Agilent Engineering Excellence Program

Automated LCD Color Temperature Testing System

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***Abstract*—The LCD display has become a dominant component in the television and computer industries. The performance of the LCD screen is very important for manufacturers. Uniformity in brightness is one of the most important quality standards to quantify the performance. One way to verify the uniformity in brightness is by performing a color temperature test at various points of the screen. In this paper, an automated testing system for LCD color temperature is introduced. This system is able to perform color temperature test at various points on the screen, configure the test points according to the specified size of the LCD, analyze the data during and after the measurement process and trigger alert and reset test process if the measurement does not meet specification. Agilent's DAQ and VEE are adopted as the core hardware and software to control the whole testing system. The detailed configurations of the system and its applications will be introduced in this paper.**

I. Introduction

As the LCD technology mature, LCD display has become a dominant component in the television and computer industries. Thus, the performance quality of the LCD screen has become an important issue for both the producers and consumers. There are many standards to follow during LCD manufacturing to ensure quality. One of the most important standards is the uniformity in brightness. Uniformity in brightness requires that the LCD display field should have same brightness consistently over the LCD panel.

In actual production where the cycle time is important, there are many suitable methods to ensure the uniformity in brightness. One of them is by performing a color temperature test at various points of the screen, usually at the corners and centre points. Color temperature is a color characteristic relating to the proportion of the red, green and blue, which are known as the tricolor RGB. The color temperatures at different points can tell the differences in RGB portion in these points. Thus, the brightness of these points can be obtained based on the measurements.

In order to measure the color temperature, equipments like colorimeter are needed. In the current market, the colorimeter for normal use can cost to thousands of US dollars, and for academic use, it may cost much more. So an economical and convenient measurement system is required to meet such measurement demands. Such a system must be able to measure color temperature at various points of the LCD screen, and also able to configure the positions according to the size of LCD. This system should also offer good support with computer interface and convenient data storage for further analysis.

Hardware is needed to build and configured for the color temperature measurement at various points of the LCD display field. A measurement unit should be set up for point color temperature measurement, and a servo motion system should be set up for moving the measurement unit to the required positions. In this project, the core of the measurement unit is a color sensor module HDJD-S831-QT333 by Avago Technologies. This sensor can convert the RGB portions of the light source to analog voltage outputs, and corresponding PCB board is designed for signal conditioning to amplify the measured RGB voltages as the luminance of LCD screen usually is quite low. The core of the servo motion subsystem is the XY stage. This servo system contains two DC servo motors with build-in incremental rotary encoders. The target positions of the motors can be controlled via feedback of the signals of the motor encoders.

As part of Agilent Engineering Excellence Program, this project is sponsored by Agilent Technologies. Agilent DAQ U2353A and VEE Pro are used for the project application development. DAQ denotes for Data Acquisition and VEE stands for Virtual Engineering Environment. Agilent DAQ and VEE are adopted as the core hardware and software and are used together to control the color temperature measurement unit and XY stage. DAQ instrument provides physical connection with above build hardware subsystems and VEE provides programmable control over these systems and communication between DAQ and computer interface.

The integrated system is build based on the above subsystems and could measure the color temperature of four points at the corners and one point at the centre on the LCD screen. The color sensor module is responsible for the point measurement process while the XY stage is responsible for the point movement process. Both of them

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are controlled and configured by Agilent DAQ and VEE using SCPI commands via computer interface. The integrated system is able to check and verify the measured data during and after the measurement process. If there is one or more failing the specification, the system will trigger a warning alert, stop the current operating process, and return the sensor unit to the origin position. If all the measurement satisfies the criteria, the system will pass the current process, and store these measured data in Excel format for the convenience of further analysis

II. THEORY & METHODOLOGY

A. Color Temperature Theory

Color temperature is a characteristic of visible light, and the units of color temperature are Kelvin (K). The definition of color temperature by the International Commission on Lighting (CIE) in its International Lighting Vocabulary [1] is:

> *"Color Temperature: The temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus"*

For a better understanding, the color temperature of a light source is the perceived color of the light a perfect blackbody radiator would appear when heated to a particular temperature in Kelvin. Planck determined that the Spectral Power Density (SPD) radiated from a hot object, referred to as a blackbody radiator, is a function of the temperature to which the object is heated. The SPD of a light source is a measurement of all the spectral wavelengths that make up an objects radiated energy [2].

