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Beyond Limits of Current High Dynamic Range Displays: Ultra-High Dynamic Range Display

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Abstract

In this paper, statistics such as distribution of peak luminance, region of peak luminance in frames, colors of high dynamic range contents are analyzed Based on the analysis, essential requirements for future high dynamic range displays are discussed. For our statistical study, various types of high dynamic range content that have been provided by studios or content providers are considered. Since they have been being supplied by limited studios and network-based content providers, a large amount of the content is movies that utilize limited dynamic range, average luminance and color gamut compared with the other dynamic contents. In spite of the trend, we claim that capability of high dynamic range displays do not need to be restricted by considering the current content industry since very bright high dynamic range contents that have higher luminance and wide color information absolutely need to be also considered when defining specification of future high dynamic range displays. To support this fact, we review the analysis results and requirements which are needed to sufficiently represent vivid high dynamic range presentation to match the human visual perception capability.

Introduction

The luminous intensity of the real world scene varies in a wide range, approximately from around 10^{-3} nits (cd/m^2) of luminance of the moonlight to 10^5 nits of the sunlight [9, 14]. Ideally, high dynamic range (HDR) images store pixel values that span the whole tonal range of real world scenes. While low dynamic range (LDR) such as 8 bit/color channel JPEG format image cannot exceed the range of [0-2^8-1] code levels, HDR images of wide luminance range [0-2^{32}-1]) can show the dynamic range of real world as human eyes see. Figure 1 conceptually shows visual differences between LDR and HDR images [8, 7, 11].

For providing more realistic visual experience of the LDR and HDR contents, many of current commercial HDR displays support an extended range of luminance and color ranges. To show HDR content on screens such as LDR and HDR, two signal conversion functions are required, that is, the Opto-Electronic Transfer Function (OETF) and the Electro-Optical Transfer Function (EOTF)[9, 10]. OETF of capture devices converts the luminance intensities of real world scene to the digital code values. while EOTF converts code values to the luminance intensities in modern electronic displays. These transfer functions are defined in standards for LDRs in Rec.709 and Rec.1886, respectively.

Figure 1: LDR and HDR images. (left) LDR image (right) HDR image, peak luminance and colorfulness of HDR image are higher than LDR image.

Since Rec.1886 was designed for the display of the LDR image/video, recently, new EOTF conversion schemes for HDR displays have been defined. A perceptual quantizer (PQ) EOTF for HDR displays was defined by the Society of Motion Picture and Television Engineers (SMPTE) [5, 6] On the other hand, the British Broadcasting Corporation (BBC) proposed the Hybrid Log-Gamma (HLG) OETF. Generally, PQ is an absolute (display-referred) signal and HLG is a relative (scene-referred) signal. Scene-referred signals that represent the light intensity relatively to the peak luminance intensity are relatively conventional approach to video signal. Absolute signals such as PQ and PQ-based EOTFs (e.g. Dolby Vision, HDR10 and HDR10+) that contain the absolute luminance (10K nits) of every pixel are fundamentally different opto-electronic transfer systems.

To visualize HDR images on screen, display technologies have diversified tremendously over several decades [7, 5, 9, 10, 12, 13]. From cathode ray tube (CRT) display to the widespread organic light emitting diode (OLED), Laser based displays and state-of-the-art thin film transister (TFT)-liquid crystal displays (LCD), display industries are still working to improve display attributes. They (the capabilities of a display) can be categorized as contrast ratio, peak luminance, black Level and color gamut/volume coverage. As more full-scale HDR imaging and content emerges, display era are required to be more dramatically improved for fully supporting the HDR information such as higher peak luminance and wider color gamut than before. Fundamentally, the requirements for HDR displays came from capabilities of human eyes (i.e. human visual system, HVS) and hence HDR displays are required to allow human eyes visually experience what they see the real world on displays.

This study is initiated because HDR imaging techniques, standards and displays were developed to let people enjoy the most realistic perceptual experience as possible on screens. In that view point, we need to investigate where is the commercial HDR content and display industry today. The analysis of current HDR content and display can be meaningful for defining future HDR displays. By analyzing distribution of peak luminance, area of peak and color gamut of recent HDR contents, we want to glance at current capabilities of HDR images as containers and then estimate essential requirements for future HDR displays. In this study, many kinds of HDR contents that have been provided by studios or some kind of contents providers are analyzed. Analysis result may be limited since the large number of the contents is movie genre that has very dark tone and small peak regions. In spite of this handicap, based on the analysis result, essential requirements for future high dynamic range displays are discussed.

