Capturing Reflectance
From Theory to Practice

Acquisition Basics

Michael Goesele
GRIS, TU Darmstadt
(formerly University of Washington, Seattle)

Goal of this Section

- practical, hands-on description of acquisition basics
- general overview, caveats, misconceptions, solutions, hints, …
- biased to the techniques used in our lab

How can we measure material properties?

- color
- texture
- reflection properties
- normals
- ...

Special Purpose Tools

- gloss meter, haze meter, …
  - various appearance characteristics
- spectrophotometer
  - spectral reflectance of a surface

- often used in industry where single parameters of one material are important

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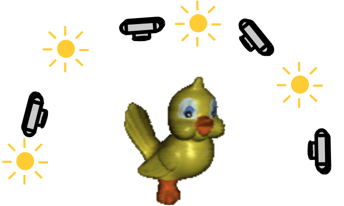
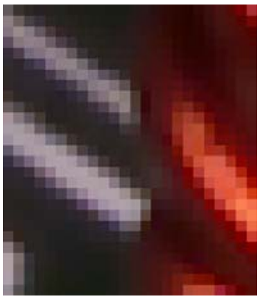
General Purpose Tools

- setup with digital camera(s), controlled lighting, …
- foundation of image-based techniques



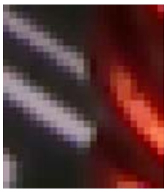
General Purpose Tools

- digital camera as
  - massively parallel sensor
  - mostly tristimulus color
  - often high quality optical system
  - tuned to make good and/or correct pictures



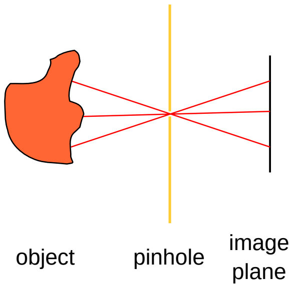
Overview Acquisition Basics

- digital cameras
  - geometric and photometric calibration
  - high dynamic range imaging
- light sources
- lab setup



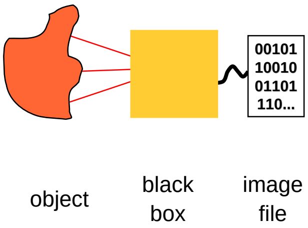
Pinhole Camera Model

- “each pixel corresponds to one ray through the pinhole onto the object”
- not valid for most digital cameras!!!

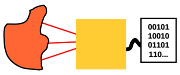


(Pessimistic) Digital Camera Model

- digital camera as a black box
- take only for granted what you measured (or what is given in the manual)



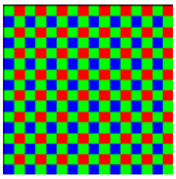
(Pessimistic) Digital Camera Model



- optical lens system instead of pinhole aperture (aberration, vignetting)
- CCD/CMOS chip and A/D conversion
- normally only one color per pixel (e.g. Bayer pattern) requires demosaicing
- camera image processing (see computational photography)
- …

Bayer Pattern

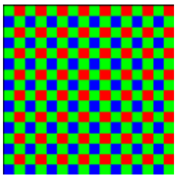
- sensor records only one color per pixel
  - higher sampling rate in green channel (luminance channel)
- remaining two color values per pixel must be reconstructed
  - artifacts possible



Bayer pattern

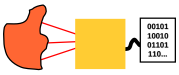
Demosaicing

- common approach
  - combining an interpolation and a pattern matching scheme
  - groups pixels into regions and makes some continuity assumption within the regions
  - “nice pictures”, but no guarantee that two of the R,G,B values per pixel are correct



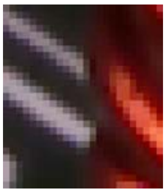
Bayer pattern

(Pessimistic) Digital Camera Model



- often globally correct image
- no guarantee that each pixel contains reliable color values
- some issues can be solved using camera calibration
- careful choice of camera for measurements

