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Kaiming He: Single Image Haze Removal Using Dark Channel Prior

CVPR’09 Best Paper

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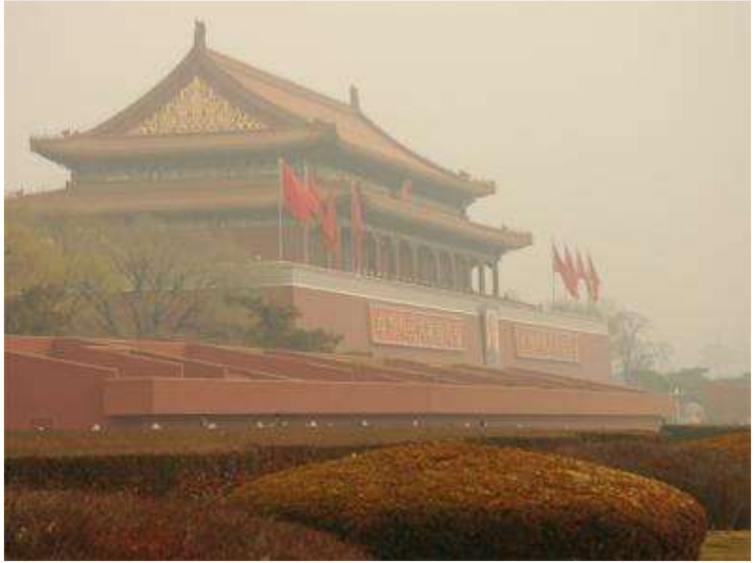
Outline

- Introduction
- Preliminaries
- Dark Channel Prior Haze Removal
- Discussions & Conclusions

Introduction

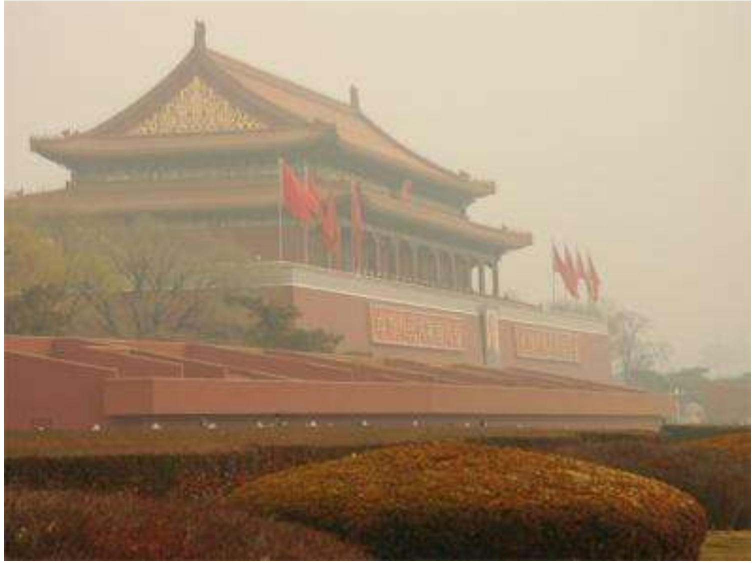
Image Degrade



Example of Hazy Image

- Haze, fog, and smoke are phenomena due to atmospheric absorption and scattering.
- Caused by turbid medium: water-droplets and small floating particles such as dust and smoke in the air.
- Images degraded: lose the contrast and color fidelity