Related Work

We are strongly motivated by related work and recent advent of display technologies. J.-U. Kwon et. al reported the statistics of Korean broadcasting videos and IEC62087 standard video in terms of peak size, accuracy for representing gray scale and black level [4]. Based on the analysis and measurement by employing the metric 'luminance error' they insisted that OLED TVs are better for representing creative intends than the other displays. To validate their claims, the authors introduced two displays (an OLED and a LCD). The output luminance capability $L_{display}(Maximum, Average)$ of the displays were L_{OLED}(410 nits, 150 nits) and L_{LCD}(810 nits, 350 nits) for the loads of input images were 10 and 100 percent full white box, respectively.

Y. Park et. al also presented similar work and analysis results [12, 13]. They described three important properties (the average luminance level maximum luminance levels and sizes of peak regions) of real HDR images obtained by analyzing contents. First, real HDR content was analyzed. The maximum content light level (MaxCLL) and maximum frame average light level luminance level (MaxFALL) $L(MaxCLL, MaxFALL)$ was L(1324.95 nits, 46.14 nits), respectively. Additionally, according to the reported analysis result of peak regions, 90 percentile value of cumulative distribution of the peak region are about 0.2 percent of input image size. For a distribution of color information in real HDR content, the authors presented an interesting analysis, which only small numbers of color pixels are over DCI-P3 color gamut. Based on the analysis, they proposed a design guideline for making HDR test patterns in various HDR display metrologies.

J.-J. Yoo et. al proposed the similar proposal for HDR display metrology [4, 12, 13]. The authors claimed that the most of current test patterns for HDR, such as Ultra High Definition Alliance (UHDA), International Committee for Display Metrology (ICDM) and International Electrotechnical Commission (IEC) cannot reflect recent HDR displays' performance. To support the authors' claim, they cited recent work above and proposed a small patch overlaying strategy which placed a patch at the center of each HDR content. The patch size was proposed as 0.2 percent size based on the authors' previous work. However, the analysis results are somewhat limited in generalizing the statistics of HDR content.

On the other hand, a psychophysical study on viewers' preferences for shadow and specular luminance of high dynamic range displays was reported [9, 10]. By building a HDR display with a 5M:1 contrast ratio, the study covered preference luminance limits which can be a useful and important design consideration for HDR displays industry. In key summary, 50 and 90 percent of a technical sub-group viewers are satisfied with [from black - diffuser white level]=[0.04 nits-690 nits] and [0.001 nits-4700 nits], respectively. Based on the psychophysical experiments and analysis, they provide luminance requirements of future HDR displays' capabilities.

HDR Content and Display

High dynamic range technologies and displays have been considered as something new for the next generation. In this field, the higher performance of displays is, the better visual experiences can be made on screen. However, display devices have their own capability limitations that can be caused by limits of light materials, efficiency, power limits and so on. Therefore, a display which is free from the limitations may have more opportunity for future high dynamic range display than others.

Content creators and providers have been releasing HDR contents that contain higher luminance and wider range of color information. The advent of new standards for containing HDR images has been driving display industry to be improved with advanced display technologies. On the contrary, technical advent of HDR displays may accelerate the HDR imaging technologies. However, HDR image formats can be regarded as kinds of containers that include scene information, that is, people cannot experience HDR scenes on screen without HDR capability even if HDR contents and imaging technology will be developed so rapidly. In this respect, HDR images and displays is highly correlated and balanced advance in both of them strongly required.