A black radiator, also referred to as a Planckian radiator, is a theoretical object with zero reflectance. Its spectral distribution is determined by Planck's radiation law:

$$M(\lambda, T) = c_1 \lambda^{-5} (\exp\left(\frac{c_2}{\lambda T}\right) - 1)^{-1} \quad (1)$$

where:
c_1=3.74183×10^{-16}W·m^2
c_2=1.4388×10^{-2}m·K
and λ is the wavelength in m and T is the blackbody temperature in Kelvin. The spectral radiant distribution $M(\lambda, T)$ is directly proportional to a given temperature T.

From Equation (1), a low color temperature looks red, and a high color temperature appears bluish. It is just counterintuitive to most people's perception of temperature and color. For example, people usually relate heat and red together, and associate cold with blue.

In order to form a color standard, as there are three types of color photoreceptors in the eye, CIE defines three elements in measuring color the XYZ primaries, which is known as CIE tristimulus values [3]:

$$X = k \sum_\lambda \Phi(\lambda) \bar{x}(\lambda) \Delta\lambda$$
$$Y = k \sum_\lambda \Phi(\lambda) \bar{y}(\lambda) \Delta\lambda \quad (2)$$
$$Z = k \sum_\lambda \Phi(\lambda) \bar{z}(\lambda) \Delta\lambda$$

where $\Phi(\lambda)$ is the spectral power distribution of the source to be measured, $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are the CIE 1931 color-matching functions and k is a normalization factor.

An important objective specification of the colorfulness of a light source irrespective of its luminance, the CIE 1931 chromaticity coordinates x and y are defined from X, Y and Z:

$$x = \frac{X}{X+Y+Z},$$
$$y = \frac{Y}{X+Y+Z} \quad (3)$$

(as $z = 1 - x - y$, z will be not used in the two dimensional diagram)

B. Color Temperature Methodology

As there is no CIE-approved or even recommended method for determining the color temperature, various photometric laboratories have adopted different algorithms. The most widely used among them all is the equation proposed by McCamy in 1992 [4], for calculating the color temperature T of a light source:

$$n=(x-x_e)/(y_e-y),$$
$$T=449.0\times n^3+3525.0\times n^2+6823.3\times n+5520.33 \quad (4)$$

where x_e=0.3320 and y_e=0.1858.

McCamy's method is claimed to give a good result for color temperature in the range of [2000K, 12500K] and it has a maximum absolute error of less than 2 K for thee measured range of [2856K, 6500K].

In order to calculate the color temperature, the chromaticity diagram coordinates (x, y) is needed. According to previous discussions, coordinates (x, y) is derived from tristimulus values XYZ; so once XYZ is fixed, color temperature can be derived. But in real situation, tristimulus values XYZ cannot be directly measured. Instead, only the tricolor RGB can be measured using specific sensors. So the method converting tricolor RGB into tristimulus values XYZ is needed.

In order to calculate XYZ from RGB, a matrix method is introduced:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (5)$$

where the coefficients $C_{00}, C_{01}, C_{02}, C_{10}, C_{11}, C_{12}, C_{20}, C_{21}, C_{22}$ are calculated from the known primaries and whitepoints.

As LCD TV display is used for test in this project, the HDTV standard is chosen as the primary and the D65 standard is chosen as the whitepoint. Thus the chosen primary is [r: (0.64, 0.33), g: (0.30, 0.60), b: (0.15, 0.06)] and the chosen whitepoint is (0.312713, 0.329016). Using the RGB-XYZ coefficient conversion algorithm provided by Oscar van Vlijmen [5], the 3×3 matrix in (5) can be solved as below:

$$\begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 0.43057 & 0.34155 & 0.17833 \\ 0.22201 & 0.70666 & 0.07133 \\ 0.02018 & 0.12955 & 0.93918 \end{bmatrix} \quad (6)$$

Using both the McCamy's method and the RGB-XYZ conversion, the color temperature of a specific light source can be calculated by the RGB values, which is measurable from practical sensors.

