H

High Dynamic Range Imaging

Erik Reinhard
InterDigital, Cesson-Sèvignè, France

Synonyms

Wide dynamic range imaging

Related Concepts

- ▶ Focus Bracketing
- ▶ Gamut Mapping
- ▶ Noise Removal
- ▶ Photogrammetry
- ▶ Saturation
- ▶ Trichromatic Theory
- ▶ Veiling Glare
- ▶ Video Alignment and Stitching

Definition

High dynamic range (HDR) imaging comprises a range of techniques for capturing, storing, editing, transmitting, and displaying images and video with an extended range of values between black and white, compared with traditional imaging techniques. This means that HDR images can be better representations of real scenes than conventional photographs, bringing associated enhanced realism and visual quality.

K. Ikeuchi (ed.), *Computer Vision*,
https://doi.org/10.1007/978-3-030-03243-2_843-1

Introduction

Light levels to which humans are routinely exposed range from dim starlight to bright sunlight. While human vision cannot resolve detail over this enormous range simultaneously, through adaptive processes active in the visual system, humans can interpret and navigate through scenes that range from 10^{-6} to $10^{8}\ cd/m^2$ [1]. This represents a range of illumination spanning around 14 orders of magnitude (log units). At any one time, the human visual system can resolve detail over a range of about 3.7 orders of magnitude [2].

Conventional technologies for capturing, processing, and displaying images are more limited, in that they typically use image data spanning no more than 2 orders of magnitude of range between black and white. Such technologies, referred to as low dynamic range (LDR) or standard dynamic range (SDR) imaging, typically represent pixel data with a bit depth of 8 nonlinearly encoded bits. This has several practical implications. First, it is easier to build sensors and display devices. Second, the demands on storage and transmission are limited.

On the other hand, SDR images do not match the capabilities of human vision. As a consequence, there is room for improvement, which is the *raison d'être* of HDR imaging. The aim of the latter is to represent a larger range of luminance values. It is often combined with employing a wide color gamut such as defined in ITU-R Recommendation BT.2020 [3], so that the range of

High Dynamic Range Imaging, Fig. 1 Left: a single capture of a challenging scene, whereby most pixels are either under- or overexposed. Right: an image captured with HDR techniques and subsequently processed for display. This image resembles the actual scene much more accurately

chroma values is also increased. HDR images often look significantly more realistic than corresponding SDR images. Some researchers have remarked that HDR images, when viewed on an HDR display, evoke a sensation of realism that is not present in SDR images, akin to looking through a window [4]. Thus, HDR imaging offers a real enhancement in image quality over SDR imaging. As an example, Fig. 1 (left) shows an image taken from a scene using standard digital photographic techniques. The image on the right shows the same scene, obtained with HDR capture techniques, and subsequently tone mapped. This image is arguably a better representation of the scene than the image on the left. HDR technologies have reached a level of maturity sufficient for market introduction.

History

The first digital images originated from scanning photographs. One of the first such images is shown in Fig. 2, where multiple binary scans were merged to obtain a digital grayscale image. By 1968, scanning technology was able to produce 12-bit images directly [5], even if the resulting images were stored in a logarithmic format while keeping the 9 most significant bits. At the time, these images could be exponentiated to control a vector graphics display with 8-bit precision [5]. Note that in this case, the difference between

High Dynamic Range Imaging, Fig. 2 One of the first digital photographs, scanned by Russell Kirsch at the National Institute of Standards and Technology (NIST) in 1957. (From https://en.wikipedia.org/wiki/Russell_A._Kirsch; this image is in the public domain)

capture and display bit depth is 4 bits. Thus, to be able to display the images, their dynamic range had to be reduced: in essence, removing the n least significant bits can be seen as an early form of dynamic range reduction, which is also known as tone mapping or tone reproduction (see the section on "Tone Management" below).

From that moment, a trickle of research papers emerged that broadly addressed the problem of tone reproduction, starting in 1972 [6]. In 1984, this topic was used to introduce computer graphics to the field of lighting design [7]. Computer graphics became a fertile ground for research on HDR imaging, as rendering algorithms naturally produce high dynamic range images which require tone mapping prior to display [8]. The Radiance rendering software, for example, [9], which was first released in 1987, included a HDR image file format which was used widely.

Due to limitations in sensor design, digital photography was not able to natively produce HDR images. However, multiple image captures from the same vantage point, while varying the exposure time, allow an extended range to be captured. In a post-processing step, the individual captures are merged to form the final HDR image [10]. This has broadly solved the problem of image capture of static scenes without the need for upgrading capture hardware. With this method, however, scenes with movement are difficult to capture without additional processing, as outlined in the "Capture" section below.

The availability of HDR image data has then opened up the possibility to use that data inside a renderer as complex spatially varying illuminants [11]. The visual quality of computer-generated imagery has thus greatly improved, paving the way for a large array of special effects.