Haze Removal



Hazy Image

Haze Free Image

Goal

Raw Hazy Image

Haze Free Image

Depth Information

Preliminaries

Haze Imaging Model

Atmospheric light

$$I = J \cdot t + A \cdot (1 - t)$$

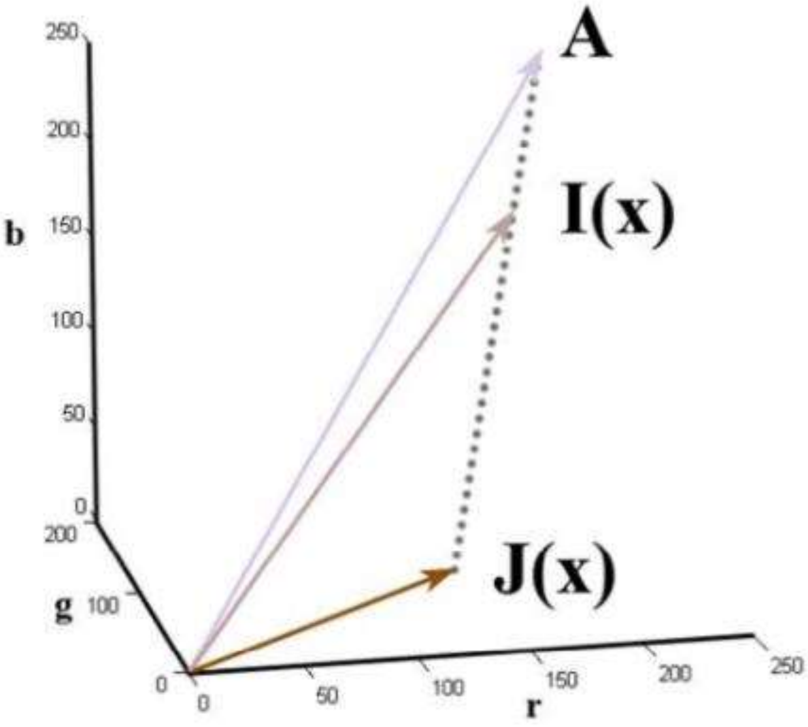
Hazy Image

Scene radiance
(Haze Free Image)

Transmission

- Transmission: 描述无法散射并到达照相机的光的介质传输率

RGB Color Space



$$t(x) = \frac{|A - I(x)|}{|A - J(x)|} = \frac{A^c - I^c(x)}{A^c - J^c(x)}$$

where $c \in \{r, g, b\}$

- vectors **A, I(x), and J(x)** are coplanar and their end points are collinear

Haze Imaging Model

$$I = \underbrace{J \cdot t}_{\text{Direct attenuation}} + \underbrace{A \cdot (1 - t)}_{\text{Airlight}}$$

- Direct attenuation (直接衰减): 描述了场景辐射和其在介质中的衰减
- Airlight (空气光): 来自于之前所提的散射的光并会导致场景颜色的偏移

Haze Imaging Model

$$I = J \cdot t + A \cdot (1 - t)$$

Atmosphere is homogenous
(大气介质均匀?)

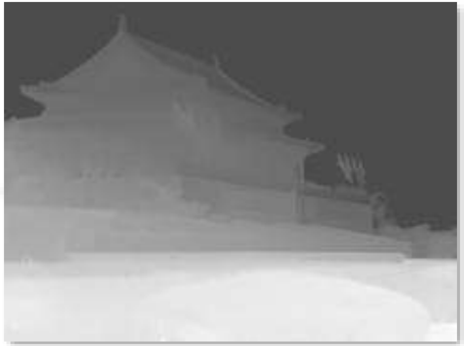
$$\mathrm{t} = \mathrm{e}^{-\beta\,\mathrm{d}}$$

Scattering Coefficient
(大气散射系数)

Scene Depth

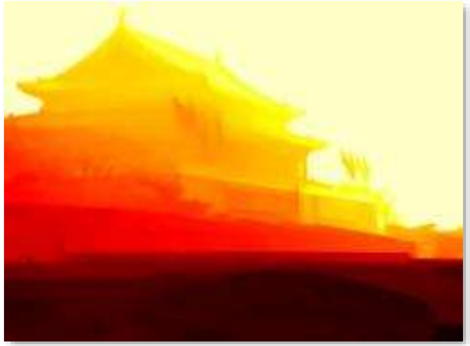
Scene Depth

Raw Image



Transmission

$$d = -\beta \ln t$$



Depth

Dark Channel Prior Haze Removal

Dark Channel Prior

In most of the non-sky patches, at least one color channel has very low intensity at some pixels.

Dark Channel Prior

For an image **J**, define:

$$\mathrm{J}^{\mathrm{dark}}(\mathrm{x}) = \min_{y}\left(\min_{\mathrm{c}}\left(\mathrm{J}^{\mathrm{c}}(\mathrm{y})\right)\right)$$

where:

- $\mathrm{c} \in \{\mathrm{r}, \mathrm{g}, \mathrm{b}\}$, J^{c} is a color channel of J
- $\Omega(\mathrm{x})$ is a local patch centered at x
- $\mathrm{J}^{\mathrm{dark}}$ is the dark channel of J

Dark Channel Prior

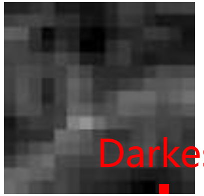
For an image **J**, define:

$$J^{\mathrm{dark}}(\mathrm{x}) = \min_{y}\left(\min_{\mathrm{c}}(J^{\mathrm{c}}(\mathrm{y}))\right)$$

