Simultaneous HDR image reconstruction and denoising for dynamic scenes

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High Dynamic Range Imaging (HDR)

Capture a scene containing a large range of intensity levels...

Limited contrast range in the picture → loss of details in bright and/or dark areas.

High Dynamic Range Imaging (HDR)

... using a regular digital camera.

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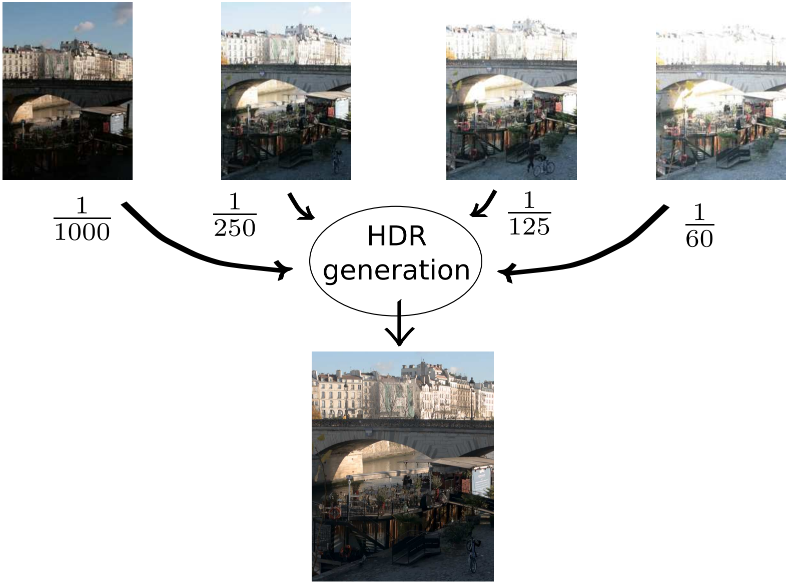
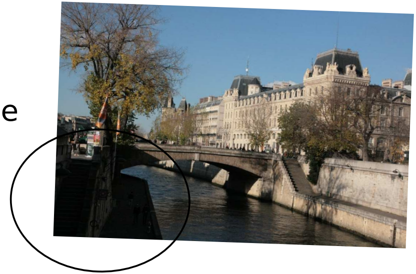
HDR Imaging



HDR Imaging Examples

Challenges of HDR imaging in dynamic scenes

noise



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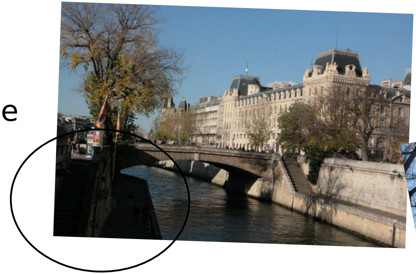

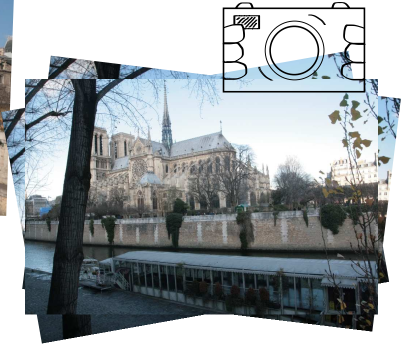

camera
motion

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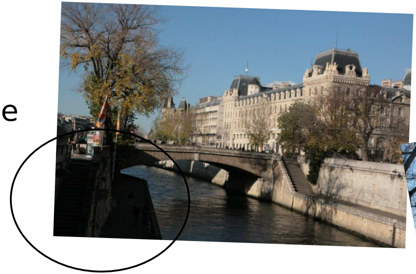
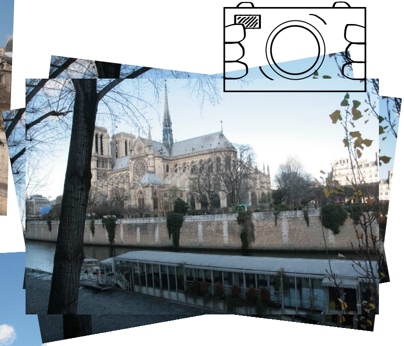
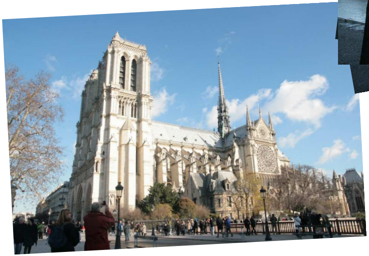