Research into HDR imaging picked up pace dramatically in 2002, when a batch of papers once again addressed the problem of tone reproduction [12–15].

Direct display of HDR imagery became a reality in 2003 when the first HDR display system was demonstrated [16]. HDR camera systems followed in 2001 [17]. The first standards governing HDR video transmission appeared in 2014, paving the way for HDR broadcast systems [18–20]. HDR cinema projection systems have been demonstrated [21], while HDR movie cameras are now a reality. For those wishing to experiment with HDR images and videos, there are several resources available online, including the HDR Photographic Survey [22], a database of cinematic HDR video sequences [23] and a dataset of test materials for the assessment of picture quality [24].

Capture

To capture a high dynamic range image, a common technique is to take several photographs from the same vantage point, usually by employing auto-bracketing, resulting in a sequence of SDR exposures obtained with different exposure times. The difference between each successive exposure may, for example, be 1 f-stop apart. The idea is that each part of the scene will be well exposed in at least one of the exposures.

In a post-process, the exposures are then combined into an HDR image [10]. This requires knowledge of the camera response curve, i.e., the nonlinear relationship between scene light and pixel value. Each exposure is first linearized by applying the inverse camera response curve and then scaled by its exposure time. A windowing function may then be applied to reduce the effect of noise in underexposed pixels and the lack of information in overexposed pixels. After that, the exposures are simply averaged to produce the HDR image.

In the presence of noise, further noise removal may be applied [25]. Image alignment may be required to account for movement of the camera [26], especially when the camera was handheld. If objects move while the exposures are taken, then the averaging process may result in ghosting. Detection and elimination of such ghosting artifacts has proven to be a challenging problem [27, 28].

Alternatively, the exposures may be merged into an SDR image, albeit one with more detail and information than any of its constituent exposures. This is a process called exposure fusion [29].

Rather than recording several exposures one after the other, cameras may be constructed that divert light to multiple sensors using beam splitters [17]. Optical filters may optionally be applied to attenuate the light reaching each sensor differently. The advantage of such an approach is that no ghosting or alignment issues are present and that the achievable video frame rate is not reduced due to the capture of multiple exposures.

Tone Management

HDR and SDR technologies will coexist for the foreseeable future. This means that SDR content may be displayed on HDR displays, and HDR content may have to be displayed on SDR displays. A significant amount of research has been devoted to develop perceptually plausible algorithms that map HDR data to SDR levels [30] – a process known as tone mapping or tone reproduction. The mapping of SDR data to HDR levels is known as inverse tone mapping or inverse tone reproduction [31].

Tone reproduction often includes a nonlinear mapping which can be applied identically to all pixels of an image. By attenuating light pixels more than dark pixels, a range reduction can be achieved that matches human visual experience well [30]. Especially sigmoidal (s-shaped) tone mapping functions are close to the static behavior of photoreceptors [32].

In addition, spatially varying processing may be applied to locally increase contrast, although such procedures tend to be computationally much more costly. Spatially varying operators that relate to human visual perception include Retinex processing [33], image appearance models [34–36], and a display-adaptive tone reproduction operator [37].

A variety of other tone reproduction operators are known, including those based on bilateral filtering [13], gradient domain processing [14], and histogram adjustment [38].

Mapping SDR data to HDR levels, also known as inverse tone reproduction or inverse tone mapping, has proven to be a viable approach to creating HDR data. Color grading in post-production studios now routinely involves the creation of HDR grades, and these are often produced with the aid of inverse tone reproduction tools. A key requirement of such tools is that the processing is semiautomatic, so that the results can be adjusted or edited by the colorist.

Quality Assessment

Image quality assessment can either be accomplished through visual inspection, through carrying out a psychophysical experiment, or by applying metric. For HDR images and video, visible difference predictors [39] and quality assessment metrics are available [40, 41], allowing the automatic assessment of differences between images and quality of video, respectively.

Encoding, Compression, and Standards

Currently, HDR images are often stored as EXR files [42], a file format developed by Industrial Light & Magic (See http://www.openexr.com/). The JPG XT image compression standard [43] includes support for HDR images, while the aforementioned Radiance format is supported through the JPEG XR format [44].

In (movie) production and post-production, HDR is nowadays routinely employed, for example, through the ACES format (See https://www.oscars.org/science-technology/aces/aces-documentation). Guidelines for live production are available as well [45].

For the transmission and broadcast of HDR video, a current approach is to preprocess the HDR video data so that it can subsequently be compressed with a standard codec, such as AVC or HEVC. To this end, each video frame is first passed through a compressive curve, known as an optoelectronic transfer function (OETF). Such curves are not unlike tone mapping curves, albeit that they are not necessarily optimized to match human visual perception, but to maximize compression efficiency of any subsequent encoder. In practice, such curves may still be based on insights from human visual perception. Curves currently in use are the Perceptual Quantizer [46] (PQ) and Hybrid Log-Gamma [47], as standardized by ITU-R, SMPTE, and ARIB [18–20].

