High Dynamic Range Techniques in Graphics: from Acquisition to Display

Eurographics 2005 Tutorial T7

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Abstract

This course is motivated by tremendous progress in the development and accessibility of high dynamic range technology (HDR) that happened just recently, which creates many interesting opportunities and challenges in graphics. The course presents a complete pipeline for HDR image and video processing from acquisition, through compression and quality evaluation, to display. Also, successful examples of the use of HDR technology in research setups and industrial applications are provided. Whenever needed relevant background information on human perception is given which enables better understanding of the design choices behind the discussed algorithms and HDR equipment.

Description of images, from left to right:

- Acquisition of HDR data: two HDR cameras (IMS-CHIPS and LarsIII) and a high quality LDR camera Jenoptik C14.
- HDR video: a broad range of luminance values can be stored in the HDR video without loss of any perceivable details. Even the bare light bulb is faithfully registered, as visible in the blue window which scales down the luminance range.
- HDR video: a conventional video in this shot could be exposed either for the interior or exterior of the cafeteria. With the HDR video it is possible to capture and store all details of the recorded scene.
- Tone mapping: most display devices are still limited in the dynamic range of luminance and contrast that can be reproduced (right inset illustrates a naive display of an HDR image). Various tone mapping techniques allow for reduction of such a contrast. Here the image is decomposed into the areas of consistent illumination (left inset) and the contrast ratio between these areas is optimized.
- HDR display: a display system developed by the Sunnybrook company that is capable of displaying images with a dynamic range much more similar to that encountered in the real world.

Contents

Tutorial Schedule

- Introduction - Myszkowski (10 mins)
- HDR Acquisition Techniques for Still Images and Video - Goesele and Krawczyk (35 mins)
  - Overview over HDR Acquisition Techniques
  - Multi-exposure Techniques
  - HDR Cameras and their Photometric Calibration
  - Absolute Luminance Calibration
- HDR Image Sensors for Video - Hoefflinger (20 mins)
  - CMOS Active-pixel (APS)
  - Extended Dynamic Range Sensor (XDR)
  - HDRC Imager (Very High Dynamic Range of 170 dB)
- HDR Image and Video Compression - Myszkowski (30 mins)
  - HDR Image and Video Formats
  - HDR Quality Metrics and Their Validation
  - Real-time Post-processing of HDR Video Stream (Live demo)
- Break
- HDR Displays - Heidrich and Trentacoste (35 mins)
  - Foundations: Limitations of Human Perception
  - Hardware Design
  - Processing Algorithms
- HDR Applications - Goesele, Krawczyk, and Hoefflinger (45 mins)
  - Image-based Measurements of Object and Material Properties
  - Virtual Scene Re-lighting: CAVE System for Car Interior Modeling
  - HDR Lighting in Mixed-Reality Applications
  - Application Examples in Automotive Industry and Computer Vision
- Final Remarks and Open Discussion (10 mins)

HDR Project Pages

The updated version of slides presented at Eurographics 2005 can be found under this URL:

`http://www.mpi-inf.mpg.de/resources/hdr/`

This Web page contains also links to many papers listed in the References section often along with accompanying materials. Also, source code useful for handling HDR images and video is available. Finally, HDR video samples acquired using the IMS CHIPS cameras are posted.

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References

[1] M. Aggarwal and N. Ahuja. Split Aperture Imaging for High Dynamic Range. *Proc. of International Conference on Computer Vision (ICCV)*, 2:10–17, 2001.

[2] M. Ashikhmin. A Tone Mapping Algorithm for High Contrast Images. In *Rendering Techniques 2002: 13th Eurographics Workshop on Rendering*, pages 145–156, 2002.

[3] P. G. Barten. *Contrast sensitivity of the human eye and its effects on image quality.* SPIE – The International Society for Optical Engineering, P.O. Box 10 Bellingham Washington 98227-0010, 1999. ISBN 0-8194-3496-5.

[4] R. Bogart, F. Kainz, and D. Hess. OpenEXR Image File Format. In *ACM SIGGRAPH 2003, Sketches & Applications*, 2003.

[5] V. Brajovic, R. Miyagawa, and T. Kanade. Temporal Photoreception for Adaptive Dynamic Range Image Sensing and Encoding. *Neural Networks*, 11(7-8):1149–1158, October 1998.

[6] P. Burt and R. J. Kolczynski. Enhanced Image Capture Through Fusion. *Proc. of International Conference on Computer Vision (ICCV)*, pages 173–182, 1993.

[7] S. Chen and R. Ginosar. Adaptive Sensitivity CCD Image Sensor. *Proc. of SPIE 2415: CCD and Solid State Optical Sensors V*, February 1995.

[8] CIE. *An Analytical Model for Describing the Influence of Lighting Parameters Upon Visual Performance*, volume 1. Technical Foundations, CIE 19/2.1. International Organization for Standardization, 1981.

[9] S. Daly. The Visible Differences Predictor: An Algorithm for the Assessment of Image Fidelity. In A. Watson, editor, *Digital Image and Human Vision*, pages 179–206. Cambridge, MA: MIT Press, 1993.

[10] P. Debevec and J. Malik. Recovering High Dynamic Range Radiance Maps from Photographs. In *Proceedings of SIGGRAPH 97*, Computer Graphics Proceedings, Annual Conference Series, pages 369–378, Aug. 1997.

[11] K. Dmitriev, T. Annen, G. Krawczyk, K. Myszkowski, and H.-P. Seidel. A CAVE System for Interactive Modeling of Global Illumination in Car Interior. In R. Lau and G. Baciu, editors, *ACM Symposium on Virtual Reality Software and Technology (VRST 2004)*, pages 137–145, Hong Kong, 2004. ACM.

[12] H. Doi, Y. Hara, Y. Kenbo, and M. Shiba. Image sensor. Japanese Patent 08-223491, August 1986.

[13] F. Drago, K. Myszkowski, T. Annen, and N. Chiba. Adaptive Logarithmic Mapping For Displaying High Contrast Scenes. In P. Brunet and D. W. Fellner, editors, *Proc. of EUROGRAPHICS 2003*, volume 22 of *Computer Graphics Forum*, pages 419–426, Granada, Spain, 2003. Blackwell.

[14] H. Farid. Blind Inverse Gamma Correction. *IEEE Trans. on Image Processing*, 10(10):1428–1433, October 2001.

[15] R. Ginosar and A. Gnusin. A Wide Dynamic Range CMOS Image Sensor. *IEEE Workshop on CCD and Advanced Image Sensors*, June 1997.

[16] R. Ginosar, O. Hilsenrath, and Y. Zeevi. Wide dynamic range camera. U.S. Patent 5,144,442, September 1992.

[17] M. Goesele, W. Heidrich, and H.-P. Seidel. Color Calibrated High Dynamic Range Imaging with ICC Profiles. In *Proc. 9th IS&T Color Imaging Conference*, 2001.

[18] M. Goesele, H. P. A. Lensch, J. Lang, C. Fuchs, and H.-P. Seidel. DISCO – Acquisition of Translucent Objects. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2004)*, 23(3), 2004.

[19] M. Grossberg and S. Nayar. Determining the camera response from images: What is knowable? *PAMI*, 25(11):1455–1467, November 2003.

[20] R. P. Harvey. Optical Beam Splitter and Electronic High Speed Camera Incorporating such a Beam Splitter. U.S. Patent 5,734,507, May 1998.

[21] V. Havran, M. Smyk, G. Krawczyk, K. Myszkowski, and H.-P. Seidel. Interactive System for Dynamic Scene Lighting using Captured Video Environment Maps. In *To appear in 16th Eurographics Symposium on Rendering*, 2005.

[22] E. Ikeda. Image data processing apparatus for processing combined image signals in order to extend dynamic range. U.S. Patent 5801773, September 1998.

[23] IMS CHIPS. HDR Video Cameras. *http://www.ims-chips.de*.

[24] S. Kang, M. Uyttendaele, S. Winder, and R. Szeliski. High Dynamic Range Video. *ACM Transactions on Graphics*, 22(3):319–325, 2003.

[25] M. Konishi, M. Tsugita, M. Inuiya, and K. Masukane. Video camera, imaging method using video camera, m ethod of operating video camera, image processing apparatus and method, and solid-state electronic imaging device. U.S. Patent 5420635, May 1995.

[26] G. Krawczyk, M. Goesele, and H.-P. Seidel. Photometric Calibration of High Dynamic Range Cameras. MPI Informatik Technical Report MPI-I-2005-4-005, 2005.

[27] G. Krawczyk, K. Myszkowski, and H.-P. Seidel. Lightness Perception in Tone Reproduction for High Dynamic Range Images. In *The European Association for Computer Graphics 26th Annual Conference EUROGRAPHICS 2005*, volume 24 of *Computer Graphics Forum*, Dublin, Ireland, 2005. Blackwell.

[28] G. Krawczyk, K. Myszkowski, and H.-P. Seidel. Perceptual Effects in Real-Time Tone Mapping. In B. Jüttler, editor, *Spring Conference on Computer Graphics 2005*, Budmerice, Slovakia, 2005. ACM.

[29] G. W. Larson. LogLuv Encoding for Full-Gamut, High-Dynamic Range Images. *Journal of Graphics Tools*, 3(1):15–31, 1998.

[30] G. W. Larson, H. Rushmeier, and C. Piatko. A Visibility Matching Tone Reproduction Operator for High Dynamic Range Scenes. *IEEE Transactions on Visualization and Computer Graphics*, 3(4):291–306, 1997.

[31] P. Ledda, G. Ward, and A. Chalmers. A Wide Field, High Dynamic Range, Stereographic Viewer. In *GRAPHITE 2003*, pages 237–244, 2003.

[32] H. P. A. Lensch, J. Kautz, M. Goesele, W. Heidrich, and H.-P. Seidel. Image-based Reconstruction of Spatial Appearance and Geometric Detail. *ACM Trans. Graph.*, 22(2):234–257, 2003.

[33] S. Lin, J. Gu, S. Yamazaki, and H. Shum. Radiometric calibration from a single image. In *CVPR04*, pages II: 938–945, 2004.

[34] J. Lubin and A. Pica. A Non-uniform Quantizer Matched to the Human Visual Performance. *Society of Information Display Int. Symposium Technical Digest of Papers*, (22):619–622, 1991.

[35] B. Madden. Extended Intensity Range Imaging. Technical Report MS-CIS-93-96, Grasp Laboratory, University of Pennsylvania, 1993.

[36] S. Mann. Comparametric equations with practical applications in quantigraphic image processing. *IEEE Trans. on Image Processing*, 9(8):1389–1406, August 2000.

[37] S. Mann and R. Picard. Being 'Undigital' with Digital Cameras: Extending Dynamic Range by Combining Differently Exposed Pictures. *Proc. of IST's 48th Annual Conference*, pages 442–448, May 1995.

[38] R. Mantiuk, S. Daly, K. Myszkowski, and H.-P. Seidel. Predicting Visible Differences in High Dynamic Range Images - Model and its Calibration. In B. E. Rogowitz, T. N. Pappas, and S. J. Daly, editors, *Human Vision and Electronic Imaging X, IS&T/SPIE's 17th Annual Symposium on Electronic Imaging (2005)*, volume 5666 of *SPIE Proceedings Series*, pages 204–214, San Jose, California USA, January 2005. SPIE.

[39] R. Mantiuk, G. Krawczyk, K. Myszkowski, and H.-P. Seidel. Perception-motivated High Dynamic Range Video Encoding. *ACM Transactions on Graphics*, 23(3):733–741, July 2004.

[40] S. Nayar and V. Branzoi. Adaptive Dynamic Range Imaging: Optical Control of Pixel Exposures Over Space and Time. In *Proc. of IEEE International Conference on Computer Vision (ICCV 2003)*, pages 1168–1175, 2003.

[41] S. Nayar, V. Branzoi, and T. Boult. Programmable imaging using a digital micromirror array. In *CVPR04*, pages I: 436–443, 2004.

[42] S. Pattanaik, J. Tumblin, H. Yee, and D. Greenberg. Time-Dependent Visual Adaptation for Realistic Image Display. In *Proceedings of ACM SIGGRAPH 2000*, Computer Graphics Proceedings, Annual Conference Series, pages 47–54, July 2000.

[43] E. Reinhard, G. Ward, S. Pattanaik, and P. Debevec. *High Dynamic Range Imaging: Acquisition, Display, and Image-based Lighting.* Morgan Kaufmann, 2005. ISBN: 0125852630.

[44] M. Robertson, S. Borman, and R. Stevenson. Dynamic Range Improvement Through Multiple Exposures. In *Proceedings of the 1999 International Conference on Image Processing (ICIP-99)*, pages 159–163, Los Alamitos, CA, Oct. 24–28 1999.

[45] M. A. Robertson, S. Borman, and R. L. Stevenson. Estimation-Theoretic Approach to Dynamic Range Enhancement using Multiple Exposures. *Journal of Electronic Imaging*, 12(2):219–285, April 2003.

[46] Y. Schechner and S. K. Nayar. Generalized Mosaicing. *Proc. of International Conference on Computer Vision (ICCV)*, 1:17–24, 2001.

[47] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, and A. Vorozcovs. High Dynamic Range Display Systems. *ACM Transactions on Graphics*, 23(3):760–768, Aug. 2004.

[48] G. Spencer, P. Shirley, K. Zimmerman, and D. Greenberg. Physically-Based Glare Effects for Digital Images. In *Proceedings of ACM SIGGRAPH 95*, pages 325–334, 1995.

[49] Spheron VR. HDR Camera Manufacturer. *http://www.spheron.com/*.

[50] S. Stevens and J. Stevens. Brightness function: parametric effects of adaptation and contrast. *Journal of the Optical Society of America*, 50(11):1139A, Nov. 1960.

