Removal of Image Artifacts Due to Sensor Dust

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Dust Artifacts

Physical Removal of Dust

From www.luminous-landscape.com

Editing Tools

Clone tool, healing brush

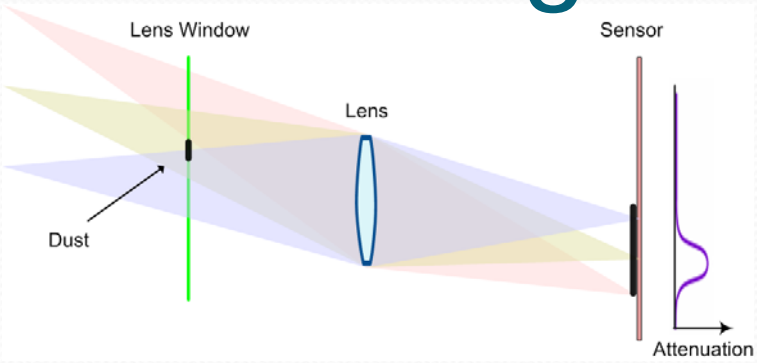
From www.ophrysphotography.co.uk

Editing Tools

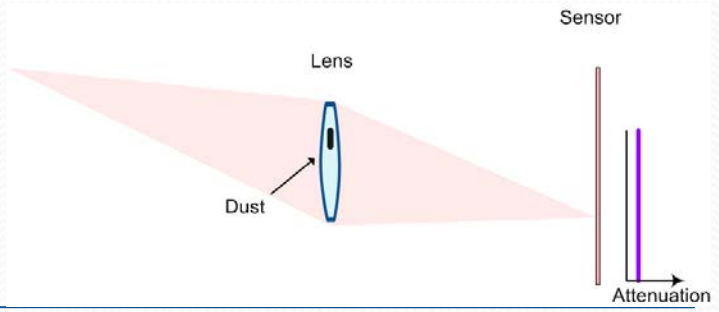
Irregular backgrounds??

Related Work: Dust Modeling

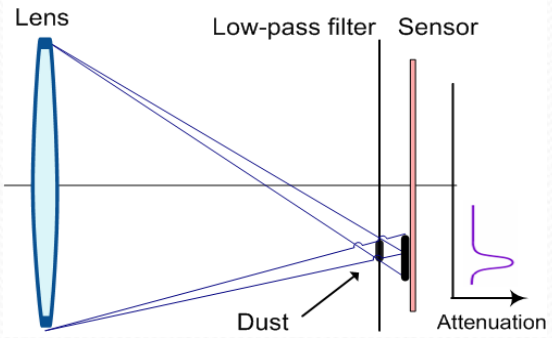
On lens window:
[Willson et al., 2005]



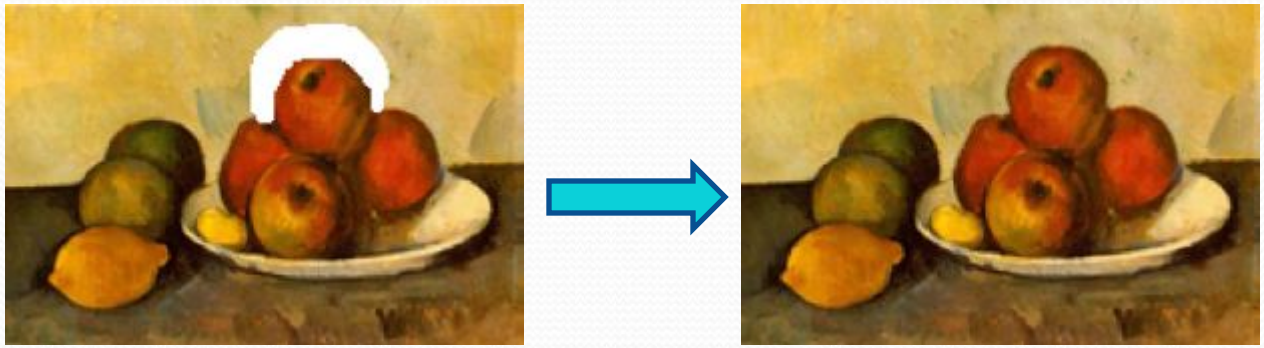
On lens:



On sensor:



Related Work: Image Completion

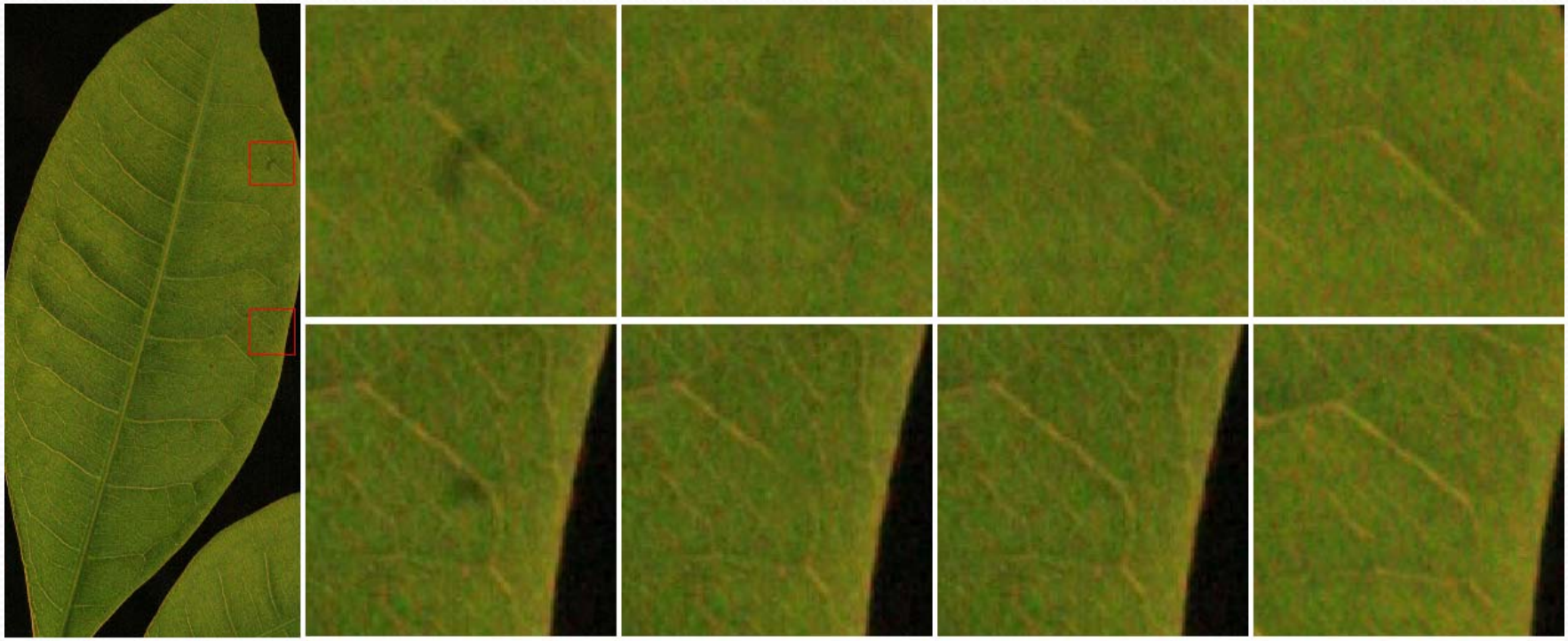


Assumes no significant information within region

Our Approach

- Image information within dust region
- Physical model of dust formation
- Constraints on dust properties
- Contextual data

Some Results



(a) Image Thumbnail (b) Dust Regions (c) Texture Synthesis (d) Our Results (e) Ground Truth

Talk Outline

- Formation of Dust Artifacts
- Single-Image Input
  - Ordered list of candidate dust regions
- Multiple-Image Input
  - Improved dust detection

Formation of Dust Artifacts

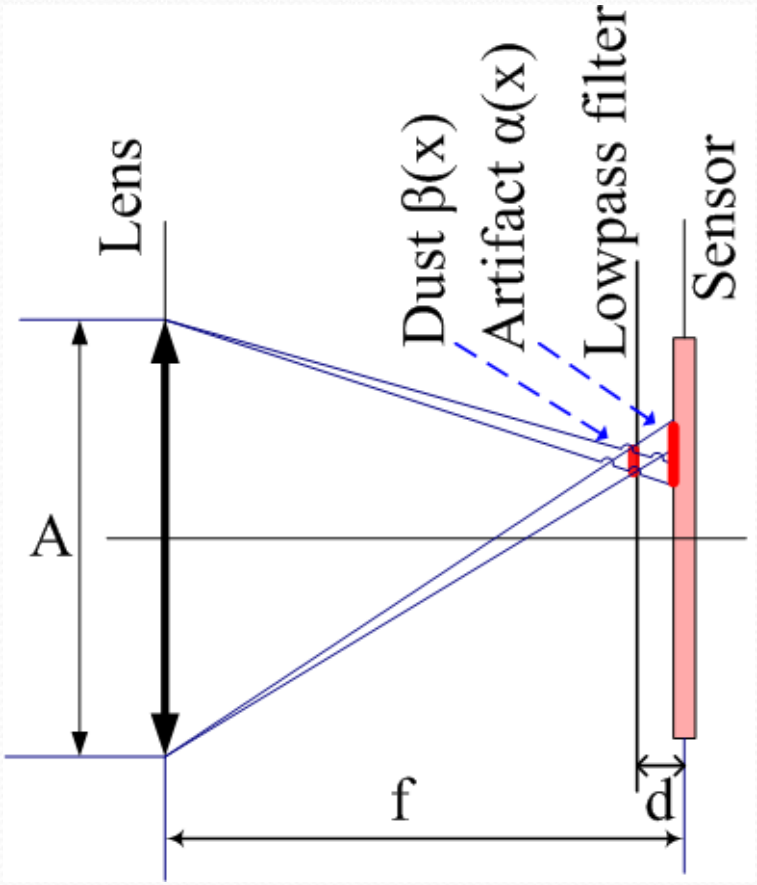
- Light attenuator:

$$I(x) = U(x) \cdot \alpha(x)$$

- Lowpass filter:

$$\alpha = \beta * \sqcap_{\tau}$$

$$\tau = d \cdot A / f$$



Space of dust artifacts

$$\mathscr{D}_\tau = \{\alpha : \beta * \sqcap_\tau = \alpha, 0 \leq \beta \leq 1\}$$

$$\tau = d \cdot A / f$$

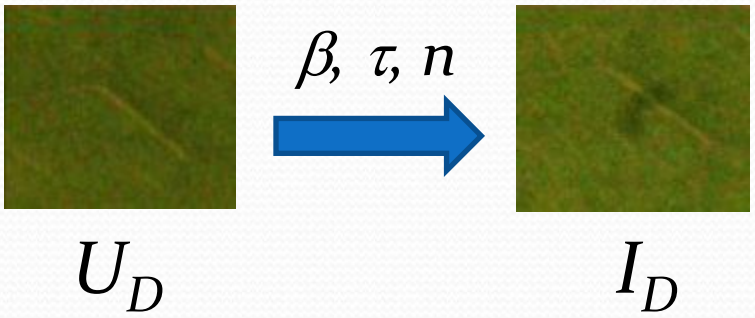
- For τ=*0*, all artifact fns are valid
- Larger τ, smaller artifact space $\mathscr{D}_\tau$

Dust Removal in a Single Image

- Artifact formation model:

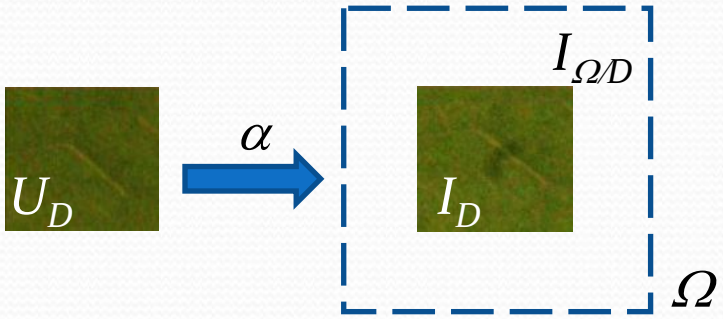
$$I_D = U_D \cdot \underbrace{(\beta * \sqcap_\tau)}_{\alpha} + n$$

additive noise



U_D I_D

Formulation



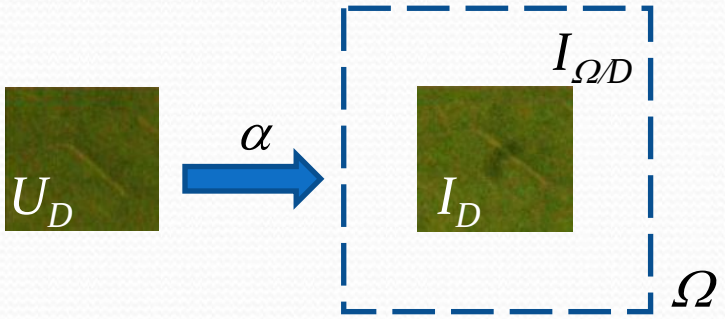
- MAP estimation problem:

$$\begin{aligned}\hat{U}_D &= \arg\max P(U_D, \alpha | I) \\ &= \arg\max P(I_D | U_D, \alpha) \cdot P(U_D | I_{\Omega/D}) \cdot P(\alpha)\end{aligned}$$

- Energy function:

$$E(U_D, \alpha | I) = \lambda_1 E_1(I_D | U_D, \alpha) + \lambda_2 E_2(U_D | I_{\Omega/D}) + \lambda_3 E_3(\alpha)$$