A receiver such as a television or a set-top box may then decode the signal before applying an electro-optical transfer function (EOTF). This function may be the mathematical inverse of the corresponding OETF (PQ systems operate in this manner), but it may incorporate further processing to adapt the signal to the capabilities of a specific display (HLG systems work like this).

An alternative to encoding HDR video, while enabling backward compatibility, is to augment SDR video data with dynamic metadata that allows a receiver to reconstruct HDR video data [48]. Thus, a receiver not able to decode the metadata will simply display the SDR video, while an HDR-enabled television would be able to reconstruct HDR video and adapt it to its own capabilities. This approach is standardized by ETSI [49].

Provisions for the transmission of HDR are made in various other standards, including ATSC 3.0, DVB, and in China.

While broadcasters are implementing HDR broadcast channels, currently HDR video content can be enjoyed by consumers through streaming applications, as well as through Ultra HD Blu-ray disks, provided they have access to an HDR-capable television and Blu-ray player.

Discussion

High dynamic range imaging offers an improved range of light levels between black and white, creating a higher visual quality. Research has found solutions for most if not all of the problems associated with high dynamic range imaging and video. Standardization and industry adoption are in an advanced state of progress, so that HDR will be broadly available soon.

References

1. Hood DC, Finkelstein MA (1986) Sensitivity to light. In: Boff KR, Kaufman LR, Thomas JP (eds) Handbook of perception and human performance. Wiley, New York
2. Kunkel T, Reinhard E (2010) A reassessment of the simultaneous dynamic range of the human visual system. In: Proceedings of the 7th symposium on applied perception in graphics and visualization. APGV ’10. ACM, New York, pp 17–24
3. ITU-R (2015) Recommendation ITU-R BT.2020-2, parameter values for ultra-high definition television systems for production and international programme exchange
4. Vangorp P, Mantiuk RK, Bazyluk B, Myszkowski K, Mantiuk R, Watt SJ, Seidel HP (2014) Depth from HDR: depth induction or increased realism? In: Proceedings of the ACM symposium on applied perception, pp 71–78
5. Oppenheim AV, Schafer R, Stockham T (1968) Nonlinear filtering of multiplied and convolved signals. Proc IEEE 56(8):1264–1291
6. Stockham T (1972) Image processing in the context of a visual model. Proc IEEE 60(7):828–842
7. Miller NJ, Ngai PY, Miller DD (1984) The application of computer graphics in lighting design. J IES 14:6–26
8. Tumblin J, Rushmeier H (1993) Tone reproduction for computer generated images. IEEE Comput Graph Appl 13(6):42–48
9. Ward GJ (1994) The radiance lighting simulation and rendering system. In: Proceedings of the 21st annual conference on Computer graphics and interactive techniques. SIGGRAPH ’94. ACM, New York, pp 459–472
10. Debevec P, Malik J (1997) Recovering high dynamic range radiance maps from photographs. In: SIGGRAPH ’97: proceedings of the 24th annual conference on computer graphics and interactive techniques. ACM, New York, pp 369–378
11. Debevec P (1998) Rendering synthetic objects into real scenes: bridging traditional and image-based graphics with illumination and high dynamic range photography. In: SIGGRAPH 98 conference proceedings. Annual conference series, pp 45–50
12. Ashikhmin M (2002) A tone mapping algorithm for high contrast images. In: Proceedings of 13th Eurographics workshop on rendering, pp 145–155
13. Durand F, Dorsey J (2002) Fast bilateral filtering for the display of high-dynamic-range images. ACM Trans Graph 21(3):257–266
14. Fattal R, Lischinski D, Werman M (2002) Gradient domain high dynamic range compression. ACM Trans Graph 21(3):249–256
15. Reinhard E, Stark M, Shirley P, Ferwerda J (2002) Photographic tone reproduction for digital images. ACM Trans Graph 21(3):267–276
16. Seetzen H, Whitehead LA, Ward G (2003) A high dynamic range display using low and high resolution modulators. In: The society for information display digest
17. Tocci MD, Kiser C, Tocci N, Sen P (2011) A versatile HDR video production system. ACM Trans Graph 30(4):41
18. SMPTE (2014) ST 2084:2014 – SMPTE standard - high dynamic range electro-optical transfer function of mastering reference displays