camera
motion

moving
objects



Existing methods

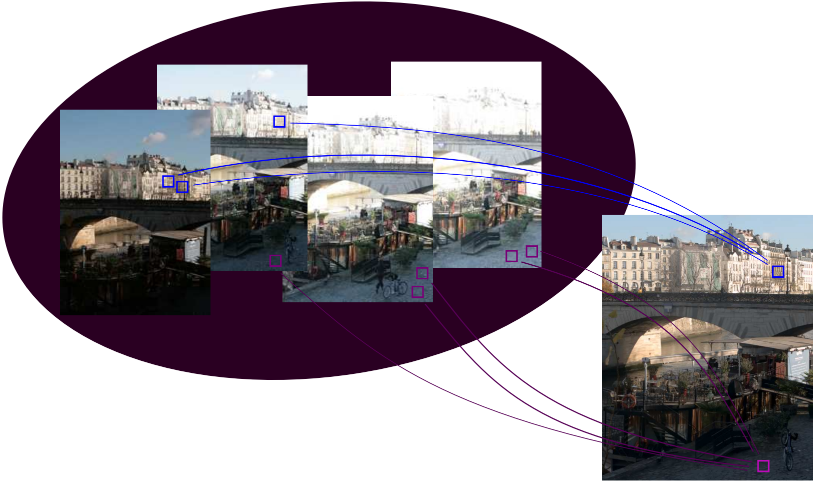
Treat each problem **separately**.

Camera motion: Global alignment adapted to different exposures [Ward2003]

Dynamic scenes: De-ghosting techniques [Grosch2006,Jacobs2008,Sidibe2009,Gallo2009,Heo2010]

Noise: Denoising techniques [Buades2005,Dabov2007]

Our approach: simultaneous HDR imaging and denoising



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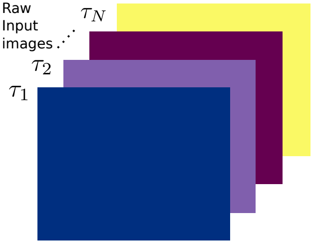

Why use a patch based approach?

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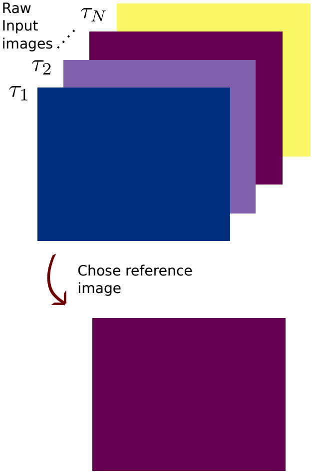

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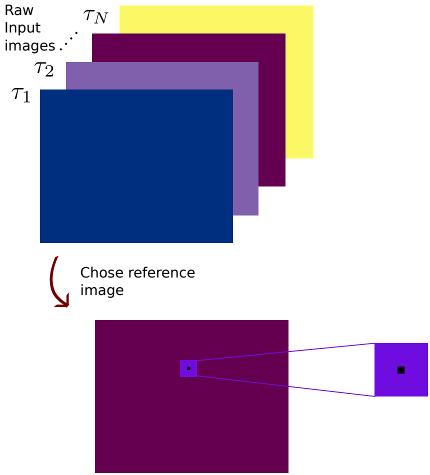

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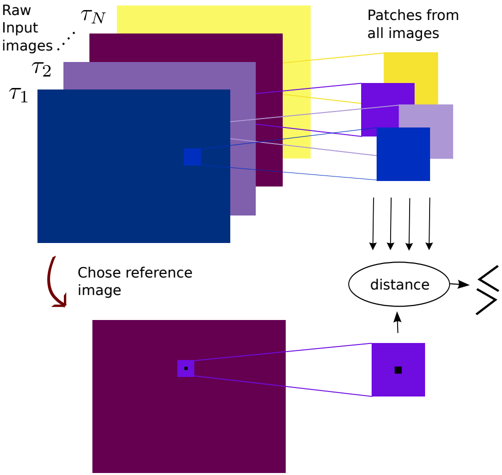

