Robust Testing of Displays using the Extreme Linear Dynamic Range CAOS Camera

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***Abstract*— Proposed and demonstrated for the first time is robust testing of optical displays using the extreme linear Dynamic Range (DR) CAOS camera. Experiments highlight accurate and repeatable CAOS camera-based testing of standard 8-bit (i.e., 48 dB DR) and modified DR 10-bit (i.e., 60 dB DR) computer Liquid Crystal Displays (LCDs). Results are compared with CMOS camera and light meter-based LCD testing highlighting the robustness of the CAOS camera readings.**

Keywords— Camera, Display Calibration, Display Testing

I. Introduction

The world is inundated with information that is being optically displayed to humans by a variety of display technologies of all sizes, shapes, types including classic 2-D displays, heads-up displays, and 3-D projection displays [1]. Dominant today are 2-D displays called LCDs, although other technologies have also emerged that include using LED array displays, flexible organic optoelectronic displays, and MEMS displays. Wide spread LCD technology is based on 8-bit gray-scale pixel brightness control, i.e., 48 dB Dynamic Range (DR) with 256 gray-levels, although interest in High Dynamic Range (HDR) displays has existed for over a decade [2-3]. The first commercial HDR LCDs are specified for 10-bits gray-scale or equivalently a 60 dB DR with 1024 independently controllable pixel gray-levels, e.g., HDR-10 standard. Very recently, Apple Corp. has announced an Extreme Dynamic Range (XDR) LCD [4] with very high 1600 nits (where nit = cd/m^2; Candela cd=W/sr; Lux= $Lumen/m^2$, Lumen= cd-sr; Lux= $cd\text{-}sr/m^2=W/m^2$) brightness with a 10^6: 1 contrast level indicating a 120 dB DR between the extreme pixel values. Clearly, there is a need for HDR displays given HDR camera technologies are also emerging to capture light information with XDR. Thus there is a need to make and test HDR and XDR displays for robust quality control of manufactured displays.

So far, display testing has mainly evolved using CCD and CMOS sensor cameras [5-7] that are suited for testing classic low DR 8-bit displays. Given both very high brightness and very low brightness measurement requirements for next generation HDR and XDR displays, typical CCD and CMOS sensors are facing a serious challenge for robustly testing such extreme DR linear gray-scale visible band displays, particularly for uncooled test systems. Specifically, CCD and CMOS sensors have non-linear responses over HDR and XDR levels, fundamentally limiting their use in reliable HDR/XDR display testing. Recently a new full spectrum XDR linear camera technology called CAOS (Coded Access Optical Sensor) has been proposed [8] and demonstrated. This camera has not only demonstrated a 177 dB linear XDR camera response, but it has also shown acquired image data to be robust versus deployed CMOS camera technology [9]. Given these two strengths, this paper for the first time proposes and demonstrates an approach to optical display testing using the CAOS camera.

II. Display Testing using CAOS Camera

Although most colour cameras ideally produce pixel specific electrical outputs that are proportional to the incident irradiance (W/m^2) values in the red (R), Green (G) and Blue (B) colour bands, these pixel-based light luminance (W) values are modified using a nonlinear gamma encoding transfer function to mimic the non-linear (e.g., log function by Weber-Fechner law (1834) [10] or power function by S. Steven (1961) [11]) perceptual response of human vision in order to show perceptual uniformity and minimal image artifacts in the recreated image on the display. It is claimed by prior art psychophysical experiments that human vision sensory systems cannot differentiate between luminance (which is proportional to intensity) level differences of <1% , i.e., ratio of two luminance levels is less than 1.01 [12]. This prior-art data in-turn implies that not all gray-scale levels in the higher brightness gray-scale region in an N-bit image with 2^N gray-scale values have visual utility to humans, thus one reduces the total number of stored gray-scale levels (i.e., equivalent encoded relative levels between a black 0 level and a maximum level, e.g., 255) required for effective human viewing of displays. Hence, most modern human vision displays are fed by data storage efficient gamma encoded image data that undergoes an inverse gamma transformation within the display unit to produce the selected human viewed optical display gray-scale pixel values [13]. For example, raw image data generated by modern HDR (e.g., 10-bit) cameras are stored as compressed 8-bits/pixel JPEG image files using the mentioned nonlinear gamma encoding. Note that if gamma encoding is not used to exhibit perceptual uniformity in a displayed image, each colour channel needs 11 bits or higher versus the fewer 8-bits/pixel per colour channel. Both next generation displays and cameras are being designed for HDR and XDR levels representing relative luminance (dimensionless units) with 10 bits (e.g., for 10-bit studio digital video) and higher per colour channel capabilities, including 12-bits relative luminance (symbol Y) from 0 black state to 4095 brightest state for digital cinema images and some studio digital video standards. Motion picture digital cinema standards are using 16-bits for logarithmic encoding of motion picture scene referred image data, and the benefits of perceptual uniformity are present for scenes with contrast levels reaching 2^{30}, i.e., XDR= 180.62 dB [14]. With these motivations in mind, this paper explores a robust and accurate test method for such advanced HDR & XDR displays, specifically, LCDs.

