Rethinking the camera pipeline to improve photographic and scientific applications

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Today's talk

Making your smartphone capture images better.
Today's talk

Making your smartphone capture images better.

Focus on the *in-camera processing pipeline*
Talk's road map

• Motivation
• How I got involved
• Current work
• Where I'd like things to go
Motivation

Where I'd like things to go

Current work

How I got involved
Shifting landscape of cameras

- Film
- Point-and-shoot
- DSLR/Mirrorless
- Smartphone
Units of each device sold 1933 - 2016

- DSLR/Mirrorless
- Point-and-shoot
- Film
Photography = smartphone camera
Imaging is at our finger tips
In many applications, a human will never see the captured image.
Scientist's view of a photo

Assume that pixel values accurately record "intensity" measurement of the physical world.
Simple imaging model assumes an image is an array of scene radiance measurements.
Many problems in computer vision operate under the assumption.
Image deblurring equations are linear with respect to the physical image formation.
Camera = light measuring device

Medical imaging explicitly requires accurate measurements.
Camera = light measuring device?
Cameras make nice photographs

Three different cameras with **same aperture, exposure, white balance** and **picture style**, etc. . .
Cameras apply "photo-finishing"

- **Standard**: Glowing prints with crisp finishes. It is the basic color of EOS DIGITAL.
- **Portrait**: For transparent, healthy skin for women and children.
- **Landscape**: Crisp and impressive reproduction of blue skies and green trees in deep, vivid color.
- **Neutral**: Subjects are recorded in rich detail, giving the greatest latitude for image processing.
- **Faithful**: Accurate recording of the subject’s color, close to the actual image seen with the naked eye.
- **Monochrome**: Filter work and sepia tone with the freedom of digital monochrome.

From Canon’s user manual
Neutral
Nikon D7000
Picture styles

Standard
Vivid
Nikon D7000
Picture styles

Landscape
This type of processing is not suitable for scientific applications!

Which one is correct?
Many problems encountered in application development are due to the photo-centric design of the in-camera color processing pipeline.
How I got involved

Motivation

Current work

Where I’d like things to go
Two papers on radiometric calibration

Revisiting Radiometric Calibration for Color Computer Vision

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2Korea Advanced Institute of Science and Technology, South Korea
3Ecole Polytechnique Fédérale de Lausanne

Abstract

We present a study of radiometric calibration and the impact it has on image quality. We analyse a systematic analysis of more than 10,000 images from over 30 cameras. The goal is to uncover the radiometric calibration techniques that are the most effective. The analysis shows that many cameras have significant issues with radiometric calibration, and that the most common issues are low radiometric calibration accuracy, low radiometric calibration efficiency, and high dynamic range. Digital cameras, however, are much more likely to have these issues than analog cameras. Moreover, the primary goal of many cameras is to provide as much information as possible. The results of this study suggest that radiometric calibration is an important factor in the quality of images. As such, we provide a new evaluation of radiometric calibration and present an effective calibration scheme that allows for the minimization of the error in color correction and the minimization of the error in color correction.

1. Introduction

Many computer vision algorithms assume that cameras are accurate light measuring devices that capture images that are directly related to the actual scene radiance. Representative algorithms include photometric stereo, shape from shading, color constancy, intrinsic image computation, and high dynamic range imaging. Digital cameras, however, are much more likely to have low radiometric calibration accuracy. Therefore, we propose a new model for radiometric calibration and present an effective calibration scheme that allows for the minimization of the error in color correction.

A New In-Camera Imaging Model for Color Computer Vision and its Application

Seon Joo Kim, Member, IEEE, Hai Ting Lin, Student Member, IEEE, Zheng Lu, Student Member, IEEE, Sabine Süsstrunk, Senior Member, IEEE, Stephen Lin, Member, IEEE, and Michael S. Brown, Member, IEEE

Abstract—We present a study of in-camera image processing through an extensive analysis of more than 10,000 images from over 30 cameras. The goal of this work is to investigate if image quality can be transformed to physically meaningful values, and if so, how this can be done. From our analysis, we show that the conventional radiometric model fits well for image patches with low color saturation, and fail to detect image patches with high color saturation. This is due to the robustness of the radiometric processing, which makes it difficult to correct pixels with high color saturation.

