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”Rendition techniques for HDR Scenes in Painting, Photography, and Electronic Imaging”

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RENDITION TECHNIQUES FOR HDR SCENES IN PAINTING, PHOTOGRAPHY, AND ELECTRONIC IMAGING

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ABSTRACT

Painters have reproduced High Dynamic Range (HDR) scenes for 5 centuries; photographers have used multiple exposures for 165 years; scientists have used electronic imaging modifications of range for 50 years. This paper reviews the history of the different rendition techniques. Some techniques use trial and error to find the best rendition. Others use psychophysical models of human vision, or physical models of color cameras. All techniques use the partnership of the physics of light, and the psychophysics of human vision.

Index Terms - HDR reproduction, HDR scene capture, glare, models of vision, models of cameras

1. INTRODUCTION

The range of diffuse surface reflectances of objects is small. A white object reflects roughly 30 times more light than a black one. High-Dynamic-Range (HDR) scenes are the result of nonuniform illumination caused by shadows, and light sources in the field of view.

Painters, photographers and early HDR electronic imaging algorithms reproduced the appearance of HDR scenes in Low-Dynamic-Range (LDR) reflective media. The key element used by these approaches was the Human Visual System (HVS). Painters observed the appearances in the HDR scene and then found, by trial and error, the mixture of paints' reflectances that matched those appearances.

Since the earliest days of silver halide (AgX) photography, multiple exposures have been used to capture scene radiances that exceeded the sensitivity range of primitive emulsions. Again, the photographers matched the appearances of the scene, since they could not capture and reproduce the actual radiances.

Early electronic image processing in the 1970's used scans of high-dynamic-range films to capture as wide a range of radiances as possible. In this imaging chain, an algorithm introduced a model of human vision to calculate appearance. The final step was to write the calculated appearances on LDR film. [1; Ch 7]

Later in the late 1990s, digital imaging hardware reached maturity and a new set of goals evolved. This new generation of HDR imaging attempts to capture and reproduce the scene's radiances. These applications redefined the century-old multiple exposure techniques to measure scene radiances.[2] A new generation of HDR displays introduced brighter whites and lower luminance blacks in displays by combining LED emitters and LCD light modulators [3]. The combination of digital scene capture and HDR displays attempts to meet a new challenge, not used in earlier HDR reproductions. It attempts to accurately reproduce the scene radiances. It goes without saying, that if every point of light in the observer's field of view is an exact reproduction of the scene's radiances, then the scene and the reproduction must appear identical. However, practical technology issues prevent us from reproducing accurate radiances at every pixel.

2. PAINTING

For centuries, artists have created paintings that reproduce the appearance of HDR scenes in Low-Dynamic-Range (LDR) reflective media. Early Chinese scroll paintings reproduced people in uniform illumination on an unpainted scroll background. Early Renaissance painters reproduced their subjects in uniform illumination. Da Vinci, Caravaggio, Rembrandt, van Honthorst, Constable, and Martin, synthesized HDR scenes in Low-Dynamic-Range (LDR) media - oil on canvas. [Examples of painting that illustrate this review of HDR techniques are found in the Supplementary Materials File.] [4] The painters technique for reproducing HDR scenes used the approach of matching the appearance of the scene. The painter used his Human Visual System (HVS) to render the scene as it appeared to him. There was no attempt to reproduce scene radiances. Painters matched appearances. Skilled painters learned how to spatially render the scene to create HDR appearances in LDR media. The painter's HVS was the most important signal processing component.

3. PHOTOGRAPHY

Multiple exposures of silver halide photographs are found in the early 1850's. Edouard Baldus used 10 negatives to make the print "*Cloisters of the Church of St. Trophime, Arles,*" in 1853.[4, 5] The emulsions of that era had limited dynamic range. Taking a series of photographs with different exposures recorded different light ranges of the scene. Combining these exposures resulted in images of the entire scene's range. There were many examples of AgX multiple exposure techniques until the 1930's. [1; Ch 5]

3.1. C.E.K. Mees-20th Century AgX Photography

In 1912, George Eastman persuaded C.E.K. Mees to move from London to Rochester to become Kodak's Director of Research. Mees described the use of multiple exposures to extend range in his First Edition (1920) of the "*Fundamentals of Photography*"[6]. Also, he introduced the term "Tone Scale" as the amateur-photographer-friendly substitute term for Camera Response Function (CRF). For achromatic images, it was today's equivalent of a One-Dimensional Look Up Table (1-D LUT).

