Panoramas and High-Dynamic-Range Imaging

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Light

Are you getting the whole picture?

- **Compact Camera FOV = 50 x 35°**

Slide from Brown & Lowe

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°

Slide from Brown & Lowe

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°
- Panoramic Mosaic = 360 x 180°

Slide from Brown & Lowe

Panorama

A wide-angle representation of the scene

Panorama of *Along the River During Qingming Festival*

18th century remake of a 12th century original by Chinese artist Zhang Zeduan

Image from Wikipedia

Panorama: Cinema for the early 19th century

Burford's Panorama, Leicester Square, London, 1801

Painting by Robert Mitchell

Panoramas with wide-angle optics

http://www.0-360.com

AF DX Fisheye-NIKKOR 10.5mm f/2.8G ED

Rotation cameras

- **Idea**
  - rotate camera or lens so that a vertical slit is exposed
- **Swing lens**
  - rotate the lens and a vertical slit (or the sensor)
  - typically can get 110-140 degree panoramas
- **Full rotation**
  - whole camera rotates
  - can get 360 degree panoramas

Swing-lens panoramic images

San Francisco in ruins, 1906

101 Ranch, Oklahoma, circa 1920

Flatback panoramic camera

wide-angle lens, limited vertical FOV

Lee Frost, Val D'Orcia, Tuscany, Italy

Disposable panoramic camera

wide-angle lens, limited vertical FOV

Building a Panorama

M. Brown and D. G. Lowe. Recognising Panoramas. ICCV 2003

Summary of perspective stitching

- Pick one image, typically the central view (red outline)
- Warp the others to its plane
- Blend

Example

common picture plane of mosaic image

perspective reprojection

Pics: Marc Levoy

Using 4 shots instead of 3

Back to 3 shots

surface of cylinder

cylindrical reprojection

Cylindrical panoramas

- What if you want a 360° panorama?

- Project each image onto a cylinder
- A cylindrical image is a rectangular array

Cylindrical panoramas

- What if you want a 360° panorama?

- Project each image onto a cylinder
- A cylindrical image is a rectangular array
- To view without distortion
  - reproject a portion of the cylinder onto a picture plane representing the display screen

2nd reprojection to a plane for display

Imagine photographing the inside of a cylinder that is wallpapered with this panorama

- **if your FOV is narrow, your photo won't be too distorted**

Demo http://graphics.stanford.edu/courses/cs178/applets/projection.html

A pencil of rays contains all views

Can generate any synthetic camera view
as long as it has **the same center of projection**!
… and scene geometry does not matter …

Changing camera center

- **Does it still work?**

Where to rotate the camera?

Figure 3. Configuration to reveal the presence or absence of parallax. The subject is first placed at the left side of the frame, and subsequently at the right side after rotation of the camera about a vertical axis with the help of a panoramic tripod head.

Figure 2. Diagram of a 135/2.8 lens with rotation axes through the front nodal point N and entrance pupil E.

http://toothwalker.org/optics/cop.html#stitching

Correct center of rotation → no parallax

Figure 4. Rotation about an axis through the entrance pupil.

Figure 5. Rotation about an axis through the front nodal point.

Assembling the panorama

- Stitch pairs together, blend, then crop

Problem: Drift

- Vertical Error accumulation
  - small (vertical) errors accumulate over time
  - apply correction so that sum = 0 (for 360° panorama)
- Horizontal Error accumulation
  - can reuse first/last image to find the right panorama radius

Registration in practice: tracking

Viewfinder alignment for tracking

Andrew Adams, Natasha Gelfand, Kari Pulli
Viewfinder Alignment
Eurographics 2008

http://graphics.stanford.edu/papers/viewfinderalignment/

Project gradients along columns and rows

… diagonal gradients along diagonals …

… and find corners

Overlap and match the gradient projections and determine translation

Apply the best translation to corners

Match corners, refine translation & rotation

System overview

System overview

System overview

System overview

Photo by Marius Tico

System overview

Photo by Marius Tico

Problems with setting the camera exposure level

- Under-exposed
  - Highlight details captured
  - Shadow details lost
- Over-exposed
  - Highlight details lost
  - Shadow details captured

Dynamic range

- Eye can adapt from ~ 10^{-6} to 10^{8} cd/m^2
- Sometimes 1 : 100,000 in a scene

