

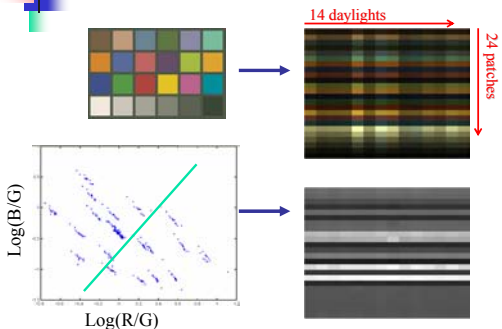
# Illumination Invariant Image Enhancement

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## Outline

- Illumination invariant image formation
  - Color constancy theory
  - Why need enhancement
- Invariant image enhancement
  - Optimization routines
  - Invariant image smoothing
  - Image linearization on nonlinear images
- Conclusions and future work

## Invariant Image Formation



## Color Constancy at a Pixel

[Finlayson et al. CIC8, 2000]

Image Formation for Lambertian Surfaces:

$$\rho_k = (\mathbf{a} \cdot \mathbf{n}) \int E(\lambda) S(\lambda) Q_k(\lambda) d\lambda$$

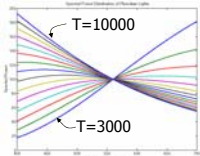
$k=1..3$  shading | light SPD | reflectance | sensor

*Now let's make some assumptions:*

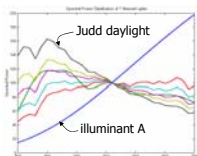
## Assumption 1: Planckian Light

Wien's approximation of a Planckian source:

$$E(\lambda) = I c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}$$



planckian light SPDs

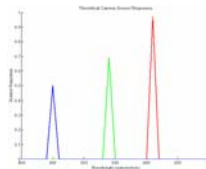


natural light SPDs

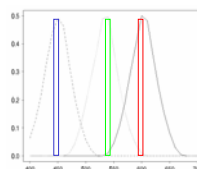
## Assumption 2: Narrow Band Sensors

Camera sensor sensitivities are delta-functions:

$$Q_k(\lambda) = q_k \delta(\lambda - \lambda_k)$$



theoretical camera sensors



SONY camera sensors

## Modified Image Formation

$$\rho_k = (\mathbf{a} \cdot \mathbf{n}) \int E(\lambda) S(\lambda) Q_k(\lambda) d\lambda$$

$$= (\mathbf{a} \cdot \mathbf{n}) I c_1 S(\lambda_k) \lambda_k^{-5} e^{-\frac{c_2}{\lambda_k T}} q_k$$

$$\log \rho_k = \log((\mathbf{a} \cdot \mathbf{n}) I) + \log(c_1 S(\lambda_k) \lambda_k^{-5} q_k) - \frac{c_2}{\lambda_k T}$$

dependent on illumination  $\rightarrow$   $(\mathbf{a} \cdot \mathbf{n}) I$   
dependent on surface reflectance  $\rightarrow$   $\log(c_1 S(\lambda_k) \lambda_k^{-5} q_k)$   
determined by camera sensors  $\rightarrow$   $-\frac{c_2}{\lambda_k T}$

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## Modified Image Formation

$$\log \rho_k = \log((\mathbf{a} \cdot \mathbf{n}) I) + \log(c_1 S(\lambda_k) \lambda_k^{-5} q_k) - \frac{c_2}{\lambda_k T}$$

$$\log \rho_2 = \dots$$

$$\log \frac{\rho_1}{\rho_2} = \log \frac{S(\lambda_1) \lambda_1^{-5} q_1}{S(\lambda_2) \lambda_2^{-5} q_2} + \left(-\frac{c_2}{\lambda_1} + \frac{c_2}{\lambda_2}\right) \frac{1}{T}$$

$$\log \frac{\rho_3}{\rho_2} = \log \frac{S(\lambda_3) \lambda_3^{-5} q_3}{S(\lambda_2) \lambda_2^{-5} q_2} + \left(-\frac{c_2}{\lambda_3} + \frac{c_2}{\lambda_2}\right) \frac{1}{T}$$

$\alpha + \frac{\beta}{T}$   $\leftarrow$  reflectance term ( $\alpha$ ) light color term ( $\beta/T$ )

