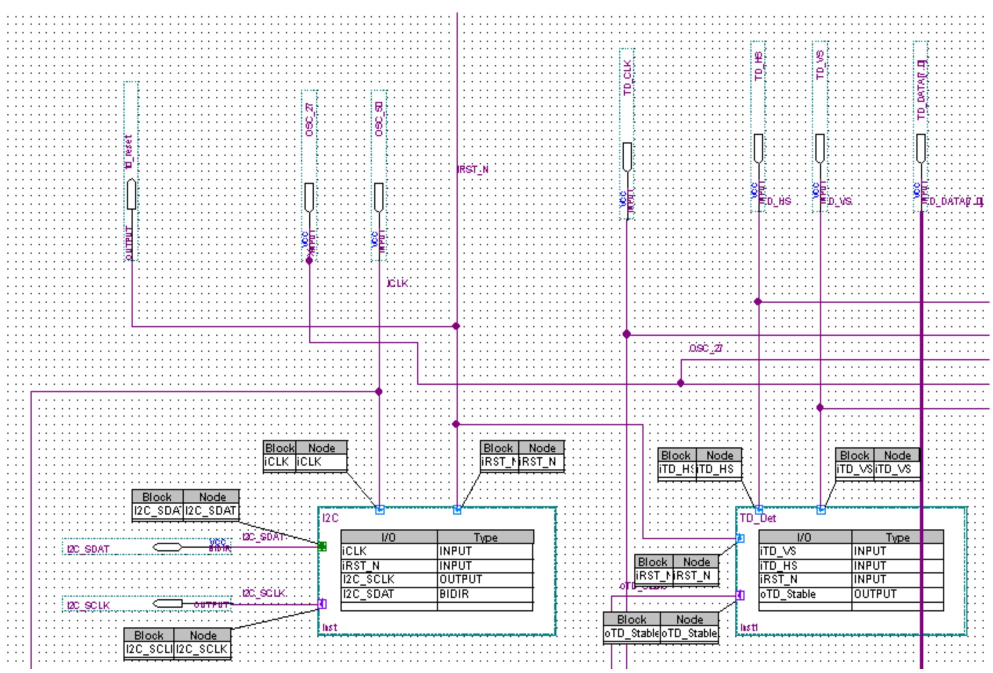

Figure 9.a A schematic diagram showing the implementation of the I2C

The decoder block extracts YCrCb 4:2:2 video signals from the input data coming from the TV decoder ADV7181B. It also generates a data valid control signals. SDRAM frame buffer and a multiplexer (MUX) to select the field which is controlled by the VGA controller are used to perform the de-interlacing. The yuv422to444 block converts the YCrCb 4:2:2 video data to the YCrCb 4:4:4 video data format. Finally, the RGB block converts the YCrCb data into RGB to send the data to VGA. The generator block generates standard VGA horizontal (OVGA_HS) and vertical sync signals (OVGA_VS) in order to display on a VGA monitor. The design process is shown in the following Figures 9.b to 9.f.

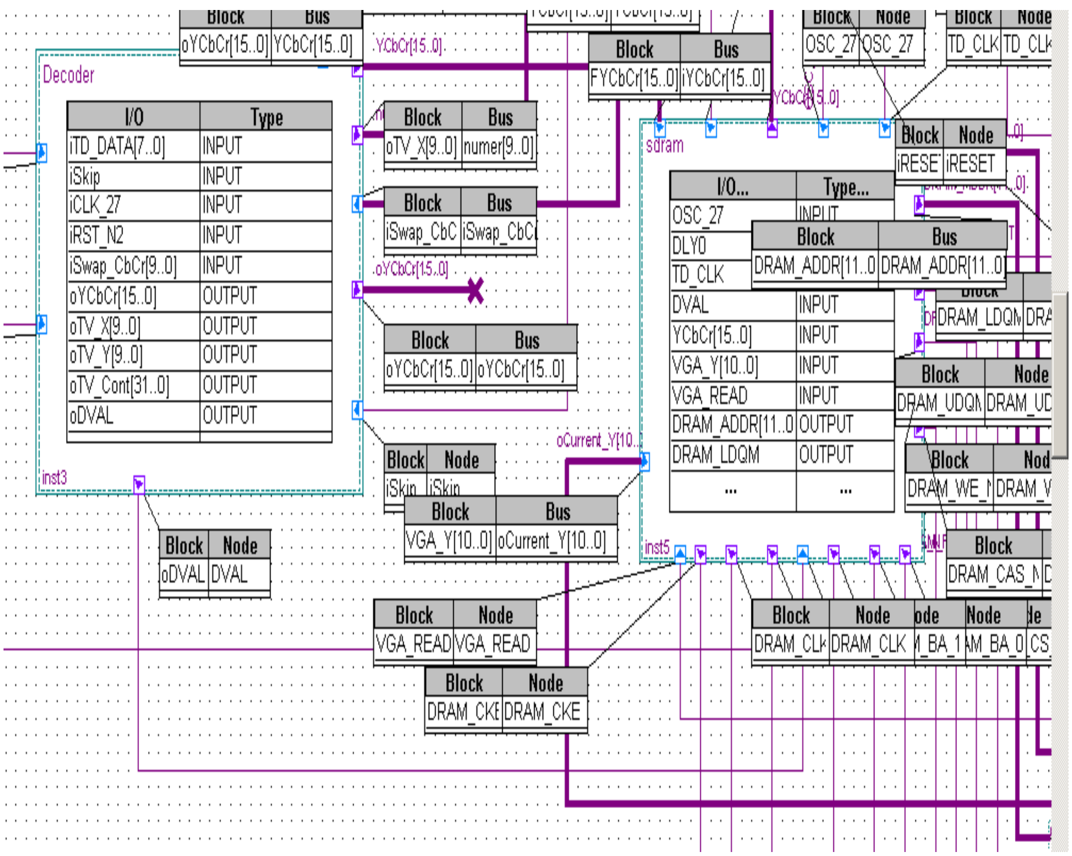

Figure 9.b A schematic diagram showing the decoder and SDRAM frame buffer blocks.