Input Image

min (r, g, b)

Dark Channel Prior



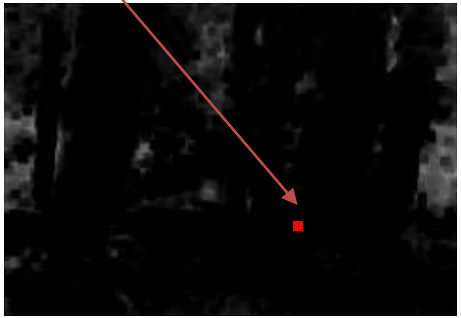
15 x 15 patch

For an image **J**, define:

$$J^{\mathrm{dark}}(x) = \min_{y}\left(\min_{c}\left(J^{c}(y)\right)\right)$$

Input Image

min (r, g, b)



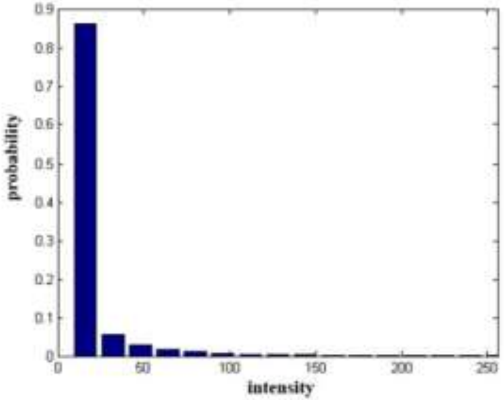
Dark Channel

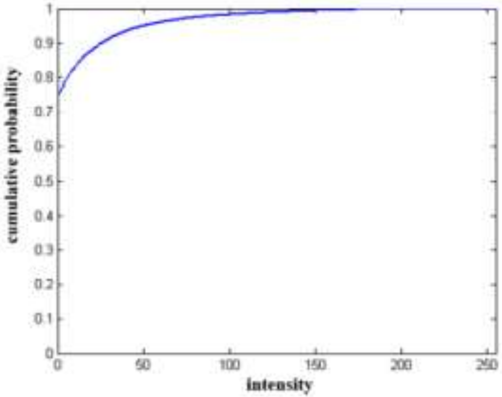
Observation: Hazy Image

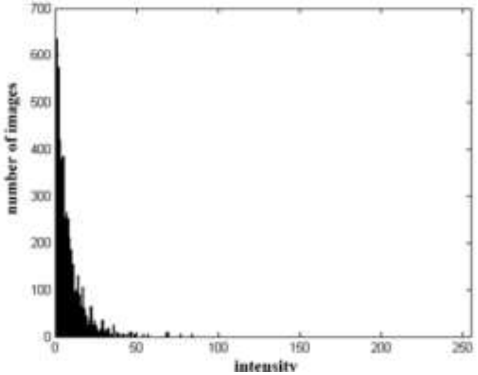
Observation: Haze Free Image

Observation: Haze Free Image

Observation: Statistics







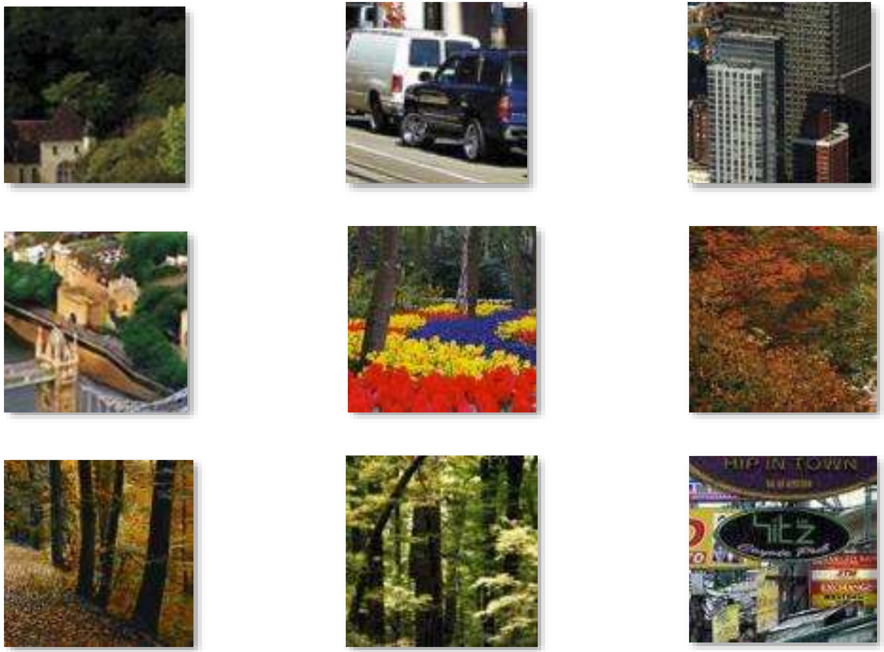
Observation

In most cases, for an outdoor haze free image **J**:

$$J^{dark}(x) = \min_{y}\left(\min_{c}\left(J^{c}(y)\right)\right) \to 0$$

What makes it dark?

- Shadow
- Colorful object
- Black object



Estimating the Transmission

Atmospheric light
(Assume Given)

$$I = J \cdot t + A \cdot (1 - t)$$

Hazy Image

Scene radiance
(Haze Free Image)

Transmission

Estimating the Transmission

$$I = J \cdot t + A \cdot (1 - t)$$

Normalization for each RGB channel:

$$\frac{\mathrm{I}^c}{A^c} = \frac{J^c}{A^c} t + 1 - t$$

Estimating the Transmission

$$\frac{I^c}{A^c} = \frac{J^c}{A^c}t + 1 - t$$

Assume the Atmospheric light A is given and the transmission t in a local patch $\Omega(x)$ is constant:

$$\min_c \left(\min_{y \in \Omega(x)} \left(\frac{I^c(y)}{A^c} \right) \right) = \tilde{t}(x) \min_c \left(\min_{y \in \Omega(x)} \left(\frac{J^c(y)}{A^c} \right) \right) + \left(1 - \tilde{t}(x)\right)$$

where: $\tilde{t}(x)$ is the transmission of patch $\Omega(x)$

Recall: Dark Channel Prior

In most cases, for an outdoor haze free image **J**:

$$J^{dark}(x) = \min_{y}\left(\min_{c}\left(J^{c}(y)\right)\right) \rightarrow 0$$