- Without adaptation eye can handle about 1 : 10000
  - Scotopic Mesopic Photopic
  - Even 1 : 1000 easily enough for scenes with non-specular reflectance
- Most displays can handle less than 1 : 100

Range of Typical Displays:

from ~1 to ~100 cd/m^2

How humans deal with dynamic range

- We're sensitive to contrast (multiplicative)
  - A ratio of 1:2 is perceived as the same contrast as a ratio of 100 to 200
  - Use the log domain as much as possible
- Dynamic adaptation (very local in retina)
  - Pupil (not so important)
  - Neural & chemical
    - can adapt ~ 10^{10}
- Transmit the signal to brain
  - only 10^3 – 10^4
  - spatial contrast-based processing already in the eye

Dim Light

~6 mm
Pupil dilates
More light enters the eye

Area ratio
~16 : 1

Bright Light

~1 mm
Pupil constricts
Less light enters the eye

Cone and Rod Response

Mesopic vision

- 3 cones + 1 rod map to 3 signals from eye to visual cortex

Perceptually Based Tone Mapping for Low-Light Conditions

Adam G. Kirk James F. O'Brien
University of California, Berkeley

Images copyright Adam Kirk and James O'Brien.

Figure 4: *Left: An HDR night scene with no tone mapping featuring UC Berkeley's Sather Tower. Right: The image has been tone mapped for low-light conditions. Artifacts on the clock face occur because the hands moved during image acquisition.*

ges copyright Adam Kirk and James O'Brien.

ure 6: *Top: An HDR image of the Fremont Troll with no tone mapping. Bottom: The image has been tone mapped for low-light conditions.*

Multiple exposure photography

Multiple exposure photography

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Multiple exposure photography

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Multiple exposure photography

Early HDR photos: Gustave Le Gray (~1850)

- Take two shots
  - one for the sky – direct light
  - one for the rest – reflected light
  - cut and paste the negatives, and develop

HP Robinson (1858) Fading Away, 5 negatives

Camera Response Curve

Response Curve Calibration

[Debevec & Malik 97]

$\Delta t =$ 1/64 sec	$\Delta t =$ 1/16 sec	$\Delta t =$ 1/4 sec	$\Delta t =$ 1 sec	$\Delta t =$ 4 sec

$$\text{Pixel Value } Z = f(\text{ Exposure })$$

$$\text{Exposure} = \text{Radiance} * \Delta t$$

$$\ln \text{Exposure} = \ln \text{Radiance} + \ln \Delta t$$

Adjust exposure to find a smooth response curve

Assuming the same exposure for each pixel

After adjusting radiances to obtain a smooth response curve

The Math

- Let f be the response function: $Z_{ij} = f(R_i \, \Delta \, t_j)$
- Let g be the logarithm of the inverse response function: $g(Z_{ij}) = \ln f^{-1}(Z_{ij}) = \ln R_i + \ln \Delta \, t_j$
- Solve the overdetermined linear system:
  - unknown R_i, $g(\,)$

$$\underbrace{\sum_{i=1}^{N}\sum_{j=1}^{P}\left[g(Z_{ij}) - \ln R_i - \ln \Delta t_j\right]^2}_{\text{fitting term}} + \underbrace{\lambda \sum_{z=Z_{min}}^{Z_{max}} g''(z)^2}_{\text{smoothness term}}$$

Matlab code

```
%
% gsolve.m - Solve for imaging system response function
%
% Given a set of pixel values observed for several pixels
% in several images with different exposure times, this
% function returns the imaging system's response function
% g as well as the log film irradiance values for the
% observed pixels.
%
% Assumes:
%
% Zmin = 0
% Zmax = 255
%
% Arguments:
%
% Z(i,j) is the pixel values of pixel location number i
%          in image j
% B(j)   is the log delta t, or log shutter speed, for
%          image j
% l      is lamdba, the constant that
%          determines the amount of smoothness
% w(z)   is the weighting function value for
%          pixel value z
%
% Returns:
%
% g(z) is the log exposure corresponding to pixel value z
% lE(i) is the log film irradiance at pixel location i
%
```

```
function [g, lE] = gsolve( Z, B, l, w )
n = 256;   N = size(Z,1);  P = size(Z,2);
A = zeros( N * P + n + 1,  n + N );
b = zeros( N * P + n + 1,  1 );

%% Data-fitting equations  g(Zij) - ln(Ri) = ln(dt)
k = 1;
for i = 1:N     % loop over image locations
  for j = 1:P   % loop over captured photos
    wij                 =  w( Z(i,j) + 1 );
    A( k, Z(i,j) + 1 )  =  wij;            %  g(Zij)
    A( k, n + i )       = -wij;            % -ln(Ri)
    b( k, 1 )           =  wij * B(i,j);   %  ln(dt)
    k = k+1;
  end
end

%% Fix the curve by setting its middle value to 0
A( k, 129 ) = 1;  b(k) = 0;
k = k+1;

%% Include the smoothness equations
for i = 2:n-1
  A( k, i-1 )   =      l * w( i );
  A( k, i   )   = -2 * l * w( i );
  A( k, i+1 )   =      l * w( i );
  k = k+1;
end

%% Solve the A x = b system using SVD
x  = A\b;
g  = x(1:n);              % log expos. of pixel value
lE = x(n+1:size(x,1));  % log expos. of point i
```