Mees and his colleagues measured scene radiances, camera optics, and film response functions. Using that data they designed AgX emulsions that extended film's dynamic range to exceed the range of light falling on the film in cameras. They measured the dynamic range limits imposed by optical glare.[1-Chapter 5.9] Single exposures are very important for making photography convenient.

3.2. Ansel Adams and the Zone System

Ansel Adams was the unique combination of skilled technician and superb artist. His Zone System provides detailed instructions about how to capture scene information and render it. The process begins with what Adams called the "Visualization" of the final print. He assigned the desired appearance of individual objects in the image to specific photographic zones in the print. His 1983 book "Examples: The Making of 40 Photographs"[7], provides many fascinating descriptions of this process. In visualizing and capturing the scene information Adams:

- Used a spot photometer to measure scene luminances;
- Mentally assigned print zones to scene regions;
- Selected both exposure and development procedure for that individual photograph.

By over-exposing and under-developing the negative Adams lowered the negative's response slope, thus extending its dynamic range. By under-exposing and over-developing it, he raised the slope and reduced its dynamic range. Adam's Zone system individually tuned his Camera's Response Function (CRF) for each scene. Adams, a concert pianist in his youth, described the exposed and developed negative as the "score".[8] In making the print Adams:

- Made a test print to find the best baseline exposure;
- Spatially manipulated local exposures to render his 'Visualization" of the scene;
- Locally decreased exposure (dodge) with an out-of-focus mask to lighten an image segment;
- Locally increased exposure (burn) with a moving baffle to darken an image segment;
- Developed the print.

Adams described this step as the "performance of the score".[8] In his scene-capture step, Adams used AgX emulsions that had wide-range, linear response functions that accurately captured the relationships of scene radiances. He used large-format cameras with lens shades that minimized optical glare. His score was a highly accurate record of scene information. The dynamic range compression of the score was achieved by the spatial manipulation of the exposure in the "performance".[9]

Adams used his mastery of technical photography as his tool, his paint brush, to render his aesthetic intent. He never reproduced scene radiances. He captured their spatial information, and rendered his "Visualization". He used his photographic skills to synthesize his art. He rendered his aesthetic Visualization of the scene.

4. ELECTRONIC IMAGING

Early electronic HDR imaging was stimulated by an experiment studying human vision. In 1967 Edwin Land used an array of white, gray and black papers in a gradient of illumination. He arranged the illumination to cancel the difference in radiance coming from white and black papers. He had weak illumination on a near-white paper at the top of the display, and strong illumination on a near-black paper at the bottom. Land adjusted the illumination intensity so that measurements showed equal radiances from both White and Black papers at the same time in the same HDR scene. Observers reported that the papers appeared white and black despite identical retinal stimuli. The spatial content of the scene generated sensations independent of the radiance at a point.[10] This observation is critical in understanding the limits of Tone Scale mapping in HDR imaging. Pixel-based tone scale maps cannot make identical input values lighter in one spatial region, and darker in another. Spatial comparisons are necessary for modeling this HDR scene.

4.1. Ratio-Product-Reset Models of Lightness

Land and McCann described a computational model for calculating lightness from radiance.[10, 11,12] It calculated the average of many paths that used scene radiance as input:

- Local radiance ratios as the sensor output;
- Product of ratios for long-distance interactions;
- Reset of Products greater than 1.0 to normalize output.

The algorithm's output calculated observer sensations. The ground truth for the model was observer matches that measured appearance from a large set of test targets. Comparisons of observer matches with model predictions were used to standardize model parameters.[1; Ch 32, 35]

In Land's Ives Medal Address to the OSA, he demonstrated a primitive HDR electronic imaging device. It used pairs of photocells to measure ratios as input; calculated reset products as output sensations, and displayed them on light boxes. It used analog electronics.[10]

4.2. Multiresolution Digital Model of Lightness

Although Land and McCann's paths predicted lightnesses for many spatial test targets, it is computationally inefficient. In 1980 Frankle and McCann[13] introduced multiresolution image processing with an embodiment with O(N) computational efficiency. The algorithm used image processing hardware to calculate the lightnesses of 512 by 512 pixel arrays in seconds using digital hardware made in 1975. [14,15]

Fig. 1. *John at Yosemite*, 1981 (left top) Standard photograph of John exposed for shade. (left bottom) Standard photograph of John exposed for sun. (right) Retinex algorithm output made from a calibrated scan of a standard color negative.