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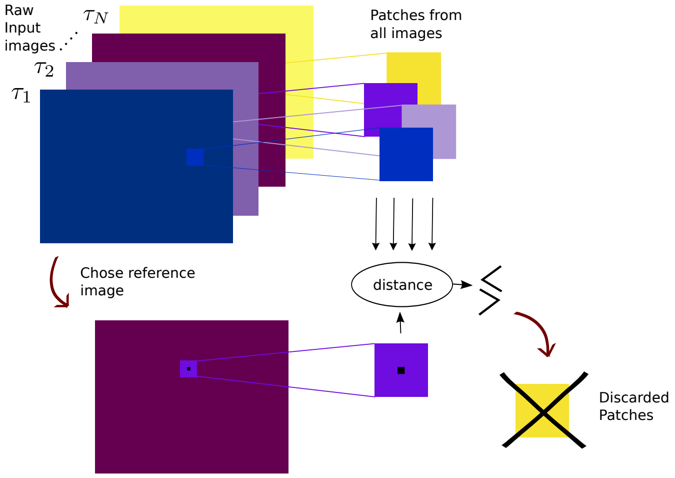

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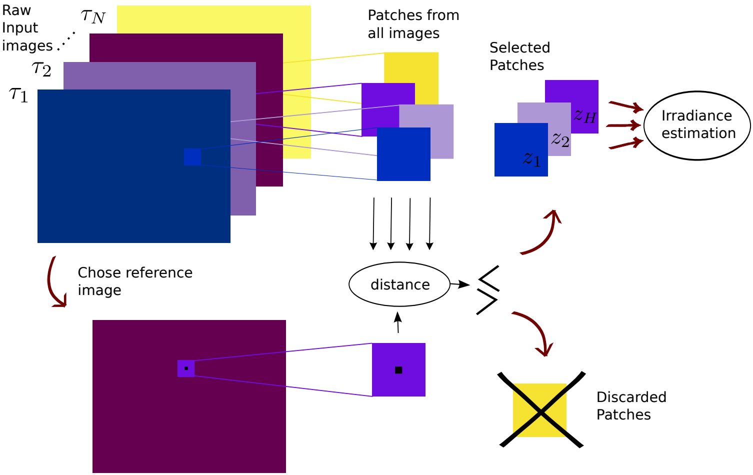

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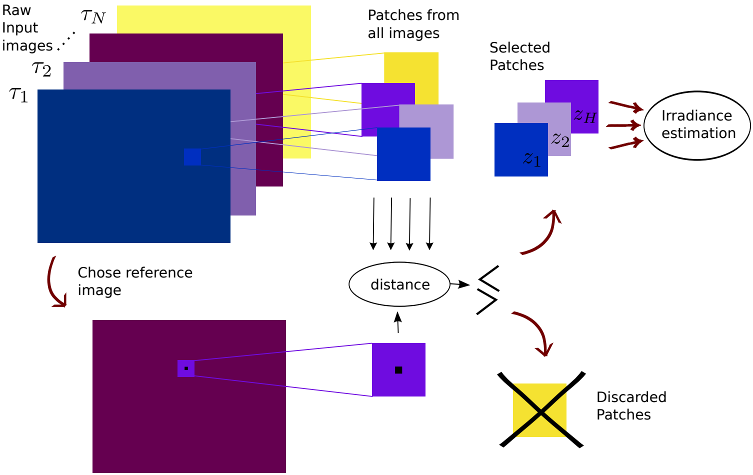

Why use a patch based approach?

Advantages of the non-local patch based approach

Denoising power most state-of-the-art methods use patches (NL-means, BM3D).

Motion / Alignment No need for explicit motion detection or image registration.