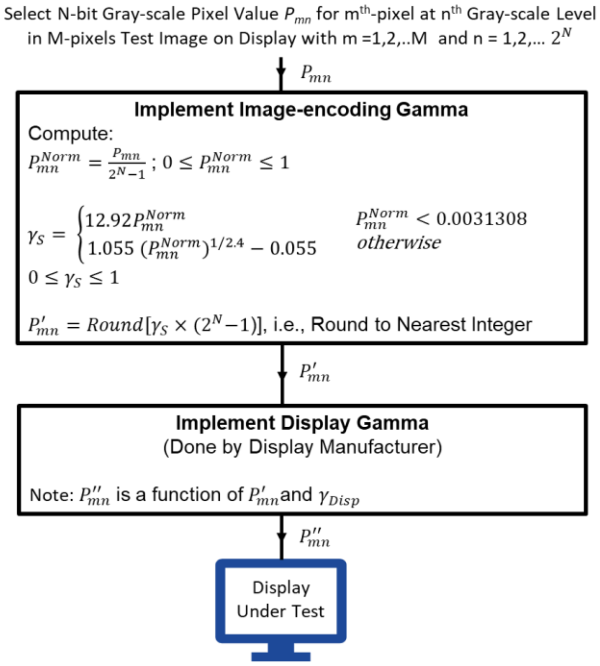

Fig. 1.Proposed CAOS camera based display test system - Flow chart step 1.

Fig.1 shows step 1 in the flow chart of the proposed display test system using the CAOS camera while Fig.2 shows the second step of the proposed display test system. Known N-bit n[th] gray-scale pixel value P_{mn} at the m[th] pixel is fed to the test system that generate light values I'_{mn} for the M pixels of the display that are measured by the CAOS camera. Pixel-based calibration errors for all M pixels and 2^N gray-levels is computed to determine the accuracy of the display gamma within the display system, indicating a measure of the quality of display image generation that furthermore allows optimization of the display under test. The CAOS camera is based on the TI Digital Micro-mirror Device (DMD) and its basic design is shown in Fig.3. The CAOS camera, as described in detail in earlier works [9], uses a coded time-frequency modulation of the incident light from the display to capture a linear XDR image of the displayed image. PD1 and PD2 are point detectors and L1, L2, and L3 are spherical lenses.

III. Experiments

The starting experiments conducted use a Dell latitude model 5480 colour FHD anti-glare 8-bit 1920 x 1080 (32.09 cm x 20.56 cm) LCD display with pixel pitch of 161 microns and a maximum brightness of 220 nits. The full 14-inch (35.56 cm) screen laptop is first programmed as a black-and-white display to generate 8-bits of 256 gray-scale levels of white light representations. A light meter is used to measure the programmed different light levels directly at the display surface. The Radionics light meter is model RS PRO RS-3809 with a 2.5 cm diameter semi-sphere, light reading levels ranging from 40 to 40,000 lux, spectral sensitivity near the CIE photopic standard curve, & best accuracy of ± 3%. Here, a single gray-level is put on the LCD per optical measurement. This LCD did not exhibit any optical flicker noise during testing, an important part of reliable testing. LCDs do not flicker when the LCD pixel drive voltage electronics is biased correctly by manufacturer for net zero voltage average signal on the LCD pixels.