With reflecting our point of view as described above, statistical analysis is conducted with real HDR movie contents in this paper. The real HDR movie contents are examined in terms of peak luminance, its region in scenes and color distributions on CIE1931 chromaticity *xy* color gamut area. Most of all, peak luminances of the HDR movies and the ratio of the size of peak luminance region are analyzed. For the peak luminance of each content, the average, maximum and percentile peak levels of the HDR content are measured, since these luminance attributes may affect the HDR displays' performance. Furthermore, we investigated the statistics of peak regions since it is a kind of main factor that determine HDR display's driving scheme with respect to their maximum load of them. Generally, to reproducing higher peak luminance on screen means that it can make human eyes experience images with better HDR effect. For the analysis of color distribution for HDR contents, pixel information is sampled and plotted on CIE color gamut space In the next section, the results of analysis are presented.

Content Analysis

There are so many variances in luminance range, peak areas and color distribution in high dynamic range contents (see Figures below). Even though the analysis process should be done further, we believe that we can conclude this paper as follows. The HDR display needs to have a wide variety of color palettes that are capable of expressing rich colors like the natural world provides. In addition, the display must be capable of expressing high brightness so that the color can be accurately expressed for any luminance ranges. These should be essential requirements of high dynamic range displays for the future.

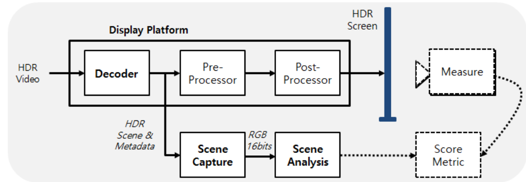

Figure 2: Bock diagram of our display system used for analysis. Dashed lines and boxes are our future work.

HDR content

Total 13 HDR contents consisting of 11 HDR movies and 2 HDR documentary contents were selected by examining SEI message which contains mastering information such as peak luminance and color gamut of the mastering display and contents information like MAX-CLL and MAXFALL. All the contents were played in Blu-ray disc player, where each frame information per every 5 seconds was examined by implemented FPGA module with software programs for analysis. Most of them were encoded by PQ HDR encoding standard and they have [minimum-maximum]=[0.0001-1000] nits luminance and DCI-P3 color information. In the Table 1, the summary of statistical analysis is presented. For the color distribution analysis, extremely low level (under 0.01 nits) pixel information was excluded since the low luminance pixels have useless color information while plotting them on CIE1931 chromaticity *xy* color gamut area.

Analysis system

Figure 2 shows the our display system for obtaining and analyzing scene information. The decoder part parses every HDR information (metadata) with respect to peak luminance level and color range) and captures statistics of HDR images which are used for analysis and an inverse tone mapper (reverse PQ) and bit depth operations are employed in our display system to visualize the images on SDR screens. For all HDR contents, statistical informations are grabbed periodically with original image resolution.

Average, peak and percentiles of luminance levels

For a given frame information, peak luminance level, average luminance level and peak luminance levels

Table 1: Summary of statistical analysis of 13 HDR contents. (from left to right) labels of contents, peak luminance of the contents, 99.9 percentile value of the peak luminance of each content, average peak luminance of all frames, 99.9 percentile of average peak luminance, average luminance of content, ratio of pixels in BT.709 color space, ratio of pixels in DCI-P3 color space and ratio of pixels out of DCI-P3.

Label	Peak Lv /Content	99.9Prct Peak Lv	Avg. of Frame Peaks	Avg. of 99.9Prct	Avg. Lv /Content	Ratio(%) In BT709	Ratio(%) In DCI	Ratio(%) Out of DCI
1	399.2	182.7	138.3	14.4	14.5	89.2	99.5	0.5
2	1022.5	926.2	469.3	41.9	42.4	93.9	99.5	0.5
3	985.3	216.5	153.8	17.2	17.4	98.5	99.9	0.1
4	997.1	782.7	432.9	29.5	29.8	82.2	98.9	1.1
5	227.1	118.1	99.6	20	20	80.8	85.9	14.1
6	893.2	576.2	301	25.1	25.4	97.5	99.8	0.2
7	989	581.4	268.5	19.9	20.2	98.5	100	0
8	544.1	202.6	134.5	13.7	13.8	86.5	95.7	4.3
9	964.6	447.8	190.6	12.8	13	82.5	98.2	1.8
10	650.6	275.6	186.9	17.2	17.4	94.3	99.5	0.5
11	943	822.3	564.7	33.1	33.7	82.4	97.3	2.7
12	3820.8	849.6	534.3	36	36.4	87.9	98.9	1.1
13	2978.2	731.7	432.9	15.9	16.3	98	99.8	0.2

and content were analyzed and illustrated in the figure 3. They luminance values are represented in nits (cd/m^2). There are two types of information, one is for each frame information (labeled as 'Frame') and another is for each content (labeled as 'Content'). Sampled frame information is analyzed one by one. The statistical information presented in the Table 1 is average values of these frame information. As can be seen in the figures for each content, there are wide variation in peak luminance of each frame. Content No. 12 and 13 have very higher peak values since they were mastered in the display with 4000 nits max luminance.