Fig. 1, *John at Yosemite*, 1981, is an example of an HDR image in sun and shade. The photometer reading from the white card in John's hand in shade was equal to that from the black paper in the ColorChecker® in sunlight. The scene was captured on color negative film, scanned and converted to scene radiances by calibration. These scene radiances were used as input to separate RGB Frankle & McCann Retinex calculations. The calculated sensations were scaled by standard tone scale and color enhancement algorithms to match the expected color space to be printed on film. This algorithm realized that calculated sensations are in the middle of the image processing chain.[13]

4.3. CRF Digital Processing

In the late 1990's digital imaging hardware (cameras and computers) reached a level of maturity and accessibility that led to an explosion of digital imaging applications, e.g., [2], Ward's applications[16], and Fairchild's Survey[17]. This explosion included a redefinition of the goals of HDR imaging. Instead of rendering the appearance of HDR scenes, the new idea was to capture and reproduce the scene's actual radiances. It replaced the psychophysical approach with a pure physics mechanism.

The two central assumptions of physics-based HDR scene reproduction are:

- Multiple exposures extend the range of accurate scene capture. Using them one can calibrate the Cameras Response Function (CRF); and an inverse CRF gives scene radiances.[2,18]
- HDR displays that extend the range of radiances, so as to accurately reproduce scene radiance.[3]

The ground truth for the CRF technique is that calibrated camera digits must be linearly proportional to scene radiances. To achieve that the inverse CRF must remove both the tone scale nonlinearities and the color enhancements found in standard images.

4.3.1. Standard Camera Images

The unifying principle in making good photographs is scene enhancement. Cameras that make beautiful pictures never reproduce the scene radiances accurately. All cameras, film and digital, introduce nonlinear transformations of scene radiance to make more desirable pictures. These transforms include:

- S-shaped Camera Response Function (CRF) used in film and digital cameras. (1-D LUTs);
- Chroma enhancement in film and digital cameras;
- 3-D Lookup Tables (3-D LUTs) nonlinear enhancement of the entire color space. They provide independent control of all parts of the color space.[19] These transformations are essential to maximizing the full color potential of displays and printers.

Figure 2 (left) shows a 3-D plot of the 24 color squares in the ColorChecker® captured by a Canon D60 camera as a Jpeg image. This illustrates the color space used by standard digital images. We see that these digital RGB color values nearly fill the entire 3-D output color space.

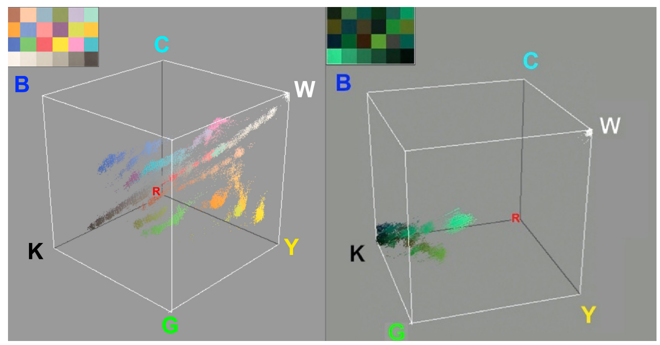

Fig. 2 (left) RGB digit plot of the 24 ColorChecker® squares taken from a standard camera image. The digits cover most of the volume of the output color space. (right) RGB digit plot of the 24 ColorChecker® squares taken from the same camera's RAW camera image. The digits cover only a cigar-shaped portion of the output color space.

While in principle, the sensors respond linearly to photon catch, camera systems introduces unspecified nonlinear transformations. We should never use good-looking standard photographs as a source of accurate scene radiances.

4.3.2 RAW Images

Around 2000, camera makers introduced RAW data formats to allow access to data much earlier in the camera's signal processing chain. RAW is a digital file of camera response data before the camera's image enhancement firmware. There is no international standard for RAW. Each company provides a different software package that gives the photographer more control. However, this does not mean that all RAW images acquired this way are linear. The same nonlinear processes performed by the camera's firmware are now performed in a computer, by the RAW reading software provided by the camera manufacturer. It is just that the photographer can choose manually which parameters to use, rather than automatic selection by the camera's firmware engine.