Reconstructed radiance map

Tone mapping is not easy

Tone mapping is not easy

Tone mapping is not new

- Painters needed to deal with HDR forever
  - dynamic range of the world is much higher than that of paints
  - change the contrasts to give an effect

- Photographers have done it for a long time
  - dynamic range of the film is much higher than that of paper
  - developing prints required manual tone mapping

http://19lights.com/wp/2011/09/17/leonardo-da-vinci-hdr-painter/

Early painters couldn’t handle HDR

Paris Psalter, 10th century

Leonardo invents Chiaroscuro

Madonna by Giotto

Madonna by Leonardo

Caravaggio

Ansel Adams

- Design and plan the photo while you are taking it
  - know the medium: both the film, development, and paper
  - standard film & development for the masses using Kodak Brownie
    - global tone map curve, OK on the average
  - virtuosos like Adams
    - capture full dynamic range on the film
    - add spatially varying contrast during development

Dodging and burning

- Hide a part of the print during exposure
  - dodge → keep the bright color of the paper
- Let more light be exposed to a region
  - burn → creates a darker print
- Smooth circular motions & blurry mask avoid artifacts

Dodging *holds back light during the basic printing exposure to lighten an area.*

Burning *adds light after the basic exposure to darken an area.*

Manual instructions –

repeat for each print

Straight print

After dodging & burning

Contrast reduction in the digital world

- Scene has *1:10,000* contrast, display has *1:100*
- Simplest contrast reduction?

Naïve: Gamma compression

- $X \rightarrow X^{\gamma}$ (where γ=0.5 in our case)
- But… colors are washed-out

Gamma encoding

- With 6 bits available (for illustration below) for encoding
  - linear loses detail in the dark end

- Raise intensity X to power X^{γ} where $\gamma = 1/2.2$
  - then encode

Gamma compression on intensity

- **Colors are OK,**
  but details (intensity high-frequency) are blurred

Let highlights saturate

- Darkest 0.1% scaled to display device

Simple global operator (Reinhard et al.)

- Compression curve needs to
  - bring everything within range
  - leave dark areas alone
- In other words
  - asymptote is 1
  - derivative at 0 is 1

http://www.cs.utah.edu/~reinhard/cdrom/tonemap.pdf

$$L_{display} = \frac{L_{world}}{1 + L_{world}}$$

The same in log L
closer to brightness perception

Local tonemapping

$$L_d(x,y) = \frac{L(x,y)}{1 + V_1(x,y,s_m(x,y))}$$

- V_1 = average of the "center"
  - dark pixel (L) on light (V_1)? Lowers L_d more, increased contrast
  - bright pixel (L) on dark (V_1)? Lowers L_d less, increased contrast
- Choose scale right to avoid halos

Reinhard operator

Darkest 0.1% scaled to display device

Histogram adjustment [Ward et al. 1997]

- Histogram equalization
  - well-known method to increase contrast
  - luminance is not evenly spread, spread it
- Basic approach
  - lump pixels with 1deg area together
  - calculate histogram in log(luminance) space
- Problem
  - doesn’t just compress contrast, but also expands it
- Solution
  - put a ceiling to contrast by trimming large bins
  - not equalization, but adjustment

Equalization vs. adjustment

Linear

Equalization

Adjustment

Oppenheim 1968, Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep high frequencies

The halo nightmare

- For strong edges
- Because they contain high frequencies

Durand & Dorsey 2002: Bilateral filtering

- **Use non-linear filtering**
  - **to better separate details**
  - **without blurring across edges**

Fast Bilateral Filter

Reduce contrast

Preserve!