[51] Sunnybrook Technologies. HDR Displays. *http://www.sunnybrooktech.com/*.

[52] Y. Tsin, V. Ramesh, and T. Kanade. Statistical calibration of the ccd imaging process. pages I: 480–487, 2001.

[53] Z. Wang and A. Bovik. A Universal Image Quality Index. *IEEE Signal Processing Letters*, 9(3):81–84, 2002.

[54] G. Ward. Real Pixels. In *Graphics Gems II*, pages 80–83. 1991.

[55] G. Ward. Fast, Robust Image Registration for Compositing High Dynamic Range Photographs from Hand-Held Exposures. *Journal of Graphics Tools*, 8(2):17–30, 2003.

[56] G. Ward and M. Simmons. Subband Encoding of High Dynamic Range Imagery. In H. Bülthoff and H. Rushmeier, editors, *Proceedings of the 1st Symposium on Applied Perception in Graphics and visualization (APGV 2004)*, pages 83–90. ACM, Los Angeles, USA, August 2004.

[57] G. J. Ward. The RADIANCE Lighting Simulation and Rendering System. In *Proceedings of SIGGRAPH 94*, Computer Graphics Proceedings, Annual Conference Series, pages 459–472, July 1994.

[58] C. W. Wyckoff and S. A. Feigenbaum. An Experimental Extended Exposure Response Film. *SPIE*, 1:117–125, 1963.

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Tutorial 7
High Dynamic Range Techniques in Graphics: Acquisition to Display

HDR Acquisition Techniques for Still Images and Video

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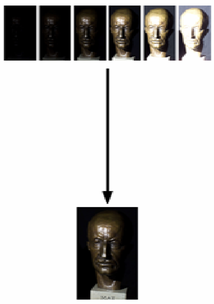
Dynamic Range of Cameras

- example: photographic camera with standard CCD sensor
  - dynamic range of sensor — 1:1000
  - exposure variation (handheld camera/non-static scene): 1/60th s – 1/6000th s exposure time — 1:100
  - varying aperture f/2.0 – f/22.0 — ~1:100
  - exposure bias/varying “sensitivity” — 1:10
  - total (sequential) — 1:100,000,000
- simultaneous dynamic range still only 1:1000
- similar situation for analog cameras

High Dynamic Range (HDR) Imaging

- basic idea of multi-exposure techniques:
  - combine multiple images with different exposure settings
  - makes use of available sequential dynamic range
- other techniques available (e.g. HDR video)



A Brief History of HDR Imaging

- analog film with several emulsions of different sensitivity levels by Wyckoff in the 1960s
  - Charles W. Wyckoff and Stan A. Feigenbaum. An Experimental Extended Exposure Response Film. *SPIE*, 1:117–125, 1963.
  - dynamic range of about $1:10^8$ or 160 dB

A Brief History of HDR Imaging

- some methods assume linear response
  - Brian C. Madden. Extended Intensity Range Imaging. Technical report, University of Pennsylvania, GRASP Laboratory, 1993.
  - correct for raw CCD data
  - takes value from brightest non-saturated image

A Brief History of HDR Imaging

- response curve first recovered by Mann and Picard
  - Steve Mann and Rosalind W. Picard. On being ‘undigital’ with digital cameras: Extending Dynamic Range by Combining Differently Exposed Pictures. In *IS&T’s 48th Annual Conference*, pages 422–428, 1995.
  - looks only at a single pixel in several images with varying exposure times

A Brief History of HDR Imaging

- method for digital photography by Debevec and Malik
  - Paul Debevec and Jitendra Malik. Recovering High Dynamic Range Radiance Maps from Photographs. In *Proceedings of SIGGRAPH 97*, pages 369–378, August 1997.
  - selects a small number of pixels from the images
  - performs an optimization of the response curve with a smoothness constraint

A Brief History of HDR Imaging

- method for digital photography by Debevec and Malik
  - objective function to be minimized

$$\mathcal{O} = \sum_{i=1}^{N}\sum_{j=1}^{P}\{w(Z_{ij})\,[g(Z_{ij}) - \ln E_i - \ln \Delta t_j]\}^2 + \lambda \sum_{z=Z_{min}+1}^{Z_{max}-1} [w(z)g''(z)]^2$$

A Brief History of HDR Imaging

- method by Robertson et al.
  - Mark A. Robertson, Sean Borman, and Robert L. Stevenson. Estimation-Theoretic Approach to Dynamic Range Improvement Using Multiple Exposures. Journal of Electronic Imaging, vol. 12, no. 2, pages 219--228, April 2003.
  - optimization over all pixels in all images
  - more stable for noisy input data

A Brief History of HDR Imaging

- several methods from the CAVE group
  - T. Mitsunaga and S. K. Nayar. Radiometric Self Calibration. Proceedings of IEEE Conference on Computer Vision and Pattern Recognition, Fort Collins, June, 1999.
  - parametric function (n^{th} degree polynomial) to describe response curve
  - estimates also (relative) exposure settings
  - noise removed in a preprocessing step

A Brief History of HDR Imaging

- several methods from the CAVE group
  - objective function

$$\mathcal{E} = \sum_{q=1}^{Q-1}\sum_{p=1}^{P}\left[\sum_{n=0}^{N} c_n M_{p,q}{}^n - R_{q,q+1}\sum_{n=0}^{N} c_n M_{p,q+1}{}^n\right]^2$$

$$R_{q,q+1}{}^{(k)} = \sum_{p=1}^{P} \frac{\sum_{n=0}^{N} c_n{}^{(k)} M_{p,q}{}^n}{\sum_{n=0}^{N} c_n{}^{(k)} M_{p,q+1}{}^n}$$

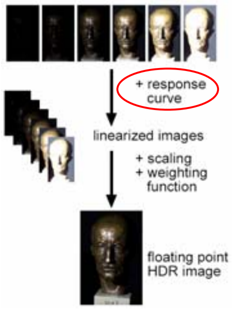
A Brief History of HDR Imaging

- Michael D. Grossberg and Shree K. Nayar . What can be Known about the Radiometric Response Function from Images? Proc. of European Conference on Computer Vision (ECCV), Copenhagen, May 2002.
- like above but derivation from histogramm
- allows for (moderate) scene movement

A Brief History of HDR Imaging

- other methods around in the literature
  - graphics community
  - vision community
  - imaging community
- see part on HDR sensors
- see list of references in course notes

High Dynamic Range Imaging



Algorithm of Robertson et al.

- Principle of this approach:
  - calculate a HDR image using the response curve
  - find a better response curve using the HDR image
- (to be iterated until convergence)
- assume initially linear response

Algorithm of Robertson et al.

- input:
  - series of i images with exposure times t_i
  - pixel value at image position j is $y_{ij} = f(t_i x_j)$
- find irradiance x_j and response curve $I(y_{ij})$
  - $t_i x_j$ is proportional to collected charge/radiant energy
  - f maps collected charge to intensity values

$$f^{-1}(y_{ij}) = t_i x_j =: I(y_{ij})$$

Algorithm of Robertson et al.

- additional input:
  - a weighting function $w(y_{ij})$ (bell shaped curve)
  - an initial camera response curve $I(y_{ij})$ – usually linear
- calculate HDR values x_j from images using

$$x_j = \frac{\sum_i w(y_{ij}) t_i^2 \cdot \frac{I(y_{ij})}{t_i}}{\sum_i w(y_{ij}) t_i^2} \qquad x_j = \quad y_{ij}$$

Algorithm of Robertson et al.

- optimizing the response curve I:
  - start again with definition $f^{-1}(y_{ij}) = t_i x_j =: I(y_{ij})$
- minimization of objective function O

$$O = \sum_{i,j} w(y_{ij})(I(y_{ij}) - t_i x_j)^2$$

- using Gauss-Seidel relaxation yields

$$E_m = \{(i,j) : y_{ij} = m\}$$

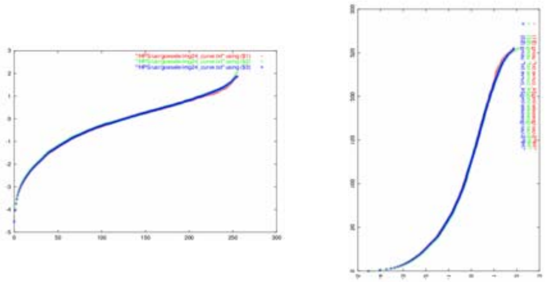
$$I(m) = \frac{1}{\mathrm{Card}(E_m)} \sum_{i,j \in E_m} t_i x_j$$

- $\mathrm{Card}(E_m)$ = number of elements in E_m

Algorithm of Robertson et al.

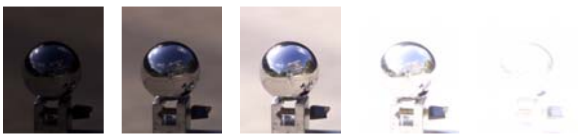
- both steps are iterated
  - calculation of a HDR image using *I*
  - optimization of *I* using the HDR image
    - ➔ *I* needs to be normalized, e.g., *I*(128)=1.0
- stop iteration after convergence
  - criterion: decrease of *O* below some threshold
  - usually only a couple of iterations

HDR Imaging: Algorithm of Robertson et al.



$\log(I(y_{ij}))$

HDR Example: Capturing Environment Maps



1/2000s 1/500s 1/125s 1/30s 1/8s

series of input images

HDR Example: Capturing Environment Maps

Algorithm of Robertson et al.

- choice of weighting function $w(y_{ij})$ for response recovery

$$w_{ij} = \exp\left(-4\frac{(y_{ij}-127.5)^2}{127.5^2}\right)$$

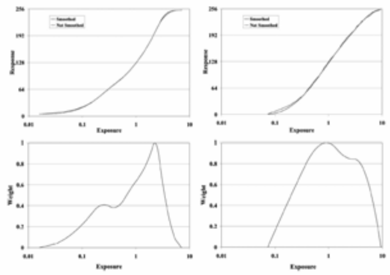
  - for 8 bit images
  - possible correction at both ends (over/underexposure)
  - motivated by general noise model

Algorithm of Robertson et al.

- choice of weighting function $w(y_{ij})$ for HDR reconstruction
  - introduce certainty function *c* as derivative of the response curve with logarithmic exposure axis
  - approximation of response function by cubic spline to compute derivative

$$w_{ij} = w(y_{ij}) = c(I_{y_{ij}})$$

Algorithm of Robertson et al.



from Mark A. Robertson, Sean Borman, and Robert L. Stevenson. Estimation-Theoretic Approach to Dynamic Range Improvement Using Multiple Exposures. Journal of Electronic Imaging, vol. 12, no. 2, pages 219--228, April 2003.

Input Images for Response Recovery

- my favorite:
  - grey card, out of focus, smooth illumination gradient
- advantages
  - uniform histogram of values
  - no color processing or sharpening interfering with the result

Input Images for HDR Generation

- how many images are necessary to get good results?
  - depends on scene dynamic range and on quality requirements
  - generally a difference of two steps (factor of 4) between exposures is sufficient
  - see also:
    M. D. Grossberg, S. K. Nayar: High Dynamic Range from Multiple Images: Which Exposures to Combine? Proc. ICCV Workshop on Color and Photometric Methods in Computer Vision, 2003.

Algorithm of Robertson et al.

- discussion
  - method very easy
  - doesn't make assumptions about response curve shape
  - converges fast
  - takes all available input data into account
  - can be extended to >8 bit colordepth

Handheld Acquisition of Image Series

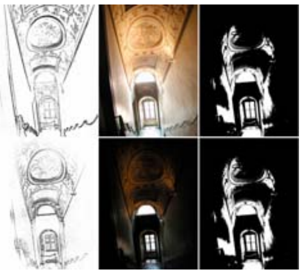
- assumption: static scene, only translation of camera
  - Ward, Greg, "Fast, robust image registration for compositing high dynamic range photographs from hand-held exposures," Journal of Graphics Tools, 8(2):17-30, 2003.
- general problems
  - stable registration between images with different exposure
  - response curve not necessarily known
  - fast algorithm

Handheld Acquisition of Image Series

- median threshold bitmap (MTB)
- definition:
  - determine median 8-bit image value from low-resolution histogram
  - create a bi-level bitmap with
    - 0 where image value ≤ median
    - 1 where image value > median

Handheld Acquisition of Image Series

edge bitmap

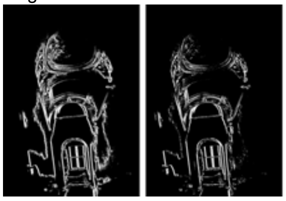


MTB bitmap

from Ward, Greg, "Fast, robust image registration for compositing high dynamic range photographs from hand-held exposures," Journal of Graphics Tools, 8(2):17-30, 2003.

Handheld Acquisition of Image Series

- threshold noise
  - values right at the median threshold are not reliable
  - removed using a mask



from Ward, Greg, "Fast, robust image registration for compositing high dynamic range photographs from hand-held exposures," Journal of Graphics Tools, 8(2):17-30, 2003.

Handheld Acquisition of Image Series

- fast registration
  - use image pyramid
  - depth determined by maximum displacement

$$\text{depth} = \log_2(\text{max\_displacement})$$

  - requires only 9 comparisons per level
  - 1 bit MTB allows fast XOR operation for comparison

from Ward, Greg, "Fast, robust image registration for compositing high dynamic range photographs from hand-held exposures," Journal of Graphics Tools, 8(2):17-30, 2003.