Overview Acquisition Basics



- digital cameras
  - **geometric and photometric calibration**
  - **high dynamic range imaging**
- light sources
- lab setup

Geometric Camera Calibration

- get transformation between points in space and image coordinates
- intrinsic camera parameters
  - focal length, distortion coefficients, …
- extrinsic parameters
  - position, orientation

Geometric Camera Calibration

- several methods commonly used, e.g., [Tsai ’87, Heikkila ’97, Zhang ’99]
- Matlab calibration toolbox by Jean-Yves Bouguet
  - http://www.vision.caltech.edu/bouguetj/calib_doc/
  - also included in the OpenCV Open Source Computer Vision library distributed by Intel

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Camera Model (simplified from Bouguet)

- point in camera reference frame is mapped to normalized pinhole coordinates

$$x_n = \begin{bmatrix} x_n(1) \\ x_n(2) \end{bmatrix} = \begin{bmatrix} X_c / Z_c \\ Y_c / Z_c \end{bmatrix}$$

Camera Model (simplified from Bouguet)

- normalized point coordinates are computed using distortion model
  - only parameterized by distance from center

$$x_d = \begin{bmatrix} x_d(1) \\ x_d(2) \end{bmatrix} = (1 + kc(1) r^2 + kc(2) r^4 + kc(3) r^6) x_n$$

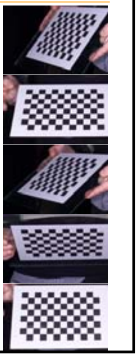
$$r^2 = x_n(1)^2 + x_n(2)^2$$

Camera Model (simplified from Bouguet)

- final pixel coordinates are computed using focal length and principal point

$$\begin{bmatrix} x_p(1) \\ x_p(2) \end{bmatrix} = \begin{bmatrix} fc(1)\cdot x_d(1) \\ fc(2)\cdot x_d(2) \end{bmatrix} + \begin{bmatrix} cc(1) \\ cc(2) \end{bmatrix}$$

Calibration Approach

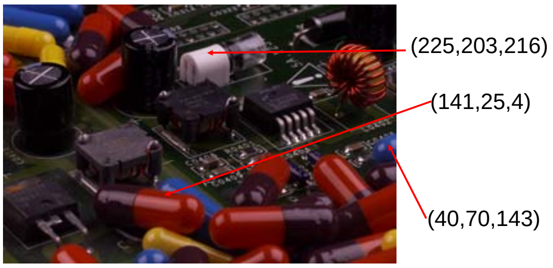


- capture images of test target with known geometry
  - cover space and angles with planar target
- solve for intrinsic and extrinsic parameters
- quality can be checked by reprojection

An Alternative Way …

- PTLens database with distortion parameters for many camera/lens combinations available
  http://epaperpress.com/ptlens/
- identifies camera via EXIF tags
- can apply undistortion parameters
- good approximation

Photometric Calibration



What do these RGB values (digital counts) mean?

Camera Response Curve (OECF)

- relationship between digital counts and luminance is unknown (and often non-linear)
  - gamma correction
  - image optimizations
  - ...
- can be described by response curve or OECF (Opto-Electronic Conversion Function)

Camera Response Curve (OECF)

- direct measurement via test chart
  - patches with known gray levels
  - uniform illumination
- patches arranged in a circle to suppress lens effects (e.g. vignetting)
- inversion using OECF leads to pixel values linearly related to luminance values

Definition of Dynamic Range

- dynamic range is the ratio of brightest to darkest (non-zero) intensity values in an image
  - assuming linear intensity
- often given as
  - ratio: 1:100.000
  - orders of magnitude: 5 orders of magnitude
  - in decibel: 100 dB

Sources of Dynamic Range

- diffuse materials reflect 0.5% – >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