Estimating the Transmission

$$\min_c\left(\min_{y\in\Omega(x)}\left(\frac{I^c(y)}{A^c}\right)\right)=\tilde{t}(x)\min_c\left(\min_{y\in\Omega(x)}\left(\frac{J^c(y)}{A^c}\right)\right)+\left(1-\tilde{t}(x)\right)$$

$$\downarrow$$

$$\tilde{t}(x)=1-\min_c\left(\min_{y\in\Omega(x)}\left(\frac{I^c(y)}{A^c}\right)\right)$$

Aerial Perspective

- The atmosphere is not absolutely free of any particle even in clear days.
- The haze still exists when we look at distant objects.
- The presence of haze is a fundamental cue for human to perceive depth.
- If the haze is removed thoroughly, the image may seem unnatural and the feeling of depth may be lost.

Estimating the Transmission

$$\tilde{t}(x) = 1 - \min_{c}\left(\min_{y\in\Omega(x)}\left(\frac{I^c(y)}{A^c}\right)\right)$$

$\downarrow$

Keep a very small amount of haze for the distant objects by introducing a constant parameter ω $(0<\omega\leq 1)$

$$\tilde{t}(x) = 1 - \omega \min_{c}\left(\min_{y\in\Omega(x)}\left(\frac{I^c(y)}{A^c}\right)\right)$$

Example

$$\tilde{t}(x) = 1 - \omega \min_{c}\left(\min_{y\in\Omega(x)}\left(\frac{I^c(y)}{A^c}\right)\right)$$

$$I = J \cdot t + A \cdot (1 - t)$$

Input I

Estimated t

Haze Free Image J

Soft Matting

Contains some block effects since the transmission is not always constant in a patch.

Input I

Estimated t

Haze Free Image J

Soft Matting

Haze imaging model $I = J \cdot t + A \cdot (1 - t)$

Matting model [Levin et al., CVPR '06] $I = F \cdot \alpha + B \cdot (1 - \alpha)$

Foreground Color Background Color Foreground Opacity

Therefore, let $t \Leftrightarrow \alpha$ and use soft matting algorithm to refine transmission.

