# Quadratic Model for Reference Based Image Filtering

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**Abstract** We introduce a reference-based filtering method that transforms the local color distribution of each image patch. In the method, the color of a reference image is transformed so as to get close to a noisy input image by patch-wise color transformation. Our filter formula can be regarded as a generalized version of the reference-based filtering approaches including our previous method [1] and the *guided filter* [2], and it realizes more flexible transformations. Additionally, we apply our filter to a multiple exposure image integration problem in which we use a flash/no-flash image pair to acquire a dark scene and perform denoising of the no-flash image deteriorated with sensor noise. Our method is especially useful for the acquisition of dark scenes without losing the contrast of images. Simulations with actual noisy images show the validity of the proposed method.

## 1 Introduction

Recently, reference image based image processing [1–3] has been actively studied. In this study and related studies [1–3], an input image is filtered using the information of a reference image. Our previous work [1] aims to transfer the color information of a no-flash image to a flash image, generating a denoised image. In the method, they focus on the color-line image property [4], *i.e.*, the color distribution of each local region becomes linear or planar. As a result, the appearance of a noise-free flash image is converted into a no-flash-like image while keeping its sharp edges and vivid colors. However, this model is often insufficient to represent a local color distribution of natural scene.

Meanwhile, the dynamic ranges of many commercial camera devices are quite narrower than the *human visual system*. Many authors proposed multiple exposure image integration techniques [5, 6] to generate a *high dynamic range* (HDR) image, which can represent a greater range of scene irradiance without pixel saturation. When we take a photograph in a dark scene, high ISO sensitivity is needed and yields a noisy image. Moreover, the dark area of the HDR image is emphasized by tone-mapping, which makes the noise more perceivable.

In this paper, we introduce the quadratic *local color distribution projection* (LCDP) filter, which is more suitable to represent the natural image local color distribution property. Moreover, we apply the LCDP filter to flash/no-flash integration for acquiring HDR images.

In the following sections, we explain the proposed quadratic LCDP filter. In Sect.3, we propose the noiseless HDR image generation technique with the LCDP filter. We demonstrate the validity of our methods in Sect. 4.

## 2 Local Color Distribution Projection Filter

Most of the reference-based filters [1–3] are designed on the basis of the distribution characteristics of local regions in an image. The approaches perform image conversion by affine transformation for approximating the distribution of color pixel values in a reference image to the desired distribution. Filters based on the linear model can provide reasonably good results in some actual cases. However, this model is often insufficient to represent a local color distribution of natural scene. Thus, we further generalize the filter by using a homogeneous coordinate system to realize a nonlinear model.

We define the problem of the filter design as the quadratic form in the homogeneous coordinate system:

$$\min_{\mathbf{y},\mathbf{T}} \sum_i \sum_{j\in\mathcal{N}(i)} w_{ij}\rho(\mathbf{T}_i\mathbf{g}'_j - \mathbf{y}_j), \text{ s.t. } \|\mathbf{T}_i\|_F \le \eta. \tag{1}$$

where $w_{ij}$ is weights based on a Gaussian function, and $\rho(\cdot)$ is a robust function. $\mathbf{T}_i = [\,\mathbf{Q}_i \,|\, \mathbf{A}_i \,|\, \mathbf{b}_i\,] \in \mathbb{R}^{3\times 10}$ is the transformation matrix[1] consisted by the quadratic part $\mathbf{Q} \in \mathbb{R}^{3\times 6}$, the linear part $\mathbf{A}_i \in \mathbb{R}^{3\times 3}$, and shift vector $\mathbf{b} \in \mathbb{R}^{3\times 1}$. The vector $\mathbf{g}'_j$ is given as $\mathbf{g}'_j = [r_j^2, g_j^2, b_j^2, r_jg_j, g_jb_j, b_jr_j, r_j, g_j, b_j, 1]^\top$ ($r_j, g_j$ and $b_j$ are $j$-th $RGB$ value of a reference image). $\mathbf{y}_j$ is a $j$-th $RGB$ vector of an input image. To solve this problem, we employ the IRLS and approximate $\rho(\cdot)$ by the weighted $l_2$ norm. The solution is obtained by solving the problem w.r.t. $\mathbf{T}$ and $\mathbf{y}$ (for the detail please refer our previous work [7]).

## 3 Multiple Exposure Image Integration

Figure 1 shows the flow of the proposed image integration algorithm. First, we use the LCDP filter to restore a noisy long exposure image. A flash image is simply transformed by LCDP filtering to a long exposure image. Then we obtain the restored (noiseless) long exposure image by applying the method discussed in Sect. 2. In our method, the restored image is used as a long exposure image instead of a noisy input. Next, to acquire a noiseless HDR image, we propose two types shrinkage which is an inter-shrinkage and a wavelet shrinkage for integration of multiple exposure image.