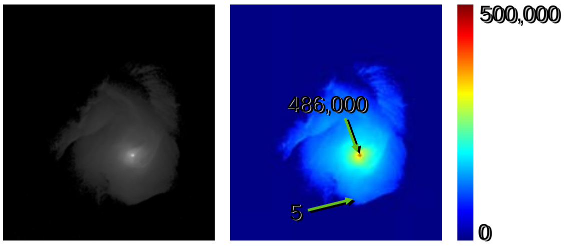
Sources of Dynamic Range

Dynamic Range of Cameras

- example: photographic camera with standard CCD sensor

– dynamic range of sensor	1:1000
– exposure variation 1/60th s – 1/6000th s (handheld camera/non-static scene)	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

High Dynamic Range (HDR) Imaging

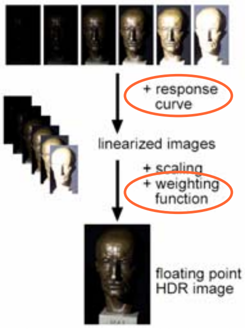


High Dynamic Range (HDR) Imaging

- analog false-color film with several emulsions of different sensitivity levels by Wyckoff in the 1960s
  - dynamic range of about 10^8
- modern CMOS sensors can achieve a dynamic range of $10^6 – 10^8$
  - logarithm in analog domain
  - multiple exposure techniques

High Dynamic Range Imaging

- extending dynamic range of ordinary camera
- combining multiple images with different exposure



Determining the Response Curve

- [Madden 1993] assumes linear response
  - correct for raw CCD data
- [Debevec and Malik 1997]
  - selects a small number of pixels from the images
  - performs an optimization of the response curve with a smoothness constraint
- [Robertson et al. 1999, 2003]
  - optimization over all pixels in all images

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

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

Algorithm of Robertson et al.

- optimizing the response curve I:
  - start again with definition $f^{-1}(y_{ij}) = \boxed{t_i x_j =: I(y_{ij})}$
- 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

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

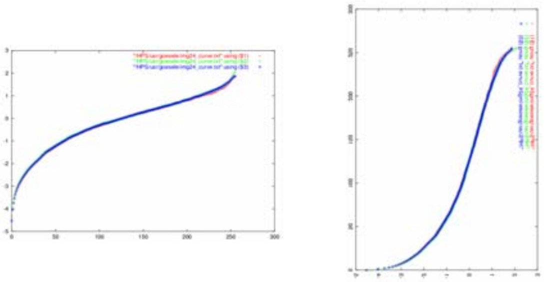
$$I(m) = \frac{1}{\mathrm{Card}(E_m)} \sum_{i,j \in E_m} t_i x_j$$

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

Algorithm of Robertson et al.

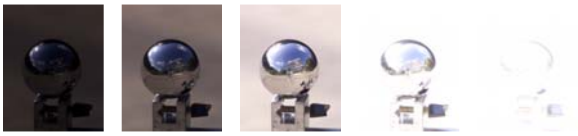
- both steps are iterated
  - calculation of a HDR image using *I*
  - optimization of *I* using the HDR image
    - ➔*I* needs to be normalized, e.g., *I*(128)=1.0
- stop iteration after convergence
  - criterion: decrease of *O* below some threshold
  - usually only a couple of iterations

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

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

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

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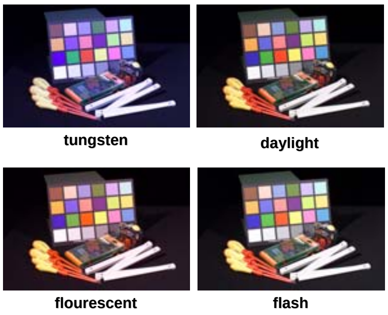
White Balance

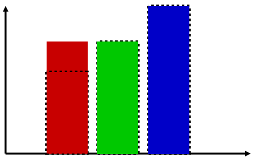
capture the spectral characteristics of the light source to assure correct color reproduction


tungsten
daylight
flourescent
flash

images taken with different camera settings

White Balance

- capture white surface under target illumination
- scale color channels to achieve uniform intensity values
- often built-in function