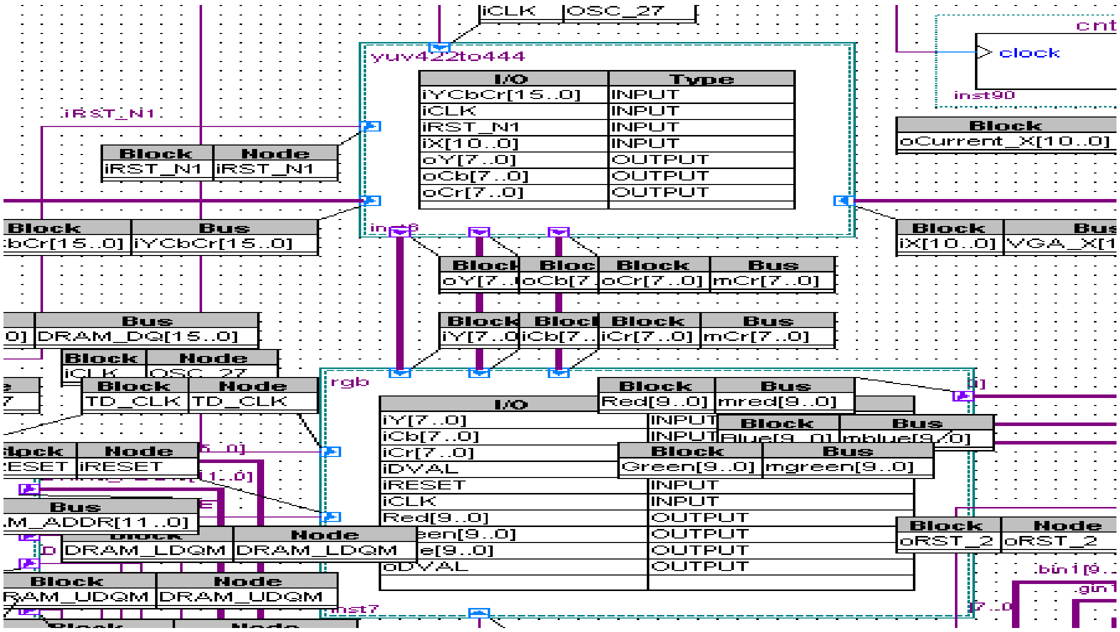

Figure 9.c A schematic diagram showing the yuv422 to yuv444 converter and RGB converter.

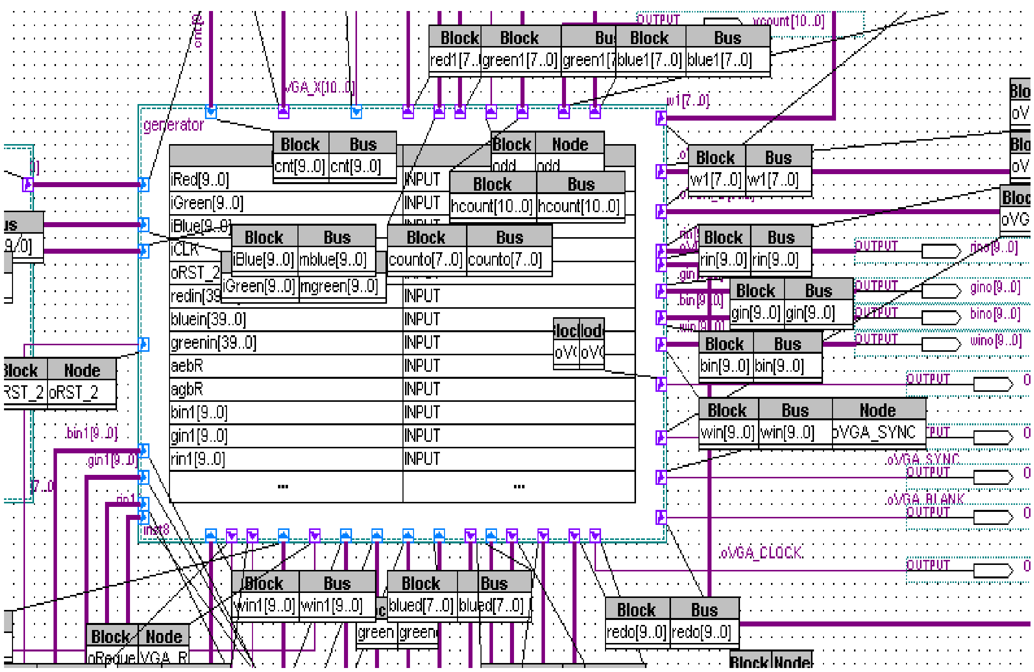

Figure 9.d A Schematic diagram showing the generator which generates the synchronization signals.

After receiving the RGB data from the RGB convertor, it is sent as input to the RGB to RGBW convertor where the data is compared with each other to determine the color that has the minimum value as shown in Figure 9.e. The logic levels of the comparator's outputs are used along with a lookup table to set the multiplexer to the value that needs to be subtracted from RGB and fed to the white LED.