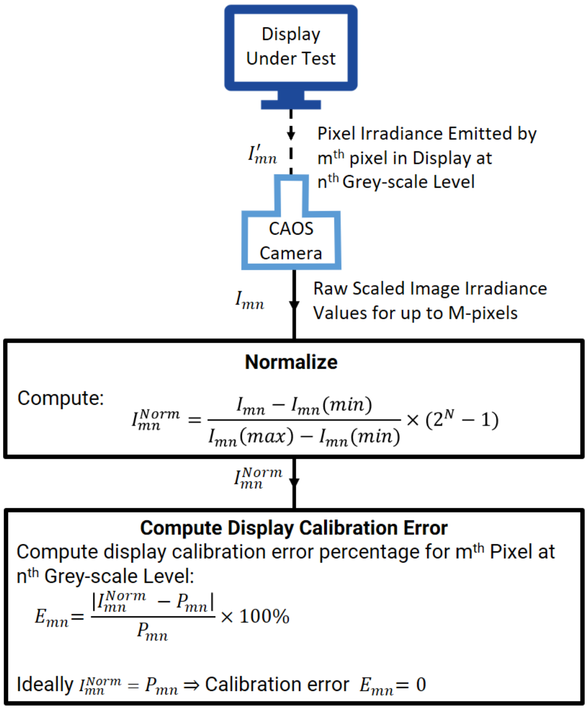

Fig. 2. Proposed CAOS camera based display test system - Flow chart step 2.

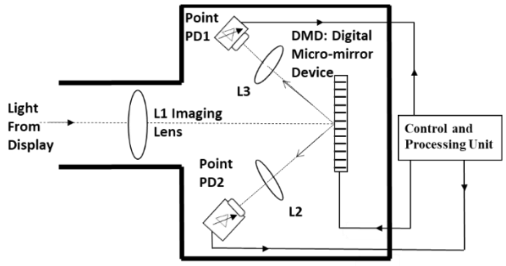

Fig. 3. Extreme linear dynamic range CAOS camera design.

Fig.4 light meter experimental data confirms that the 8-bit laptop LCD uses a display gamma as a linear pixel value input produces a non-linear displayed light output. Fig.5 shows the gamma encoded pixel values that should be input to the 8-bit display for its 256 gray-levels. The gamma encoded (i.e., corrected) pixel values are computed using the Fig.1 flow chart step 1 mathematical transformation. Next these gamma corrected pixel values are fed to the LCD and again the light meter is used to measure the light levels. As shown in Fig.6, the gamma encoded input to the LCD undergoes an inverse gamma in the LCD to produce the desired linear output light at the display that exhibits perceptual uniformity. Next, the LCD is imaged with a demagnification factor of 13.83 by the CMOS camera and the CAOS camera where the imaging lens L1 is a 2 inch diameter 6 cm focal length lens. The distances for experiment are: Display: L1=89 cm; L1: CMOS sensor = 6.4 cm; For CAOS camera Lens L2: Point PD1 PMT=8 cm. L2 has a 1 inch diameter and 4 cm focal length. The CMOS camera is an 87 dB DR camera from Thorlabs model CS2100M-USB Quantalux sCMOS sensor while the PMT is a Thorlabs model PMM02. The TI DMD is a Vialux DMD model V-7001. To take the gray-scale light readings using the CMOS and CAOS cameras, a 8.7 cm x 6.5 cm sub-section of the screen of the LCD (with the surrounding LCD border assigned a black 0 pixel value) is driven by a specific gray-

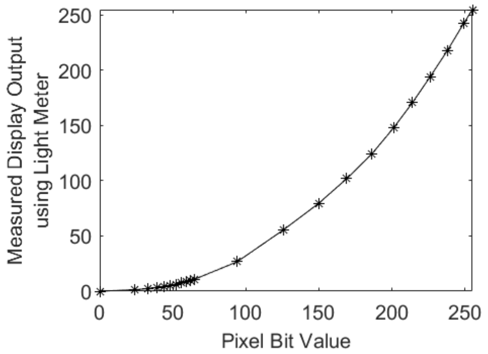

Fig. 4. Measured display irradiance from 8-bit Dell Computer LCD plotted vs applied pixel 8-bit linear gray-scale value.

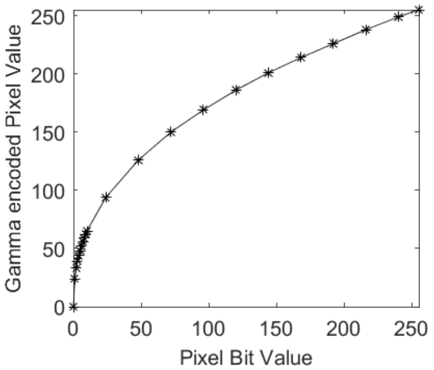

Fig. 5. Computed Gamma encoded (i.e., corrected) pixel value plotted vs pixel 8-bit linear gray-scale value