Energy Function



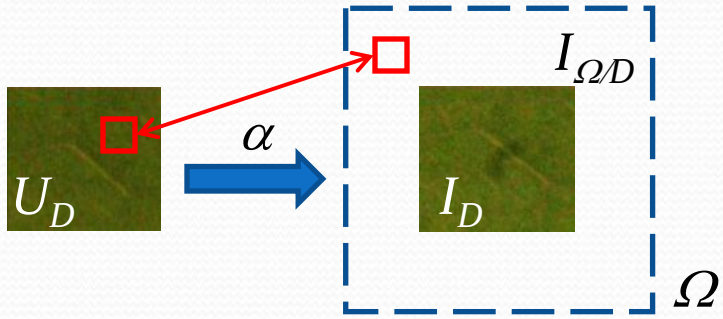
$$E(U_D, \alpha | I) = \lambda_1 E_1(I_D | U_D, \alpha) + \lambda_2 E_2(U_D | I_{\Omega/D}) + \lambda_3 E_3(\alpha)$$

Based on artifact formation model:

$$E_1(I_D | U_D, \alpha) = \frac{1}{2} ||I_D - U_D \cdot \alpha||^2$$

Utilizes image information within dust region to constrain solution

Energy Function



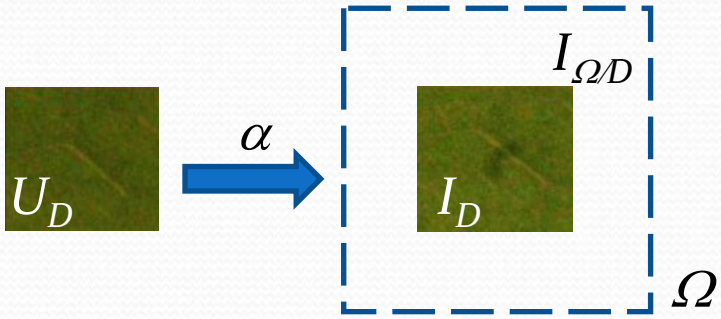
$$E(U_D, \alpha | I) = \lambda_1 E_1(I_D | U_D, \alpha) + \lambda_2 E_2(U_D | I_{\Omega/D}) + \lambda_3 E_3(\alpha)$$

Contextual constraints from surrounding image :

$$E_2(U_D | I_{\Omega/D}) = \sum_{D_i \in D} dist(U_{D_i}, I_{\Omega/D})^2$$

Favors sub-blocks in dust removal solution similar to context

Energy Function



$$E(U_D, \alpha | I) = \lambda_1 E_1(I_D | U_D, \alpha) + \lambda_2 E_2(U_D | I_{\Omega/D}) + \lambda_3 E_3(\alpha)$$

From space of valid dust artifacts:

$$E_3(\alpha) = \frac{1}{2} ||\alpha - \mathcal{P}_{\mathscr{D}_\tau}(\alpha)||^2$$

Penalizes solutions that lie outside of artifact space

Optimization

$$E(U_D, \alpha | I) = \lambda_1 E_1(I_D | U_D, \alpha) + \lambda_2 E_2(U_D | I_{\Omega/D}) + \lambda_3 E_3(\alpha)$$

Alternating minimization:

$$u_D^{(0)} \rightarrow \alpha^{(0)} \rightarrow u_D^{(1)} \rightarrow \alpha^{(1)} \rightarrow \ldots \rightarrow u_D^{(n)} \rightarrow \alpha^{(n)} \rightarrow \ldots$$

$$\begin{aligned} \alpha^{(n)} &= \arg\min E(\alpha | I, U_D^{(n)}) \\ U_D^{(n+1)} &= \arg\min E(U | I, \alpha^{(n)}) \end{aligned}$$