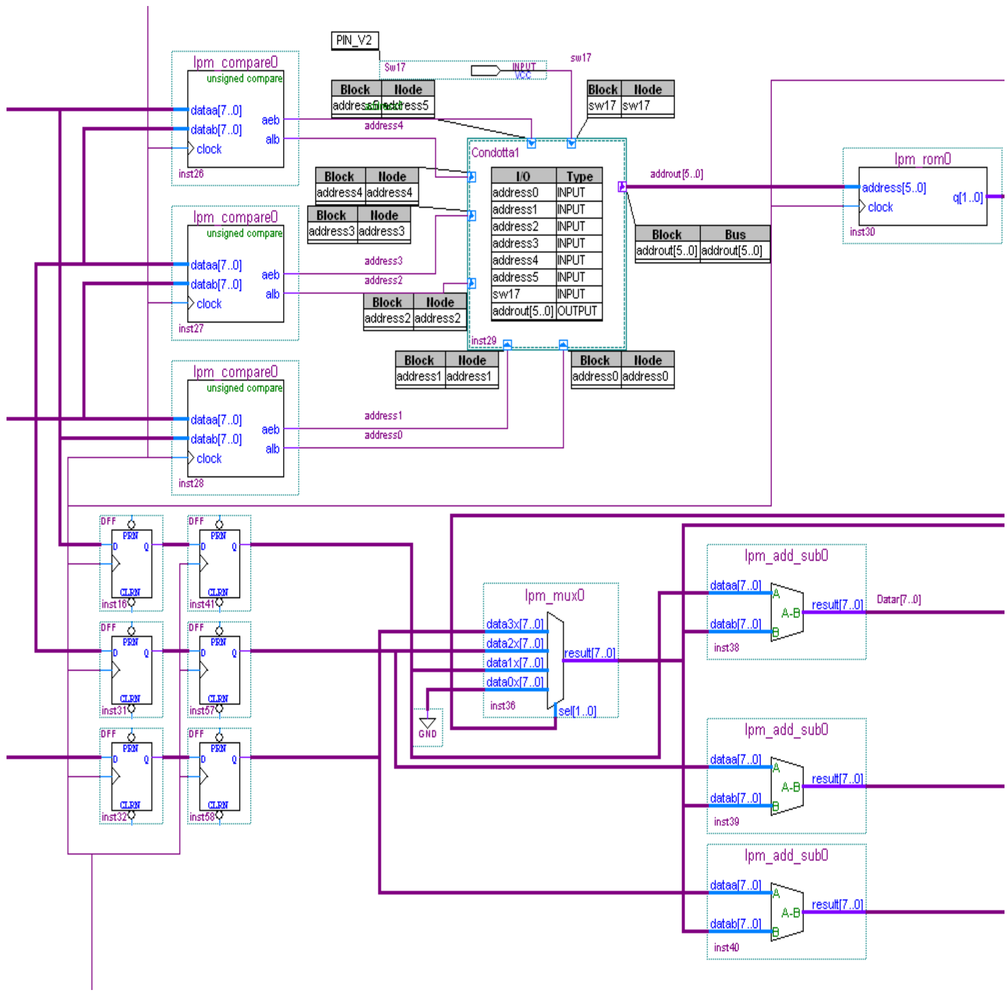

Figure 9.e A schematic diagram showing the implementation of the RGB to RGBW converter.

After the conversion of RGB to RGBW, the RGBW data is inputted to the memory to crop the data to 32inch x 16inch video display. The 8 bit RGBW data lines are pulse width modulated which provides the ability to display 256 different intensities.

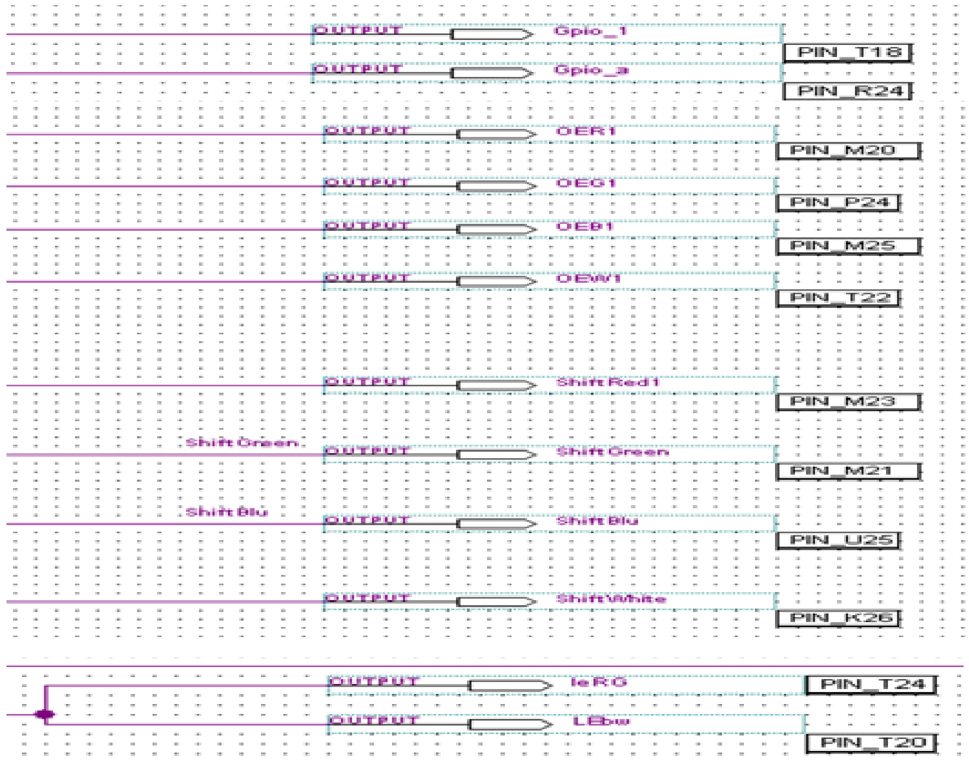

Figure 9.f A schematic diagram showing the pins for clock, data signals, LE and OE.

After outputting each bit, latch enable (LE) has to be pulsed once and then output enable (OE) has to be pulsed. The duration of the OE pulse width determines the intensity of the LED for each level from lowest 0^{th} bit to highest 7^{th} bit. Figure 9.f shows the pin configuration for clock, data, Latch enable and Output enable. These signals are fed to the display board to display the desired video.

Subtask 3.4: Study Performance

Results and discussions are presented in this chapter. Experiment details based on human perception of colors from two different technologies (RGB and RGBW) and energy calculations based on measured currents are presented and discussed.

<u>Human Perception Experiments</u>

<u>Experimental Procedure</u>

To conduct human perception experiments, it is required to have a special approval (refer to Appendix II) since human subjects were involved. To test on how people perceive the difference between the traditional (RGB) and the new (RGBW) LED display architectures, it was necessary to conduct an experimental survey which involves sample of people. To obtain the approval, the Institutional Review Board (IRB) reviews the research project which involves human subjects to ensure subjects are not subjected to unjustified risks and that test subjects are given informed consent at the time of participation. In addition, researchers must undergo IRB training through the collaborative institutional training initiative (CITI). Researchers focused on **Biomedical Science** (Biomed) must complete the CITI Biomedical Research Course Modules which gives the guidance to researchers in order to minimize risks.

Recruiting of subjects was done at UNLV, an educational institution and they were selected at random; therefore, majority of subjects were students between the ages of 18 and 30. Majority of them were willing to take the survey directly after a brief explanation about the experiment. They were instructed that they would have to compare colors displayed on LED display panel and to make a note of perceptual differences they notice. Upon their arrival to the display setup where the experiment was conducted, more detailed instructions were given to them along with a handout that contains detailed instructions (refer to Appendix III for the informed consent), the approval and the survey questions (refer to Appendix IV).