Index Terms—Radiometric calibration, in-camera imaging, image processing, gamut mapping, white balance.

1 INTRODUCTION

Many computer vision algorithms assume that cameras are accurate light measuring devices which capture images that are directly related to the actual scene radiance. Representative algorithms include photometric stereo, shape from shading, color constancy, intrinsic image computation, and high dynamic range imaging. Digital cameras, however, are much more likely to have low radiometric calibration accuracy. Therefore, we propose a new model for radiometric calibration and present an effective calibration scheme that allows for the minimization of the error in color correction.
Ideal in-camera pipeline

Sensor Image (RAW) → White balance → Color Space Transform (CST) → CIE XYZ → Linear-sRGB → Apply sRGB encoding gamma.

STEP 1: White-balanced camera-specific raw-RGB

STEP 2: CST maps from camera color space to CIE XYZ, then to linear-sRGB.

STEP 3: sRGB Output
Tone-curve is camera-specific

Sensor Image (RAW) ➔ White balance ➔ Color Space Transform (CST) ➔ CIE XYZ Linear-sRGB

CV community has known for a long time that cameras do not only apply an sRGB gamma.

Large body of "radiometric calibration" research to estimate these camera-specific tone-curves $f$. All assume this is fixed per camera.

Mann and Picard, SPIE’95
Debevec and Malik, SIG’97
Mitsunaga and Nayar, CVPR’99
Farid, TIP’01
Grossberg and Nayar, TPAMI’03
Grossberg and Nayar, TPAMI’04
Lin et al, CVPR’04
...
Manders et al, ICIP’04
Pal et al, CVPR’04
Lin et al, ICCV’05
Kim and Pollefeys, TPAMI’08
Chakrabarti et al, BMVC’09
Sensor Image (RAW) \[\xrightarrow{\text{White balance}}\] Color Space Transform (CST) \[\xrightarrow{\text{CIE XYZ Linear-sRGB}}\] 

CV community has known for a long time that cameras do not only apply an sRGB gamma. Large body of "radiometric calibration" research to estimate these camera-specific tone-curves $f$. All assume the $f$ is fixed per camera.
Tone-curve is camera-specific?
More complex color model needed

Sensor Image (RAW) → White balance → Color Space Transform (CST) → CIE XYZ

Linear-sRGB

3D RGB Warp

Lin et al, ICCV 2011
Kim et al, TPAMI 2012
Parameters change by camera settings

Canon EOS1Ds Mark III

CST

White Balance

Sensor Image (RAW)

White balance

Color Space Transform (CST)

CIE XYZ

Linear-sRGB

3D RGB Warp

h₁, f₁
Parameters change by camera settings

Canon EOS1Ds Mark III

White Balance

CST

WB

WB₁

WB₂

Picture Styles

S Standard

P Portrait

L Landscape

h₁

f₁

h₂

f₂

h₃

f₃

Sensor Image (RAW)

White balance

Color Space Transform (CST)

CIE XYZ

Linear-sRGB

3D RGB Warp

h₂

f₂
Parameters change by camera settings

Canon EOS1Ds Mark III

CST

White Balance

WB1, WB2

Picture Styles

Standard, Portrait, Landscape

Picture Styles

h1, f1

h2, f2

h3, f3

Sensor Image (RAW)

White balance

[ #  #  # ]

Color Space Transform (CST)

[ #  #  #  #  #  #  #  #  #  #  #  #  #  #  #  #  # ]