Patch comparison based on camera noise model

Distance between patches centered at pixels p and q

$$d(p,q) = \frac{1}{N}\sum_{j=1}^{N}\frac{(\mathbf{x}_{pj}-\mathbf{x}_{qj})^2 - 2\sigma_{pj}^2}{2\sigma_{pj}^2}$$

where

- $\mathbf{x}_{pj}$ pixel value in the irradiance domain (j-th pixel of patch p)
- σ_{pj}^2 variance of $\mathbf{x}_{pj}$
  - Denoising level at pixel $\mathbf{x}_{pj}$ is controlled by its variance σ_{pj}^2
- N number of pixels in the patch

How to set the denoising parameter σ_{pj}^2?

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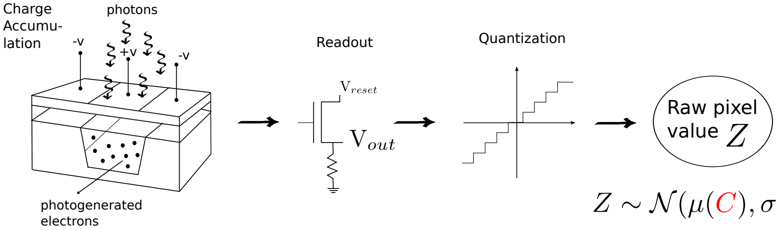

$$Z \sim \mathcal{N}(\mu(C), \sigma^2(C))$$

C irradiance
τ exposure time
g camera gain
a photo-response non-uniformity factor
μ_r, σ_R^2 readout noise mean and variance

$$\mu(C) = ga\tau C + \mu_R$$
$$\sigma^2(C) = g^2 a\tau C + \sigma_R^2$$

Known variance model $\quad \sigma_{pj}^2(C) = g^2 a\tau C + \sigma_R^2 \quad \approx \quad g(z_{pj} - \mu_R) + \sigma_R^2$

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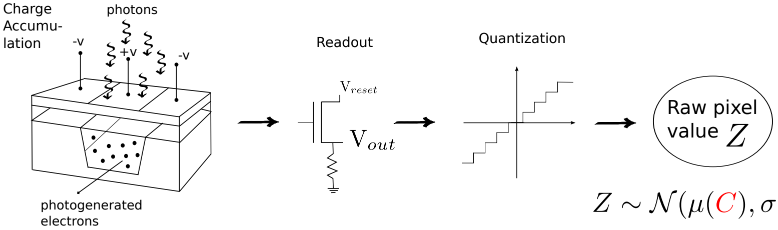

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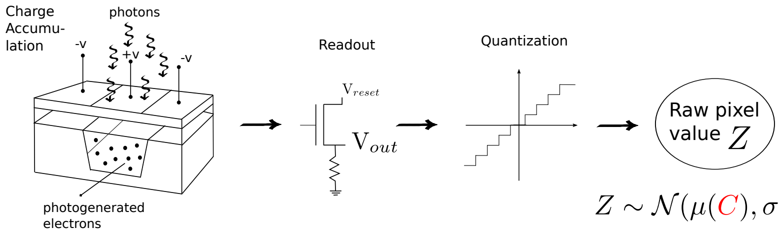

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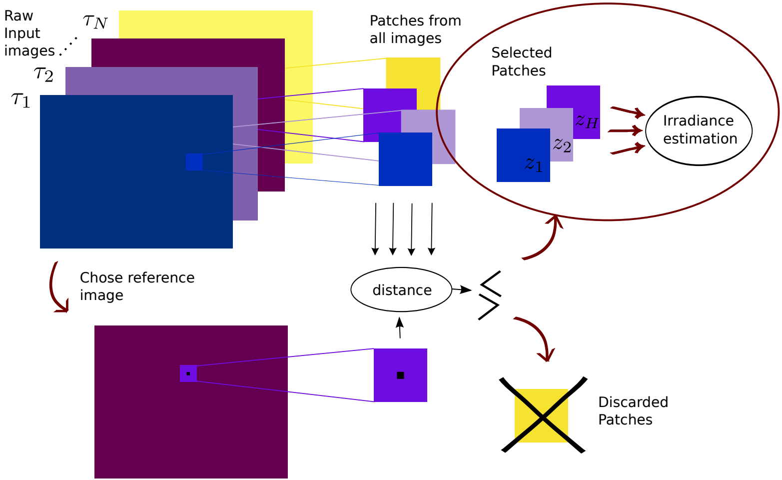
Irradiance estimation