III. HARDWARE

A. Color Temperature Measurement Unit

Light is a type of energy, which makes up a small portion of the electromagnetic spectrum. The visible region of light consists of 7 colors that human eye can distinguish; each light color has its own wavelength. In order to measure the RGB portion of the light source separately, the light source must be filtered only allowing red, green and blue light pass and converted into electrical signals that the DAQ could understand.

The HDJD-S831-QT333 color sensor module by Avago Technologies is adopted in this system. It consists of two inputs, power supply and ground, and three outputs, voltages of red, green and blue channels correspondingly.

This color sensor comprises a RGB color filter at the first layer. [6] Behind the color filter, there is an array of three photodiodes and an integrated current-to-voltage conversion circuit. With properly designed RGB transmissive color filter, the spectral response of the photodiode can be reshaped and optimized such that it mimics that of the human eye, which has cones with peak sensitivities at wavelengths of red, green and blue. Light falling on each of the photodiodes is converted to a photocurrent. The photocurrents from each of the three photodiodes are converted to VRout, VGout and VBout using a current-to-voltage converter. These VRout, VGout and VBout are proportional to the RGB values needed in calculating the color temperature. The voltage output of each R, G, B channel increases linearly with increasing light intensity, but the ratio of R, G and B will still keep the same as it is linearly increasing.

B. Signal Conditioning

As LCD has a relatively low luminance, the VRout, VGout, VBout values measured by the color sensor are usually small, around hundreds of millivolts. In order to make better use of the resolution of the DAQ and to increase the immunity from noise, signal conditioning and amplification is needed.

In the color measurement subsystem, INA128 manufactured by Texas Instruments is used. INA128 is a low-power but high performance general purpose amplifier. It provides amplified gain up to 10,000 and has a good linear response [7]. After signal conditioning, the measured VRout, VBout and VGout can be normalized to unipolar signals, with maximum voltage range of 10Volts.

C. Automated Motion

The color temperature testing requires testing several points on the LCD screen. This requires an automated motion subsystem which can hold and move the color temperature measurement subsystem. So the XY stage is used in this subsystem.

The XY stage consists of two DC servo motors, for the x and y direction respectively. Each the servo motor contains an incremental rotary encoder inside. This increment rotary encoder gives three output channels, A, B and index. The index signal supplies a single pulse per revolution. This single pulse can be used for precise determination of a reference position, such as positioning systems. So a specific position can be easily located via the index signal.

D. Data Acquisition

The U2300A series of Agilent multifunction data acquisition (DAQ) are high performance DAQ modules. U2353A is the basic multifunction DAQ in U2300A series. U2353A can sample up to 500kSa/s with a resolution of 16 bits [8]. There are four types of operations in U2353A, which includes analog input operation, analog output operation, digital input/output and general purpose counter [9].

1) Analog Input: U2353A provides 16 single-ended or 8 differential analog input channels. Analog signal is converted to digital values by A/D converter. There are two different modes: polling mode and continuous mode. Polling mode is well suited in applications that need to process A/D data in real time, and is fully controlled by software command. Continuous mode has two types: single-shot and continuous acquisition. In single-shot, the data is acquired at specified sample points and processed once, while in continuous type the data is acquired continuously until a stop command is sent.

2) Analog Output: There are two D/A channels available in U2353A, with two modes: voltage output and continuous output mode. In voltage output mode, AO is capable of supplying output voltages in up to 10volts. In continuous output mode, AO can supply predefined function generator or arbitrary waveforms.

3) Digital I/O: U2353A provides 24-bit of digital I/O, segmented into four channels: 2 channels consist of 8 data bit and 2 channels consist of 4 data bits. All these four channels are programmable as input and output.