HDR for Dynamic Scenes

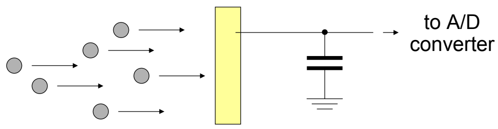
- capture at multiple time steps and compensate for movements in scene/camera position
  - Sing Bing Kang, Matthew Uyttendaele, Simon Winder, Richard Szeliski: High dynamic range video. ACM Transactions on Graphics (Proc. ACM SIGGRAPH 2003), Volume 22 (3), pages: 319 – 325, 2003.
  - solution of a vision problem

HDR for Dynamic Scenes

- capture extended dynamic range in a single acquisition step
  - generally some kind of hardware solution
  - Manoj Aggarwal, Narendra Ahuja: Split Aperture Imaging for High Dynamic Range. International Conf. on Computer Vision, Vol. 2, pp. 10-17, 2001
  - beam from lens is split into several components and imaged by multiple sensors
  - relative exposure determined by geometry of split system

HDR for Dynamic Scenes

- use of specialized sensor chips
  - CCD sensor is inherently a linear device
  - dynamic range limited by noise, capacity, …



HDR for Dynamic Scenes

- use of specialized sensor chips
  - S. K. Nayar, T. Mitsunaga : High Dynamic Range Imaging: Spatially Varying Pixel Exposures. Proc. of IEEE Conf. on Computer Vision and Pattern Recognition, 2000.
  - add neutral density filters on top of individual sensels
  - similar to Bayer pattern for color capture

HDR for Dynamic Scenes

- use of specialized sensor chips
  - multiple technologies to implement multi-exposure techniques in hardware
  - sensels with logarithmic instead of linear response (i.e., perform logarithm in analog domain)

    ➔ see part on HDR image sensors for video
  - images are usually processed and quantized by camera software
  - photometric calibration?

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Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

HDR Cameras and their Photometric Calibration

Grzegorz Krawczyk
MPI Informatik

Why do we need calibration?

- Obtain meaningful data from cameras
- Have common data in heterogeneous camera systems
- Use the camera as a measurement tool

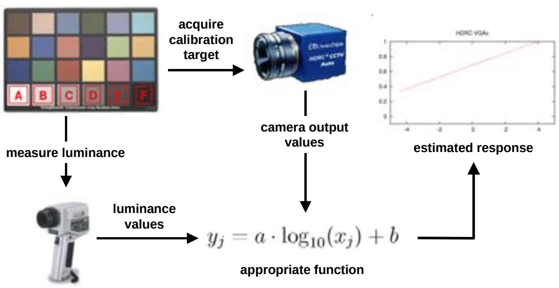
Overview

- Two approaches to calibration
- Choice of appropriate calibration target
- Camera response recovery
- Example calibration of 2 cameras
- Accuracy of HDR sensor vs. multi-exposure techniques

Two Approaches to Calibration

1. Fit an *a priori* response to measurements
   - Requires measurement tools (luminance meter, color checker board)
   - Varied, controlled lightning conditions are preferable (known light sources, dark room)
2. Recover the camera response curve
   - Multiple exposures of arbitrary scene
   - Requires high contrast scene

1. Response Function Fit



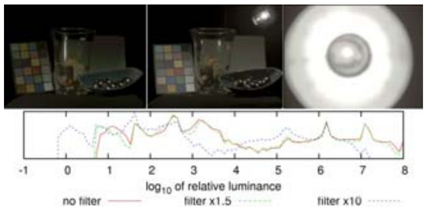
Limitations of Function Fit Approach

- High confidence only in the sampled data
- Difficult to verify that the assumption on the response curve is correct
- Multiple illumination conditions required to calibrate the response in high dynamic range

2. Camera Response Recovery

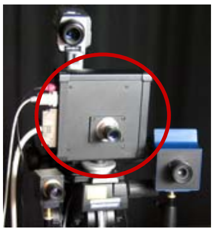
- Use LDR multi-exposure techniques to recover the full shape of the response curve
- Need appropriate calibration target
- Pitfalls of various methods
  - Assumption on continuous response
  - Polynomial approximation of the response
  - Very high computational complexity for >8bits
- Appropriate method: [Robertson et. al 2003]

Calibration Target



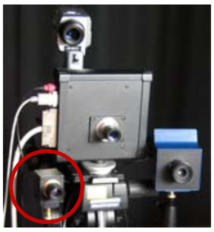
- Scene with very wide dynamic range
- ND filters to simulate different exposures

Example Calibration



- Silicon Vision LarsIII camera
  - Locally auto-adaptive sensor (16bit)
  - Individual integration time for each pixel
  - Information per pixel:
    - ➔Collected signal
    - ➔Integration time
  - A type of multi-exposure sensor

Example Calibration

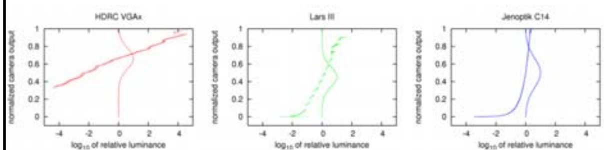


- Silicon Vision LarsIII camera
  - Locally auto-adaptive sensor (16bit)
- HDRC VGAx camera
  - Logarithmic response CMOS (10bit)
  - Transforms collected charge to logarithmic voltage (analog logarithm)
  - Approximation of eye-like vision
  - More details will follow

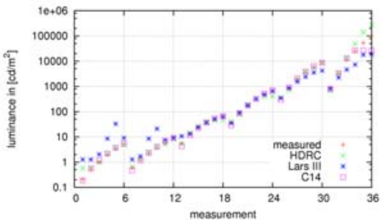
Example Calibration

- Silicon Vision LarsIII camera
  - Locally auto-adaptive sensor (16bit)
- HDRC VGAx camera
  - Logarithmic response CMOS (10bit)
- Jenoptik C14
  - High-end CCD camera (14bit LDR, linear)

Recovered Response Curves



Absolute Calibration

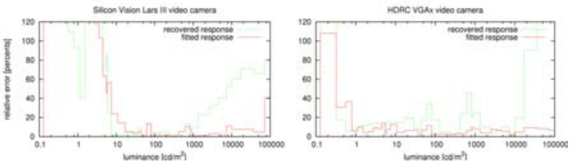


- Luminance in [cd/m^2] calculated from the camera output values (at a known aperture value)

Sample Measurements

Measurement [cd/m^2]	HDRC (abs. calibration)	LarsIII (abs. calibration)	C14 (multi-exposure)
5.3	4.57	8.69	5.38
9.3	8.12	11.52	9.05
70.9	62.65	61.33	66.07
741.2	695.22	663.00	704.43
8,796.0	8,924.89	7,822.66	8,734.86
194,600.0	225,010.00	50,415.00	n/a

Relative Measurement Errors



- HDRC camera: relative error **<13%** in range 1 .. 10,000 [cd/m^2]
- Silicon Vision: relative error **<9.5%** in range 10 .. 1,000 [cd/m^2]
- C14: relative error **<7%** in range 0.1 .. 25,000 [cd/m^2]
- Using function fit: relative error **<6%** for both HDR cameras

HDR sensor vs. multi-exposure

- HDR camera
  - Fast acquisition of dynamic scenes at 25fps w/o motion artifacts
  - Typically lower resolution
  - Quality almost reaches the multi-exposure techniques
- LDR camera + multi-exposure technique
  - Slow acquisition (impossible in some conditions)
  - Higher quality and resolution
  - High accuracy of measurements

Conclusions

HDR cameras can be used
for photometric measurements.

- Function fit results in lower relative error
- Response recovery estimates the function without prior knowledge

  (Limited precision due to sensor noise or artifacts related to ND filters)
- Response recovery is more accessible than taking measurements required for function fit
- See section on HDR applications for example use of HDR cameras

See MPI Technical Report MPI-I-2005-4-005

Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

HDR Image Sensors

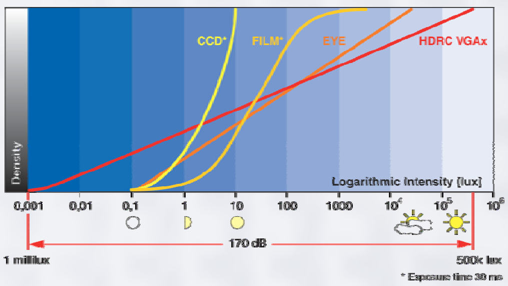
Prof. Dr. Bernd Höfflinger
Institute for Microelectronics Stuttgart

Imaging

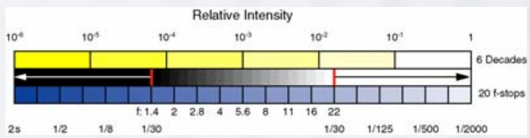
IMAGING	RESPONSE	SCENE DYNAMIC RANGE	COLOR CONSTANCY
Our eyes	Logarithmic	Very high	Yes
Painting	Eye-like, logarithmic	High	Depending on the artist
Film	Pseudo eye-like, pseudo logarithmic	High	Yes
Vidicon	Linear	Small	No
CCD	Linear	Small	No
Other CMOS	Linear	Small	No
HDRC	Eye-Like, logarithmic	Very high	Yes

HDRC®, CCD, FILM, AUGE

Response curve of the HDRC VGAx and other sensors



Dynamic Range



Contrast Sensitivity

Contrast Sensitivity of a Logarithmic OECF

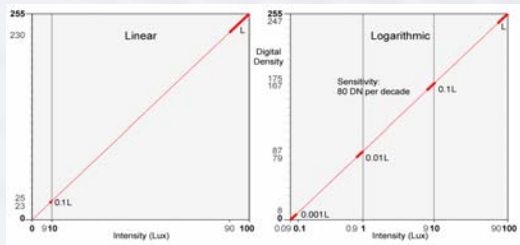
Output N Bit / Input M Decades	8 Bit	9 Bit	10 Bit	11 Bit	12 Bit
2 Dec	1.8	0.90	0.45	0.225	O.112
3 Dec	2.7	1.35	0.675	0.336	0.168
4 Dec	3.6	1.8	0.900	0.45	0.225
5 Dec	4.5	2.25	1.175	0.56	0.280
6 Dec	5.4	2.7	1.350	0.67	0.336
7 Dec	6.3	3.15	1.575	0.784	0.392
8 Dec	7.2	3.6	1.80	0.9	0.45

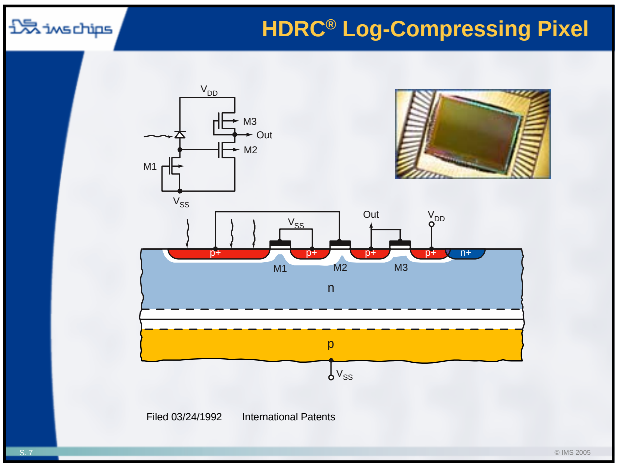
Input Dynamic Range: M Decades
Output Signal Range: N Bit

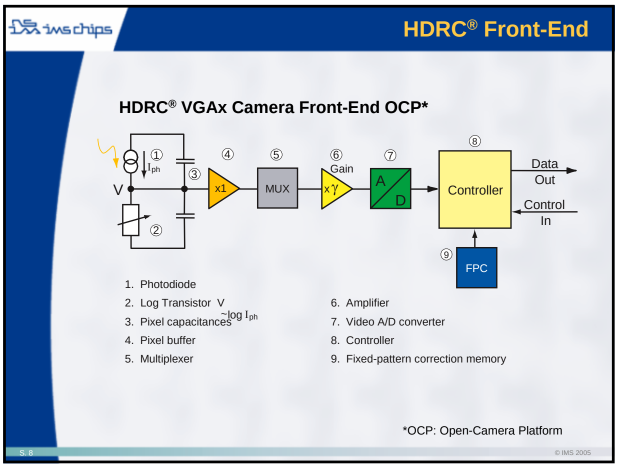
Contrast Sensitivity is the percent input change, which will be noticed as a change of 1 LSB (1DN) in the output.

