Single Image Haze Removal Using Dark Channel Prior

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Hazy Images

- Low visibility
- Faint colors
Goals of Haze Removal

• Scene restoration
• Depth estimation
Haze Imaging Model

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

- **Hazy image**
- **Scene radiance**
- **Transmission**

Atmospheric light
Haze Imaging Model

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

\[ d = -\beta \ln t \]
Ambiguity in Haze Removal

scene radiance

input

depth
Previous Works

• Using additional information
  – Polarization filter [Shwartz et al., CVPR’06]
  – Multiple images [Narasimhan & Nayar, CVPR’00]
  – Known 3D model [Kopf et al., Siggraph Asia’08]
  – User-assistance [Narasimhan & Nayar, CPMCV’03]
Previous Works

• Single image

  – Maximize local contrast [Tan, CVPR 08]
Previous Works

• Single image
  – Maximize local contrast  [Tan, CVPR 08]
Previous Works

• Single image
  – Maximize local contrast [Tan, CVPR 08]
  – Independent Component Analysis [Fattal, Siggraph 08]
Previous Works

• Single image
  – Maximize local contrast [Tan, CVPR 08]
  – Independent Component Analysis [Fattal, Siggraph 08]
Priors in Computer Vision

- Smoothness prior
- Sparseness prior
- Exemplar-based prior

Ill-posed problem → prior → well-posed problem

Dark Channel Prior
Dark Channel

- \( \text{min (rgb, local patch)} \)
Dark Channel

- $\min (\text{rgb, local patch})$
  - $\min (r, g, b)$
Dark Channel

- min (rgb, local patch)
  - min (r, g, b)
  - min (local patch) = min filter

15 x15

darkest
dark channel
Dark Channel

- \( \min (\text{rgb, local patch}) \)
  - \( \min (r, g, b) \)
  - \( \min (\text{local patch}) = \min \text{ filter} \)

\[
J_{\text{dark}}(x) = \min (\min J^c(y)) \\
\text{subject to } y \in \Omega(x), c \in \{r, g, b\}
\]

- \( J^c \): color channel of \( J \)
- \( J_{\text{dark}} \): dark channel of \( J \)
**Dark Channel**

- $\min (\text{rgb, local patch})$
  - $\min (r, g, b)$
  - $\min (\text{local patch}) = \min \text{ filter}$

$$J_{\text{dark}} = \min_{\Omega} \left( \min_{c} J^c \right)$$

- $J^c$: color channel of $J$
- $J_{\text{dark}}$: dark channel of $J$
A Surprising Observation

Haze-free
A Surprising Observation

Haze-free
A Surprising Observation

Haze-free
A Surprising Observation

Haze-free
A Surprising Observation

Haze-free
A Surprising Observation

Haze-free
A Surprising Observation

86% pixels in [0, 16]

5,000 haze-free images
Dark Channel Prior

• For outdoor haze-free images

\[ \min_{\Omega} \left( \min_{c} J^c \right) \to 0 \]
What makes it dark?

- Shadow
- Colorful object
- Black object
Dark Channel of Hazy Image

- The dark channel is no longer dark.
Transmission Estimation

Haze imaging model

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

Normalize

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

Compute dark channel

\[ \min_{\Omega} \left( \min_c \frac{I^c}{A^c} \right) = \left\{ \min_{\Omega} \left( \min_c \frac{J^c}{A^c} \right) \right\} t + 1 - t \]
Transmission Estimation

Dark Channel Prior

\[ \min_{\Omega} \left( \min_{c} J^c \right) \rightarrow 0 \]

Compute dark channel

\[ \min_{\Omega} \left( \min_{c} \frac{I^c}{A^c} \right) = \left( \min_{\Omega} \left( \min_{c} \frac{J^c}{A^c} \right) \right)^{t + 1 - t} \rightarrow 0 \]
Transmission Estimation

Estimate transmission

\[ t = 1 - \min_{\Omega} \left( \min_{c} \frac{I_c}{A_c} \right) \]

Compute dark channel

\[ \min_{\Omega} \left( \min_{c} \frac{I_c}{A_c} \right) = \left\{ \min_{\Omega} \left( \min_{c} \frac{J_c}{A_c} \right) \right\} t + 1 - t \]
Transmission Estimation

Estimate transmission

\[ t = 1 - \min_\Omega \left( \min_c \frac{I_c}{A_c} \right) \]
Transmission Optimization

Haze imaging model

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

Matting model

\[ I = F \cdot \alpha + B \cdot (1 - \alpha) \]

Refined transmission
Transmission Optimization

\[ E(t) = \lambda \|t - \tilde{t}\|^2 + t^T L_t t \]

- **L** - matting Laplacian [Levin et al., CVPR '06]
- **Constraint** - soft, dense (matting - hard, sparse)
Transmission Optimization

before optimization
Transmission Optimization

after optimization
Atmospheric Light Estimation

\[ A: \text{most hazy} \]

- brightest pixel
- hazy image
- dark channel

brightest pixels
Scene Radiance Restoration

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

- **Hazy image**
- **Scene radiance**
- **Transmission**
Results

input
Results

recovered image
Results

depth
Results

input
Results

recovered image
Results

depth
Results

input
Results

recovered image
Results
Comparisons

input

[Fattal Siggraph 08]
Comparisons

input

our result
Comparisons

input

[Tan, CVPR 08]
Comparisons

input

our result
Comparisons

input  [Kopf et al, Siggraph Asia 08]  our result
Results: De-focus

recovered scene radiance

input

depth
Results: De-focus
Results: Video

output

input
Results: Video

output

input
Limitations

- Inherently white or grayish objects
Limitations

- Haze imaging model is invalid
  - e.g. non-constant $A$
Summary

• Dark channel prior
  – A natural phenomenon
  – Very simple but effective
  – Put a bad image to good use
Thank you