RAW digits, extracted using LibRAW algorithms[20], are linear with respect to the sensor's quanta catch. The volume in RGB linear color space is much smaller than that of the Jpeg image, even though they both were recorded with the same camera. Fig. 2(right) plots the linear RAW digits scaled to 8-bit RGB. As well, the entire volume of all 24 ColorChecker squares occupies a small cigar-shaped space. The innate sensor RAW response to all colors shows a very limited response to chroma, compared to the range of responses to white/black reflectances. Both CRF and LibRAW algorithms provide more linear scene data, compared to the typical sRGB output of cameras.

Smart sensors that measure quanta catch rates, rather than amount have demonstrated sensor dynamic ranges of more that 10 log units.[21] Even if we assume a sensor with unlimited reciprocity and perfect linearity, we still have to consider other parameters that make up a working camera. They include: the spatial content of each scene; the optical properties of the imaging system (glare); sensor signal readout; noise reduction firmware; and signal (1-D LUTs) firmware. They all influence the limits of a camera's linearity. These limits have to be measured for each scene content.

5.0 THREE TECHNIQUES

There are three very different approaches to making HDR reproductions. Each uses a different ground truth used to measure the success of the process.

5.1. Painters Technique

In the first approach, painting is usually thought of as an art, rather than a scientific process. The painter's ground truth is the appearance of the image. The theory is all psychophysics. The painter's HVS does the spatial transformation of the HDR radiances to generate the sensations. The reflectance gamut of paints is so small that the painter cannot reproduce the scene's radiances. The painter has to learn how to synthesize the spatial patterns that create HDR sensations. The painter's HVS provided the feedback needed to generate spatial patterns that have very similar sensations from vastly different radiances.

The same theory applies to many examples of HDR photography. Multiple exposures capture different spatial records of the HDR scene. In 1853, Baldus found a way to combine the 10 different negative exposures to generate a print that reproduced the entire dynamic range of the Baldus's *Cloisters at Arles*. As well today, there are many examples of digitally fused multiple exposures that are made with human trial and error. By combining the highest contrast portion of multiple exposures with desirable LUTs, one can create merged images that conform to the rendering artist's aesthetic intent. Regardless of the media (oil, AgX, or Jpeg images) this first approach is built around the mechanisms of the artist's HVS. Whether using paint, film, or LUTs, image manipulations based on observer preference are all examples of the *Painter's Techniqu*e

5.2. Display Calculated Sensation Technique

In the second approach, cameras capture scene radiances, and digital algorithms calculate sensations. It incorporated both physical and psychophysical disciplines. It used the best practices of capturing the widest range of radiances possible. It recognized that the capture process include technology-limited accuracy. It used a spatial-comparison model of vision that calculated sensations. It recognized that the vision model is in the middle of the image processing chain. The final step rendered an HVS model's output into the colorspace of the display device. The goal is to render calculated sensation. The ground truth here is appearance matches of test areas in many different complex images. Psychophysical matching measurements were used to determine the best parameters of the model. They used the vision model that calculated sensations most accurately.

5.3. Capture and Reproduce Radiances Technique

In the third approach, renditions are based on accurately reproducing light. Here, the ground truth is whether the reproduced image has identical radiances everywhere in the image. If the HDR system does that, then the reproduction must match the scene. However, there are two problems that this technique needs to consider. First, camera makers do not want accurate scene reproduction. As shown in Fig 2 left, enhanced images are preferred. Second, camera optics limit the range of accurate scene capture. As with all physical systems, cameras have physical limits to the critical assumptions of: reciprocity, linearity and optical glare. Measurements of camera limitations show that reciprocity is generally good; linearity can be accurate with inverse CRF, and LibRAW digital extraction.[22, 23] Glare in the image on the camera's sensor presents the most serious challenge to inverse CRF calibration. Camera responses are highly scene dependent, particularly in HDR scenes.[1 Chapters 10-13; 24]

Although the *reproduce radiance technique* begins the process with pure physics, the final rendition needs the addition of psychophysical transformation. The processing that follows the step that calculates radiances enhances the limited accurate radiance color space (Fig. 2 right) to fill the display device's color space. Those transformations are the results of psychophysical measurements in the design of the display devices.

When we test the use of HDR camera multiple exposures as a meter for measuring scene radiances, we find that optical glare limits the cameras performance. Cameras cannot compete with telephotometers as a tool for measuring scene radiance.[25]

6.0 SUMMARY

All three techniques described in this review can make beautiful HDR images. All successful examples require psychophysical transformations, a kind of visual impedance match, to the human visual system. All successful HDR images are the result of the partnership of the reproduction technology and the observer's spatial imaging mechanisms.