Seven different colors with 76 subjects were tested. Every subject was shown a pair of colors and asked to determine whether the color and intensity are:

- Identical
- almost the same
- slightly different
- completely different

Subjects were divided into four different groups. For the first experimental group, each color was displayed twice with RGB. This set is one of the control groups. This group consists of 14 subjects. For the second group, each color was displayed twice once with RGB and once with RGBW. This set is one of the experimental groups which consist of 24 subjects. Figure 10 shows the colors shown to the human subjects using two different technologies. For the third group, each color was displayed twice first with RGBW and then with RGB. This is second experimental group which consist of 23 subjects. For the final group, each color was displayed twice with RGBW and it is the second control group which also had 15 subjects. The purpose behind the control groups 1 and 4 was to assess the reliability and consistency of the results obtained in groups 2 and 3.

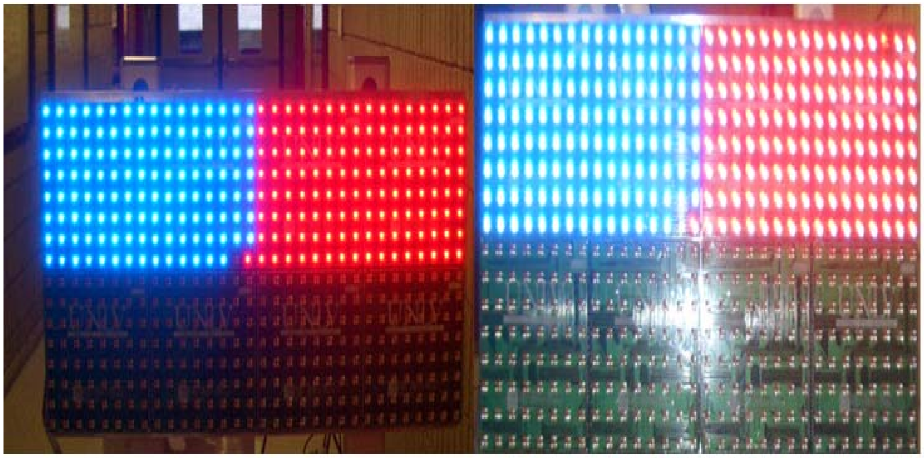

Figure 10 Colors shown using two different technologies

Results and Discussion

Data of human perception for all the seven colors are shown in the following Table 1 and Table 2.

Table 1 Human Perception data for the colors (i) Pale blue (ii) Magenta (iii) Cyan (iv) Yellow (v) Purple (vi) Light green and (vii) White where (4) Identical, (3) almost the same, (2) slightly different, (1) completely different.

(i)

Pale blue	4	3	2	1	Total
B - RGB	12	2			14
B - RGBW	18	5		1	24
BW -RGB	21	2			23
BW -RGBW	12	1	1	1	15

(ii)

Magenta	4	3	2	1	Total
B - RGB	12	2			14
B - RGBW	18	5		1	24
BW -RGB	21	2			23
BW -RGBW	12	1	1	1	15

(iii)

Cyan	4	3	2	1	Total
B - RGB	9	5			14
B - RGBW	16	6	1	1	24
BW -RGB	21	2			23
BW -RGBW	12	2	1		15

(iv)

Yellow	4	3	2	1	Total
B - RGB	9	5			14
B - RGBW	16	6	1	1	24
BW -RGB	21	2			23
BW -RGBW	12	2	1		15

(v)

Purple	4	3	2	1	Total
B - RGB	10	1	3		14
B - RGBW	18	2	3	1	24
BW -RGB	21	1		1	23
BW -RGBW	10	4		1	15

Light green	4	3	2	1	Total
B - RGB	10	1	3		14

(vi)

RGB - RGBW	18	2	3	1	24
RGBW -RGB	21	1		1	23
RGBW -RGBW	10	4		1	15

(vii)

White	4	3	2	1	Total
RGB - RGB	12	1		1	14
RGB - RGBW	15	7	1	1	24
RGBW -RGB	16	6	1		23
RGBW -RGBW	15				15

Table 2

Human Perception data for the colors based on intensity (i) Pale blue (ii) Magenta (iii) Cyan (iv) Yellow (v) Purple (vi) Light green and (vii) White where (4) Identical, (3) almost the same, (2) slightly different, (1) completely different.

(i)

Pale blue	4	3	2	1	Total
RGB - RGB	11	2		1	14
RGB - RGBW	18	3	2	1	24
RGBW -RGB	18	3	2		23
RGBW -RGBW	8	4		3	15

(ii)

Magenta	4	3	2	1	Total
RGB - RGB	11	2		1	14
RGB - RGBW	18	3	2	1	24
RGBW -RGB	18	3	2		23
RGBW -RGBW	8	4		3	15

(iii)

Cyan	4	3	2	1	Total
RGB - RGB	9	4		1	14
RGB - RGBW	20	2		2	24
RGBW -RGB	21	1	1		23
RGBW -RGBW	6	6	1	2	15

(iv)

Yellow	4	3	2	1	Total
RGB - RGB	9	4		1	14
RGB - RGBW	20	2		2	24
RGBW -RGB	21	1	1		23
RGBW -RGBW	6	6	1	2	15

(v)

Purple	4	3	2	1	Total
RGB - RGB	11	1	1	1	14
RGB - RGBW	13	8	3		24
RGBW -RGB	17	3	2	1	23
RGBW -RGBW	10	2	1	2	15

(vi)

Light green	4	3	2	1	Total
RGB - RGB	11	1	1	1	14
RGB - RGBW	13	8	3		24
RGBW -RGB	17	3	2	1	23
RGBW -RGBW	10	2	1	2	15

(vii)

White	4	3	2	1	Total
RGB - RGB	9	4		1	14
RGB - RGBW	14	8	2		24
RGBW -RGB	11	8	3	1	23
RGBW -RGBW	9	4		2	15

Most subjects found all the colors to be identical or almost the same in terms of the color and the intensity. In the experiment involving with white, it appears that most subjects perceived minor difference in color and intensity as it is expected because of the architecture as it does not allow a separate calibration control for the white LEDs.