19. ARIB STD-B67 (2015) Essential parameter values for the extended image dynamic range television (eidrtv) system for programme production
20. ITU-R (2016) Recommendation ITU-R BT.2100, image parameter values for high dynamic range television for use in production and international programme exchange
21. Damberg G, Gregson J, Heidrich W (2016) High brightness HDR projection using dynamic freeform lensing. ACM Trans Graph 35(3):24
22. Fairchild MD (2007) The HDR photographic survey. In: Proceedings of the fifteenth color imaging conference: color science and engineering systems, technologies, and applications, vol 15, The Society for Imaging Science and Technology, pp 233–238
23. Froehlich J, Grandinetti S, Eberhardt B, Walter S, Schilling A, Brendel H (2014) Creating cinematic wide gamut HDR-video for the evaluation of tone mapping operators and HDR-displays. In: Proceedings SPIE. Volume 9023. 9023–9023–10
24. ITU-R (2018) Report ITU-R BT.2245-5, HDTV and UHDTV including HDR-TV test materials for assessment of picture quality
25. Akyüz AO, Reinhard E (2007) Noise reduction in high dynamic range imaging. J Vis Commun Image Represent 18(5):266–276
26. Ward G (2003) Fast, robust image registration for compositing high dynamic range photographs from hand-held exposures. J Graph Tools 8(2):17–30
27. Khan E, Akyuz A, Reinhard E (2006) Ghost removal in high dynamic range images. In: IEEE International conference on image processing. IEEE Computer Society, Washington, DC, pp 2005–2008
28. Granados M, Tompkin J, Kim KI, Theobalt C (2013) Automatic noise modeling for ghost-free HDR reconstruction. ACM Trans Graph 32(6):201
29. Mertens T, Kautz J, van Reeth F (2007) Exposure fusion. In: IEEE Pacific conference on computer graphics and applications, pp 382–390
30. Reinhard E, Heidrich W, Debevec P, Pattanaik S, Ward G, Myszkowski K (2010) High dynamic range imaging: acquisition, display and image-based lighting, 2nd edn. Morgan Kaufmann
31. Banterle F, Ledda P, Debattista K, Chalmers A (2006) Inverse tone mapping. In: GRAPHITE ’06: proceedings of the 4th international conference on computer graphics and interactive techniques in Australasia and Southeast Asia, pp 349–356
32. van Hateren JH (2006) Encoding of high dynamic range video with a model of human cones. ACM Trans Graph 25(4):1380–1399
33. McCann JJ, Rizzi A (2011) The art and science of HDR imaging, vol 26. Wiley
34. Fairchild MD, Johnson GM (2002) Meet iCAM: an image color appearance model. In: Proceedings of the 10th IS&T/SID color imaging conference, Scottsdale, pp 33–38
35. Kuang J, Fairchild MD (2007) iCAM06, HDR, and image appearance. In: Proceedings of the 15th IS&T/SID color imaging conference, pp 249–254
36. Reinhard E, Pouli T, Kunkel T, Long B, Ballestad A, Damberg G (2012) Calibrated image appearance reproduction. ACM Trans Graph 31(6):201
37. Mantiuk R, Daly S, Kerofsky L (2008) Display adaptive tone mapping. ACM Trans Graph 27(3):68
38. Ward G, Rushmeier H, Piatko C (1997) A visibility matching tone reproduction operator for high dynamic range scenes. IEEE Trans Vis Comput Graph 3(4):291–306
39. Narwaria M, Mantiuk R, Da Silva MP, Le Callet P (2015) HDR-VDP-2.2: a calibrated method for objective quality prediction of high-dynamic range and standard images. J Electron Imaging 24(1):010501
40. Aydın TO, Čadík M, Myszkowski K, Seidel HP (2010) Video quality assessment for computer graphics applications. ACM Trans Graph 29(6):161
41. Yeganeh H, Wang Z (2013) Objective quality assessment of tone-mapped images. IEEE Trans Image Process 22(2):657–667
42. Kainz F, Bogart R, Hess D (2003) The OpenEXR image file format. In: SIGGRAPH technical sketches
43. ISO/IEC 18477-2:2016 (2016) Information technology – Scalable compression and coding of continuous-tone still images – Part 2: Coding of high dynamic range imaging
44. ISO/IEC 29199-2:2012 (2012) Information technology – JPEG XR image coding system – Part 2: Image coding specification
45. ITU-R (2018) Report ITU-R BT.2408-1, operational practices in HDR television production
46. Miller S, Nezamabadi M, Daly S (2013) Perceptual signal coding for more efficient usage of bit codes. SMPTE Motion Imaging J 122(4):52–59
47. Borer T (2014) Non-linear opto-electrical transfer functions for high dynamic range television. Technical Report WHP 283, BBC
48. François E, van de Kerkhof L (2016) A single-layer HDR video coding framework with SDR compatibility. In: International broadcasting convention
49. ETSI TS 103 433 (2016) High-performance single layer directly standard dynamic range (SDR) compatible high dynamic range (HDR) system for use in consumer electronics devices (SL-HDR1)