Edge Detection

Edge between 2 surfaces A,B with reflectance R_B=0.9 R_A





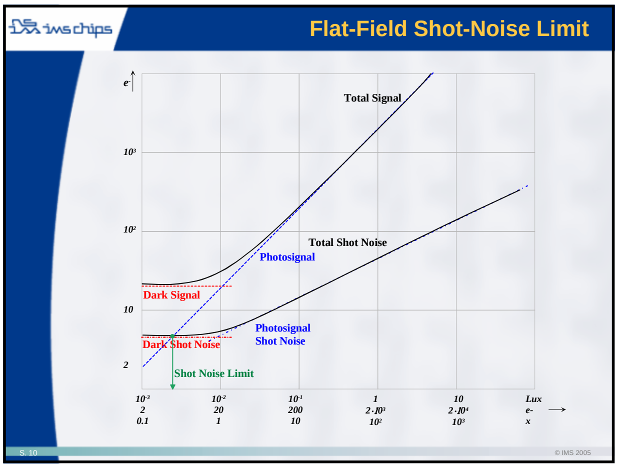


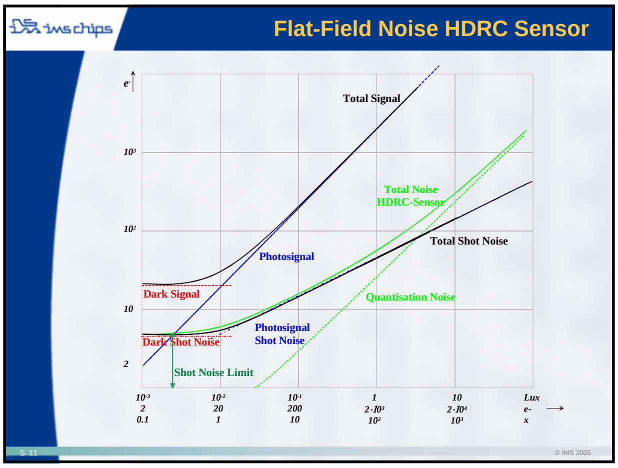
Reference CMOS Pixel

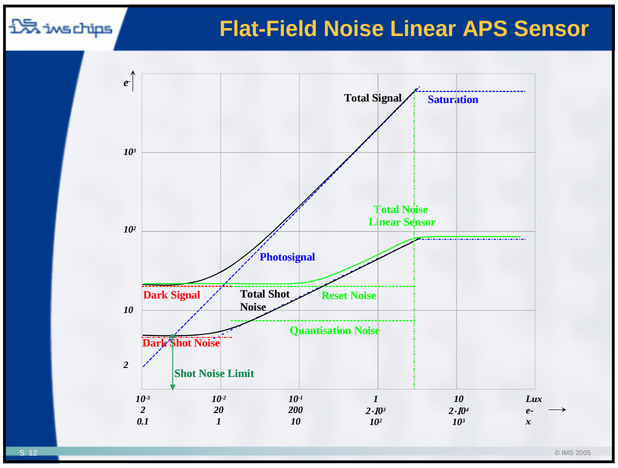
Pixel Area	(µm²)	7.4 x 7.4
Photodiode (PD) Area	(µm²)	5.0 x 5.0
Capacitance	(fF)	2.5
Dark Charge	(e)	20
Dark Shot Noise	(e)	4.5
Conversion Efficiency	(e/mLux) (DN/mLux)	2 0.33
Sensitivity	(V/Lux * s)	5.4
Reset Noise	(e)	20
Quantisation: (1 DN)[1]	(e) (mV)	6 0.4
Conditions: T = 20 °C, T_{int} = 25 ms		

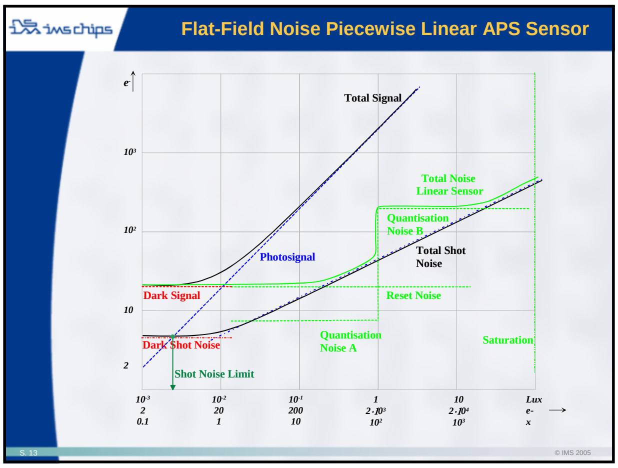
[1] Linear 10 Bit

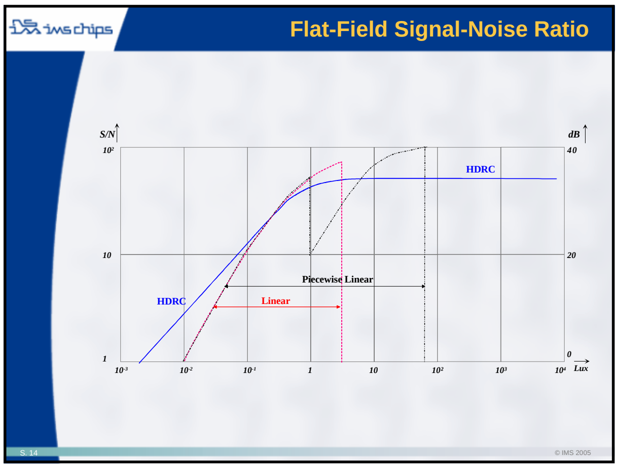
S. 9 © IMS 2005

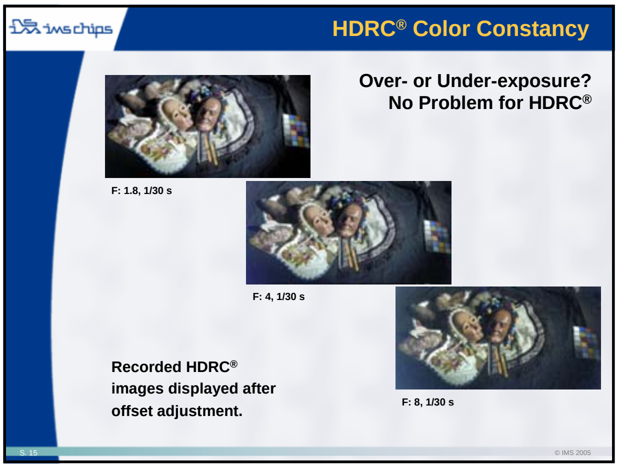


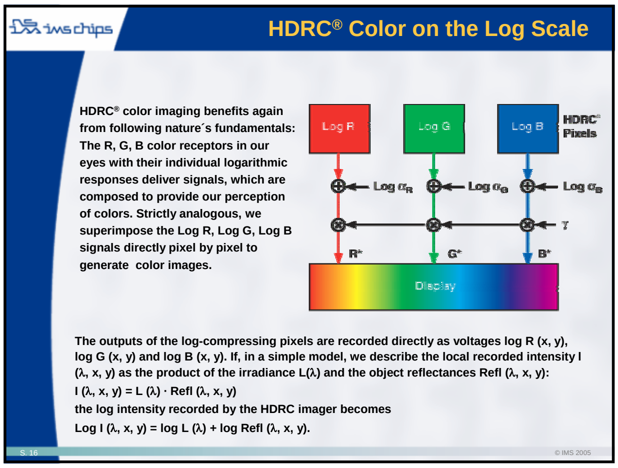


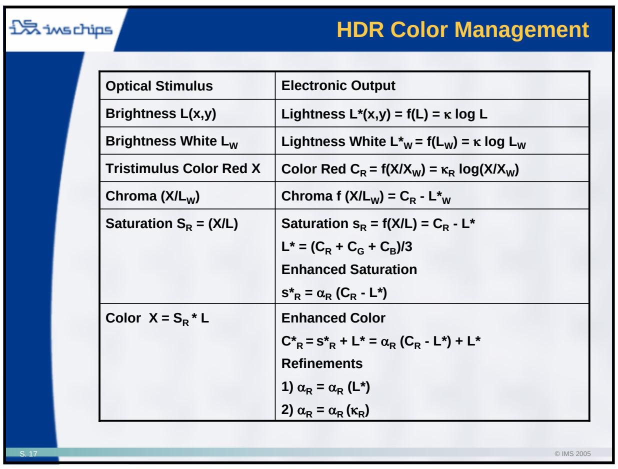




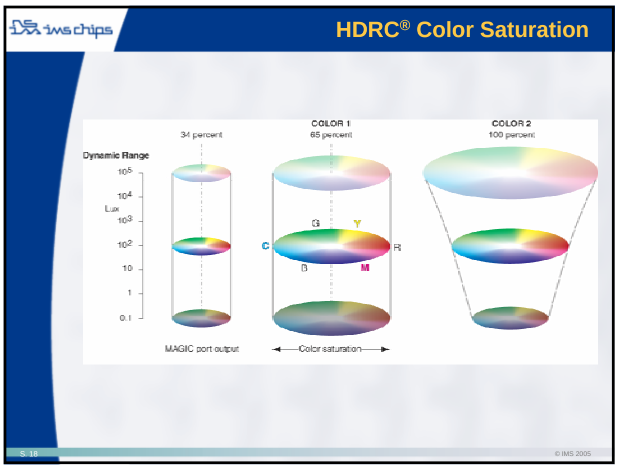








Optical Stimulus	Electronic Output
Brightness L(x,y)	Lightness $L^*(x,y) = f(L) = \kappa \log L$
Brightness White L_W	Lightness White $L^*_W = f(L_W) = \kappa \log L_W$
Tristimulus Color Red X	Color Red $C_R = f(X/X_W) = \kappa_R \log(X/X_W)$
Chroma (X/L_W)	Chroma $f(X/L_W) = C_R - L^*_W$
Saturation $S_R = (X/L)$	Saturation $s_R = f(X/L) = C_R - L^*$ $L^* = (C_R + C_G + C_B)/3$ Enhanced Saturation $s^*_R = \alpha_R (C_R - L^*)$
Color $X = S_R * L$	Enhanced Color $C^*_R = s^*_R + L^* = \alpha_R (C_R - L^*) + L^*$ Refinements 1) $\alpha_R = \alpha_R (L^*)$ 2) $\alpha_R = \alpha_R (\kappa_R)$

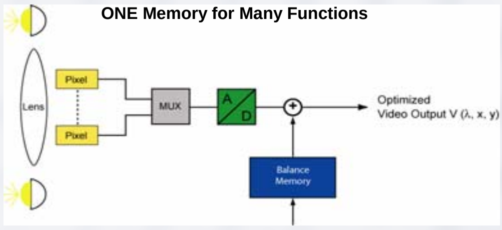


Steps towards a HDRC Color Image

1. For the R, G, B pixels, record the output voltages VR, VG, VB of the log-converting HDRC sensor and convert to digital numbers (DN).
   a. With a grey opaque diffuser filter, shift the centers of the recorded RGB histograms to coincide = white balance.
   b. Remove filter, and for each captured frame, get Min and Max of the frame histogram.
2. Expand and shift all DN to fully utilize the lightness range L^*_W.
3. Depending on the RGB mosaic topology, perform center-surround operations to obtain the tri-color values CR, CG, CB for each pixel.
4. Perform color enhancement operations to obtain C^*_R, C^*_G, C^*_B per pixel.

HDRC® Balance Memory

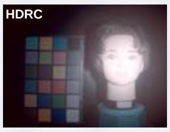
ONE Memory for Many Functions



Adjustment for:
- Lens Nonuniformities T(λ,x,y)
- Nonuniform Illuminance L(λ,x,y)
- Pixel Nonuniformity FP(λ,x,y)
- Spectral Sensitivity α(λ)

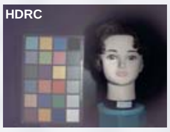
$$V_R(x, y) = \log Refl_R(x, y) + \log L(x, y) + \log \alpha_R + \log T_R(x, y) + FP(x, y)$$

HDRC® Illuminance Equalisation



Original HDRC® Frame

Log Illuminance (Spotlight)



HDRC® Frame after Log Illuminance Offset

Spotlight Illumination of the Face

Excellent Face Recognition with HDRC®

Improvement by Irradiance Equalisation

White and black saturation of the CCD pixels limits any gains from pre-processing

HDRC® Log Imaging

- Vision: Natural and Film
- High-Dynamic-Range Logarithmic Vision
- No Shutter-or Integration-Time
- Separating Illuminance and Features of Objects
- HDRC® sensors
  - track photon flux continuously
  - are free from control loops (with their dead times and delays)
  - absolutely cannot be blinded (white-saturated)
  - offer constant contrast resolution over many decades of grey
  - keep colors constant independent of luminance or aperture
- Illuminance Equalisation
- Robust Preprocessing
- High-Latitude Post-Production

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Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

HDR Image and Video Compression

Karol Myszkowski
MPI Informatik

Overview

1. HDR Image Encoding
2. HDR Video Encoding
   – Luminance Quantization
   – Edge Coding
3. HDR Visible Differences Predictor
   – LDR VDP
   – HDR extensions
4. HDR Video Player demo

Traditional RGB Image Formats

- Tailored for display devices
  – Color gamut: constrained by red, green, and blue monitor phosphors
  – Luminance encoding: often limited to 2 orders of magnitude
- Not suitable to encode color gamut and luminance of the real world scenes

HDR Image Encodings: Requirements

- Luminance encoding:
  – 12 orders of magnitude
  – 5 orders simultaneously visible
  – Quantization error below 1%
- Full visible color gamut represented
- Possibly perceptually uniform luminance and color gamut quantization steps

Non-lossy HDR Image Formats

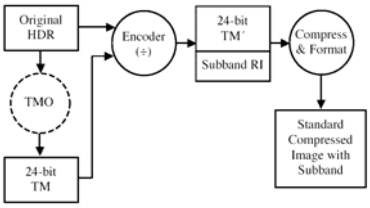
- Radiance RGBE Encoding: 32 bits [Ward 1991]
  – 76 orders of magnitude, 1% luminance steps
  – Does not cover visible gamut
  – Perceptually non-uniform quantization steps
- LogLuv (part of TIFF library): 32 bits [Larsen 1998]
  – 36 orders of magnitude, 0.3% luminance steps
    ➔16 bits log luminance – very conservative, better perceptual uniformity still possible
  – Covers full visible gamut
    ➔8 bits for each of perceptually uniform **CIE *u*v*** color coordinates

Non-lossy HDR Image Formats

- OpenEXR: 48 bits [Bogart et al. 2003]
  – 9.6 orders of magnitude, 0.1% luminance steps
  – Covers full visible gamut
    ➔Perceptually non-uniform color representation
  – 16-bit floating point
    ➔Suitable for extensive image operations which may result in error accumulation
  – *De facto* industrial standard
- Lossy OpenEXR soon

HDR JPEG [Ward and Simmons 2004]

- Backward compatible JPEG encoding
  - Tone mapped original (*TM*) accompanied by a ratio image (*RI*) needed to recover full *HDR* image
  - *RI* carried in a subband of a standard 24-bit RGB format



HDR image = *TM* * *RI*

HDR JPEG [Ward and Simmons 2004]