Statistical Analysis

Theory of Statistical Analysis

The binomial probability model is applicable for the data collected from experiments 1, 2, 3 and 4, as shown in the following. Binomial probability in general deals with the probability of several successive decisions, each of which has two possible outcomes. Let X denote the number of subjects out of N_i for Experiment i *(i* = 1, 2, 3) who determined that the colors shown were "Identical or Almost the Same". The probability distribution of X then can be modeled by the following binomial probability distribution:

$$P(X = x) = \binom{N}{x} p_i^x (1 - p_i)^{N-x}, x = 1,2,..., N \quad (1)$$

where p_i is the proportion of subjects in the total population who concluded that the colors produced with the two technologies are "identical or almost the same". The population proportion pi is estimated by the sample proportion

$$\hat{p}_i = \frac{x_i}{N_i} \quad (2)$$

where x_i is the number of subjects who determined the colors in two trials were identical, for experiment i (i = 1, 2, 3). Confidence intervals for p_i can be computed using approximated formula for 95% confidence as shown in the following:

$$p_i(95\% Confidence - Intervals) = \hat{p}_i \pm 1.96 \times \sqrt{\frac{\hat{p}_i(1 - \hat{p}_i)}{N_i}} \quad (3)$$

Accurate confidence intervals can be calculated using the MINITAB software package. The later approach is used in this work. The 95% confidence interval for p_i *has* the property that the repeated use of the formula for computing the 95% confidence interval, over similar experiments, will include the true unknown p_i 95% of the time.

Data Analysis

Using the data obtained from the Table 1 and equation 3 the estimate, p_i and the upper and lower 95% confidence intervals were determined using the software MINITAB and are presented in the following Tables for all the seven colors. The data for "Identical" and "almost the same" were combined together to calculate the estimate p_i. Thus, values of $\hat{p}_i$ indicate that the pair of colors appear the same. The 95% confidence interval (U95, L95) indicates the distribution or the variability of the data.

Table 3 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for pale blue and magenta.

	Pale blue- Magenta based on color				Pale blue - Magenta based on intensity			
	RGB - RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.8074	0.7888	0.8779	0.5954	0.6613	0.6764	0.7196	0.4490
$\hat{p}$	1	0.9583	1	0.8667	0.9286	0.8750	0.9130	0.7333
U95	1	0.9989	1	0.9834	0.9982	0.9734	0.9893	0.9221

As shown in Table 3 and Figure 11, 97% (+3% /-14%) of test subjects for pale blue and magenta, found the colors shown through RGB and RGBW to be "almost the same or identical". 89% (+8% /-9%) of subjects found that there is no difference in the intensity.

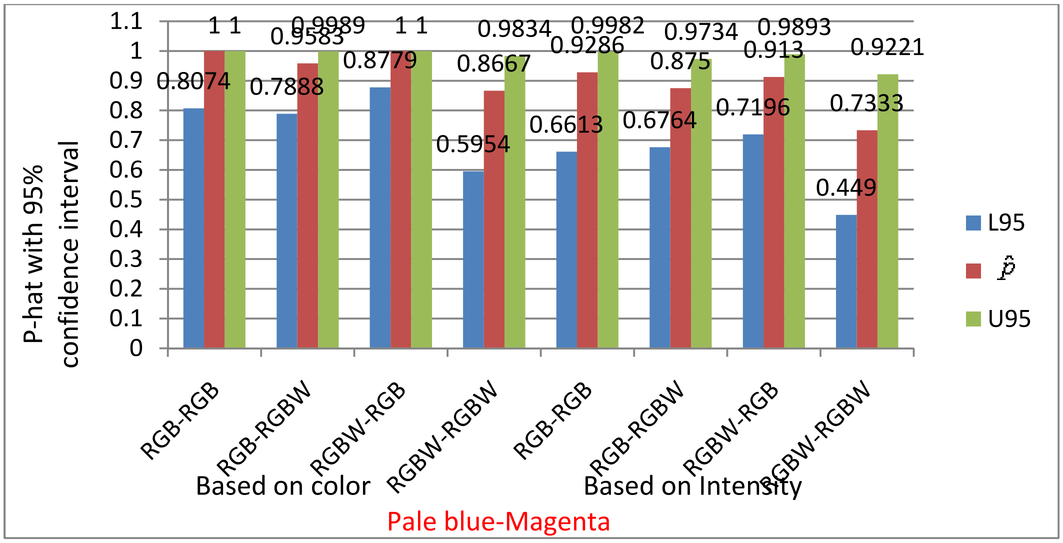

Figure 11 Estimate, $\hat{p}$, with 95% confidence interval for pale blue and magenta.

Table 4 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for cyan and yellow.

	Cyan -Yellow based on color				Cyan –Yellow based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.8074	0.7300	0.8779	0.6805	0.6613	0.6764	0.7805	0.4490
$\hat{p}$	1	0.9167	1	0.9333	0.9286	0.8750	0.9565	0.7333
U95	1	0.9897	1	0.9983	0.9982	0.9734	0.9989	0.9221

As shown in Table 4 and Figure 12, 95% (+4% /-10%) of test subjects for cyan and yellow, found the colors shown through RGB and RGBW to be "almost the same or identical". 91% (+7% /-17%) of subjects found that there is no difference in the intensity.