On the other hand, ratios of peak areas on each frame information were analyzed. There is very important meaning of this analysis for HDR metrologies. Most of the LDR or HDR metrologies have been introducing white patches (from 0 to 100 percent white box) for measuring output luminance on screens. It is highly related with the load of input images, that is, conventional metrologies have been referred the ratio of peak areas as load of scenes. According to the papers in [12, 4, 13], the ratio of peak regions in a frame were found to be very small, which may need a change on the display measurement methodology. However, since the analysis was conducted with very limited number of test contents, we did the similar analysis with more test contents instead, for finding better statistical ground.

Our analysis shows different result from previous result in [12, 4, 13]. To detect the peak region, the sampled frame information of input videos are filtered by employing edge-preserving smoothing filter [15]. In this step, a parameter for smoothing is minimized and parameters for preserving strong edges were maximized for avoiding expansion of peak areas by this processing. And then all pixels over 80 percent (800 and 3200 nits in 1000 andd 4000 nits contents respectively) of peak luminance were regarded as lighted pixels and they were counted for measuring the ratio of peak area in a given frame. As a result of our analysis, average ratio of peak regions for 1000 nits and 4000 nits HDR contents were 4.86% and 6.17%, respectively. What we definitely want to say is that the ratio of peak regions were much larger than expected. In that sense, we may consider the patch sizes of conventional UHD and HDR metrologies are quite reasonable. Note that the ratios cannot be representative values for all HDR contents. They should be limited in our analysis method and contents. Therefore most of the metrologies have been introducing reference videos or images and hence a very reasonable and representative HDR reference images or videos are strongly required for standardizing better HDR metrologies.