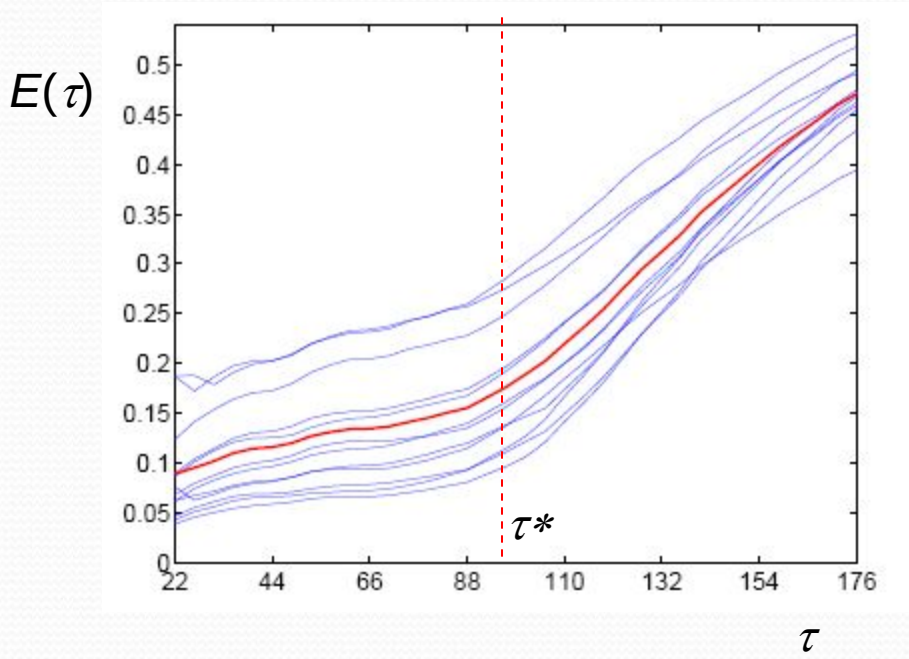
Color Consistency

- Dust assumed to have a uniform color
- Artifact function α proportional in R, G, B channels
- Additional energy term:

$$E_4(\alpha_r, \alpha_g, \alpha_b) = \frac{1}{2} \sum_{c=r,g,b} ||\alpha_c - \alpha^* \cdot \Sigma_x \alpha_c||^2$$

$$\alpha^* = \arg\min_{\Sigma\alpha(x)=1} \sum_{i=r,g,b} KL(\alpha||(\alpha_i/\Sigma_x \alpha_i))$$