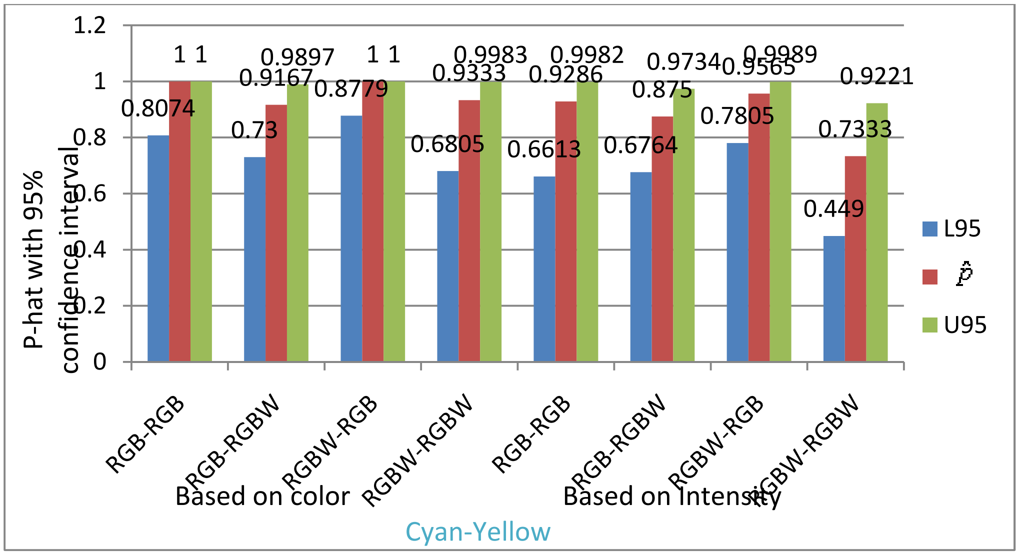

Figure 12 Estimate, $\hat{p}$, with 95% confidence interval for Cyan and Yellow.

Table 5 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for purple and green.

	Purple-Green based on color				Purple-Green based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.5435	0.6262	0.7805	0.6805	0.4920	0.6764	0.6641	0.5191
$\hat{p}$	0.8125	0.8333	0.9565	0.9333	0.7857	0.8750	0.8696	0.8
U95	0.9595	0.9526	0.9989	0.9983	0.9534	0.9734	0.9722	0.9567

As shown in Table 5 and Figure 13, 91% (+7% /-18%) of test subjects for purple and green, found the colors shown through RGB and RGBW to be identical. 86% (+10% /-18%) of subjects found that there is no difference in the intensity.

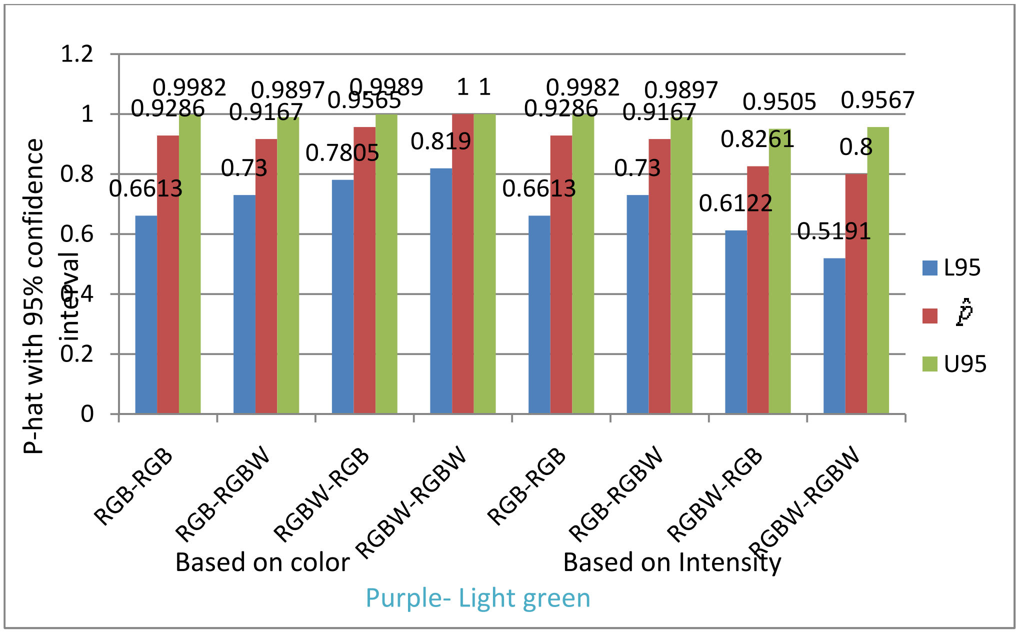

Figure 13 Estimate, $\hat{p}$, with 95% confidence interval for Purple and Green.

Table 6 $\hat{p}$, L95, and U95 values after the statistical analysis of the data for white.

	White based on color				White based on intensity			
	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW	RGB-RGB	RGB-RGBW	RGBW-RGB	RGBW-RGBW
L95	0.6613	0.7300	0.7805	0.8190	0.6613	0.7300	0.6122	0.5191
$\hat{p}$	0.9286	0.9167	0.9565	1	0.9286	0.9167	0.8261	0.8
U95	0.9982	0.9897	0.9989	1	0.9982	0.9897	0.9505	0.9567

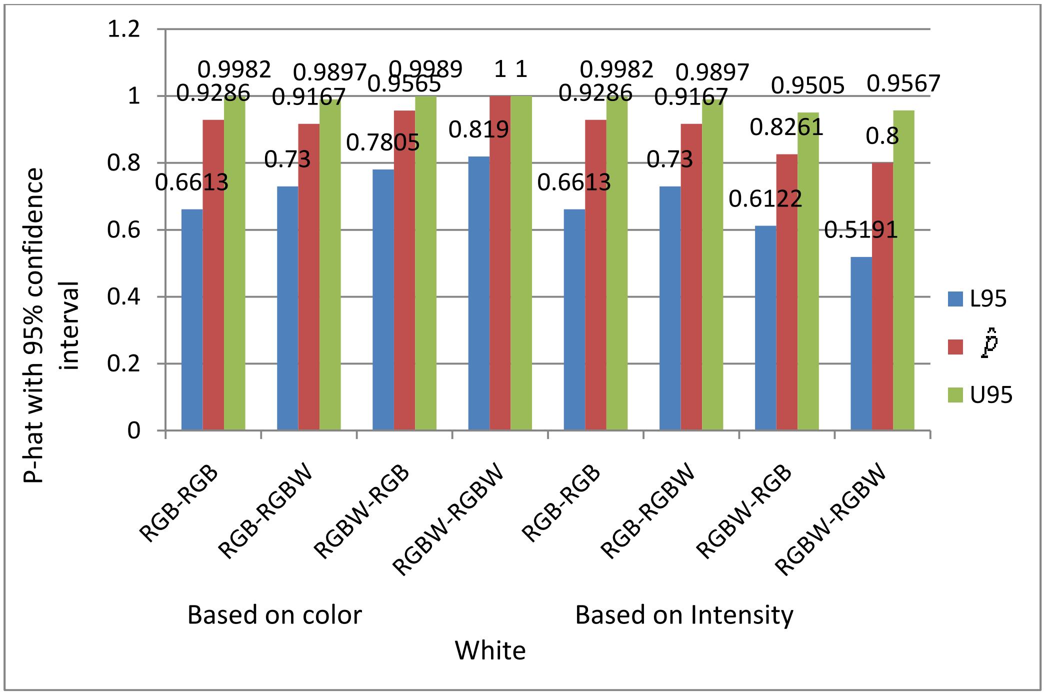

Figure 14 Estimate, $\hat{p}$, with 95% confidence interval for white.