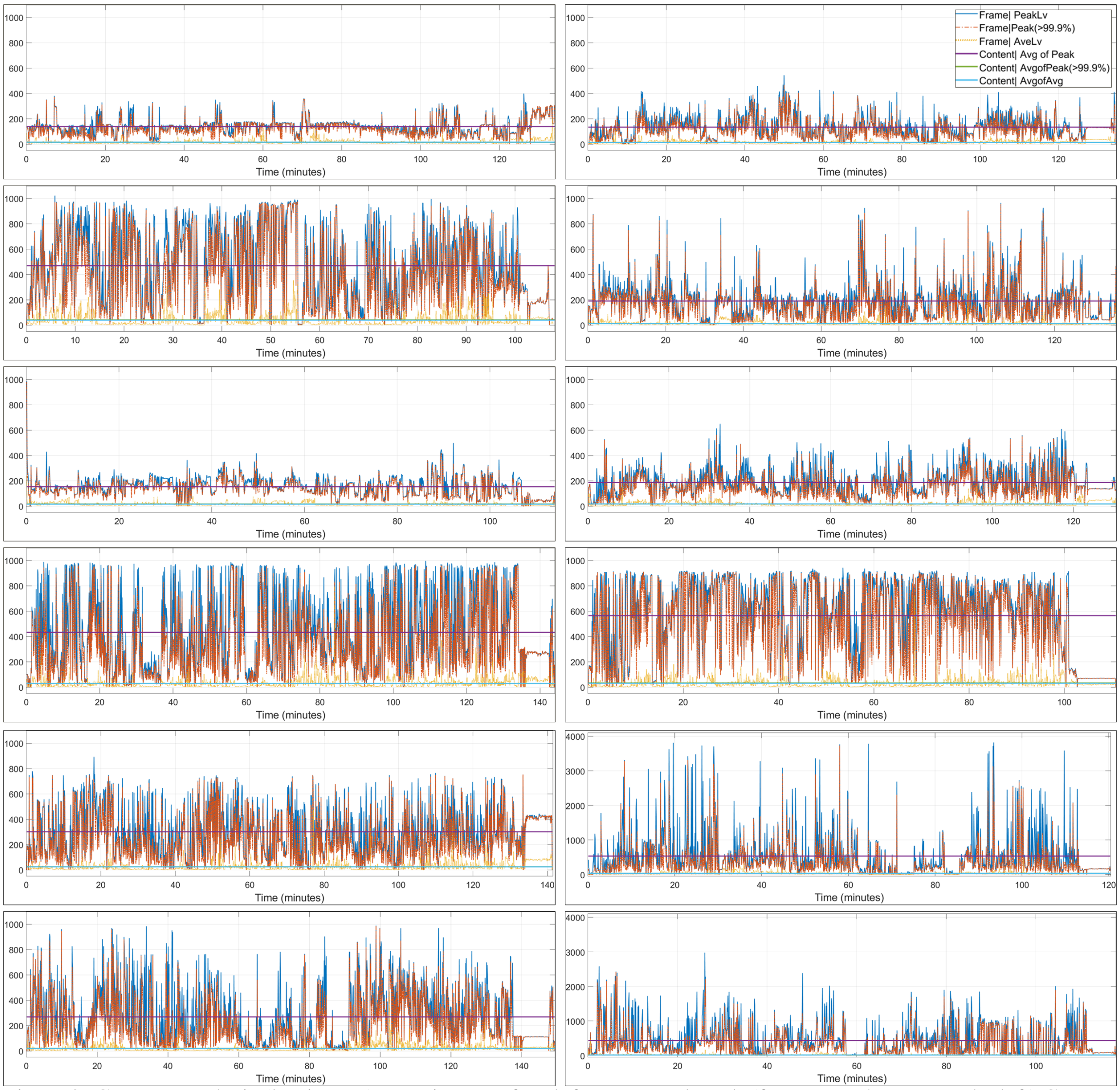

Figure 3: Contents analysis (luminance). Luminance of each frames are plotted. (from top to bottom on the left) Content No. 1 7, (from top to bottom on the right) Content No. 8 13. Content labeld as No. 5 is excluded due to page limit.

Color distribution

HDR contents analyzed in this paper have BT.2020 color gamut but it is very important how much effective pixels are sitting on the CIE1931 chromaticity *xy* color gamut area. This analysis is meaningful for designing display products like that we studied luminance information. Most of the HDR displays cover 90% of DCI-P3 color gamut at least. Is it enough for supporting the future HDR contents? Statistical analysis of color distribution for real HDR content was conducted to determine how much colors information stands in or out-of DCI-P3 color gamut. We found very interesting fact that some of the HDR contents have very wide range of color information over DCI-P3. Since most of the recent HDR displays just support 100% of DCI-P3, the specific contents cannot be visualized on such screens.

For the study, some of the pixels from each frame information were sampled uniformly and then *xy* coordinates on CIE1931 chromaticity color gamut area were obtained computationally. The results are shown in the Figure 4. As we se, so much portion among the sampled pixels are standing out of DCI-P3 color range. To show more our analysis results visually, Figure 5 is presented. Note that very low luminance information under 0.01nits are discarded in this analysis since we found that the color information of the pixels are not meaningless in this study. If they are included the statistics, the ratio of out-of DCI-P3 color range become dramatically larger than before.

Requirement of future ultra-HDR displays

In [16], authors examined the field of HDR video ecosystem (from capture to display) and its past, present and future. For the future of HDR, they pointed out a very important new wave of HDR technology, that is, the industry has been being "display referred". As the authors stated in the paper, HDR technology already has sufficient ability to provide a better experience of the actual dynamic range in the scene. Based on the recent technical trend of HDR videos and displays, we define the requirements of future HDR displays. 10,000 nits HDR display will be preferred. Standardization of HDR video and Codecs (HDR10/10+, PQ and HLG) prove it. Considering the state-of-the-art 8K display now support up to 4,000 nits currently, that is not a unrealistic specification. To fully exploit the HDR videos, spatial resolution of HDR displays should be 8K since human eyes sense realism while seeing high resolution screens. High frame rate over 120Hz is also one of the critical requirement for HDR displays. Since human eyes are very sensitive