To integrate the images, we convert the images into irradiance. Before integration, the difference (*i.e.*, noise) between the images is reduced by an inter-image shrinkage by simple pixel-wise hard-thresholding. After inter-shrinkage, we integrate the images in the wavelet domain. Here, we try to remove the noise by shrinkage

[1] The constraint in (1) is required to guarantee the existence of a solution $\mathbf{T}$ when the variance of $\{\mathbf{g}'_j\}$ becomes $\mathbf{0}$. Thus, we set the small value to $\eta$.

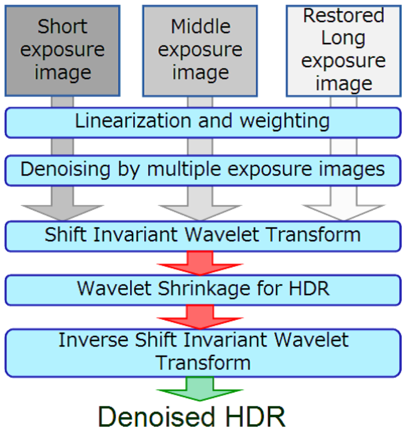


Figure 1: High dynamic range image acquisition flow.

for multiple exposure images. Before converting with a wavelet transform, we apply a weight to the images by $u_i^{l*} = \frac{\mathcal{Z}(u_i^l)\cdot\tilde{u}_i^l}{\sum_{l=1}^{L}\mathcal{Z}(u_i^l)}$, where $u_i^l$ and $\tilde{u}_i^l$ are the $i$-th pixel of the $l$-th exposure image and the irradiance of $u_i^l$ applied the inter-shrinkage. Here, we use a weight function $\mathcal{Z}$ described in [8]. Next, the weighted images $u_i^{l*}$ are converted by the Haar-based shift invariant wavelet transform. Here, the wavelet shrinkage for multiple exposure image integration is derived as follows:

$$\min_{\widehat{v}_j} E_{HDR}(\widehat{v}_j) = |\widehat{v}_j|^0 + \frac{\lambda}{L}\sum_{l=1}^{L}(\widehat{v}_j - v_j^l)^2, \tag{2}$$

where $v_j^l$ is the input $j$-th wavelet coefficient of the $l$-th weighted image, $\widehat{v}_j$ is the output $j$-th wavelet coefficient. $\lambda$ is a parameter to control the level of noise removal. By differentiating $E_{HDR}(\widehat{v}_j)$ w.r.t. $\widehat{v}_j$ and setting it to 0, we derive the optimal wavelet coefficients for multiple image integration:

$$\widehat{v}_j^* = \begin{cases} 0, & \text{if } 1 - \lambda\left(\frac{1}{L}\sum_l v_j^l\right)^2 > 0, \\ \frac{1}{L}\sum_l v_j^l, & \text{otherwise.} \end{cases} \tag{3}$$

The lowest sub-bands are simply integrated by taking the weighted mean. Note that the roles of (3) are not only the shrinkage based denoising but also multiple exposure fusion in the wavelet domain.

## 4 Experimental Results

We show the results of an HDR image acquisition obtained by applying the proposed quadratic LCDP filter. We prepare three images with different exposures and high ISO sensitivity, and a flash image with low ISO sensitivity. Figure 2 shows the results of our method, the simple integration method [5] (denoising is not performed), BM3D [9]. The ground truth HDR image is obtained by averaging fifteen photographs and using simple integration [5]. Note that BM3D [9] is performed on noisy no-flash images. The results show that our method outperforms the others.

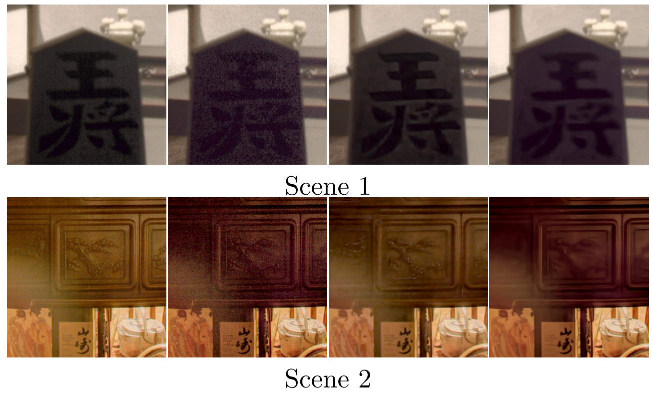


Figure 2: Result: (left to right) ground truth, simple integration [5], ours, and BM3D [9].

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