It appears that white color created by RGB, as shown in Table 6 and Figure 14, is perceived the same as that by RGBW to 93% (+5% /-16%) of the subjects. Only 86% (+10% /-19%) of the subjects found that the intensities are identical. The white LEDs in the prototype that was used for this design did not have independent intensity control. Therefore maintaining the intensity to be identical between the two whites was a challenge.

<u>Energy Measurements and Calculations</u>

<u>Experimental Procedure</u>

As the consumption of power is directly proportional to the current supplied due to constant voltage, current flowing through the display board for seven different colors are measured separately. The colors are divided into four patterns with the combination of 2 colors in 3 patterns and white in the last pattern. For every pair, the current flowing to the

32inch x 16inch pixel display is measured for RGB and for RGBW and then calculated the power savings.

Results and Discussion

The power consumption by the 32inch x 16inch pixel LED display are measured for the seven colors using RGB and RGBW in terms of current supplied and listed in Table 7. It is noted that the current values are in the range of 1A - 12A.

Table 7 Measured currents for RGB, RGBW

	I (RGB) [A]	I (RGBW) [A]
Pale blue	5.4	4.4
Magenta	5.18	4.3
Cyan	9.8	8.93
Yellow	10.02	9.25
Purple	6.62	6.54
Light green	10.0	9.2
White	12	8.6

The power consumed (P) by the 32inch x 16inch pixel LED display is given by:

$$P = V \times I \qquad (4)$$

where 'V' is the voltage supplied to the board, and 'I' is the current flowing through the device. For this display, the voltage required was 5V.

Data Analysis

The amount of power savings as a result of using RGBW alternative to RGB, P_s, is given by:

$$\% P_s = (P_{RGB} - P_{RGBW})/ P_{RGB} \times 100 \qquad (5)$$

Table 8 Power consumed by pixels for RGB, RGBW and % power savings of RGBW over RGB

	P (RGB) [W]	P(RGBW) [W]	P savings %
Pale-Blue	27	22	18.5
Magenta	25.9	21.5	17
Cyan	49	44.6	9
Yellow	50	46.25	8
Purple	33.1	32.68	2
Light green	50	46	8
White	60	43	29

Using the data presented in table 7 and the equations 4 and 5, P_{RGB}, P_{RGBW}, and $\%P_s$ were calculated and reported in Table 8 for all the seven colors. % power saving for various colors is plotted in Figure 15.

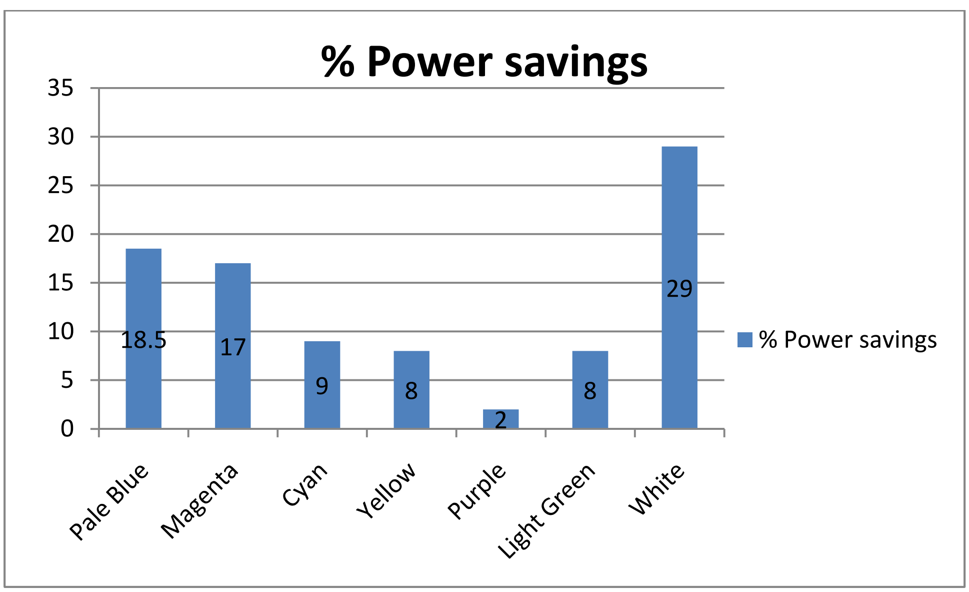

Figure 15 % power savings for seven colors.

The data presented in Figure 15 shows the power savings for all the colors (pale blue, magenta, cyan, yellow, purple, green and white). Power savings for the colors, such as magenta, pale blue and cyan is much higher than power savings for yellow, light green and cyan since the white content is less in high saturated colors. Power savings for the white is higher than any other color. As demonstrated, using the new RGBW pixel architecture saves power in most cases predominantly in case of the color which has more white content.

Further energy saving can be obtained using higher efficiency white LED now available and using two different power sources: one 5 V for the BLUE, GREEN and WHITE Led’s with higher junction voltage (3.2 V) and 3.3 V for the RED that has a 2 V junction forward voltage.

Subtask 4: Stress Testing

Three sets of experiment were conducted for the CFLs and LED luminaires. In experiment 1, lamps are subjected to vibrations for 24-hours and the intensity measurements are taken after stopping vibration. In experiment 2, lamps are subjected to vibrations for 10 minutes for every single vibrational frequency and intensity measurements are taken after the vibration is stopped. The intensity measurements were conducted for 546.78nm, the wave length of maximum human eye sensitivity. In experiment 3, an experiment was conducted to observe the effect of effect of temperature (heating) over time on the light output. The intensity values are measured for every 5 minutes with no vibrations. The intensity measurements were conducted for 546.78nm, the wave length of maximum human eye sensitivity. Two different types, CFL (Nuvue) and CFL (Ecosmart), and one type of LED luminaire (Nuvue), were used in our experiments.