Exposure Fusion: Simplified HDR

Mertens, Kautz, van Reeth PG 2007

- **Choose the best pixel from one of the images**
  - **Use heuristics for a smooth selection, such as**
    - **Exposure**
    - **Color saturation**
    - **Contrast**

LDR images

Weight maps

Weights from the paper

- **Contrast:** we apply a Laplacian filter to the grayscale version of each image, and take the absolute value of the filter response [16]. This yields a simple indicator C for contrast. It tends to assign a high weight to important elements such as edges and texture. A similar measure was used for multi-focus fusion for extended depth-of-field [19].

- **Saturation:** As a photograph undergoes a longer exposure, the resulting colors become desaturated and eventually clipped. Saturated colors are desirable and make the image look vivid. We include a saturation measure S, which is computed as the standard deviation within the R, G and B channel, at each pixel.

- **Well-exposedness:** Looking at just the raw intensities within a channel, reveals how well a pixel is exposed. We want to keep intensities that are not near zero (underexposed) or one (overexposed). We weight each intensity i based on how close it is to 0.5 using a Gauss curve: $\exp\left(-\frac{(i-0.5)^2}{2\sigma^2}\right)$, where σ equals 0.2 in our implementation. To account for multiple color channels, we apply the Gauss curve to each channel separately, and multiply the results, yielding the measure E.

Similar to weighted terms of a linear combination, we can control the influence of each measure using a power function:

$$W_{ij,k} = (C_{ij,k})^{\omega_C} \times (S_{ij,k})^{\omega_S} \times (E_{ij,k})^{\omega_E}$$

with C, S and E, being contrast, saturation, and well-exposedness, resp., and corresponding "weighting" exponents ω_C, ω_s, and ω_E.

To obtain a consistent result, we normalize the values of the N weight maps such that they sum to one at each pixel (i, j):

$$\hat{W}_{ij,k} = \left[\sum_{k'=1}^{N} W_{ij,k'}\right]^{-1} W_{ij,k}$$

The Laplacian pyramid

Multi-resolution fusion

O.Gallo, W-C Chen, N.Gelfand, M.Tico, K.Pulli

Artifact-free High Dynamic Range Imaging

IEEE International Conference on Computational Photography 2009

Reference Frame Selection

Consistency Detection

HDR Generation

Poisson Blending

Log-Exposure of the pixel from patch 4
Log-Exposure of the pixel from patch 3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2

2
1
0
-1
-2
-3
$ln(X_4)$
-3
-2
-1
0
1
2
$ln(X_3)$

5 exposures
4 exposures
3 exposures
2 exposures
1 exposure

HDR video

- Kang et al. 2003
  - automatic exposure control
  - register neighboring frames (motion compensation)
  - tonemapping

Pick image with most valid number of pixels as reference
Pairwise register
Pairwise register
Pairwise register
Pairwise register
Propagate warping to reference
Radiance map recovery
HDR Image
Includes consistency check wrt reference

A Versatile HDR Video Production System

ACM SIGGRAPH 2011

Figure 2: A traditional beamsplitting HDR optical system. *Here a beamsplitting prism breaks up the light into three parts, one for each sensor fitted with different filters. Designs that use absorptive filters like this one make inefficient use of light.*

Figure 3: Illustration of our optical architecture. *We also use beamsplitters between the lens and sensors, but the key difference is that we re-use the optical path to improve our light efficiency. In the end, 99.96% of light entering the aperture arrives at the sensors. Light efficiency is important in all imaging applications.*

A Versatile HDR Video Production System

ACM SIGGRAPH 2011

LDR image processing = asking for trouble

- Physically accurate image processing requires floats
  - 8bit or 16bit ints are not enough
    - inherent quantization between operations
    - e.g., applying gamma to brighten or darken maps levels that were separate to the same levels, can’t separate any more
  - saturation
    - at the high end
    - can’t deal with really bright pixels (direct light sources)
  - non-linearity
    - for better encoding, but not for physical processing

Image processing example: motion blur

- Processing LDR gamma-corrected images (sRGB) yields artifacts

blurred LDR

blurred HDR

blurred real photo