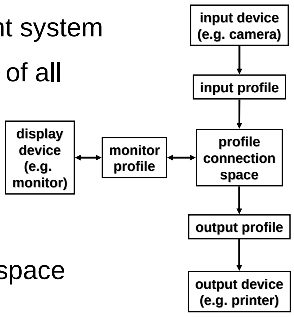


Color Calibration

- BRDF model of real object
- long processing pipeline
- which image is (more) correct?

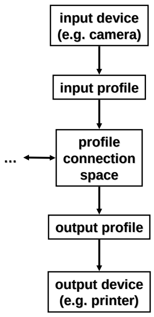
Color Calibration

- ICC color management system
- capture the properties of all devices
  - camera and lighting
  - monitor settings
  - output properties
- common interchange space


input device (e.g. camera)
input profile
display device (e.g. monitor)
monitor profile
profile connection space
output profile
output device (e.g. printer)

Color Calibration

- profile connection spaces
  - CIELAB (perceptual linear)
  - linear CIEXYZ color space
- can be used to create an high dynamic range image in the profile connection space
- allows for a color calibrated workflow


input device (e.g. camera)
input profile
...
profile connection space
output profile
output device (e.g. printer)

Color Calibration

[Goesele et al. 2004]

Limits of White Balance and Color Calibration

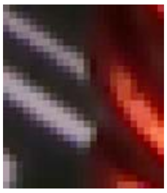
- fluorescence effects
  - signal colors
  - optical brighteners
  - test targets
- color calibration impossible
- cannot be solved using white balance

daylight (HMI)

green LED

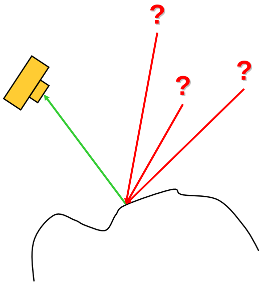
Overview Acquisition Basics

- digital cameras
  - geometric and photometric calibration
  - high dynamic range imaging
- **light sources**
- lab setup
- geometry acquisition



General Measurement Approach

- find relation between incoming and outgoing light at a surface point
- derive information from this data
- knowledge and control over light sources needed



Lighting Requirements

- photometric properties
  - uniform spatial distribution
  - color constant over time
  - even spectral distribution
  - very bright and efficient

Lighting Requirements

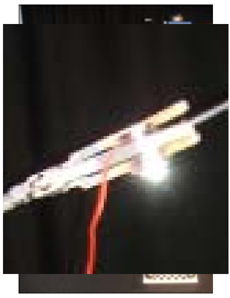
- emission pattern
- requirements depend on application, e.g.,
  - well defined light source
  - incident angle as small as possible
    - ➔ *parallel light source (e.g. laser beam)*
    - ➔ *point light source*
  - lens or reflector based systems are not ideal

Point Light Source Example

- 800 W HMI light source
- very efficient
  (equals 2500 W tungsten light)
- (almost) daylight spectrum
- constant colors
- point light source

Point Light Source Example

- high power LED (e.g. 5 W Luxeon systems)
  (require passive cooling)
- smaller and easier to handle
- keep an eye on LED safety regulations
- more information about lighting in the individual sections of the course …



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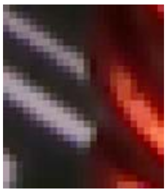

Lab Setup

- part of the lighting considerations
- often low and diffuse reflection required to minimize the influence of the environment
- MPI photo studio
  - walls and ceiling covered with black felt
  - black needle fleece carpet

Lab Setup

Lab Setup

- tuned for efficiency and flexibility
  - enough space
  - enough stands, supporting materials, …
- have some lighting available in dark areas
  - e.g., radio controlled light switch
- safety concerns