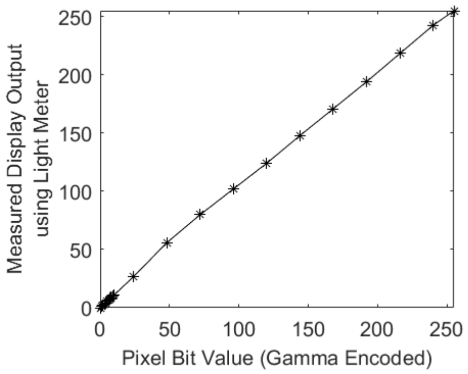

Fig. 6. Measured display irradiance from 8-bit Dell Computer LCD plotted vs applied pixel 8-bit Gamma corrected gray-scale value.

scale pixel value and the camera outputs are recorded. The PMT signal is fed to a 16-bit National Instruments DAC that connects to a control and processing Dell laptop. The CMOS camera produces 16 bit pixel readouts and are also processed in the laptop. Table I shows the implemented gray-scale level designed value versus measured data for the 8-bit gray-scale with 256 levels starting at 0 and ending at 255. Data shows 21 different gray-levels used in the testing. Table I shows that CMOS camera fails at the lower gray-scale levels and CAOS camera readings demonstrate good accuracy and robustness through the full 8-bit range even when compared to the light meter. To test a higher bits gray-scale range to form a 10-bit HDR display, the 1 gray-scale pixel value light level of the 8-bit LCD is optically attenuated one at a time by two different ND filters (i.e., with Transmission Factors T=0.5 and T=0.25 where $T=10^{-OD}$ and OD is Optical Density of filter) to give a 1020:1 light contrast between the 1 pixel value and the 1020 (i.e., 255/0.25) pixel value. Table II shows the relevant 23 readings of the chosen design pixel values versus the light-meter, CMOS camera and CAOS measurement methods. CAOS camera deploys its FM-TDMA mode for enabling high linearity, XDR, and higher signal-to-noise ratio (SNR) measurements. Table II results again point to the robustness and accuracy of the CAOS camera readings for testing the gray-scale levels of an HDR 10-bit range display.

TABLE I. 8-BIT GRAY-SCALE GENERATION DISPLAY TEST USING CAOS CAMERA, CMOS CAMERA AND LIGHT METER.

Measured Optical Readings				**% Errors**		
Design	***CAOS***	***CMOS***	***Light-Meter***	***CAOS***	***CMOS***	***Light-Meter***
1	1.4	2.7	2.3	35.4	173.7	131.8
2	2.3	3.8	3.7	17.4	89.7	85.5
3	3.3	4.8	4.2	8.7	58.9	39.1
4	4.2	5.8	5.8	5.6	44.7	44.9
5	5.1	6.8	6.5	2.6	35.2	29.8
6	6.2	7.8	7.4	2.7	30.7	23.6
7	7.3	9.1	7.9	5.0	29.9	12.6
8	8.4	10.2	10.2	4.5	27.0	27.5
9	9.5	11.4	10.9	5.8	26.3	21.1
10	10.7	12.6	12.8	6.5	25.7	27.5
24	26.1	26.7	27.3	8.8	11.3	13.8
48	54.8	56.8	68.6	14.1	18.4	43.0
72	78.2	78.9	80.0	8.5	9.6	11.1
96	99.6	100.8	102.0	3.8	5.0	6.3
120	121.5	123.0	125.2	1.3	2.5	4.3
144	145.2	146.9	148.6	0.8	2.0	3.2
168	168.2	170.3	173.9	0.1	1.4	3.5
192	191.2	193.3	194.7	0.4	0.7	1.4
216	216.1	218.1	231.4	0.0	1.0	7.1
240	240.7	241.9	244.3	0.3	0.8	1.8
255	255.0	255.0	255.0	0.0	0.0	0.0

To test LCD pixel format imaging, an initial 4x3 LCD pixel grid is mapped using both CAOS and CMOS cameras (see Fig.7). The grid assigned pixel values going top to bottom pixels and left to right column are 255, 240, 216, 192, 168, 144, 120, 96, 72, 48, 24, 255. The CDMA-mode of the CAOS camera is used to locate the 4x3 LCD pixel map and as seen in Fig.7, indeed matches what the CMOS camera captures. CDMA-mode used a Pixel value reading accuracy error compared to designed pixel values for both CAOS CDMA-mode and CMOS sensing are similar with ≤ 6.4 % error for the 8-bit gray-scale imaging test. CAOS CDMA-mode image used a 63 x 65 CAOS pixels grid, each CAOS pixels contains 10 x 10 micro-mirrors. Given the L1 imaging system used is a simple singlet lens, the imaging uniformity between the input image display space and output camera sensor space when observing the 4x3 pixels grid of the imaged display is not optimally uniform, i.e., each pixel in 4x3 grid has a different attenuating weight depending for example on the lens aberration effects. This non-deal lens design modifies the final pixel values presented to the camera detection planes and Table III highlights this limitation.