11. REFERENCES

[1] McCann, J., and A. Rizzi, *The Art and Science of HDR Imaging*, Wiley, Chichester, (2012).

[2] P. Debevec, and P. Malik, “Recovering High Dynamic Range Radiance Maps from Photographs”, ACM SIGGRAPH’ 97, 369-78, (1997).

[3] Seetzen H, Heidrich W, Stuerzlinger W, Ward G, Whitehead L, Trentacoste M, Ghosh A & Vorozcovs A” High Dynamic Range Display Systems’, ACM SIGGRAPH, (2004).

[4] This paper has the authors supplementary downloadable material available at <http://ieeexplore.ieee.org> This includes examples of HDR reproductions and a readme file. This material is 6 MB in size.

[5] Flukinger, R , *The Gernsheim Collection*: Harry Ransom Center, Un. Texas Press, Austin, (2010).

[6] Mees, C.E.K, “The Fundamentals of Photography”, Eastman Kodak, Rochester, (1920).

[7] Adams, A, Examples: The Making of 40 Photographs, Little Brown & Company, Boston, (1983).

[8] Adams, A, *The Negative Exposure and Development: Book Two*, New York Graphic Society, Boston, (1981).

[9] Adams, A., The Print: Book Three, Boston: New York Graphic Society, Boston, (1983).

[10] E. H. Land and J.J. McCann, “Lightness and Retinex Theory”, J. Opt. Soc. Am. 61, 1, (1971).

[11] E. H. Land, *The Retinex Theory of Colour Vision*, Proc. Roy. Institution Gr. Britain, 47 23-58, (1974).

[12] J.J. McCann, S.P. McKee and T. Taylor, “Quantitative Studies in Retinex theory, A comparison between theoretical predictions and observer responses to Color Mondrian experiments”, Vision Res., 16, 445-58, (1976).

[13] Frankle J & McCann J (1983) Method and Apparatus of Lightness Imaging, U.S. Patent, 4384336, issued 5/17/)1983).

[14] J. J. McCann, “Lessons learned from Mondrians applied to real images and color gamuts”, IS&T/SID Color Imaging Conf., 7, 1-8, (1999).

[15] J. J. McCann, “ Capturing a Black Cat in Shade: Past and Present of Retinex Color Appearance Models”, J. Electronic Imaging, 13, 36-47, (2004).

[16] G. Ward, <http://www.anyhere.com>

[17] M. Fairchild, The HDR Photographic Survey” <http://rit-mcsl.org/fairchild/HDR.html>, (2008)

[18] Reinhard E, G. Ward, S. Pattanaik, P. Debevec, *High Dynamic Range Imaging Acquisition, Display & Image-Based Lighting*, Amsterdam: Elsevier, Morgan Kaufmann, (2006).

[19] M. Abdulwahab, J. Burkhardt, and J. McCann, “Method and Apparatus for Transforming Color Image Data on the Basis of an Isotropic Colorimetric Space”, US Patent 4,839,721, filing date 8/28/1984; issued 6/13/ (1989)

[20] J. McCann, and V. Vonikakis, "Accurate Information vs. Looks Good: Scientific vs. Preferred Rendering", Proc.IS&T, Color in Graphics, Imaging, and Vision; Amsterdam 6, 231-238 (2012).

[21] A. Spivak, A, Belenky, A. Fish, and O. Yadid-Pecht, “Wide Dynamic-range CMOS Image Sensors: A Comparative Performance Analysis”, IEEE Trans. on Electron Devices, 56, 2446-61 (2009).

[22] “LibRaw” Image Decoder Library, <http://www.libraw.org/>

[23] J. McCann and v. Vonikakis, C. Bonanomi, and A. Rizzi, "Chromaticity limits in color constancy calculations", Proc. IS&T/SID Color Imaging Conference, 21, 52-60 (2013).

[24] A. Rizzi and J. McCann,”Appearance of Radiance in Scenes with Variable HDR Content”. Proc. ICIP, Phoenix, (2016).

[25] J. McCann,”ColorChecker at the beach: dangers of sunburn and glare” Proc. SPIE 9015, Color Imaging XIX: Displaying, Processing, Hardcopy, and Applications, 90150V (2014); doi: 10.1117/12.2045379