CIE XYZ

Linear-sRGB

CIE XYZ

3D RGB Warp

h3

f3
**Canon EOS1Ds Mark III**

**White Balance**

- AWB
- $T_{w1}$, $T_{w2}$, $T_{w3}$, $T_{w4}$

**Picture Styles**

- $S$: Standard
- $P$: Portrait
- $L$: Landscape

**Gamut Mapping** $h$ with $h_1, f_1$, $h_2, f_2$, $h_3, f_3$

**Tone Mapping** $f$

**Camera (RAW)**

- RAW to CIE XYZ
- $T_s$

- Raw to $s$RGB

**sRGB (JPEG)**
Canon EOS1Ds Mark III

White Balance

AWB

T_{w1} T_{w2} T_{w3} T_{w4}

Picture Styles

<table>
<thead>
<tr>
<th>S</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Portrait</td>
</tr>
<tr>
<td>L</td>
<td>Landscape</td>
</tr>
</tbody>
</table>

Gamut Mapping

\( h_1, f_1 \)

\( h_2, f_2 \)

\( h_3, f_3 \)

Camera

(RAW)

White Balance \( (T_w) \)

RAW to sRGB \( (T_s) \)

Gamut Mapping \( (h) \)

Tone Mapping \( (f) \)

sRGB

(JPEG)
Canon EOS1Ds Mark III

White Balance

- AWB
- $T_{w1}$
- $T_{w2}$
- $T_{w3}$
- $T_{w4}$

Picture Styles

- Standard
- Portrait
- Landscape

Gamut Mapping ($h$)

Tone Mapping ($f$)

Camera (RAW)

White Balance ($T_w$)

RAW to sRGB ($T_s$)

CIE XYZ

sRGB (JPEG)
Canon EOS1Ds Mark III

White Balance

- AWB
- $T_{w1}$
- $T_{w2}$
- $T_{w3}$
- $T_{w4}$

Picture Styles

- Standard ($S$)
- Portrait ($P$)
- Landscape ($L$)

Gamut Mapping ($h$)

Tone Mapping ($f$)

Camera (RAW)

RAW to sRGB ($T_s$)

White Balance ($T_w$)

CIE XYZ

sRGB (JPEG)
What if you took a photo with the wrong settings?
Canon EOS1Ds Mark III

White Balance

AWB  $T_{w1}$  $T_{w2}$  $T_{w3}$  $T_{w4}$  …

Picture Styles

$S$  Standard  $P$  Portrait  $L$  Landscape  …

$h_1, f_1$  $h_2, f_2$  $h_3, f_3$

RAW  (JPEG)  RAW to sRGB  (Ts)

Camera (RAW)

White Balance ($T_w$)

Gamut Mapping ($h$)

Tone Mapping ($f$)
Canon EOS1Ds Mark III

**White Balance**

- **AWB**
- **Tw1**
- **Tw2**
- **Tw3**
- **Tw4**

**Picture Styles**

- **S** Standard
- **P** Portrait
- **L** Landscape

**Gamut Mapping**

- **h1, f1**
- **h2, f2**
- **h3, f3**

**Tone Mapping**

- **f-1**

**Camera (RAW)**

- White Balance (Tw⁻¹)
- RAW to sRGB (Ts⁻¹)

**sRGB (JPEG)**
Canon EOS1Ds Mark III

White Balance

Picture Styles

- Standard: $h_1, f_1$
- Portrait: $h_2, f_2$
- Landscape: $h_3, f_3$

Camera (RAW)

- RAW to sRGB ($T_s^{-1}$)
- White Balance ($T_w^{-1}$)
- Gamut Mapping ($h^{-1}$)
- Tone Mapping ($f^{-1}$)