Summary of LED luminaires measurements

The following is the summary of observations of measurements of LED luminaires. In general, 24-hour vibration effects the intensity distribution.

Vibration measurements at a distance of 34.74 inches and 39.74 inches show a decrease in peak intensity, whereas 30.74 inches measurements show an increase.

A maximum of 15% increase in peak intensity is observed for 5Hz vibration at 30.74 inches and maximum decrement in peak intensity of 25% due to vibration is observed for 10Hz at 34.74 inches.

Intensity measurements of 546.78 nm at varying vibrational frequencies (at 1Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. The lamp shows no consistency in the variation of peak intensities.

Summary of CFL(Nuvue) measurements

The following is the summary of observations of measurements of CFL (Nuvue) lamps.

In general, 24-hour vibration effects the intensity distribution.

At 5Hz at 30.74inches and 34.74inches there is no change in intensity whereas, at 39.74 there is increase of 18% of peak intensity.

At 10Hz at 30.74inches, 34.74inches and 39.74, there is increase in the peak intensity in the range of 10-25%.

At 15Hz at 30.74inches, 34.74inches and 39.74 there is increase in the range of 10-35% and the area under the curve has increased in the range of 10-40%.

A maximum of 35% increase in intensity is observed for 15Hz vibration at 34.74 inches.

Intensity measurements at varying vibrational frequencies (at 1Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. A maximum variation is observed at 25 Hz.

<u>Summary of CFL (Ecosmart) measurements</u>

The following is the summary of observations of measurements of CFL lamps. In general, 24-hour vibration effects the intensity distribution.

Vibration measurements at all the distances of show a change in intensity, which is very difficult to explain.

At 5Hz at 30.74inches, there is an increase in peak intensity whereas at 34.74 inches and 39.74inches there is no change.

A maximum of 10% increase in peak intensity is observed for 15Hz vibration at 34.74 inches and a maximum decrement due to vibration is observed for 10Hz at 39.74 inches.

In case of 15Hz, two days after the vibration, the peak intensity is lower than that for the case with no vibration.

Intensity measurements of 546.78 nm at varying vibrational frequencies (at 2Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. Intensity is in a range of 53,000-60,000 (counts). Maximum change in intensity occurs at 26Hz for all three luminaires.

Overall assessment of the effects of mechanical vibration on luminaires

Experimental data from all our measurements are summarized in Table 9. In general, all lamps show change in light intensity distribution with vibration. The change in intensity distribution is not consistent, i.e., always increase and decrease. In most cases, the vibrations result in increase in intensity distribution and lumens. The effect of vibrations is more on the CFLs compared to the LED luminaires. The effect of vibration on the CFL can be related to falling off the phosphor coatings on the inner wall of the CFL. Same effect on the LED luminaire is minimal because the phosphor distribution is unaffected as it is sandwiched between the active area and the epoxy lens.. Subjecting the lamps to varying vibrational frequencies over time makes all lamps degrade in performance with a wide variation in peak intensities. CFL (Ecosmart) performed the best of all three luminaires. LED was comparable to CFL (Ecosmart) and CFL (NUVUE) was the worst.

This study has identified that the mechanical vibrations in the frequency range of 0-30Hz that is typical in buildings and oilrigs due to heating, ventilation, air-conditioning systems (HVAC), has a serious effect on LED and CFL luminaires. This work is preliminary and a more thorough and systematic study is warranted to make definite conclusions and hence possible technological recommendations.

Table 9 Summary of all the lamps at various angles and distances in different vibrational conditions. Intensity and Lumen are the percentage change from no vibration to the vibration data. LED- light emitting diode luminaire, CFL(N) – compact fluorescent lamp (Nuvue), CFL(E) – compact fluorescent lamp, (Ecosmart), NC – No change.

Frequency (Hz)	Lamp types	30.74inches		34.74inches		39.74inches	
		Intensity (%)	Lumen (%)	Intensity (%)	Lumen (%)	Intensity (%)	Lumen (%)
5	LED	+15	+16	+11	-9	-9	-10
	CFL(N)	NC	NC	NC	NC	+18	NC
	CFL(E)	+5	+5	NC	NC	NC	NC
10	LED	+3	+6	-15	-15	-6	-2
	CFL(N)		+14	+25	+58	+25	+42

		+10					
	CFL(E)	NC	NC	NC	NC	-10	-3
15	LED	+5	+5	-25	-26	NC	NC
	CFL(N)	+21	+39	+35	+40	+10	+11
	CFL(E)	+8	+6	+10	+5	+8	-3

R & D Collaboration:

The current economic crisis has affected the industry and our commercial partner. Despite the bad economic situation, Mr. Franco Zambiasi is willing to continue with our collaboration, but, in a limited way. Dr. Paolo Ginobbi is planning to meet with the company executives in Milan to determine the next steps in our continuing collaboration.

Cost Sharing:

Graduate student support from the Electrical and Computer Engineering department and Dr. Venkat's salary along with material and consulting support from Tecnovision, Italy were the cost share components for this project.

Patent:

None.

Publications:

The following two Electrical Engineering M.S. theses were published.

- Jayalakshmi Paladugu, “Effect of Mechanical Vibrations on LED Luminaires”, 12/2009
- John Mani Kumar Jupalli, “Energy Efficient LED Displays”, 11/2010

The following journal article was published and two more are in preparation.

- Jayalakshmi Paladugu, Rama Venkat, Paolo Ginobbi, “Effect of Mechanical Vibrations on Compact Fluorescent Luminarires”, vol. 7, p49, (2010)

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Develop Photometer System	12/08	12/08	12/08	100	100% functional and working photometer system. 12-bit digital accuracy, 120 Hz+ sampling rate available
2	Develop Self-Diagnostic Reconfigurable System	06/10			30	We have extended the motor platform to measure typical display bricks. We dropped this as the need for it is not there anymore.
3	Brightness and Grayscale Linearity	06/10	08/10		90	32” x 16” RGBW display was designed, tested for energy efficient and human perception.
4	Stress Testing	02/09	12/09		100	Completed successfully