4) General Purpose Counter: U2353A has two independent 31-bit up/down counters to measure the input channels. The counters can be programmed choosing internal or external control. The GPC consists of two modes: totalizer mode and measurement mode. In totalizer mode, the counter could count the pulses of the input signal. In measurement mode, the frequency, period and pulse width of the input signal can be measured.

5) DAQ Settings in System: As the color sensor provides three outputs: R, G, and B, correspondingly three analog inputs are needed to read and analyze RGB data. The RGB signals range from 0V to 10V after signal conditioning using amplifier, so the range and polarity of the AO is unipolar and 10V. Polling mode is used as it is more suitable with real time application like this project, and easier to control using software VEE. The XY stage consists of two motors. In order to control the moving directions of these two motors, two analog outputs are needed, with settings of bipolar and voltage output mode. As each motor has an index signal indicating its revolution numbers, in order to control the motor's positions, a total of two general purpose counters are needed, and the mode of counter is totalizer mode. So the total ports needed in the whole system are: 3 AI, 2 AO and 2 counters.

IV. SOFTWARE

A. *Agilent VEE*

VEE is an abbreviation of Visual Engineering Environment. VEE is a visual programming and dataflow programming language and development environment from Agilent Technologies. VEE is a measurement smart programming platform. It can virtually work seamlessly with any instrument from any vendor. This is because VEE supports a wide variety of hardware interfaces, like GPIB, RS-232, GPIO, USB, LAN, VXI etc. VEE also supports SCPI standard (Standard Commands for Programmable Instruments) which defines a standard set of commands for control and measurement devices that all the instrument systems must support [10].

Besides above features, VEE also has built-in Microsoft's Excel libraries and MATLAB engine. Thus VEE could use Excel and MATLAB for data storage, data analysis, 2D & 3D graphs plotting and modeling etc. VEE also can be customized and enhanced via ActiveX control and .NET control.

B. *Color Temperature Measurement*

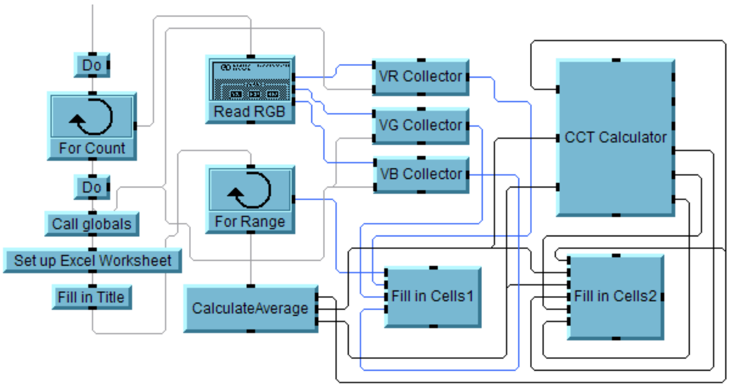

Fig. 1. VEE program for color temperature measurement

With the measured VRout, VGout and VBout from color sensor, DAQ will read them using its analog input ports in polling mode. A specific VEE program will calculate the chromaticity coordinates (x, y), and the color temperature of the light source according to these digital signals using McCamy's method. For ease of future utilization and reproduction, this VEE program will also store these measured VRout, VGout, VBout values and the computed (x, y) coordinates and color temperature in an Excel sheet. The VEE program of above functions is shown in Fig. 1.

C. *Automation Motion*

Analog outputs are set to voltage output mode to drive the motor. As the motor should be able to move forward and backward in two directions, the property of the analog input is set to bipolar, with range [-10, 10] volts. In order to count to number of pulses generated by the encoder's index signal, the general purpose counter is set to totalizer mode. The counter's input pin is set to external to trace the index signal of the motor. While other input pins are set to internal, and controlled by software commands.