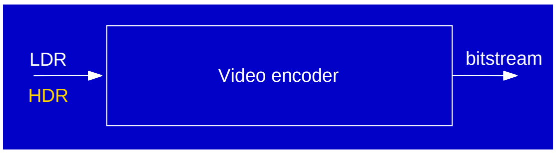
- The ratio image *RI* is often downsampled to RI_d
- Distortion reduction
  - Pre-correction of foreground image $TM' = \frac{HDR}{RI_d}$
  - Post-correction of ratio image

TM *RI*

$$RI' = RI_d \cdot \left[\frac{Lum(TM)}{Lum(TM_d)}\right]^{\sigma} \quad \text{where} \quad \sigma = \frac{\text{var}(RI_d)}{\text{var}(Lum(TM_d))}$$

HDR MPEG Encoding [Mantiuk et al. 2004]

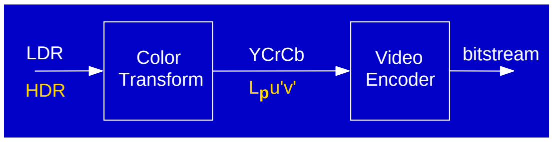
- Detail level 1: Input & Output



- White: MPEG
- Orange: HDR Encoder

HDR MPEG Encoding [Mantiuk et al. 2004]

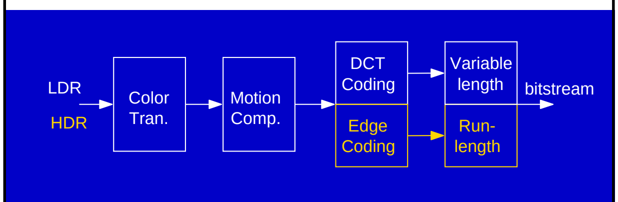
- Detail level 2: Color Transform



- White: MPEG
- Orange: HDR Encoder

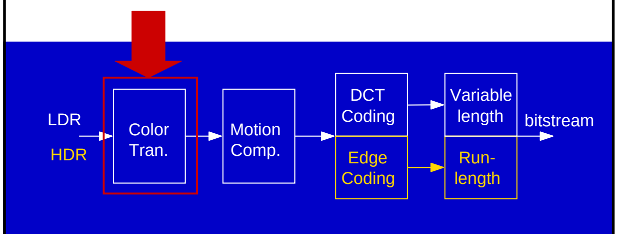
HDR MPEG Encoding [Mantiuk et al. 2004]

- Detail level 3: Edge Coding



- White: MPEG
- Orange: HDR Encoder

Encoding of Color

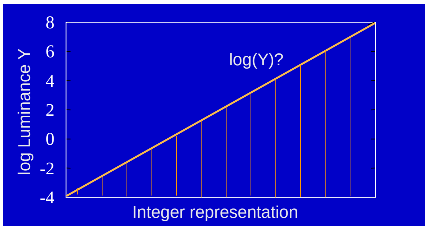


Encoding of Color

- How to represent color data?
  - Floating Points – ineffective compression
  - Integers – ok, but require quantization
- How to quantize color data?
  - Quantization errors < threshold of perception
  - Use uniform color space (L*u*v*, L*a*b*) [Ward98]
  - Find minimum number of bits
- Color (u*v*) – 8 bits are enough

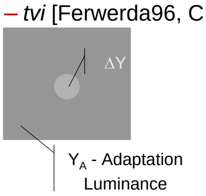
Encoding of Luminance

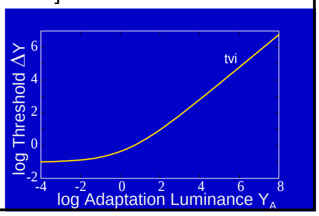
- How to quantize luminance?
  - Gamma correction? Logarithm?



Threshold Versus Intensity

- Psychophysical detection measurements
  - The smallest perceivable difference ΔY for a certain adaptation level Y_A
  - *tvi* [Ferwerda96, CIE 12/2.1]





Luminance Quantization

- Align quantization errors with thresholds of perceivable contrast using *tvi(Y_A)*

quantization $\psi : L_p \to Y[\frac{\mathrm{cd}}{\mathrm{m}^2}]$ where $L_p = [0, 2^{nbits} - 1]$

error: $e_{\max}(l) = \max\{|\psi(l+0.5) - \psi(l)|, |\psi(l) - \psi(l-0.5)|\}$

$$e_{\max}(l) \approx 0.5 \frac{d\psi(l)}{dl} \quad \text{(Taylor series expansion)}$$

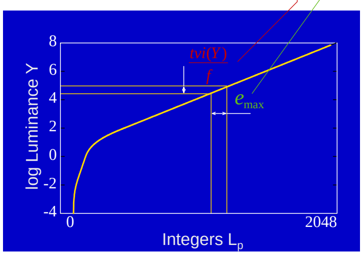
$$e_{\max}(l) = \frac{tvi(Y_A)}{f} \quad \text{(psychophysics: JND scaled by } f\text{)}$$

$$\frac{d\psi(l)}{dl} = 2 \cdot \frac{tvi(\psi(l))}{f}$$

Luminance Quantization

Just below threshold of perception

Maximum quantization error



$$\frac{d\psi(l)}{dl} = 2 \cdot f^{-1} \cdot tvi(\psi(l))$$

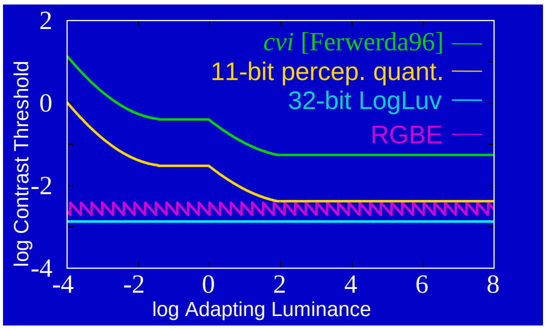
$l - L$ in L_p space

$\psi(l) - L_p$ to Y mapping

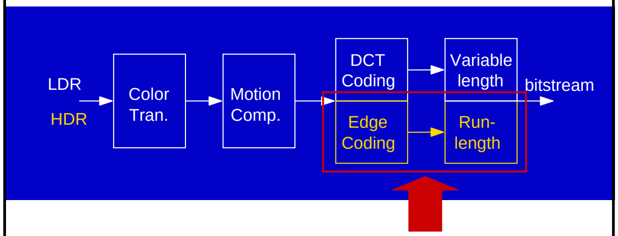
f – threshold decrease

- Capacity function [Ashkihmin02]
- Grayscale Standard Display Function [DICOM03]
- 10 – 11 bits are enough

Luminance Quantizations Comparison

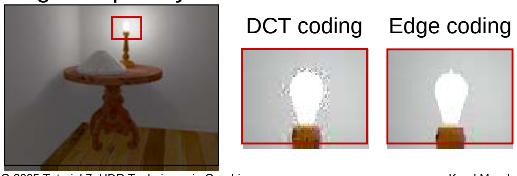


Edge Coding



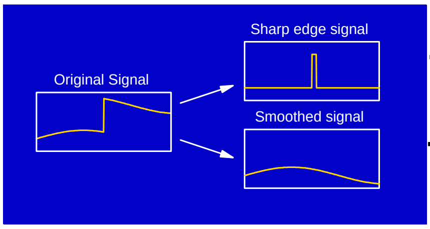
Edge Coding: Motivation

- HDR video can contain sharp contrast edges
  - Light sources, shadows
- DCT coding of sharp contrast may cause high frequency artifacts

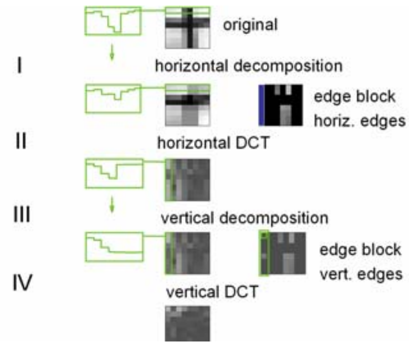


Edge Coding: Solution

- Solution: Encode sharp edges in spatial domain, the rest in frequency domain

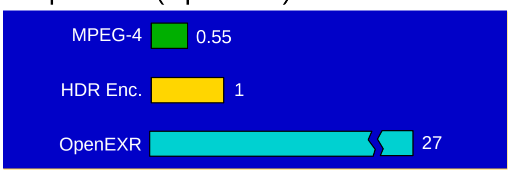


Edge Coding: Algorithm



Results

- 2x size of tone-mapped MPEG-4 video
- 20-30x saving compared to intra-frame compression (OpenEXR)

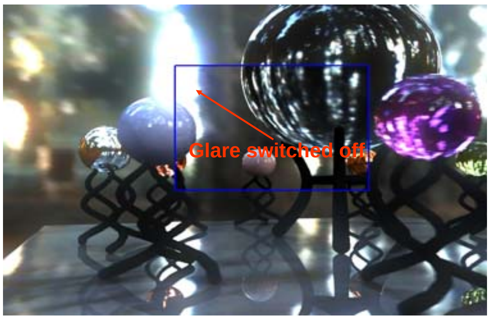


Bit-stream Size

Example Application: HDR Video Player

- Tone mapping adjusted to display device
- Inspecting various luminance ranges with a linear luminance mapping
- Physically based post-processing effects: blooming, motion blur, night vision
  - Require HDR information
  - Computed on-the-fly by graphics hardware
  - Can be scripted through annotations in video stream

HDR Video Player: Glare



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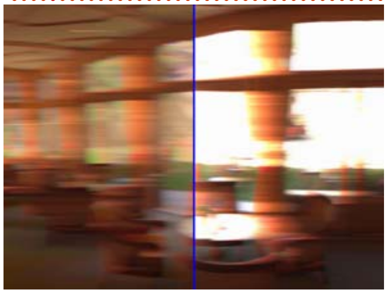
HDR Video Player: Motion Blur



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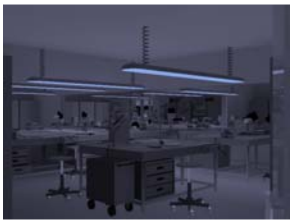
HDR Video Player: Night Vision



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Summary: HDR Video Compression

- Modest changes to MPEG-4
  - $L_p u'v'$ color space
    - ➔Luminance quantization (10-11 bits)
  - Edge coding
- Backward compatible HDR MPEG-4?

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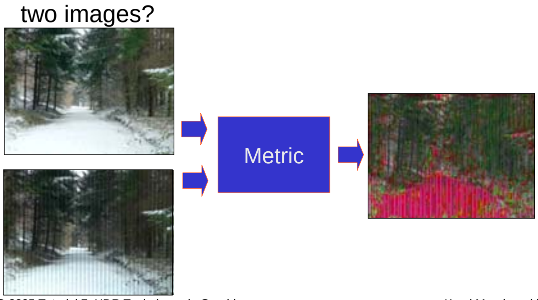
Visible Difference Metric

- Can the human eye see the differences between two images?



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Application Examples

- Lossy image compression and broadcasting
- Design of image input/output devices
  - scanners, cameras, monitors, printers
- Watermarking
- Computer graphics, medical visualization

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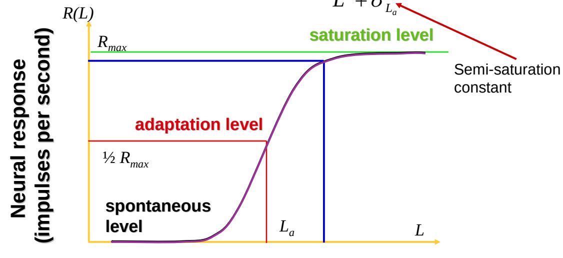
Subjective vs. Objective Methods

- Subjective methods involving human subjects
  - Very costly
- Simple objective metrics e.g. RMS Error
  - Not reliable
- Basic characteristics of the Human Visual System (HVS) must be modeled to improve difference prediction reliability:
  - + Luminance adaptation
  - + Contrast sensitivity
  - + Visual masking

Photoreceptor Response

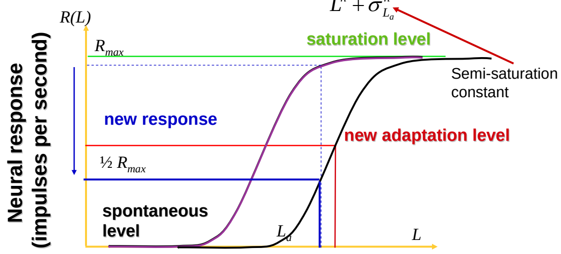
$$\text{Michelis-Menten Equation}: R(L) = \frac{L^n}{L^n + \sigma_{L_a}^n} R_{\max} \qquad n \approx 0.74$$



Luminance of light falling on receptive field's center

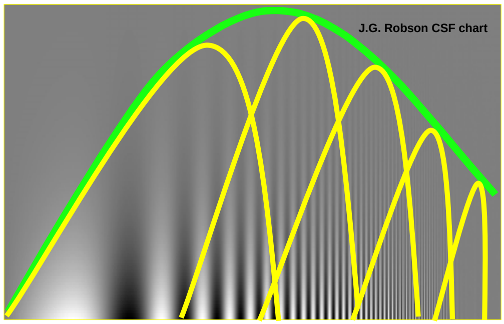
Photoreceptor Response

$$\text{Michelis-Menten Equation}: R(L) = \frac{L^n}{L^n + \sigma_{L_a}^n} R_{\max} \qquad n \approx 0.74$$



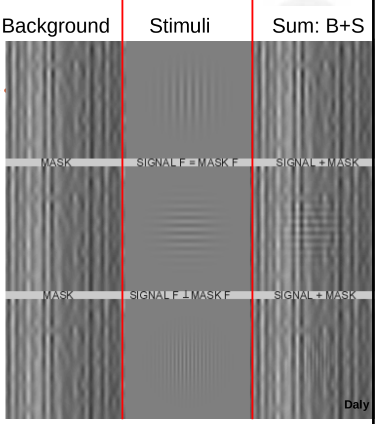
Luminance of light falling on receptive field's center