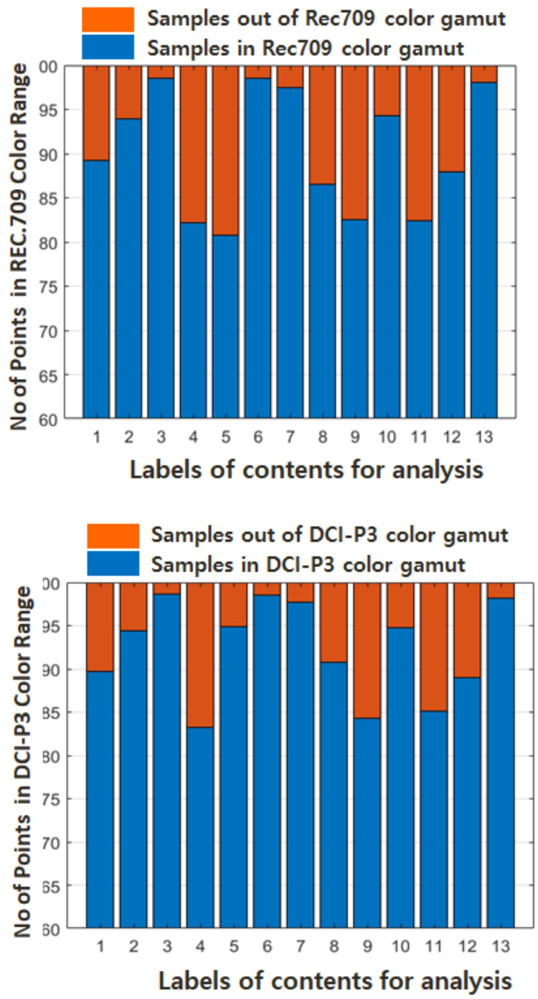

Figure 4: Contents analysis (Color distribution statistics). (top) Ratio of pixels in- or out-of Rec.709 color range, (bottom) Ratio of pixels in- or out-of DCI-P3 color range. As expected, most of pixels stand in Rec. 709 color range. However, quite so many pixels are out of DCI-P3 color range as illustrated in this figure at the bottom. To investigate if they are meaningful or not, we extracted the pixel information and plotted on the color space and then found that many of the pixels out of DCI-P3 have extremely low luminance values. That is, the color information of the pixels of DCI-P3 color range are not useful in our statistical study and visual effect on screen as well. Finally, we omitted the pixel information while counting the pixel numbers in- and out of- the color ranges and measuring the ratios.

