Bilateral filter

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A **bilateral filter** is a non-linear, edge-preserving, and noise-reducing smoothing filter for images. It replaces the intensity of each pixel with a weighted average of intensity values from nearby pixels. This weight can be based on a Gaussian distribution. Crucially, the weights depend not only on Euclidean distance of pixels, but also on the radiometric differences (e.g., range differences, such as color intensity, depth distance, etc.). This preserves sharp edges.

Left: original image. Right: image processed with bilateral filter

Contents

Definition

The bilateral filter is defined as[1][2]

$$I^{\text{filtered}}(x) = \frac{1}{W_p} \sum_{x_i \in \Omega} I(x_i) f_r(\|I(x_i) - I(x)\|) g_s(\|x_i - x\|),$$

where the normalization term

$$W_p = \sum_{x_i \in \Omega} f_r(\|I(x_i) - I(x)\|) g_s(\|x_i - x\|)$$

ensures that the filter preserves image energy and

I^{filtered} is the filtered image;
I is the original input image to be filtered;
x are the coordinates of the current pixel to be filtered;
Ω is the window centered in x;
f_r is the range kernel for smoothing differences in intensities (this function can be a Gaussian function);
g_s is the spatial kernel for smoothing differences in coordinates (this function can be a Gaussian function).

As mentioned above, the weight W_p is assigned using the spatial closeness and the intensity difference.[2] Consider a pixel located at (i, j) that needs to be denoised in image using its neighbouring pixels and one of its neighbouring pixels is located at (k, l). Then, the weight assigned for pixel (k, l) to denoise the pixel (i, j) is given by

$$w(i,j,k,l) = \exp\left(-\frac{(i-k)^2+(j-l)^2}{2\sigma_d^2} - \frac{\|I(i,j)-I(k,l)\|^2}{2\sigma_r^2}\right),$$

where σ_d and σ_r are smoothing parameters, and $I(i, j)$ and $I(k, l)$ are the intensity of pixels (i, j) and (k, l) respectively.

After calculating the weights, normalize them:

$$I_D(i,j) = \frac{\sum_{k,l} I(k,l)w(i,j,k,l)}{\sum_{k,l} w(i,j,k,l)},$$

where I_D is the denoised intensity of pixel (i, j).

Parameters

- As the range parameter σ_r increases, the bilateral filter gradually approaches Gaussian convolution more closely because the range Gaussian widens and flattens, which means that it becomes nearly constant over the intensity interval of the image.
- As the spatial parameter σ_d increases, the larger features get smoothened.

Limitations

The bilateral filter in its direct form can introduce several types of image artifacts:

- Staircase effect – intensity plateaus that lead to images appearing like cartoons[3]
- Gradient reversal – introduction of false edges in the image.[4]

There exist several extensions to the filter that deal with these artifacts. Alternative filters, like the *guided filter*,[5] have also been proposed as an efficient alternative without these limitations.

Implementations

Adobe Photoshop implements a bilateral filter in its *surface blur* tool. GIMP implements a bilateral filter in its *Filters-->Blur* tools; and it is called *Selective Gaussian Blur*. The free G'MIC plugin *Repair → Smooth [bilateral]* for GIMP adds more control.[6] A simple trick to efficiently implement a bilateral filter is to exploit Poisson-disk subsampling.[1]

Related models

The bilateral filter has been shown to be an application of the short time kernel of the Beltrami flow.[7][8]

Other edge-preserving smoothing filters include: anisotropic diffusion, weighted least squares,[9] edge-avoiding wavelets,[10] geodesic editing,[11] guided filtering,[12] and domain transforms.[13]

See also

- Gaussian filter
- Gaussian function
- Gaussian blur
- Convolution

External links

- Kaiming He: Guided image filtering (http://kaiminghe.com/publications/eccv10guidedfilter.pdf) (faster than bilateral filter and avoids staircasing and gradient reversal artifacts)
- Kunal N. Chaudhury Constant-time filtering (https://sites.google.com/site/kunalnchaudhury/Publications/journals/manuscript.pdf)
- Kunal N. Chaudhury, Daniel Sage, and Michael Unser, Fast Bilateral Filter (http://bigwww.epfl.ch/chaudhury/Fast%20bilateral%20filtering.pdf) Accelerated Shiftable Filter (http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6324435)
- Kunal N. Chaudhury, and Swapnil D. Dabhade Fast Provably Accurate Bilateral Filter (http://ieeexplore.ieee.org/document/7442856/authors)
- Kunal N. Chaudhury Fast Gauss-Polynomial Bilateral Filter (https://sites.google.com/site/kunalnchaudhury/Research/Publications/GBF.pdf)
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- Sylvain Paris, Pierre Kornprobst, Jack Tumblin, Frédo Durand, Bilateral Filtering: Theory and Applications (http://dx.doi.org/10.1561/0600000020), preprint (http://people.csail.mit.edu/sparis/#fntcgv)
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