TABLE II. 10-BIT LCD GRAY-SCALE GENERATION DISPLAY TEST USING CAOS CAMERA, CMOS CAMERA AND LIGHT METER.

Measured Optical Readings				**% Errors**		
Design	***CAOS***	***CMOS***	***Light-Meter***	***CAOS***	***CMOS***	***Light-Meter***
1	1.6	6.4	0.9	56.6	539.3	7.3
2	3.1	8.0	2.7	52.6	302.3	34.5
4	5.4	10.9	9.3	35.4	173.7	131.8
8	9.4	15.2	14.8	17.4	89.7	85.5
12	13.0	19.1	16.7	8.7	58.9	39.1
16	16.9	23.1	23.2	5.6	44.7	44.9
20	20.5	27.0	26.0	2.1	34.5	29.2
24	24.7	31.4	29.7	2.3	30.2	23.1
28	29.4	36.4	31.5	4.6	29.4	12.2
32	33.4	40.6	40.8	4.2	26.6	27.1
36	38.1	45.5	43.6	5.5	26.0	20.7
40	42.6	50.3	51.0	6.3	25.4	27.2
96	104.5	106.8	109.2	8.5	10.9	13.4
192	219.1	227.3	274.5	13.8	18.0	42.5
288	312.6	315.7	319.9	8.2	9.3	10.8
384	398.5	403.2	408.0	3.5	4.7	5.9
480	486.1	491.9	500.7	1.0	2.2	4.0
576	580.6	587.6	594.4	0.5	1.7	2.9
672	672.8	681.3	695.5	0.2	1.1	3.2
768	764.9	773.4	778.9	0.7	0.4	1.1
864	864.2	872.3	925.4	0.3	0.7	6.8
960	962.7	967.6	977.3	0.0	0.5	1.5
1020	1020.0	1020.0	1020.0	0.0	0.0	0.0

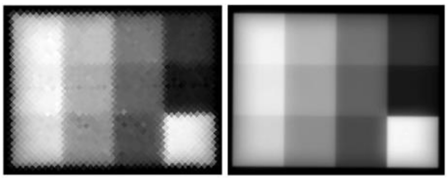

Fig.7. CAOS camera (left) and CMOS (right) camera seen LCD 8-bit gray-scale images with a 4 x 3 grid with 11 different gray-scale values.

IV. CONCLUSION

Proposed for the first time is the use of the linear XDR CAOS camera for next-generation display testing. Demonstrated are light-meter, CAOS camera and CMOS camera measurements for 8-bit and 10-bit gray-scale measurements using a commercial 8-bit LCD and modified LCD for 10-bit operations that highlight the accuracy and robustness of CAOS. Imaging of the 8-bit operation LCD is also demonstrated using CMOS and CAOS cameras. In future, one can envision a smart test system without special cooling that combines CAOS with traditional CMOS and CCD sensors to form a fault-tolerant test system that accurately and robustly measures both XDR gray-scale levels and display uniformity. As a closing comment, natural scenes have extremely varying dynamic ranges (i.e., max/min pixel light levels), adjacent pixel contrast differences, colour content and overall lighting levels. One cannot simply assume that scenes presented to the human eye always satisfy the near 1% luminance difference criteria that prior-art suggests is required to create perceptual uniformity for human vision. This in-turn may suggest that optical display provided perceptual uniformity for human vision may not be as critical an image quality requirement as one may have thought. Recent research is also suggesting that for high DR displays, conventional (gamma encoding) mapping "increasingly diverges from a perceptually uniform mapping, so 8-bit gray-levels are increasingly inadequate" [15].

TABLE III. 8-BIT LCD GRAY-SCALE IMAGE PIXEL VALUE MEASUREMENTS USING CMOS CAMERA AND CAOS CAMERA.

Design	**CMOS**	**CAOS CDMA**	**Design**	**CMOS**	**CAOS CDMA**
255	255.7	250.6	144	152.3	150.9
24	28.0	25.2	168	177.7	179.3
48	55.1	55.2	192	194.0	201.3
72	83.3	80.6	216	218.4	225.5
96	106.2	103.6	240	246.1	253.2
120	123.1	126.9	255	254.3	259.4

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