Contrast Sensitivity Function



Visual Masking

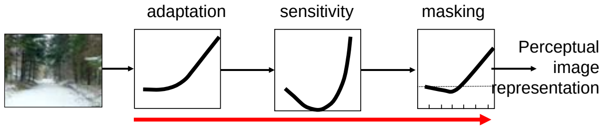
- Strong masking: similar spatial frequencies
- Weak masking: different orientations
- Weak masking: different spatial frequencies



Typical HVS Model

Detection of perceivable differences between images depends on the following characteristics of the HVS:

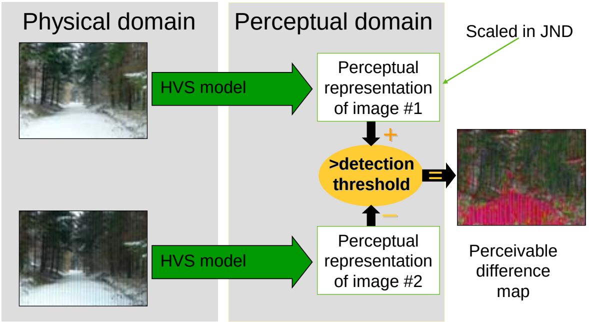
- Luminance adaptation
- Contrast sensitivity
- Visual masking



Increase of the detection threshold:

- With increase of adaptation luminance
- With increase of spatial frequencies
- With contrast increase

Perceivable Differences Predictor [Daly 1993]

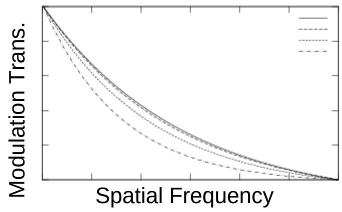


HDR VDP – Extensions [Mantiuk et al. 2005]

- Optical Transfer Function
  - Glare effect important for high contrasts
- JND scaled contrast
  - Contrast measure that does not depend on adaptation luminance
- Locally adaptive CSF
  - Instead of global adaptation for the whole image
- Assumption: The eye can adapt to luminance of very small patches (to a single pixel)

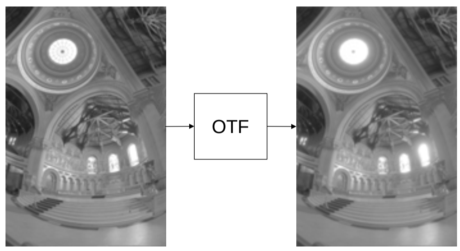
Optical Transfer Function

- Modulation Transfer function that simulates optics of the human eye [Deeley et al. 1991]



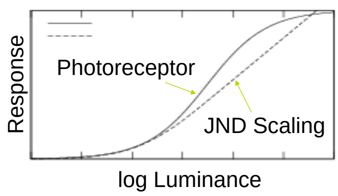
Optical Transfer Function

- OTF significantly reduces contrast in HDR scenes



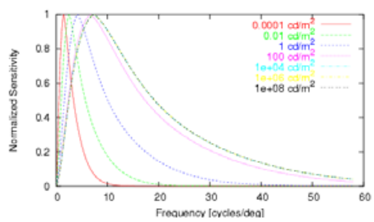
Amplitude Nonlinearity

- Introduced contrast measure independent of adaptation luminance
- Scaled in JND units



Local Adaptation for CSF

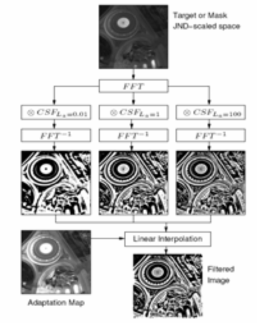
- The shape of CSF varies with adaptation luminance



- Adaptation luminance can vary significantly across an image

Local Adaptation for CSF

- 1. Use different CSF for filtering each part of an image
- 2. Interpolate filtered images depending on adaptation luminance [Durand03]



Calibration

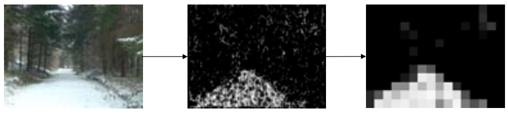
- An experiment conducted on an HDR display to find subjective difference probability map
- HDR VDP parameters optimized to fit closely subjective data

Calibration: Experiment

- Subjects were to mark visible differences using rectangular blocks
- Results averaged across subjects
  - ➢fuzzy detection probability map

Calibration: Data Fitting

- HDR VDP response converted to format of the subjective data



Distorted Image VDP Response Integrated Resp.

- Found the best fit for peak threshold contrast and masking function slope

Summary: HDR VDP

- Objective visual difference metric
  - Not limited to existing display technology
  - Predicts changing sensitivity in bright and dark regions of an image
  - Small performance overhead
- Applications
  - New display technology (HDR display)
  - Assessment of visibility for varying luminance conditions

Acknowledgments

- I would like to thank Rafal Mantiuk for sharing with me some slides used in this presentation.
- HDR images and video sequences courtesy of Paul Debevec, SpheronVR, Jozef Zajac, Christian Fuchs, and Patrick Reuter.
- HDR Camera HDRC(R) VGAx courtesy of IMS CHIPS www.hdrc.com

Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

High Dynamic Range Displays

Wolfgang Heidrich and Matthew Trentacoste
University of British Columbia

Part 1

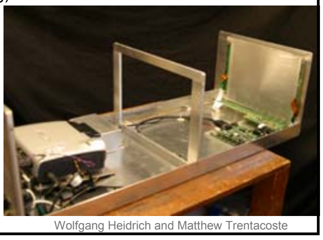
- Develop HDR display
  - Use results on visual perception
  - Easy to build
  - Easy to calibrate
  - Address software issues
  - Make it commercially viable
    - → Sunnybrook Technologies

Our Work

- Two setups:
  - Projector-based prototype
    - → Good for evaluating principle
    - → Experiment with design parameters
  - LED-based version
    - → More practical/economic design
    - → Commercially available

First Setup: Projector/LCD Panel

- Hardware setup:
  - Remove backlight from LCD panel
  - Shine image from video projector onto back of panel
    - → (Fresnel lens for focusing)
  - Multiplies dynamic range of LCD and projector
- Measured:
  - Contrast: 50,000:1
  - Intensity: 2,700 cd/m²



Screenshots

Screenshots

- Photographs taken with 4 stops different exposure time

Screenshots

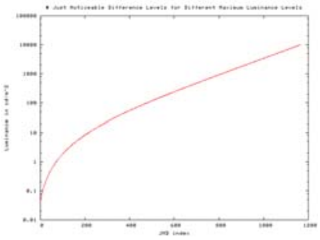
- Photographs taken with 4 stops different exposure time

Initial Discussion

- Advantages:
  - Relatively easy to build
  - Works!
- Issues:
  - Have 8bit for each of LCD, projector, but not independent!
    - → Quantization artifacts?
  - Alignment of projector/panel very hard
    - → Changes during operation (heat!)
  - How do we render for this?

Quantization?

- Just Noticeable Differences
  - Results from psychophysics [Barten 2001]:
    - → Number of intensity levels discernable for given intensity range
    - → Predicts about 950 levels for this display
    - → These are easy to create using combinations of projector/LCD values



Alignment Problems

- Problem:
  - Have to align projector pixels with LCD pixels at sub-pixel accuracy
  - Impossible (precise alignment changes due to heat deformation)
  - Any misalignment creates moiré patterns
- Solution:
  - Blur the projector image
    - → Low-frequency image – precise alignment not necessary

Software Issues

- Rendering:
  - Have to split floating point image into
    - → projector contribution
    - → LCD panel contribution
  - Have to compensate for blur in projector
  - Many ways to do this, since projector and LCD values not independent!

Discussion

- Advantages:
  - Relatively easy to built
  - Works well in lab settings
- Disadvantages:
  - Heat
  - Power consumption
  - Size
  - Needs to be re-calibrated every few days
    - → Does not take very long, but annoying

Second Setup

- Idea: Replace projector with array of LEDs
  - Very few (about 1000) LEDs sufficient
  - Every LED intensity can be set individually
  - Very flat form factor (fits in standard LCD housing)
  - Calibration issues simpler
  - Less heat/power consumption
    - → LEDs are most often not at highest intensity

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Second Setup

- Results:
  - Intensity: 8,500 cd/m^2, contrast >150,000:1
- Issue:
  - LEDs larger than LCD pixels
  - This limits maximum *local* contrast
    - → Is this a problem?

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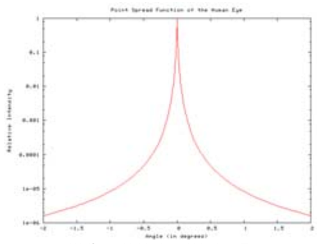
Local Contrast and Human Perception

- Maximum perceivable contrast
  - Globally very high (5-6 orders of magnitude)
    - → This is why we create these displays!
  - Locally pretty low: 150:1
    - → Point-spread function of human eye



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Local Contrast and Human Perception

- Consequence:
  - High contrast edges above 150:1 are not seen at full contrast
    - → Light scatters from light side to dark side
  - Rendering:
    - → Choose LED intensity for bright side
    - → compensate as best possible for dark side in LCD panel
    - → LCD panel has contrast of 400:1
      - Enough to push error below perceivable limit

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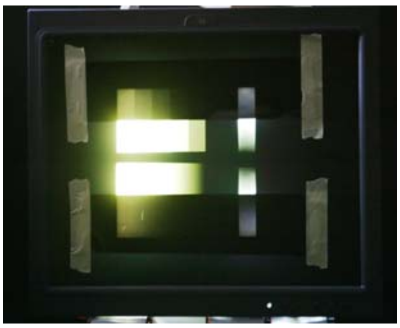
Screenshots



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Screenshots

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Rendering challenges

- Display image data in "gamut"
  - Intensities and gamut within that of display
  - Produce "best" displayed image
- Map image out of displayable range into "gamut"
  - Intensities or gamut exceed that of display
  - Tonemap / color space transformation to preserve impression
- Assume for now, image is within displayable range

Rendering

- Input
  - An image containing scene-referred information
    - → Absolute intensities
    - → Known color space
- Output
  - A set of LED values and LCD panel image that yield the "best" displayed image
  - Output-referred format targeted to a specific display

Defining "Best"

- Best has many definitions
  - Different sets of constraints
    - → Largest dynamic range
    - → Minimum error
- Inherent tradeoffs between range and quantization
  - Bits of the LCD panel can be divided between increasing the dynamic range and blur correcting
  - Larger dynamic range means less correction
- Application dependent
  - Casual viewers and experts have different requirements

Different constraints

- Maximize use of available dynamic range
  - Panel contributes to dynamic range
  - Less bits for correction
- Minimize the error in reconstruction
  - Panel only used for correction
  - Desire LCD at 50%, have most bits to correct above / below
- Conserve energy to stay within power constraints
  - DR37 would pull 4000 W if driven at full
  - Standard breaker is only 1500 W

Naïve approach

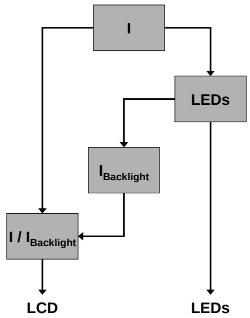
- Make as few assumptions as possible
  - Non-linear solver
  - Have function F(LCD, LEDs) = $\text{image}_{\text{displayed}}$
    - → Accurately simulate displayed image given driving levels
  - Minimize Error($\text{image}_{\text{original}}$, $\text{image}_{\text{displayed}}$)
  - Huge and slow
    - → m+n inputs, m outputs
    - → m = num LCD pixels, n = num LEDs
  - What does error function look like?

Computing error

- Error in perceptual units
  - Look to psychophysics
  - Nonlinear quantization of luminance
    - → JND-space comparison
  - Occular scatter
    - → Pointspread of eye, contrast sensitivity function (CSF)
  - Similar to HDR Visible Differences Predictor [Mantiuk 2005]

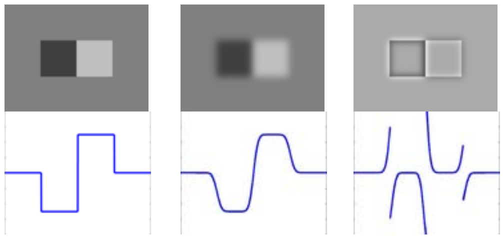
Algorithm Overview

- Given image
- Choose optimal LED values
- Simulate the backlight
- Correct original image for blurry backlight
- Write out to the display controllers



Algorithm Process

- Given image
- Simulate the backlight
- Correct original image for blurry backlight



Optimization

- Pixels are linearly independent of each other
  - Pick the LCD value that blur corrects the best
  - Reduce problem to finding “best” backlight (LED values)
- Backlight is low frequency due to optical package
  - Can work on a low resolution of backlight
  - Filter and down sample to get an ideal LED image

Optimization

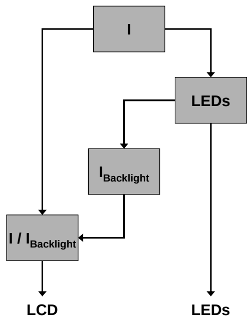
- Significant reduction in size of system
  - What was roughly a 2 million x 2 million matrix (for 1920x1080) down to roughly 1500 x 1500 matrix
- Sub-optimal choice of LEDs can be fixed with LCD
  - Don’t even have to do that good a job at the hard part

Simulation Accuracy

- LCD panel can resolve problems with LED choice
  - But not without a price
    - → The worse the LED values, the more of the panel’s driving values are needed for correcting the backlight
    - → Larger error in reconstruction, or less dynamic range
- Simulation quality
  - High quality simulation of backlight required produce acceptable final image without artifacts
  - Accuracy → calibration → measurement
  - Many attributes of the display must be measured to ensure that the simulation results correct

Required Measurements

- Preprocessing
  - Intensity range of display
  - Color space of LCD panel and backlight
- Simulation
  - LEDs / optical package pointspread
  - Positions and offset of LEDs
- Output
  - LED response to linearize
  - Individual LED characteristics (intensity)
  - LCD response to linearize



Techniques

- Weighted average
  - Each LED is determined by a weighted average of it and its neighbors
  - Similar to 1 step of an iterative solver
- Error diffusion
  - Each LED tries to minimize the remaining error
  - Greedy approach
- Non-linear solver
  - Mostly to provide ground truth to compare against

Weighted Average

- Directly address LED crosstalk
  - Each LED contributes light to a large number of pixels
  - Multiple LEDs required to reach top intensity
  - Given a desired backlight image
    - → Try to account for light contributions from other LEDs
    - → Weight according to pointspread
  - $LED_i = desired_i * total\_illum – Sum (LED_j * w_j)$

Error Diffusion

- Greedy approach
  - Iterate over all LEDs
  - For each LED, choose the value that minimizes the error with the image to that point
  - Subtract out contribution for chosen value and use resulting image as input for next LED
  - Direct solution
    - → $\min Sum(I(x,y) – P(x,y)w)^2$
    - → $w = Sum(2IP) / Sum(P^2)$

Blur correction

- Given LED values simulate backlight
  - Direct evaluation of pointspread model possible if number of LEDs sufficiently small (FPGA method)
  - Represent each LED as a texture splat modulated by its driving level (GPU method)
- Correct original image
  - LCD panel modulates backlight
  - Divide original image by backlight simulation to get blur corrected image

Future Work

- HDR tonemapping / color space transformation
  - All the same constraints on LDR still apply, only loosened
  - How well do current practices work and how should they be modified?
- Help with new psychophysical models
  - Adaptation of viewer
    - → Many applications assume infinitesimally small area of adaptation
    - → Does something displayed 25% as bright as the original still have the same appearance as long both are driving adaptation?
  - What else?