sRGB (JPEG)
Input: cloudy WB + landscape style

Result - Canon EOS 1Ds Mark III
Result - Canon EOS 1Ds Mark III

Ground truth: fluorescent WB + standard style
Result - Canon EOS 1Ds Mark III

Photoshop result
Result - Canon EOS 1Ds Mark III

Refinished result
Result - Canon EOS 1Ds Mark III

Ground truth: fluorescent WB + standard style
Result - Canon EOS 1Ds Mark III

Input

Ground truth

Photoshop

Our refined result
Result - Canon EOS 1Ds Mark III

Input: tungsten WB + standard style
Result - Canon EOS 1Ds Mark III

Ground truth: daylight WB + standard style
Result - Canon EOS 1Ds Mark III

Photoshop result
Result - Canon EOS 1Ds Mark III

Our refinished result
Result - Canon EOS 1Ds Mark III

Ground truth: daylight WB + standard style
Result - Sony α200

Input: tungsten WB + standard style
Result - Sony α200

Ground truth: daylight WB + standard style
Result - Sony α200

Photoshop result
Result - Sony α200

Our refinished result
Result - Sony α200

Ground truth: daylight WB + standard style
Result - Sony α200

Input

Ground truth

Photoshop

Our Refinished Result
Remember these guys?
So then what?
Current work

Where I'd like things to go

How I got involved

Motivation
Kept pushing the work

ECCV 2012 – Better modeling of the 3D color function

TPAMI 2013 – Rethinking deblurring considering the camera pipeline

CVPR 2014 – Mapping between camera sensors
I learned a lot more about color and cameras

If you want to learn a topic - teach it to others.

Educate the community . . .
Color and camera processing pipeline

- **Radiometric**
  - Relative Power
  - Spectral power distribution
  - 450nm, 600nm, 650nm

- **Colorimetric**
  - CIE 1931 XYZ
  - Colorimetric Encoding Standards
  - R, G, B

- **Encoding Standards**
  - Standard RGB (sRGB)

- **Camera imaging pipeline**
  - Sensor with color filter array (CFA) (CCD/CMOS)
  - ISO gain and raw-image processing
  - RGB Demoasicing
  - Mapping to sRGB output
  - Color Manipulation (Photo-finishing)
  - White-Balance & Color Space Transform (CIE XYZ)
  - Noise Reduction
  - JPEG Compression
  - Save to file

- **Spectral power distribution**
  - 450nm, 600nm, 650nm
  - Relative Power

- **Color Encoding Standards**
  - Standard RGB (sRGB)
  - CIE 1931 XYZ
  - Colorimetric Encoding Standards

- **Noise Reduction**
  - JPEG Compression
  - Save to file
Deep collaboration formed in 2013 . . .

Camera processing pipeline

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

Save to file

Sensor with color filter array (CFA) (CCD/CMOS)

Started revisiting many steps on the camera . . . with emphasis on the **fundamentals**.
Examined color constancy from a radiometric point of view.
Evaluation of traditional white balance

Illumination corrected by **white balance**

Image corrected from blue skylight to standard illuminant E

Ground truth image

Standard illuminant E
Evaluation of full color constancy

Illumination corrected by **full correction**

Image corrected from blue skylight to standard illuminant E

Ground truth image

Standard illuminant E
Color constancy

JOSA 2014 – Question why methods by on gradients work.


ICCV 2015
“True” color constancy

CVPR 2016
Double illumination + user preference
Created a new color constancy dataset

My group developed an updated color constancy dataset with over 3,000 calibrated images, from 9 cameras.

Largest prior data set was 500 from 2 cameras.

Russell  Dongliang

JOSA 2014, CVPR 2015
"Opening" the camera pipeline

On making camera pipelines more accessible for research.
A Software Platform for Manipulating the Camera Imaging Pipeline

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Abstract. There are a number of processing steps applied onboard a digital camera that collectively make up the camera imaging pipeline. Unfortunately, the imaging pipeline is typically embedded in a camera’s hardware making it difficult for researchers working on individual components to do so within the proper context of the full pipeline. This not only hinders research, it makes evaluating the effects from modifying an individual pipeline component on the final camera output challenging, if not impossible. This paper presents a new software platform that allows easy access to each stage of the camera imaging pipeline. The platform allows modification of the parameters for individual components as well as the ability to access and manipulate the intermediate images as they pass through different stages. We detail our platform design and demonstrate its use on a popular consumer-grade camera.
Software camera pipeline