Irradiance estimation

- Which is the best way to **combine samples** with the **same** underlying **irradiance**?
- **Maximum likelihood estimator** by Granados et al. is the **state-of-the-art** for pixelwise estimation for static scene / static camera [Granados2010].
- We performed theoretical and experimental study and show the **MLE** is nearly optimal [Aguerrebere2012]
  - for perfectly corregistered images
  - under model $Z \sim \mathcal{N}(\mu(C), \sigma^2(C))$
  - **Optimal = Minimum variance**
- Not obvious for non asymptotical cases ($\sim$ 4 samples per pixel)

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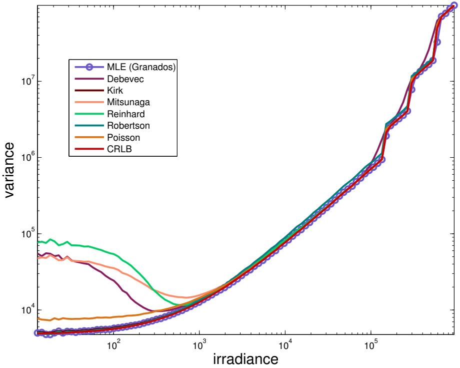
MLE nearly optimal

Cramér Rao lower bound for irradiance estimation [Aguerrebere2012]



At most 4 samples per pixel!

C. Aguerrebere, J. Delon, Y. Gousseau, and P. Musé. Best algorithms for HDR image generation. A study of performance bounds. Submitted to SIAM Journal on Imaging Sciences (SIIMS).

Irradiance estimation

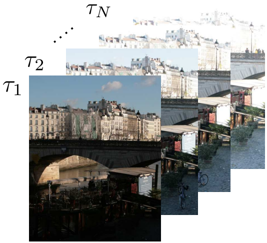
Once stated which samples follow $Z \sim \mathcal{N}(\mu(C), \sigma^2(C))$ for the given irradiance, estimate C as

$$C_{\mathsf{MLE}} = \frac{\sum_{h=1}^{H} w_{\mathsf{MLE}}^{h} \left(\frac{(z_h - \mu_R)}{a g \tau_h} \right)}{\sum_{h=1}^{H} w_{\mathsf{MLE}}^{h}}$$

$$w_{\mathsf{MLE}}^{h} = \frac{1}{\mathsf{var}\left(\frac{(z_h - \mu_R)}{a g \tau_h} \right)} = \frac{(g a \tau_h)^2}{g(z_h - \mu_R) + \sigma_R^2}$$

with z_h, $h = 1, \ldots, H$ pixels found to be similar according to $d(p, q)$.

Reference image selection



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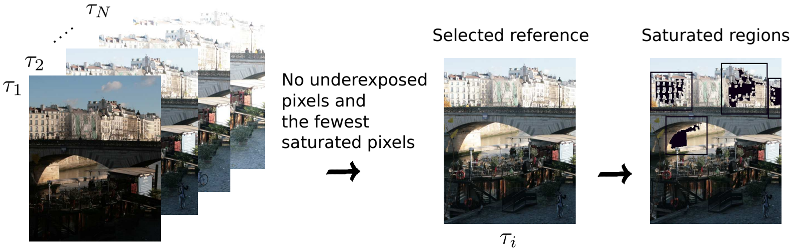

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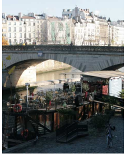
Reference image selection and filling

selected reference



τ_i

Other filling techniques are possible, e.g. work by Sen et al. [Sen2012]

P. Sen, N. K. Kalantari, M. Yaesoubi, S. Darabi, D. B. Goldman, and E. Shechtman. Robust patch-based HDR reconstruction of dynamic scenes. ACM Trans. Graph. Nov. 2012