V. INTEGRATED SYSTEM

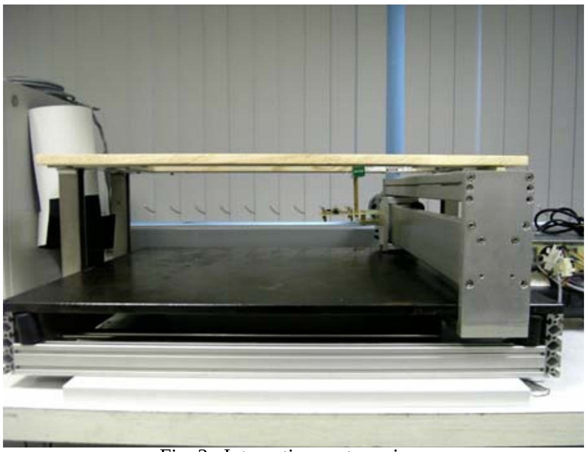

Fig. 2. Integration system view

The finished and integrated prototype is shown in Fig. 2. A wooden stand is used to hold the LCD screen during the testing process. Below the wooden stand is the XY stage. The PCB board contains the color temperature measurement unit and signal conditioning circuits. The PCB board is fixed on a square metal platform of the XY stage and it is able to move in x and y directions with the movement of the motors of the stage.

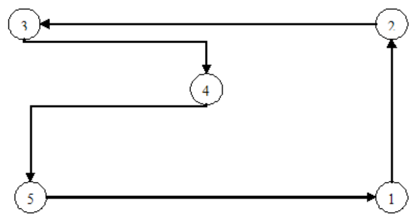

Fig. 3. Moving Trace of the XY stage system

Fig. 3 shows the trajectory of the sensor unit around the XY stage. Point 1 is the starting point, and also the origin point of the testing process. The XY stage will move the sensor unit from point 1 to point 2, point 2 to point 3, subsequently moving to point 5. At all these five points, color temperature measurement and calculation will be controlled by the VEE program and will start to execute once the motor arrive at that position. After the measurement at point 5, the sensor unit will be moved back to origin, and wait for further commands for the next test cycle. The choice of the positions of these points is based on the size of the LCD screen by modifying the preset count value for the total counter number from the index signal.

There is also a checking algorithm added in the prototype system: Absolute error checking and relative error checking. For the absolute error checking, it checks if the color temperature measurement result of a single point is in the preset range. Normally, for a good LCD screen, its color temperature can be in the range [5000K, 9300K] according to the preset of the manufacturer. If the color temperature of a single point falls out of this range, an alarm will be triggered and the sensor unit will move back to the origin. The system will stop any further measurement of this LCD in order to save time. The relative error checking will be performed after five points measurement processes have finished. Relative error checking will compare all the measurement data at these five points and check their percentage error. If it is out of the preset range (default 5%), this is treated as failure, too. An alarm will be triggered, XY stage will reset to origin, and the whole system will stop. The flow chart of the integrated system is shown in Fig. 4.