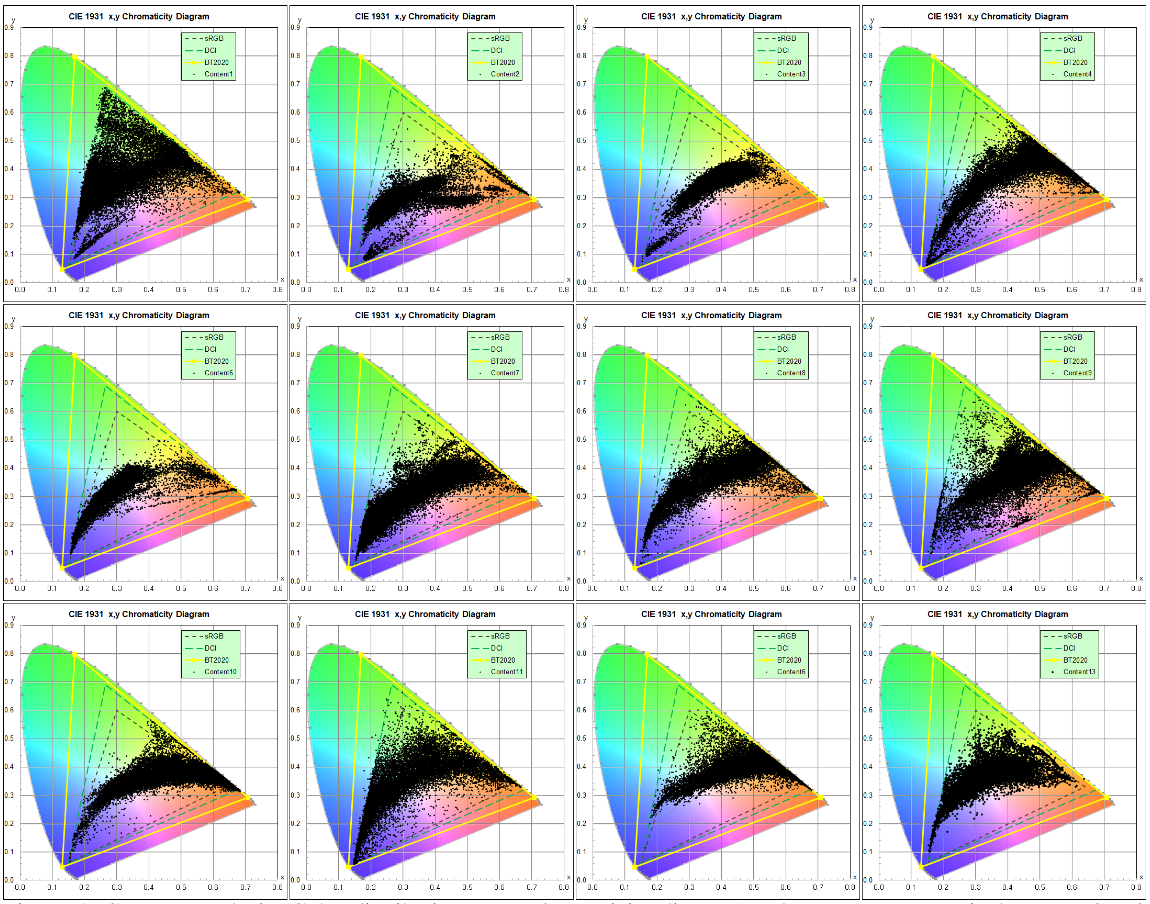

Figure 5: Contents analysis (Color distribution on *xy* chromaticity diagram). There are so many pixels over DCI-P3 color space, specifically so many pixels over DCI-P3 are standing the Red-Yellow-Green. (Content labeled as No. 5 is excluded due to page limit.)

for motion pictures and artifacts while seeing moving objects, higher frame rate display is preferred for visualizing realism of HDR videos. Finally, wider color gamut over DCI-P3 (up to BT.2020) and large color volume in high peak luminance areas are strongly required.

HDR Metrology

Standardizing metrologies for HDR displays has been one of the main issues in the HDR industry [2, 3]. To evaluate how well HDR displays represent HDR images on their screens, many kinds of HDR metrologies have been proposed. Standardization groups such as IEC and ICDM have been considering their specific measurement and evaluation method for HDR displays. It is natural that the metrologies for HDR displays be well designed to identify which displays can show better HDR videos and images. However, in this designing process, there have been a very critical 'dilemma'. 'How can a HDR metrology including measurement method, procedure, test pattern and score metric have representativeness?' that is, 'can we fairly test or evaluate every HDR display by using one standard? Probably designing every metrology is in this question as well.

To my best knowledge, most technical engineers agree that a HDR metrology should reflect the real visual perception of human eyes. In other words, if a test pattern and measurement items well reflect the perception characteristics of human eyes and hence the two (scores from evaluation and visual perception) match, that would be the best metrology. How could we make a representative HDR video or image for test matrix (measurement & dependency) of HDR? Due to this kind of reason, most evaluators have been still using various formulaic test patterns such as white patches rather than absolutely defining one metrology.

With the result of this study, we clearly learned that we still cannot clearly define anything now for HDR metrology because of the following. Specifically, it cannot be identified clearly by reflecting limited trend of current HDR contents since they are just container that include scene information and creators' intent. They shall be consistently improved for containing much wider luminance and color information so that they can meet human visual systems like we see in the real world. If a party insist that very tiny patch on real HDR video or image is used as proposed in the paper [4, 12], the others may still have the question, 'how was the size of patch defined? can it be a representativeness?'. We had better to take more time for discussion and development for fair and effective HDR metrology in standardization groups with observing the future progress of HDR content industry. If someone wanted to evaluate the performance in terms of some specific characteristics of HDR displays, some of the conventional test method such as UHDA patterns can be chosen as the evaluator's intent.