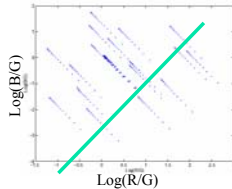
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## Implications

(1) 3 color values RGB  $\Rightarrow$  2 chromaticity values  $\log(R/G)$ ,

$$\log(B/G) \text{ in the form of } \alpha + \frac{\beta}{T}$$

(2) For a single surface viewed under different colored lights the log-chromaticities must fall on a line:

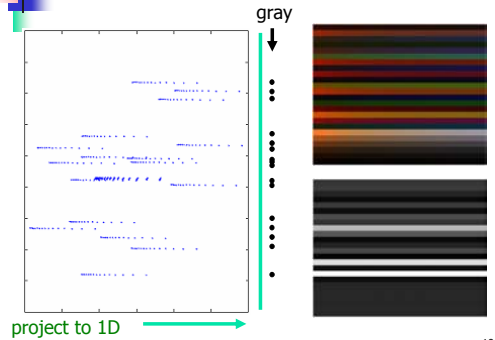


(3) Different surfaces induce lines with a \*same\* orientation : lighting-change direction

Rotating the coordination system .....

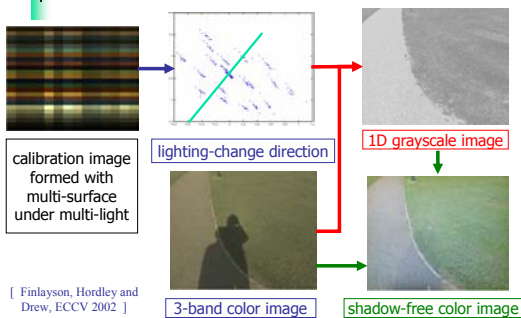
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## Invariant Image Formation



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## Using Invariant Images to...

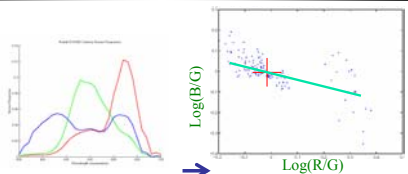


[ Finlayson, Hordley and Drew, ECCV 2002 ]

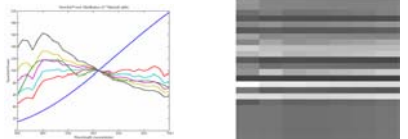
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## Problems in Practice

(1): Camera sensors are not delta-function (e.g. Kodak)

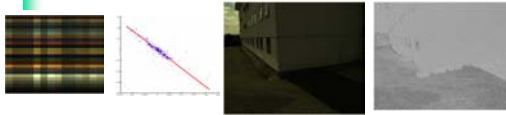


(2): Natural lights are only approximately Planckian



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## Problem 3: Nonlinearity



Forming invariant image from linear images



Forming invariant image from nonlinear images

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## To Enhance Invariant ...

(1) Sensor transform  $M$  that sharpens camera sensors and enhances invariant images

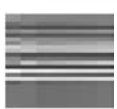
$$\begin{array}{ccc} \text{sensors} & & \text{colors} \\ \tilde{Q} = Q M & \rightarrow & \tilde{\rho} = \rho M \\ & & \uparrow 1 \times 3 \uparrow \uparrow 3 \times 3 \end{array}$$

(2) Image Linearization prior to invariant image formation

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## Use Optimization to Determine M

$$\min_M \text{Inv\_error} - \alpha \cdot \text{rank}(M)$$



relative intensity deviation plot

*Inv\_error is the sum of  $\sigma$  for each row in relative intensity deviation matrix*

with constraints

$$\begin{cases} \sum_{j=1}^3 M_{ij} = 1, i = 1..3 & L_1 \text{ normalization} \\ \rho M \geq 0 & \text{non-negative colors} \end{cases}$$

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## To Avoid "Fake" Invariant

(1) Initialize with spectral sharpening transform matrix

(2) Non-integer effective rank :  $\text{rank} = \sigma_3/\sigma_1$

where  $\sigma_i, i = 1..3$  are singular values of  $M$  from SVD

$\sigma_1 > \sigma_2 > \sigma_3 \rightarrow \text{rank}$  indicates how close the rank of  $M$  is to the full-rank.