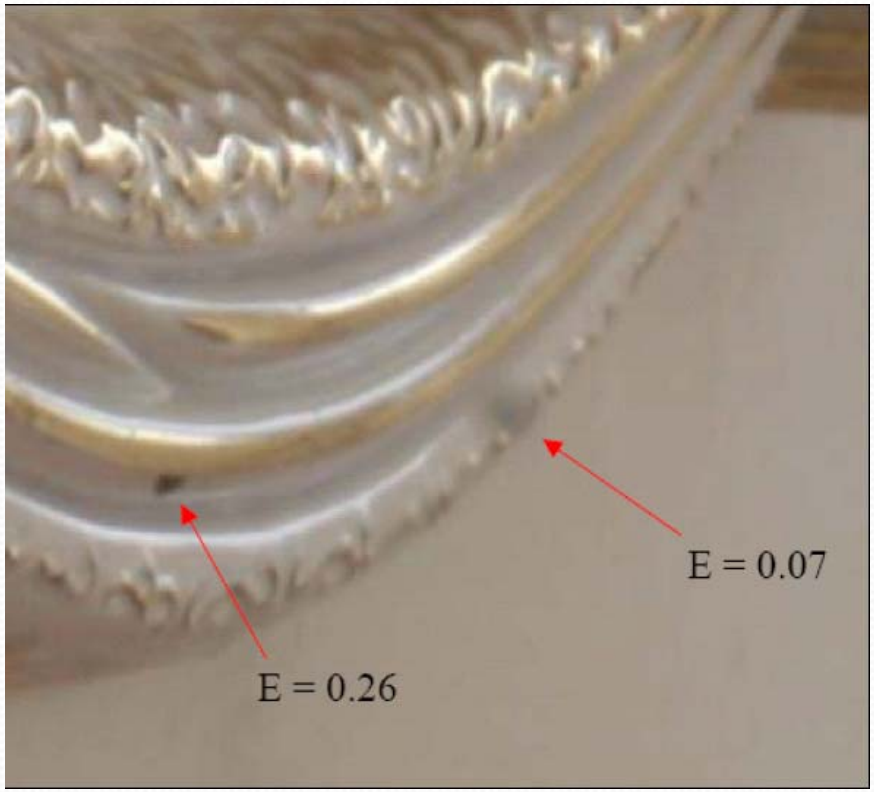
Estimation of τ

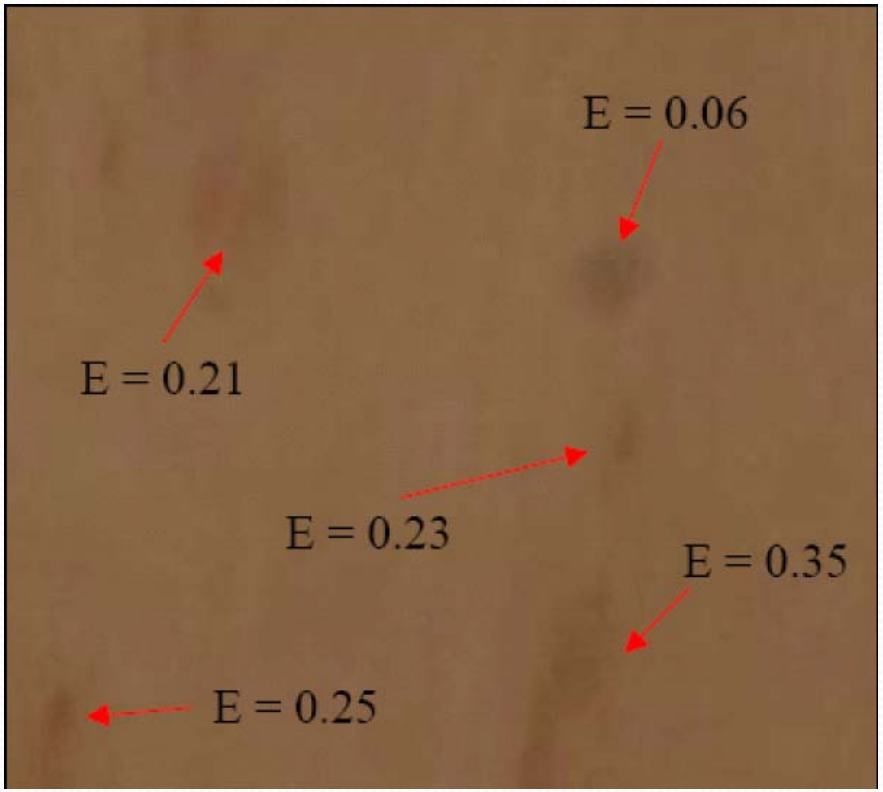


Larger τ, smaller artifact space $\mathscr{D}_\tau$:

- $\tau > \tau^*$, may not admit true artifacts
- $\tau \leqslant \tau^*$, admits true artifacts