Stages of the camera imaging pipeline and associated parameters

1- Reading raw Image
2- Black light subtraction, Linearization [Values or 1D LUT]
3- Lens correction [2D Array[s]]
4- Demosaicing [Func]
5- Noise reduction [Func]
6- White-balancing & Color space [Mats]
12- Gamma curve application [1D LUT]
11- Final color space conversion [Mat]
10- Tone curve application [1D LUT]
9- Color manipulation [3D LUT]
8- Exposure curve [EV value or 1D LUT]
7- Hue/Sat map [3D LUT]

Intermediate images for each stage
Walking through the pipeline (1)
Walking through the pipeline (2)

Black level subtraction and linearization + defective pixel mask
Walking through the pipeline (3)

Lens correction (non-uniform gain)
Walking through the pipeline (4)

Demosaicing
+ Noise Reduction
Walking through the pipeline

(5)

White balance
+ color space transform
(CIE XYZ/Pro-photo)
Walking through the pipeline (6)
Walking through the pipeline (7)
Walking through the pipeline (8)
Walking through the pipeline (9)
Walking through the pipeline (10)

sRGB gamma
Lots of opportunities

Now, we can analyze each step of the pipeline.
Lots of opportunities

Stages of the camera imaging pipeline and associated parameters

1- Reading raw Image

2- Black light subtraction, Linearization [Values or 1D LUT]

3- Lens correction [2D Array(s)]

4- Demosaicing [Func]

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8- Exposure curve [EV value or 1D LUT]

9- Color manipulation [3D LUT]

10- Tone curve application [1D LUT]

11- Final color space conversion [Mat]

12- Gamma curve application [1D LUT]
Improving color for cameras

[CVPR'18]

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Abstract

One of the key operations performed on a digital camera is to map the sensor-specific color space to a standard perceptual color space. This procedure involves the application of a white balance correction followed by a color space transform. The current approach for this colorimetric
Lots of opportunities

Current approach uses white-balance correction and interpolated CST

Proposed method 1: improved CST interpolation - minimal modification to pipeline

Proposed method 2: uses full color-balance over traditional white-balance correction

Mean angular error: 3.10° Mean angular error: 0.30° Mean angular error: 0.29°
Lots of opportunities

Stages of the camera imaging pipeline and associated parameters

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9. Color manipulation [3D LUT]
10. Tone curve application [1D LUT]
11. Final color space conversion [Mat]
12. Gamma curve application [1D LUT]
Denoising dataset

SIDD: Smartphone Image Denoising Dataset

- 30,000 images
- 5 cameras
- 160 scene instances
- 15 ISO settings
- Direct current lighting
- Three illuminations
Instant denoising improvements

Learning-based denoise architectures get better performance when trained on real noisy images.
New camera noise model

Noise Flow: Noise Modeling with Conditional Normalizing Flows

ICCV 2019

- Introduce new noise model
- Generative method based on real noise samples
- Significantly more accurate than prior models
New camera noise model
Lots of opportunities

Stages of the camera imaging pipeline and associated parameters

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10- Tone curve application [1D LUT]

11- Final color space conversion [Mat]

12- Gamma curve application [1D LUT]
Dual pixel for autofocus

From Canon’s webpage
Reflection removal via dual-pixel sensors

Abstract

Reflection removal is a challenging problem in computer vision, especially when dealing with scenes involving reflections. In this paper, we propose a novel approach to remove unwanted reflections from single images. Our method leverages dual-pixel image sensors, which have two photodiodes per pixel to capture two sub-aperture views of the scene. This setup allows for the extraction of depth information, which is then used to distinguish between the real foreground and the reflected background. Our approach outperforms existing methods in terms of accuracy and robustness, making it a valuable tool for applications requiring high-quality images without reflections.
Challenge for reflection removal is to determine what image content is part of the scene (background) and what is reflection.
Reflection removal

Left/right dual-pixel images
Reflection removal

We get this for free!
Why?
(1) we understand our camera and image formation
(2) we have access to the camera pipeline!
Lots of opportunities

Stages of the camera imaging pipeline and associated parameters

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12- Gamma curve application [1D LUT]

Remember this example

Why not just save in raw-RGB format?
raw-RGB disadvantages

- File size is too large
  raw-RGB files are significantly larger than JPEG
  (e.g. 25-80 MB vs 5-10 MB per image)

- Limited support
  Some (computer vision) image workflows do not support raw-RGB
But what if . . .