Experimental results show:

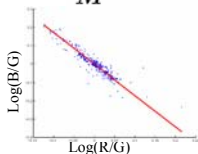
$\alpha=0 \rightarrow$  no constraint for rank  $\rightarrow$  results in similar sensors

$\alpha \neq 0 \rightarrow$  constrains rank  $\rightarrow$  results in sharper sensors

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## Another Optimization Method

$$\min_M 1 - \text{Rsquare} - \alpha \cdot \text{rank}(M)$$



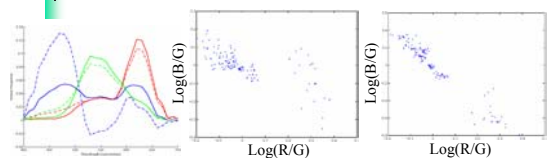
*Rsquare is the square of correlation coefficient of all points - indicating how close all the values cluster around a straight line.*

with constraints

$$\begin{cases} \sum_{j=1}^3 M_{ij} = 1, i = 1..3 & L_1 \text{ normalization} \\ \rho M \geq 0 & \text{non-negative colors} \end{cases}$$

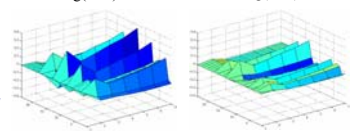
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## Optimized Kodak Camera



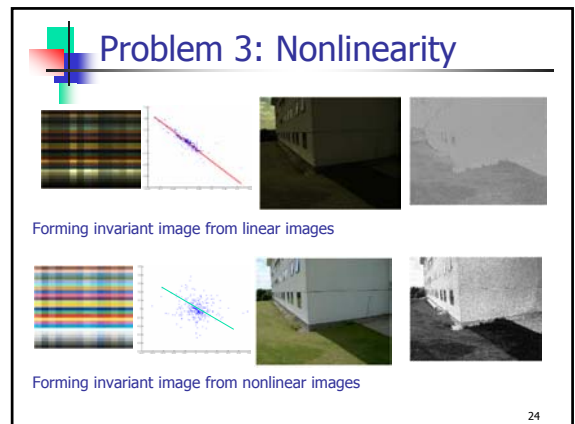
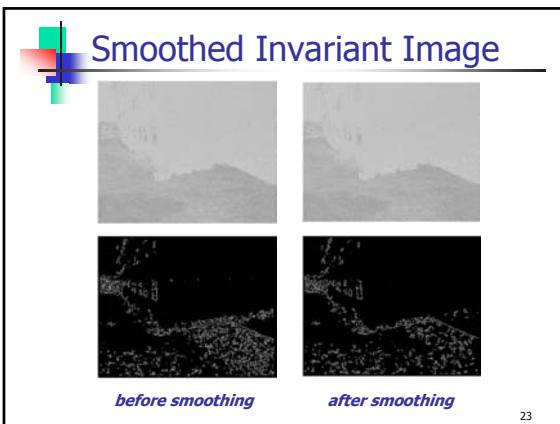
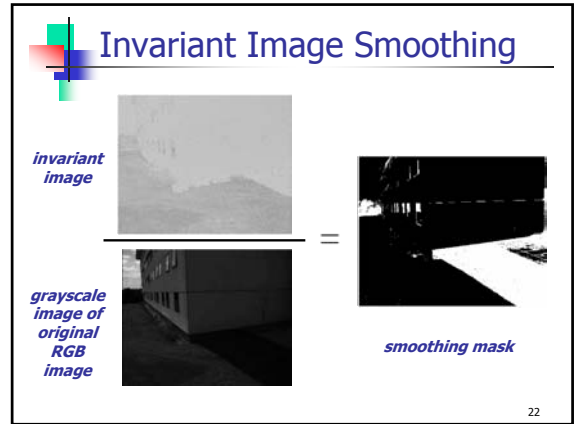
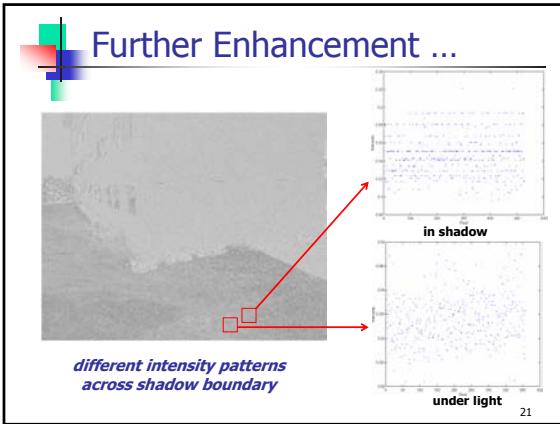
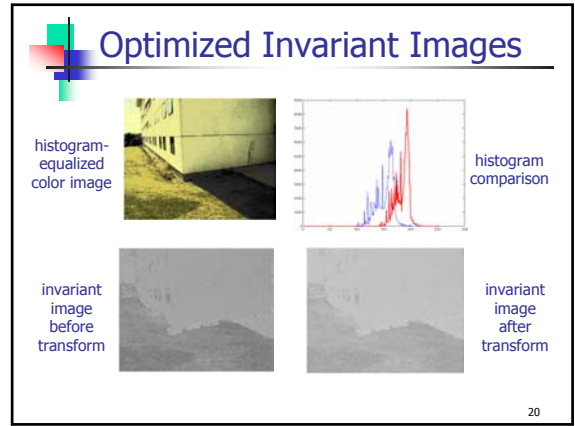
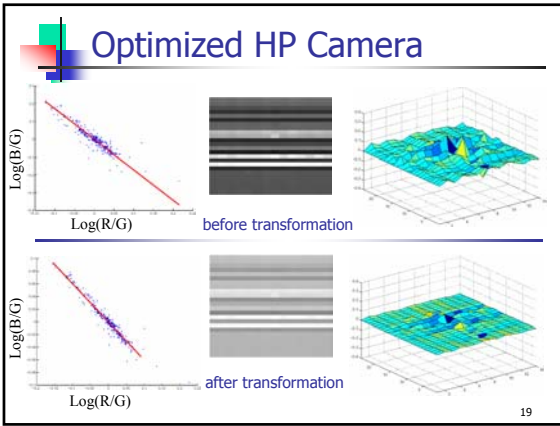
Optimization routine:

- (1) Minimizes invariance error
- (2) Sharpens sensors
- (3) Minimizes noise caused by natural lights



before transformation after transformation

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## Linear and Nonlinear Images

optical signals

opto-electronic conversion functions

camera output

linear image

nonlinear image

linear G values

nonlinear G values

**Solution:**  
nonlinear image → linearized image → invariant image

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## Linearization Model

Nonlinearity: sigmoid function + gamma function

$$X_{\text{nonlinear}} = \left( \frac{a_1}{1 + e^{-a_2 X_{\text{linear}}}} + a_3 \right)^{a_4}$$

Its inverse is the linearization model:

$$F(x) = -C_1 \cdot \log \left( \frac{C_2}{(f(x))^{C_3} + C_4} - 1 \right)$$

$x = R \text{ or } G \text{ or } B, f(x) = C_5 \cdot R + C_6 \cdot G + C_7 \cdot B$

To recover linearity: determine parameters by function fitting

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## Image Linearization

nonlinear image

linear image

nonlinear image

linearized image

linearized image

determine  $C_1, \dots, C_7$  in

$$F(x) = -C_1 \cdot \log \left( \frac{C_2}{(f(x))^{C_3} + C_4} - 1 \right)$$

$x = R \text{ or } G \text{ or } B, f(x) = C_5 \cdot R + C_6 \cdot G + C_7 \cdot B$

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## Invariant Image from Linearized Image

linearized image

linearized image

invariant image

optimized invariant image

optimization routine

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## Conclusions and Future Work

- Invariant image formation
  - › theory and issues that affect the performance
  - ? loose the assumption of Lambertian model
- Optimization routines
  - › derive a sensor transform that enhances invariant images
  - ? optimization methods applicable to different cameras
- Image smoothing
  - › further enhances invariant images
  - ? other shadow detection methods; adaptive smoothing
- Image linearization
  - › nonlinear image → linearized image → invariant image
  - ? effects of camera settings; other linearization approaches

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## Thanks to you all !

Questions please ?