Impression of a Scene

- Humans can differentiate over 12 million colors
- Can only identify about 300

- What can we learn in reproducing HDR images?
  - Does accurately reproducing exact intensity matter
  - Is the right ratio between 2 intensities sufficient
  - Or is “brighter” and “darker” sufficient

- Study the human visual system to tell how much is enough

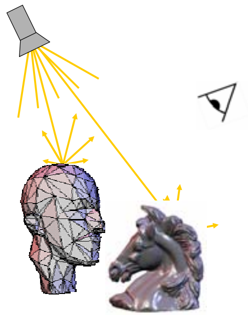
max planck institut informatik

Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

HDR Applications
Image-based Measurements of Object and Material Properties

Michael Goesele
MPI Informatik

Scene Acquisition in Computer Graphics



- object geometry
- emission patterns of light sources
- reflection properties of objects
  - local light reflection (BRDF)
  - subsurface light transport (BSSRDF)
- …

Sources of Dynamic Range

- diffuse materials reflect between 0.5% and >90% of incoming light
- specular highlights much brighter
- lit regions vs. in shadow regions
- moonless night vs. sunny day

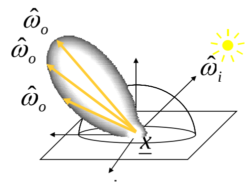
→ high dynamic range mainly caused by illumination effects
  - typical for reflectance measurement applications
  - simultaneous vs. sequential dynamic range

Surface Reflectance (BRDF)

- a BRDF (bi-directional reflectance distribution function)

$f(\hat{\omega}_o, \underline{x}, \hat{\omega}_i)$

yields the fraction of reflected to incident radiance at one point for any pair of directions.



- Our goal: reconstruct the BRDF **on the entire surface**, not just in a few selected points (gonio-reflectometer approach)

Measurement of Spatially Varying BRDFs

- Acquisition of a real world object (multiple materials)
  - several images with varying light source positions are captured
  - surface points are grouped into clusters of similar reflection properties
  - individual BRDFs are fitted for each cluster

Acquisition Setup

- 3D scanner
- digital camera (high dynamic range)
- point-light source
- dark room (reduces influence of the environment)
- calibration targets (checkerboard, metal spheres)

Results

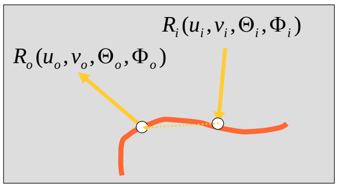
H. P. A. Lensch, J. Kautz, M. Goesele, W. Heidrich, H.-P. Seidel: Image-Based Reconstruction of Spatial Appearance and Geometric Detail. ACM Trans. Graphics 22(2), p. 234-257, 2003.

Subsurface-Scattering Properties (BSSRDF)

- bidirectional scattering-surface reflectance distribution function (BSSRDF) [Nicodemus 1977]
  – reflected radiance per incident flux for each pair of surface locations and directions
  – 8 dimensional function

$$\rho(R_i; R_o) = \rho(u_i, v_i, \Theta_i, \Phi_i; u_o, v_o, \Theta_o, \Phi_o)$$

Subsurface-Scattering Properties (BSSRDF)



$$\rho(R_i; R_o) = \rho(u_i, v_i, \Theta_i, \Phi_i; u_o, v_o, \Theta_o, \Phi_o)$$

– very general representation
– almost impossible to acquire

Translucent Objects

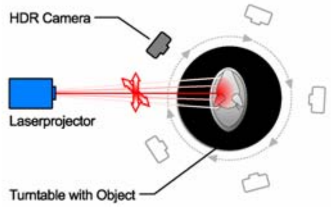
– light is scattered through the object
– incident illumination smoothed due to diffuse scattering inside media
– imperfections can be masked by scattering behavior

Translucent Objects

- multiple scattering (almost) independent of incident light direction
  – example: alabaster block illuminated by a laser from the left

BSSRDF of Translucent Objects

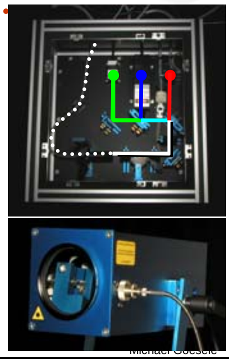
- DISCO acquisition approach
  - illuminate individual surface points
  - store impulse response of the object



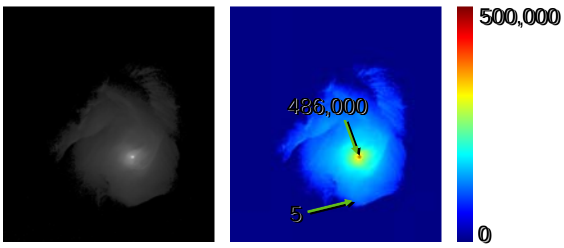
M. Goesele, H. P. A. Lensch, J. Lang, C. Fuchs, H.-P. Seidel: DISCO – Acquisition of Translucent Objects. ACM Trans. on Graphics (Proc. SIGGRAPH 2004), 2004.

Laser Projector

- three lasers
  - ➔(635nm, 532nm, 476nm)
  - ➔~10mW optical power
- constancy
- resolution 4096x4096 steps
  - ➔step size < 0.1 mm on object possible
- repeatable

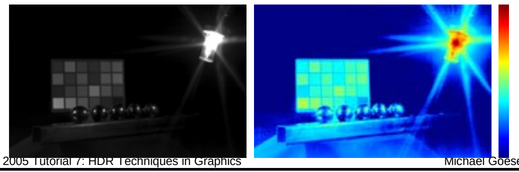


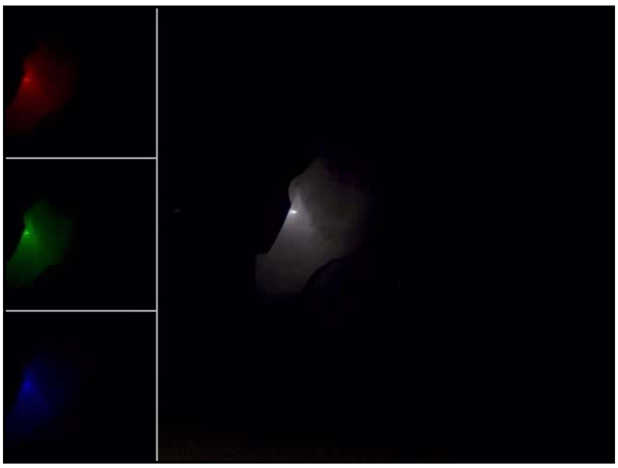
Inherent High Dynamic Range



HDR Video Camera

- Silicon Vision Lars III
- monochrome HDR
- dynamic range > 1:1,000,000
- acquisition with 15 fps





Results

- 500,000 – 1,000,000 (!) images acquired
- images yield entries in a throughtput factor matrix
- all views where the same point is illuminated yield one column of the point-to-point throughput matrix
- resample images into hierarchical model
- see [Goesele et al. 2004] for details

EG 2005 Tutorial 7: HDR Techniques in Graphics — Michael Goesele

Results

photograph

rendering

EG 2005 Tutorial 7: HDR Techniques in Graphics — Michael Goesele

Results

EG 2005 Tutorial 7: HDR Techniques in Graphics — Michael Goesele

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Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

Virtual Scene Re-lighting

CAVE System for Car Interior Modeling

Kirill Dmitriev, Thomas Annen, Grzegorz Krawczyk,
Karol Myszkowski, Hans-Peter Seidel
MPI Informatik

Motivation

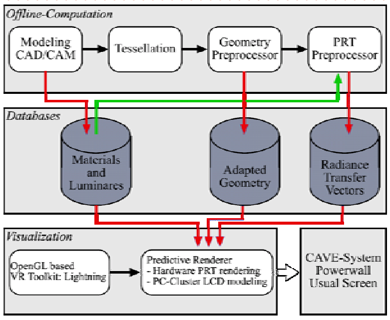
Predict impact of quickly changing environment lighting conditions on the ease of car navigation

Target application:
- VR centers of car manufacturers

System Requirements

- General
  - Illumination with HDR video environment map
  - Light changes often and abruptly
- PRT for the car interior
  - Geometry does not change so precomputation possible
  - High performance required but approximation acceptable
- Final gathering for the LCD panel
  - Precise computation of the LCD appearance is required

Architecture

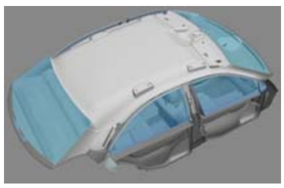


Acquisition of Environment

- Real-world driving scenarios
  - Tunnels, sunset, city driving, highways, etc
- Two HDR video cameras with fisheye lenses that capture:
  - Environment map
  - Windshield image
- Results in a complete data set for CAVE

Efficient Rendering with PRT

- Car geometry is two-sided
- Only the rays going through the windows contribute to SH coefficients



Store SH coefficients only for inside:
- Higher performance
- Lower memory use

Computing the LCD Panel

Use final gathering to compute the color for each texel.

- Ray hits the window → sample environment map
- Ray hits car geometry → query PRT for luminance at that point
- Importance sampling from known BRDF
- Emission computed for the given observer position
- Quality improves if position unchanged

Tone Mapping

- HDR data requires tone mapping
- Luminance adaptation required for temporal coherence
- Adaptation level influenced by a 10° foveal region (head tracking provides the look-at point in the CAVE)

Video Demonstration

Results

Real-world driving scenarios used to illuminate the car interior and predict the ease of the navigation panel observation.

- Efficient global illumination solution for CAVE VR applications involving static geometry and dynamic environment lighting.
- Full image tone mapping with temporal adaptation
- Car model contains approx. 500K triangles
- Visualization frame rate ~10fps

K. Dmitriev, T. Annen, G. Krawczyk, K. Myszkowski, and H.-P. Seidel
A CAVE System for Interactive Modeling of Global Illumination in Car Interior
ACM Symposium on Virtual Reality Software and Technology, 2004

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Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

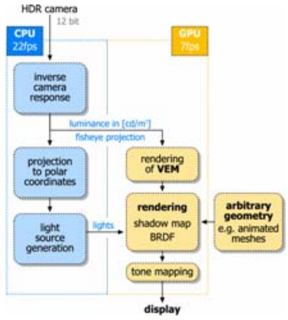
Interactive System for Dynamic Scene Lighting Using Captured Video Environment Maps

Vlastimil Havran, Miloslaw Smyk, Grzegorz Krawczyk,
Karol Myszkowski, Hans-Peter Seidel
MPI Informatik, Szczecin University of Technology

System Motivation

Illumination Acquisition → Light Sources Computation → Rendering (GPU) (+Compositing)

System Overview



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Illumination Acquisition

- Source of data: HDR camera
  - 12bits logarithmic response
  - 8 orders of magnitude dynamic range
- Fish-eye lens
- Resolution 640x480
- Photometric calibration necessary

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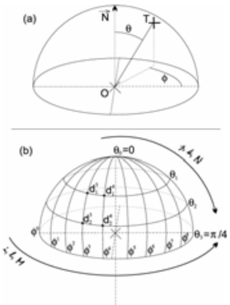
Video Environment Map

- HDR image on hemisphere defined by meridians and parallels
- Extension to time domain
- Luminance corresponds to the probability density function on the hemisphere (grid points)



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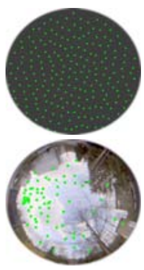
Importance Sampling Properties



- Arbitrary number of directional light sources
- The same energy for each light source
- Progressive light source sequence
- Local blue noise properties
- Small memory requirements
- Real-time performance
- Dependence on the surface normal
- Energy and position of light sources processed with FIR filters

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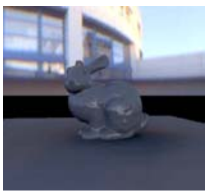
Rendering