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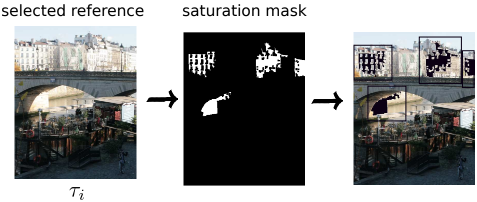

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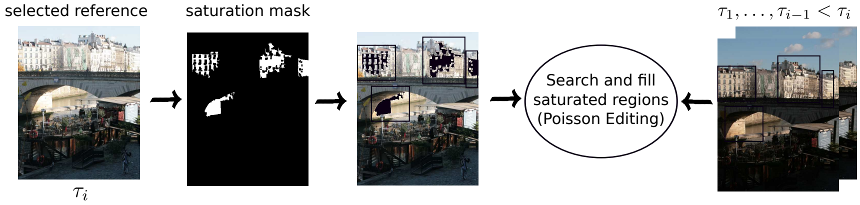

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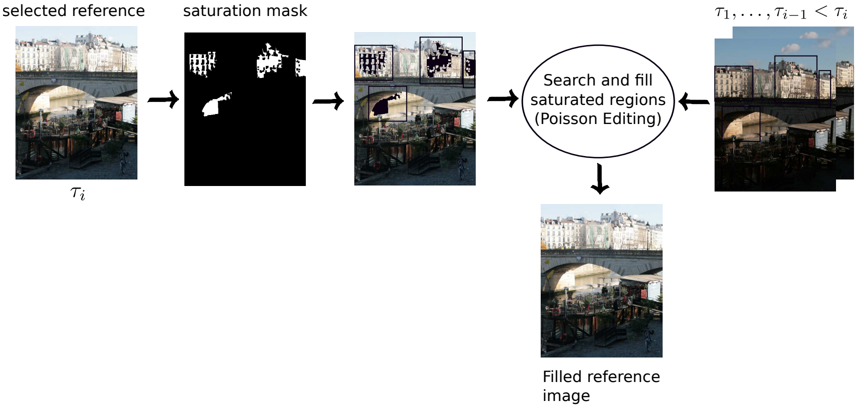

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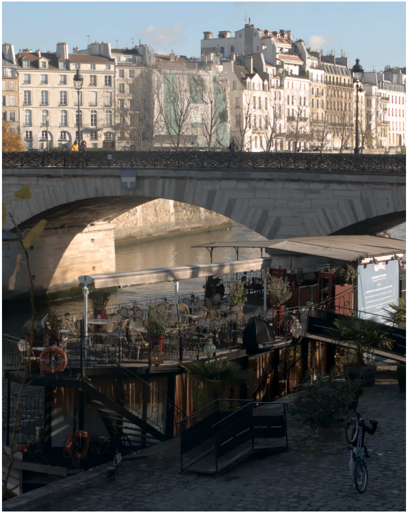
Results: Example 1

Input images

Results: Example 1

Reference image

Our approach



Results: Example 1

No ghosting artifacts

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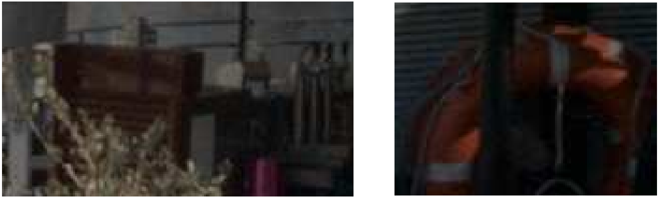
Sen et al.



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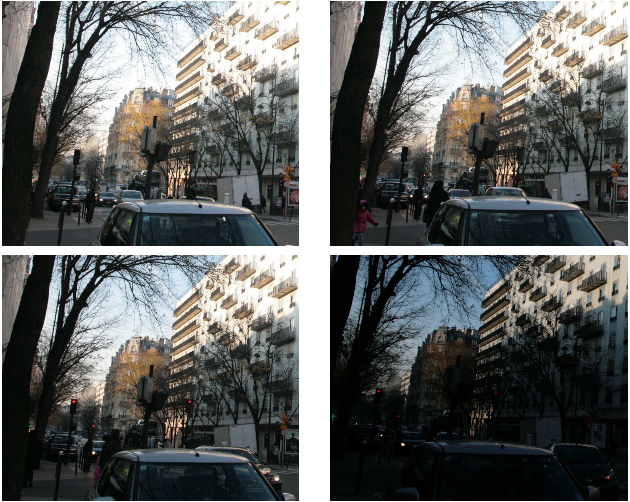
Results: Example 2