Conclusion and Future Work

In this paper, based on the analysis of various HDR contents, essential requirements for future HDR displays are discussed. In spite of the limited trend of HDR contents, we claim that capability of HDR displays does not need to be restricted by considering the current content industry. Some of very bright HDR contents absolutely need to be also considered when defining specification of future HDR displays. To support this very basic fact, we review the analysis results and defined requirements that are required to sufficiently represent vivid HDR visual appearance as human can see it in nature. Furthermore, to introduce any new metrology for HDR is very carefully considered like as all of the current metrologies have been defined based on very reasonable reason.

As illustrated in Figure 2, we did our analysis on just HDR videos. To fully support and validate our claims of this paper, we'd better show the data analysis with corresponding measurement result on HDR screen that fully supports the scene specifications indicated in the HDR metadata. Recently, state-of-the-art HDR display with 120Hz refresh rate, 8K (7680x4320 resolution), up to 4000 nits peak luminance and vivid colorfulness of DCI-P3 color range is already implemented by our expert group and it remains for our further study.

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Author Biography

Jae Sung Park received the BS and the MS degrees in college of electronics and information engineering from Kwangwoon University. Since 2007, he has been working for the Visual Display Division in Samsung Electronics in Korea. Meanwhile, in 2017, he received his Ph.D in electrical and computer engineering from Seoul National University, Seoul, Korea. His research interests include display devices, display techniques, display metrologies, image processing for enhancement, computer vision and deep learning application for display systems.

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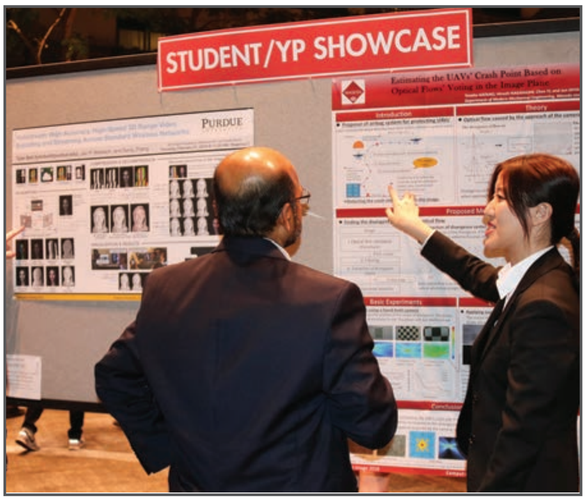
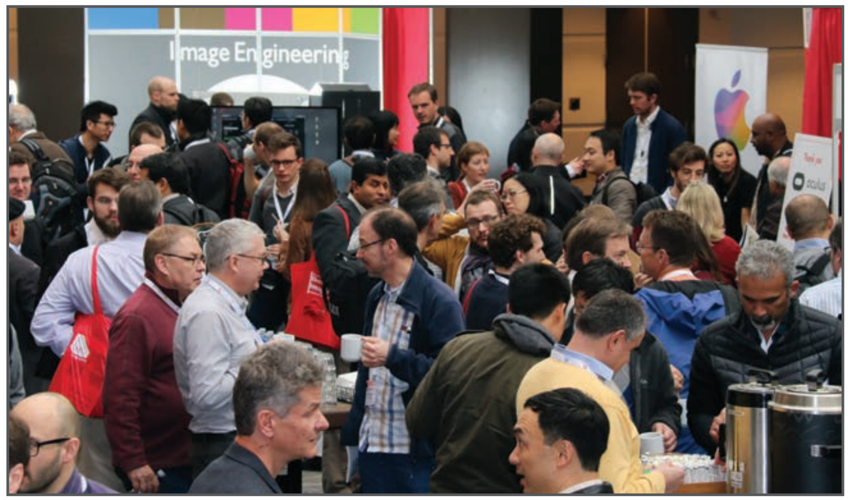

STUDENT/YP SHOWCASE
PURDUE




AR is a fundamental and transformative interface and platform.
20+ years from my initial working demo to today's AR displays
Optimistic that it won't take another 20 to reach ubiquitous consumer AR!
My first working AR prototype
Today's platforms
Ubiquitous consumer AR