Soft Matting

Cost Function

$$\mathbf{E}(\mathbf{t}) = \lambda \underbrace{\| \mathbf{t} - \tilde{\mathbf{t}} \|^2}_{\text{Data term}} + \underbrace{\mathbf{t}^{\mathrm{T}}\mathbf{L}\mathbf{t}}_{\text{Smoothness term}}$$

Regularization parameter

Matting Laplacian matrix

Soft Matting

Haze imaging model $I = J \cdot t + A \cdot (1 - t)$

Matting model [Levin et al., CVPR '06] $I = F \cdot \alpha + B \cdot (1 - \alpha)$

Input I

tri-map

α

Input I

+

Estimated $\tilde{t}$

Refined t

Estimating the Atmospheric Light

Use the dark channel to improve the atmospheric light estimation:

- Pick the top 0.1% brightest pixels in the dark channel.
- Among these pixels, the pixels with highest intensity in the input image I is selected as the atmospheric light.

Scene Radiance Restoration

Atmospheric light

$$I = J \cdot t + A \cdot (1 - t)$$

Hazy Image

Haze Free Image

Transmission

Scene Radiance Restoration

Atmospheric light

$$J(x) = \frac{I(x) - A}{\max(t(x), t_0)} + A$$

Haze Free Image

Hazy Image

Transmission

Discussions & Conclusions

Applications: Video

Applications: De-Focus

Input Image

Depth

Haze Free Image

Applications: De-Focus

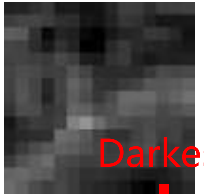
Input Image

Depth

De-Focused Haze Free Image

Recall

For an image **J**, define:

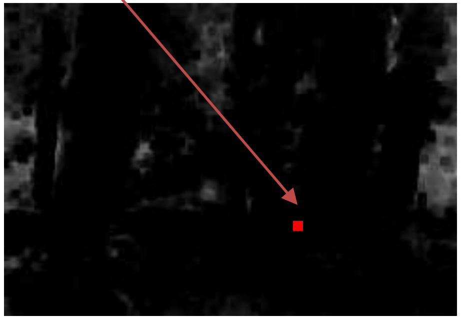


15 x 15 patch

$$J^{\mathrm{dark}}(x) = \min_{y}\left(\min_{c}\left(J^{c}(y)\right)\right)$$

Input Image

min (r, g, b)

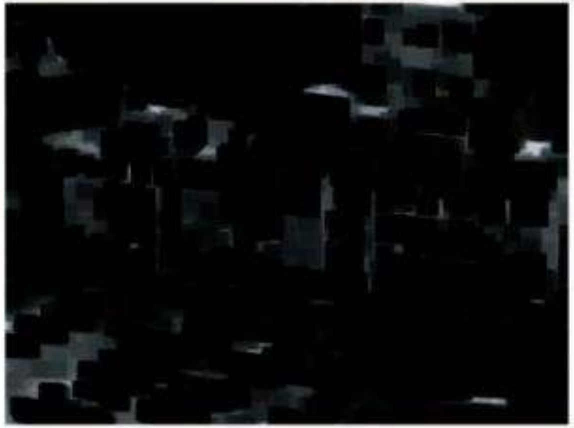


Dark Channel

Patch Size

Haze Free Image

3 x 3 patch



15 x 15 patch

- 用小窗口恢复的图像有过饱和现象，而大窗口恢复的图像有光晕现象。

Recall

In most of the non-sky patches, at least one color channel has very low intensity at some pixels.

Estimate Transmission for Sky Patches

The color of the sky is usually very similar to the atmospheric light A in a haze image.

Estimate Transmission for Sky Patches

$$\min_{c}\left(\min_{y\in\Omega(x)}\left(\frac{I^{c}(y)}{A^{c}}\right)\right)\to 1$$

$$\tilde{t}(x)\to 0$$

Limitations

- Inherently white or grayish objects

Input Image

Transmission
(大理石的传输率被低估)

Result

Limitations

- Haze imaging model is invalid

Input Image

Result
(non-constant A)

Limitations

- Soft matting is slow

Input I

+

tri-map

α

Input I

Estimated $\tilde{t}$

Refined t

Conclusions

- Dark channel prior
    - A natural phenomenon
    - Very simple but effective
    - Put a bad image to good use

- Improvements
    - Replace Soft Matting with Guided Image Filtering [He et al., ECCV '10] (Next Week)

Thank You