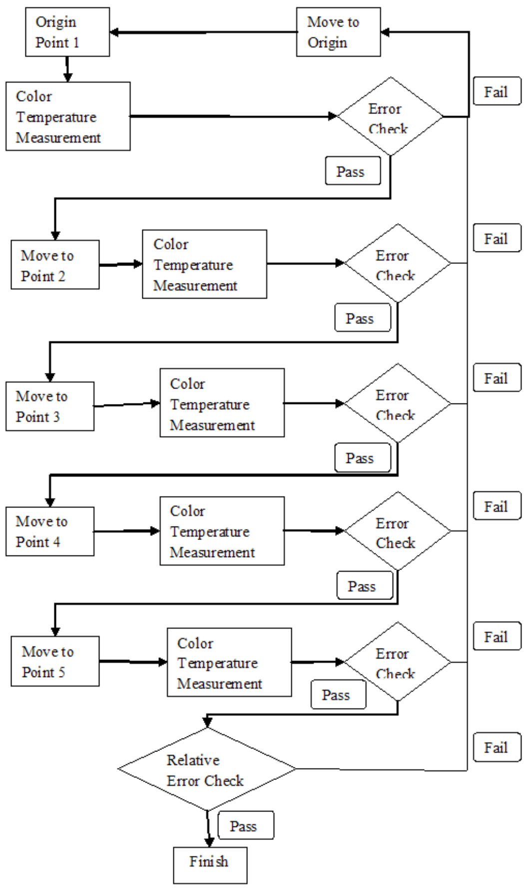

Fig. 4. Flow chart of the integrated system

Fig. 5. System user interface design

As a software emulated measurement and control system, the user interface acts as the virtual operation panel. User interface is very important as it allows the system user to use and handle the system efficiently. Fig. 5 shows the user interface design in this system. Once the user presses the “Start Measurement” button, the system will start. All the five points will be measured one by one, and the corresponding CIE chromaticity coordinates (x, y) and color temperature will be shown on a graphical scale. The result of the error checking will also be shown on this panel, by lighting a corresponding LED, where green LED means “pass” while red one means “fail”. Instead of showing both pass and fail LED as in Fig. 5, during the testing process, only one of the LED among the two can be shown each time. The single point error check is based on the required color temperature range that assigned by user. If the error checking fails at one point, meaning the measured data falls out of the range, the system will trigger an alert warning, abandon all current process and return the motors to the origin position. The final result of the current testing round will be shown on the right side in Fig. 5, after the relative error testing. The relative error check is based on the acceptable error percentage assigned by user (default is 5%). If all the results passed, then system will stop peacefully. If an unacceptable relative error was founded, an alarm will be triggered and the system will quit testing immediately.

Data samples are measured in order to observe the behavior of the LCD’s color temperature performance. As the initial objective of this project is to test the uniformity in brightness of the LCD screen, hence the main focus of the analysis is the consistency performance of the LCD color temperature on various points. If the measured color temperature results are within an accepted specified range, then the LCD passes the test. During the measurement test, a 14 inch LCD laptop monitor is used.

Table 1 shows the data measured at various points on the LCD with preset white color background, with points 1, 2, 3 and 5 are at the corner, while point 4 is at the centre. In the table, Vrout, Vgout and Vbout stand for RGB voltage output in volts correspondingly, x and y mean the chromaticity coordinates and CT means color temperature in Kelvin.

Table 1. Measured results

	Vrout	Vgout	Vbout	x	y	CT
Point 1	1.063323	1.033676	1.375928	0.296894	0.298493	7978.647
Point 2	1.065880	1.035615	1.375347	0.297118	0.298501	7983.213
Point 3	1.064325	1.038534	1.371094	0.297124	0.296365	7989.924
Point 4	1.065435	1.038130	1.374354	0.294222	0.298579	7972.282
Point 5	1.065731	1.031021	1.373537	0.297215	0.297888	7990.781

From Table 1, although the measurements are at different points on this LCD screen, the deviation of these color temperatures is very small, with the maximum deviation (which is between point 4 and point 5) only by 0.225%. This means the measured LCD's color temperature is almost equal on different points of the screen. This means the measured LCD has uniformity in brightness, which is the initially practical objective in the LCD manufacturing industry.

VI. Application in Quality Control Line

This system is designed for implementation in a quality control line in LCD manufacturing. A completed testing process includes five points color temperature measurements, measurement point movement, and data recording. A successful operation cycle of one LCD takes approximately 2 mins, so the average testing speed can be expected to be around 20-30 LCDs per hour.

The system can handle the testing of LCDs in various dimensions, by changing the parameters in the VEE program controlling the moving XY stage system. Such an easy re-configurability characteristic can guarantee the easy migration of this system for different size LCD manufacturing lines.

During the testing process, all the data measured will be stored in Excel to ease data analysis. So if any faulty LCD is figured out, the operator can trace the detailed failure reason by referring to the stored data. The Excel format is used as Excel supports many powerful data manipulation functions and is one of the most widely used formats.

VII. Future Works

In our present prototype, the XY stage is used, but it is a fixed instrument. The servo system has a limited dimension, with the measureable range is limited to approximately only 70cm by 60cm, which means the maximum screen it can measure is 35 inch. So in practical applications, in order to be capable of testing larger screens, an improved automated motion subsystem needs to be investigated. Possible solutions like the robot arms used in manufacturing industry can be considered. And for the software issue, further investigation could be taken in the current VEE programs used in this prototype system. Further improvements can be achieved in areas such as reducing the time in each LCD testing process as time is a precious and important issue in production.

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