- GPU used - NVidia GeForce 6800GT
- Shadow maps tiled in large textures
- Invisible light sources reduction enabled by progressiveness of light source sequence
- Quality improvement for glossy BRDFs
- Other issues: clustering and color estimation

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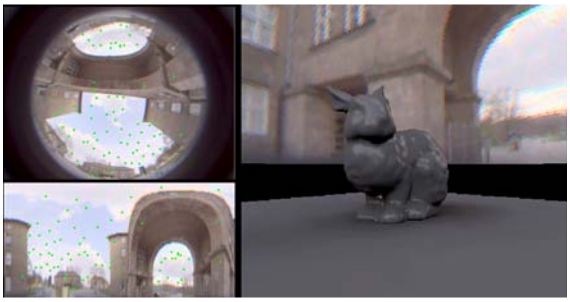
Results – Snapshots & Video



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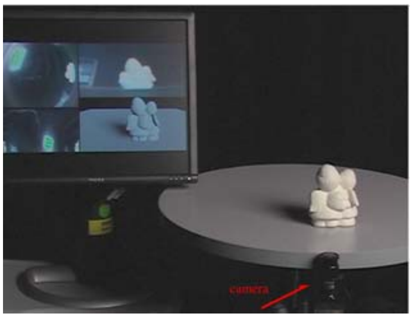
Results – Mixed Reality



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Results

System pipeline from HDR acquisition to rendering

- Real-time computation of light sources with many properties useful for rendering
- Performance 5-10 FPS for 320x240 pixels
- Principles also useful for CPU rendering systems
- Possible applications in mixed and virtual reality (virtual studio systems)

V. Havran, M. Smyk, G. Krawczyk, K. Myszkowski, H.-P. Seidel
Interactive System for Dynamic Scene Lighting using Captured Video Environment Maps
Proceedings of 16th Eurographics Symposium on Rendering, 2005

EG 2005 Tutorial 7: HDR Techniques in Graphics — Grzegorz Krawczyk

Tutorial 7
High Dynamic Range Techniques in Graphics: from Acquisition to Display

Application Examples in Automotive Industry and Computer Vision

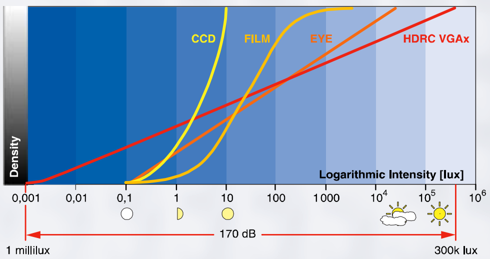
Prof. Dr. Bernd Höfflinger
Institute for Microelectronics Stuttgart

HDRC® Log Imaging

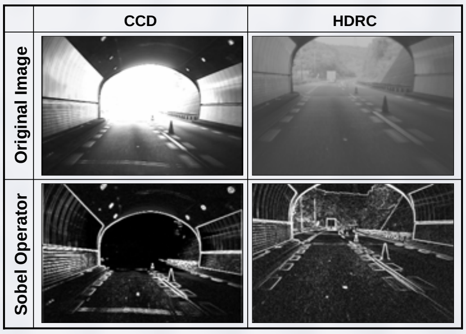
- Vision: Natural and Film
- High-Dynamic-Range Logarithmic Vision
- No Shutter-or Integration-Time
- Separating Illuminance and Features of Objects
- HDRC® sensors
  - track photon flux continuously
  - are free from control loops (with their dead times and delays)
  - absolutely cannot be blinded (white-saturated)
  - offer constant contrast resolution over many decades of grey
  - keep colors constant independent of luminance or aperture
- Illuminance Equalisation
- Robust Preprocessing
- High-Latitude Post-Production

The Revolution in Electronic Imaging

Response curve of the HDRC VGAx and other sensors



Sobel Operator HDRC vs. CCD

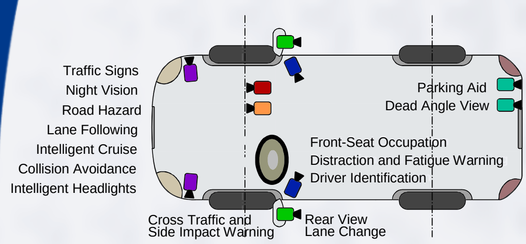


Courtesy: OMRON

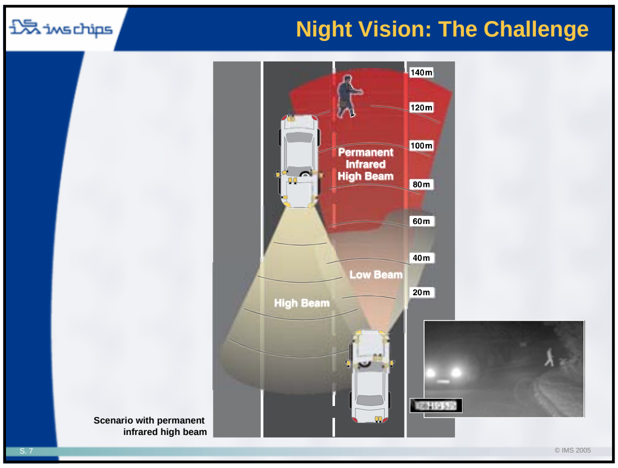
Vision in Traffic

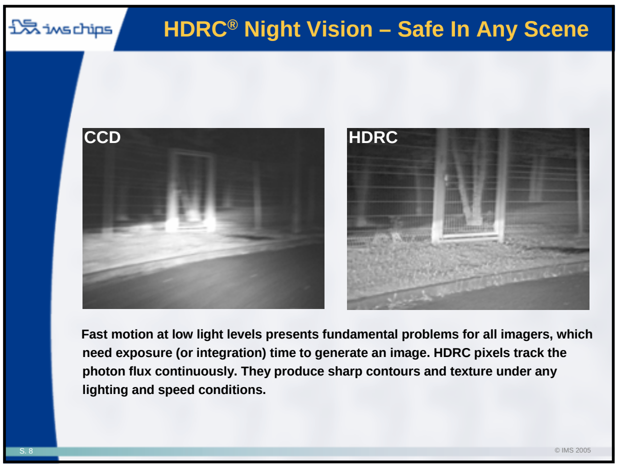
- 95 Percent of all decisions are based on visual information
- Human error, fatigue and distraction are major causes of accidents
- Machine vision can provide early warning for driver
- Night vision is ready to help drivers and to protect pedestrians, bikers, etc.
- Electronic vision offers big improvements for ageing driver population
- PROMETHEUS initiated major vision effort in Europe 1987
- Volume Appearance of "Eyes on Wheels" 2006/07

Electronic Eyes on Wheels



2010 ca. 40 Billion Euro


ims chips
Night Vision: The Challenge
140m
120m
100m
80m
60m
40m
20m
Permanent Infrared High Beam
Low Beam
High Beam
Scenario with permanent infrared high beam
S. 7
© IMS 2005


ims chips
HDRC® Night Vision – Safe In Any Scene
CCD
HDRC
Fast motion at low light levels presents fundamental problems for all imagers, which need exposure (or integration) time to generate an image. HDRC pixels track the photon flux continuously. They produce sharp contours and texture under any lighting and speed conditions.
S. 8
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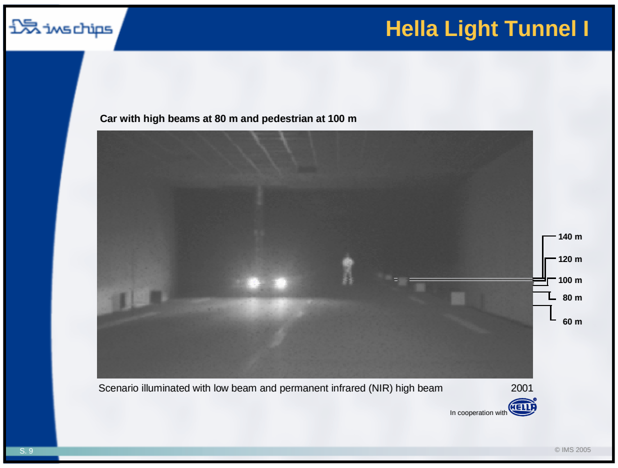
ims chips
Hella Light Tunnel I
Car with high beams at 80 m and pedestrian at 100 m
140 m
120 m
100 m
80 m
60 m
Scenario illuminated with low beam and permanent infrared (NIR) high beam
2001
In cooperation with
HELLA
S. 9
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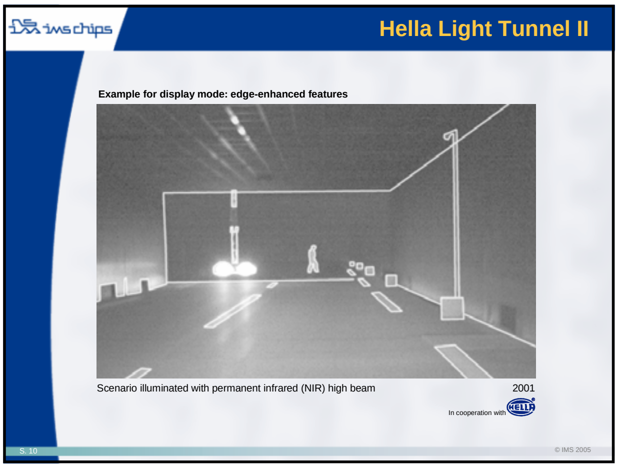
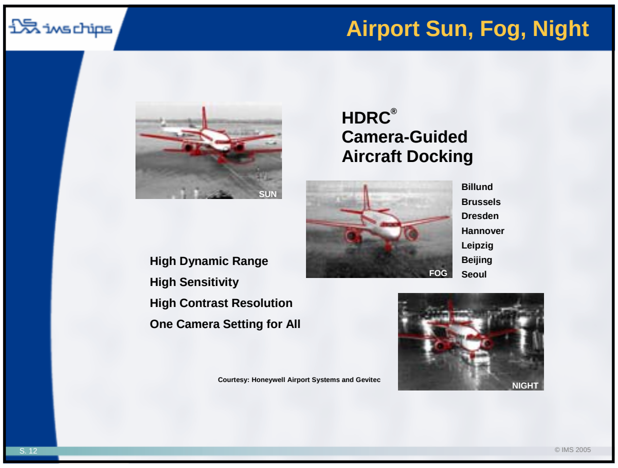

ims chips
Hella Light Tunnel II
Example for display mode: edge-enhanced features
Scenario illuminated with permanent infrared (NIR) high beam
2001
In cooperation with
HELLA
S. 10
© IMS 2005


ims chips
Turn-On of Headlight 3 Frames
CCD
HDRC
0.0 sec
0.5 sec
1.0 sec
S. 11
© IMS 2005


ims chips
Airport Sun, Fog, Night
HDRC® Camera-Guided Aircraft Docking
SUN
FOG
NIGHT
Billund
Brussels
Dresden
Hannover
Leipzig
Beijing
Seoul
High Dynamic Range
High Sensitivity
High Contrast Resolution
One Camera Setting for All
Courtesy: Honeywell Airport Systems and Gevitec
S. 12
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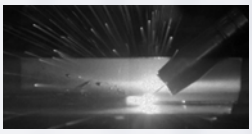
Schweissszene

CCD

HDRC



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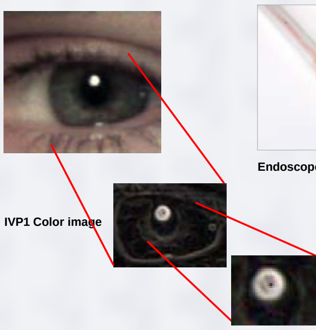
Miniaturized Video-sensors

IVP1 Color sensors



IVP1 Color image

Mini-Endoscope IVP1

Endoscope sensor with lighting

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HDR Applications: References

- B. Höfflinger: Vision Chips make Driving Safer. Europhotonics, vol. 6 (4), pp. 49 – 51, June 2001
- P. M. Knoll, H. Winner and R. Kallenbach: Surround Sensing – Collision Warning Systems and Vehicle Guidance. ATA Journal (Associazione Technica Dell/Automobile, Italia), vol. 54 (11/12), pp. 419 – 425, November 2001
- D. C. McCarthy: Hands on the Wheel, Cameras on the Road, Photonics Spectra, pp. 78 – 83, April 2001
- V. Gengenbach, K. H. Schäfer, H.-H. Nagel, K. Fleischer, H. Leuck, F. Muth, A. Backem, W. Enkelmann, F. Hemes, M. Tonko: Sichtsystemgestütztes Andocken von Flugzeugen. FhG-IITB Mitteilungen, Karlsruhe, Germany, 1998, S. 31 – 35.

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HDR Applications: References

- P. Tschirner, B. Hillers and A. Gräser: A Concept for the Application of Augmented Reality in Manual Gas Metal Arc Welding, Proc. IEEE/ACM Int´l Symp. Mixed and Augmented Reality, Darmstadt, Germany, October 2002
- M. Mössmer und B. M. Rohrbacher: CMOS-Bildsensoren- und DSP-Technologie in intelligenten Hochleistungskameras, Photonik, vol. 2, 3 pp., February 2004
- A. Arena, M. Boulougoura, H. S. Chowdrey, P. Dario, C. Harendt, D.-M. Irion, V. Kodogiannis, B. Lenaerts, A. Menciassi, R. Puers, C. Scherjon, D. Turgis: Intracorporeal Video Probe. ICMCC Conf. Int´l Council on Medical and Care Compunet, Den Haag, NL, 8 pp., June 2005

See also

www.hema.de
www.iat.uni-bremen.de
www.de.bosch.com
www.ivp.ims-chips.de
www.mpi-sb.mpg.de
www.seelector.de
www.hdrc.com
www.gevitec.com
www.airportsystems.honeywell.com

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