Input images



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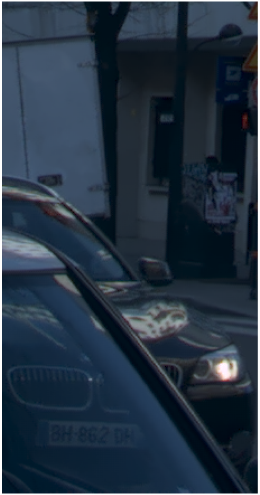

Results: Example 2

Reference image

Sen et al.

Our approach

Results: Example 3

Input images

Results: Example 3

Reference image

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Results: Example 3

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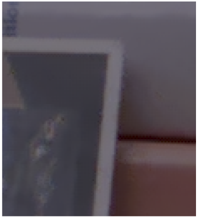

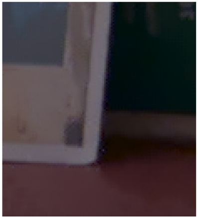

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Sen et al.

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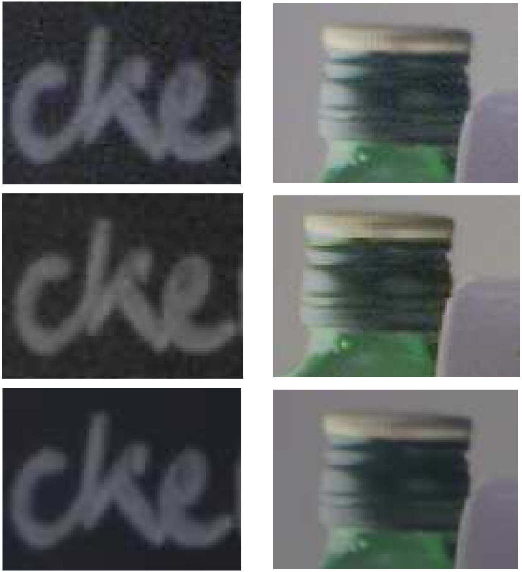

Why not denoising before or after HDR imaging?

Denoising before: denoise each LDR image before combination

Disadvantages:

- Need of accurate global registration.
- Need of motion detection.
- Removed details may be kept on multi-image denoising.

Denoising after: denoise the result of an HDR imaging method

Disadvantages:

- Depending on the method:
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- Noise model no longer valid: unknown pixels variance and difficulty to set denoising parameter for classical denoising approaches.

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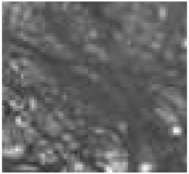
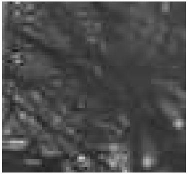
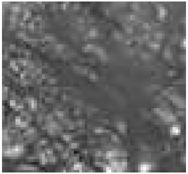
Denoised reference



Denoised Sen et al.



Our approach



Summary

- We presented a new method for HDR image generation which copes simultaneously with three important problems:
  - noise
  - camera motion (hand-held camera)
  - multiple objects motion (dynamic scenes)
- The noise reduction capacity and robustness to camera and object motion was experimentally verified in various real cases.
- The results show good denoising performance and no ghosting artifacts.

Thanks. Questions?

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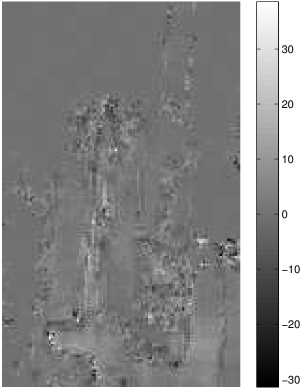
Denoised reference

Our approach

Difference %



Filled reference denoised using NL-means with adaptive denoising threshold.

Raw data processing