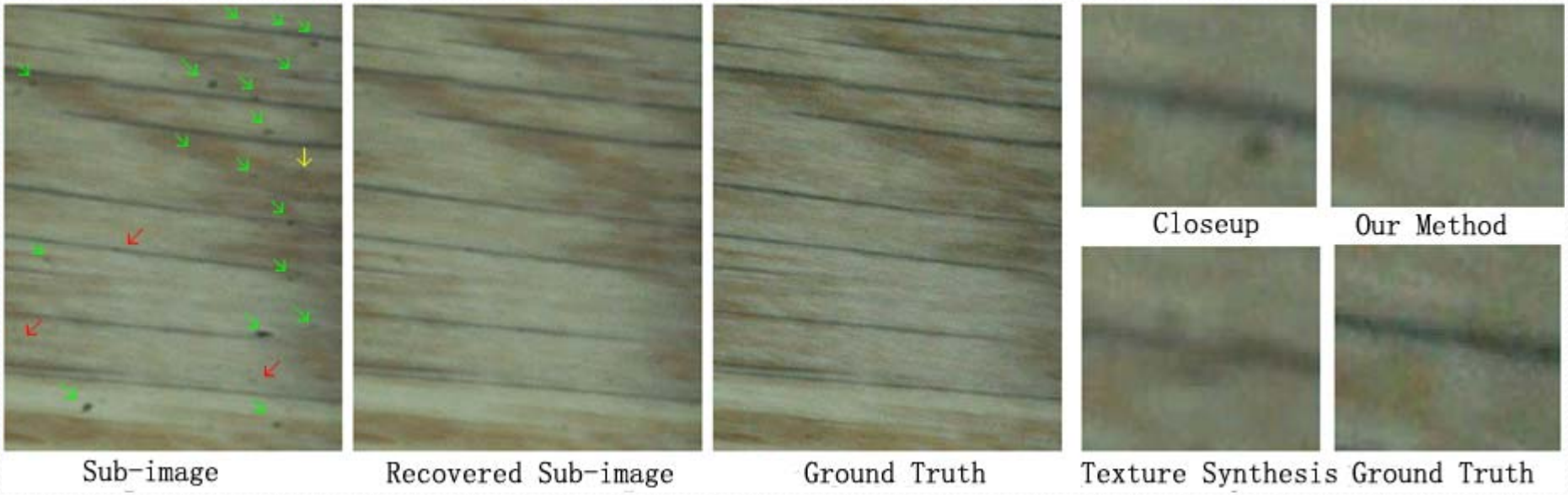
Detection of Candidate Dust Regions



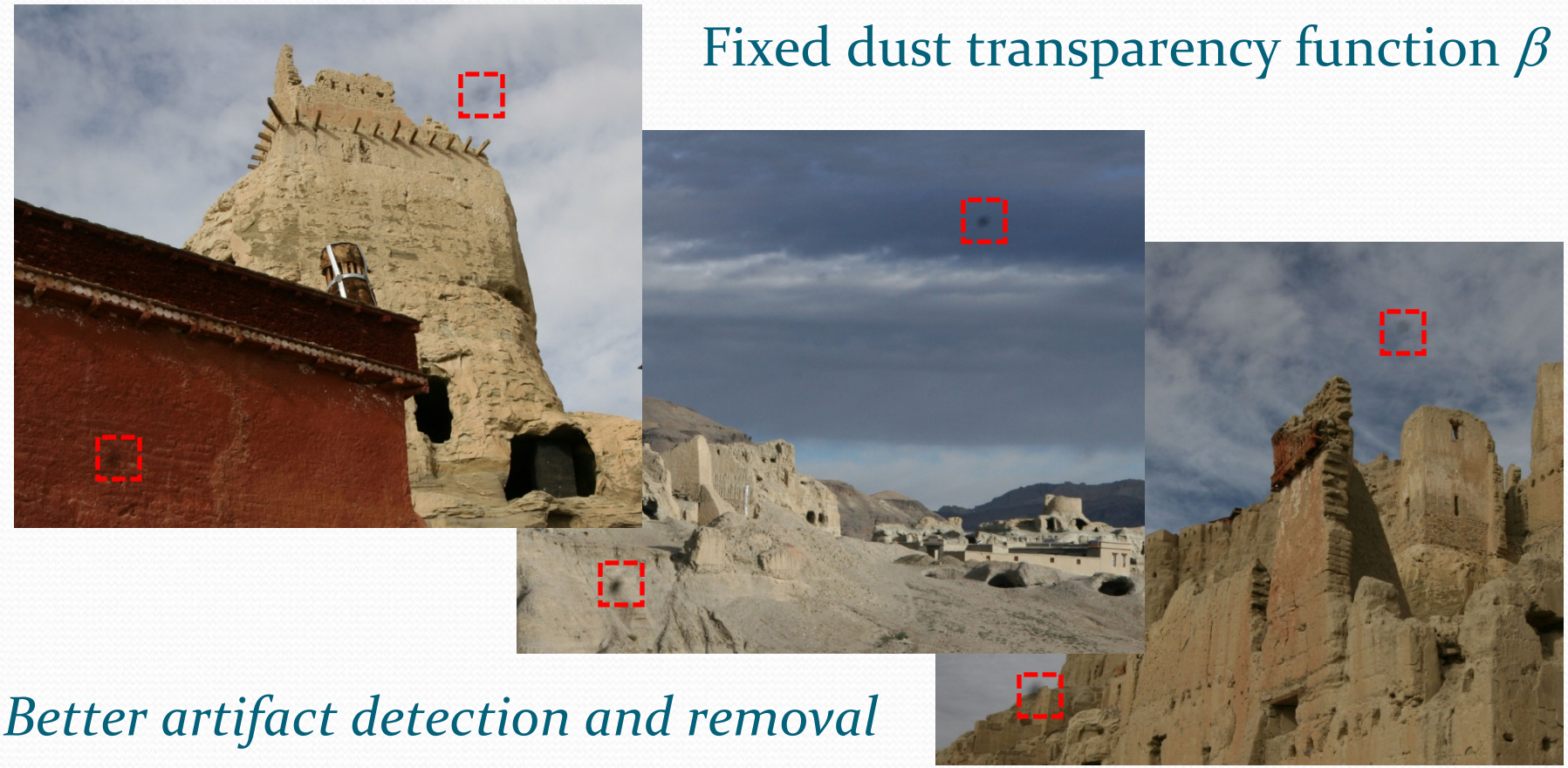


Lower energy, more consistent with artifact model

Results


Sub-image
Recovered Sub-image
Ground Truth
Closeup
Our Method
Texture Synthesis
Ground Truth

Multiple-Image Input



Fixed dust transparency function β

Better artifact detection and removal

Multiple-Image Energy Function

- Add energy term for consistency of β among images:

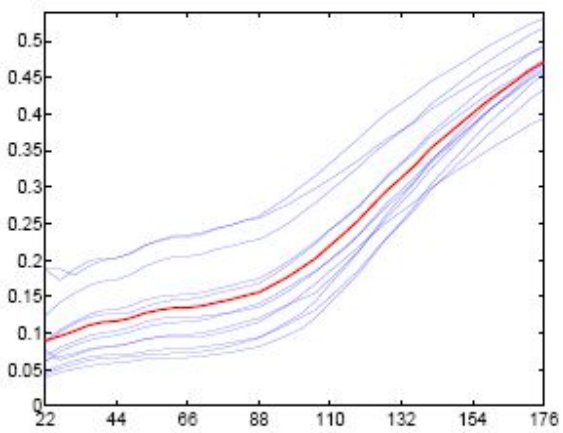
$$E_5 = E(\alpha_1, \alpha_2, \ldots, \alpha_n, d) = \frac{1}{2}\Sigma_i ||\beta * \sqcap_{\tau_i} - \alpha_i||^2$$