. . . we could encoded the RAW image *inside* the JPEG image for (almost) free?
But what if . . .

. . . we could encoded the RAW image *inside* the JPEG image for (almost) free?

extract RAW image when needed.
Hybrid image encoding

RAW Image Reconstruction using a Self-Contained sRGB-JPEG Image with only 64 KB Overhead

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Abstract

Camera images are almost exclusively saved using the JPEG image standard. JPEG is a lossy compression format that encodes images in a standard RGB color space (sRGB). This adds unnecessary overhead to network storage and transmission. Hybrid image encoding is a technique that aims to reduce this overhead by embedding metadata into the image format. This paper presents a method for reconstructing RAW images from a self-contained sRGB-JPEG image with only 64 KB overhead, demonstrating the feasibility of using hybrid image encoding for improving image compression efficiency.
Hybrid image encoding

sRGB JPEG (9,788KB + 64KB)

Groundtruth RAW (25,947KB)

Reconstructed RAW

Error Map (RMSE: 0.002)
Hybrid image encoding application
AI-methods will replace JPEG. This gives us an opportunity to develop new deep-learning compression schemes that incorporate in the need to RAW or linear data.
Where I'd like things to go

Motivation

How I got involved

Current work

Where I'd like things to go

Motivation
The big picture
Imaging is at our finger tips
Dual purpose camera

Photo-centric pipeline

Scientific pipeline
Rethinking imaging and image encoding

Scene-referred image states

1. Reading raw Image
2. Black light subtraction, Linearization [Values or 1D LUT]
3. Lens correction [2D Array(s)]
4. Demosaicing [Func]
5. Noise reduction [Func]
6. White-balancing & Color space [MATs]

12. Gamma curve application [1D LUT]
11. Final color space conversion [Mat]
10. Tone curve application [1D LUT]
9. Color manipulation [3D LUT]
8. Exposure curve [EV value or 1D LUT]
7. Hue/Sat map [3D LUT]

Display-referred image states
Devices that can be replaced

Scene-referred image states

1- Reading raw Image
2- Black light subtraction, Linearization [Values or 1D LUT]
3- Lens correction [2D Array(s)]
4- Demosaicing [Func]
5- Noise reduction [Func]
6- White-balancing & Color space [MATs]
7- Hue/Sat map [3D LUT]
8- Exposure curve [EV value or 1D LUT]
9- Color manipulation [3D LUT]
10- Tone curve application [1D LUT]
11- Final color space conversion [Mat]
12- Gamma curve application [1D LUT]
Rethink imaging and image encoding
If we can encode images that allow us to *recover* intermediate stages:

- Better scientific measurements
- Better image editing
- Better color manipulation for display
Big picture: Imaging continuum

Radiometry

Sensor

Colorimetry

Scene referred processing

Color rendering

Output referred processing

Image

Photograph

New CFA and/or controlled illumination

Scientific

CFA

Computer vision, AI applications

Photographic/Editing/Display

Wavelength ($\lambda$)

CFA

Image $s_0$

Image $s_1$

Display

Encoding

Editing
What am I interested in doing?

I want to improve the camera processing pipeline for computer vision and better AI.

- **Gain Control A/D Converter**
- **Possible LUT**
- **AFE** – Analog Front End Sensor related processing
- **Sensor with color filter array (CCD/CMOS)**
- **CFA**
- **Demoasicing**
- **White Balance**
- **Noise Reduction/Sharpening**
- **Tone Reproduction**
- **Color Space Transform + Color Preferences**
- **JPEG Compression**
- **Exif File Info**
- **Save to storage**
Conclusion

• Cameras are being used for more than photography

• Time to rethink the camera pipeline

• There are lots of opportunities

• Must work to influence industry and smartphone companies
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Thank You!

Questions?