$$\beta = \arg\min_{\beta} \sum_i ||\beta * \sqcap_{\tau_i} - \alpha_i||^2$$

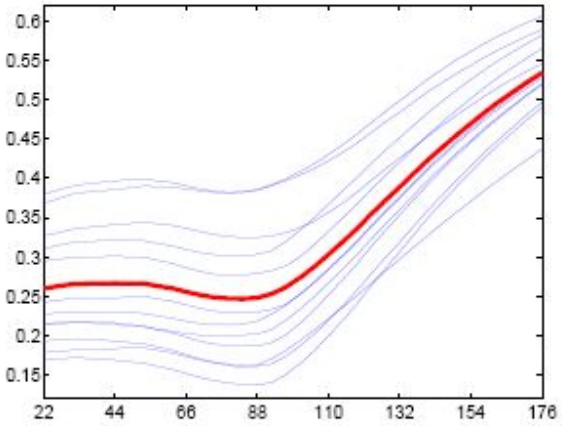
- New energy function:

$$E^{multi} = \sum_{i=1}^{m} E_d^i + \lambda_5 \cdot E_5$$

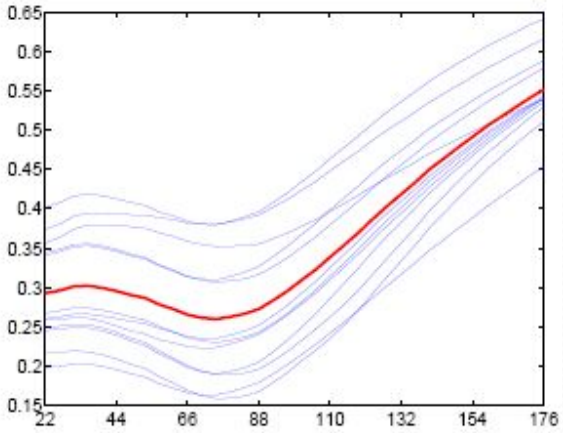
Estimation of τ



One Image

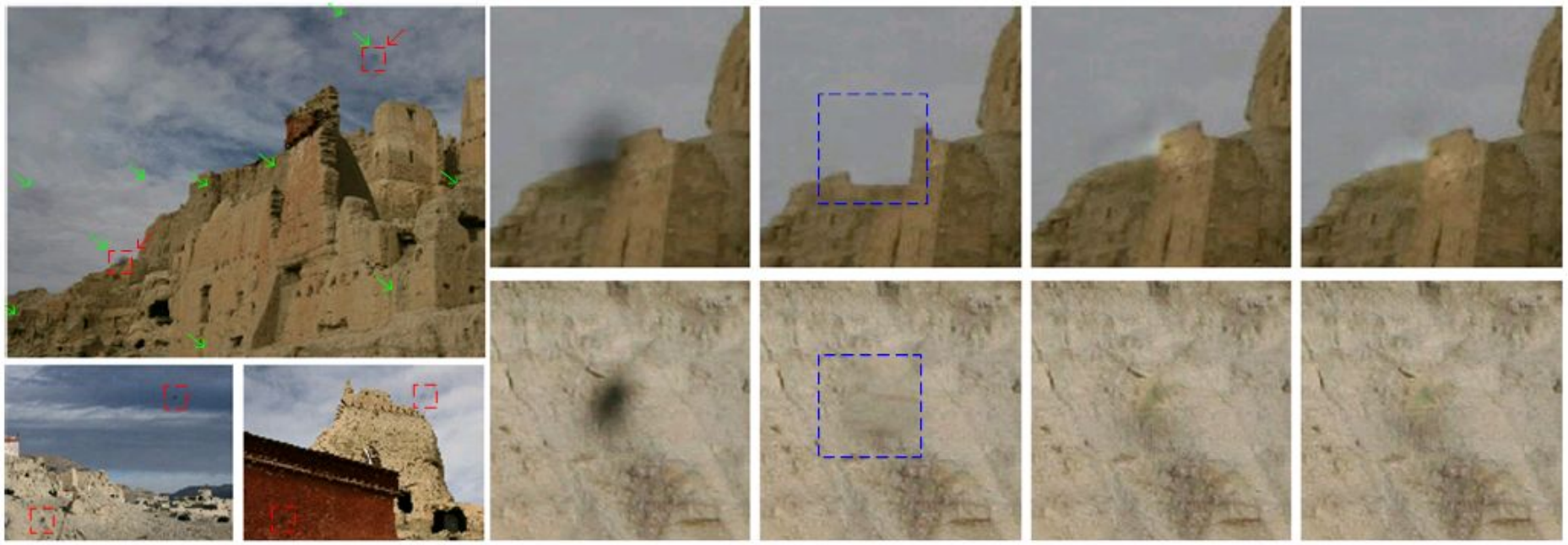


Two Images



Four Images

Results



a. Image Thumbnails | b. Dust Regions | c. Texture Synthesis | d. Single Image Recovery | e. Multiple Image Recovery

Conclusion

- Physical modeling of dust artifact formation + Contextual consistency + Info within dust region

- Future work: Other degradations that partially obscure images

Thank you

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