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HDR Image Artifact Compensation

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Abstract
High dynamic range (HDR) imaging technology is becoming increasingly popular in recent years. A standard and most common approach to obtain an HDR image is the multiple exposures fusion method that consists of combining multiple images of the same scene captured with different exposure times. This technique works perfectly only on static scenes. However, if there is a motion in the scene during the sequence acquisition, the resultant HDR image contains ghosting artefacts due to moving objects in the captured scene. In this paper, de-ghosting methods are reviewed and two of them - a bitmap movement detection based on a median threshold and a histogram based ghost detection - are proposed as the suitable techniques for a real-time video capturing and implementation on an FPGA (Field-Programmable Gate Array) architecture.

Keywords: HDR, high dynamic range imaging, de-ghosting, FPGA, real-time, video

Supplementary Material: *N/A*

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1. Introduction

Common digital cameras can only capture a limited luminance dynamic range. The human visual system (HVS) can adapt to a dynamic range of up to 10,000:1 for parts of a scene and over $10^{12} - 10^{14} : 1$ of magnitude in total. In contrast to HVS, digital cameras have a much lower dynamic range of typically less than 1000:1. When a photograph of a scene with a big range of brightness is taken, a bright areas tend to be over-exposed while dark regions tend to be under-exposed. These extreme areas appear saturated in the image. Therefore, a very interesting and powerful technique has been developed in the last two decades to capture wider dynamic range by conventional cameras called high dynamic range imaging (HDRI). There is a special hardware which allows to take high dynamic range images directly. However, this specialized hardware is very expensive and for commercial use only. This fact encourages a lot of researches in the field of HDRI.

The most common and widely used method to obtain HDR images is a multiple exposures combination. The sequence of single-exposure low dynamic range (LDR) images of the same scene are captured at different exposure times by traditional camera technology and combined into a final HDR image. Each image in the sequence of multiple exposures will have different pixels properly exposed, under-exposed or over-exposed. However, individual parts of images in the sequence must overlap for the successful restoration of the dynamic range. Therefore, it is possible to ignore very dark and very bright pixels from computations of the resulting image.

The biggest limitation of the multiple exposures combination technique is the requirement of a completely static scene when the sequence of images is being captured, because any object movement in the scene during capturing can cause ghosting artefacts in the final image. However, there have been already developed various methods to detect and remove ghost artefacts in HDR images. Different methods produce divergent results and can be classified into two main categories - keeping a single occurrence of moving objects and complete removing of moving objects.

1.1 Real-Time HDR FPGA Video Camera

This work is a part of a research project dealing with the real-time HDR FPGA video camera. The FPGA video camera captures three different exposures and combines them together in the real-time processing to display the resulting HDR video on common LDR monitors. The video camera captures 60 frames per second. However, there can still appear some small artefacts in the final video. The goal of this paper is to find or propose a de-ghosting algorithm (or more algorithms) to eliminate these ghosting artefacts. One of the proposed algorithms will be included into processing of the captured images on this FPGA video camera to prevent ghost artefacts in the final real-time HDR video. Because the FPGA architecture has some specifications, the proposed algorithms have to respect few requirements. The implementation has to consume small amount of memory and cannot go back for some old data. It has to use elements which can be easily implemented in FPGA, such as look-up tables. Due to the real-time application, the implementation has to be efficient and non-iterative. Moreover, the selected algorithms have to remove as many ghosting artefacts as possible and keep a single occurrence of the moving objects in the video.

2. Related Work

The multiple exposure fusion can be done in a radiance or image domain (see Figure 1).

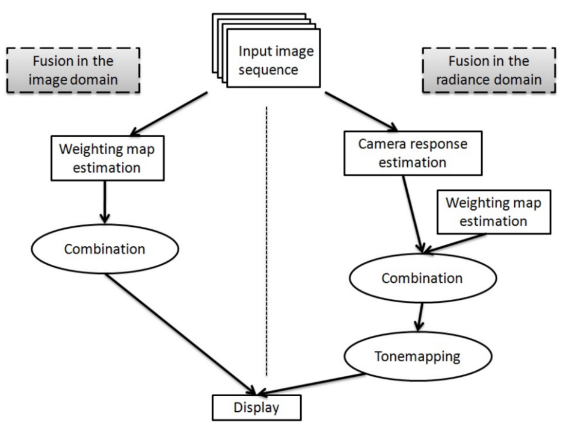


Figure 1. HDR image generation process (taken from [1])

Fusion in the radiance domain

This type of fusion was proposed by Debevec et al. [2] and consists of three steps. First, the camera response function is recovered to bring the pixel brightness values into the radiance domain. Next, the radiance maps are combined into an HDR image encoded specially to store the pixel values that span the entire tonal range of the scene. Finally, a tone mapping operator is used to make the HDR image able to display on common LDR monitors [1]. Methods that combine exposures in the radiance domain give a true HDR radiance map which might be useful for later processing or display applications. The precision of these methods highly depends on an accurate estimation of the camera response function, which is sensitive to image noise and misalignment. Moreover, these methods require tone mapping operators for HDR images reproduction.

Fusion in the image domain

Second type of methods presented by Mertens et al. [3] combine multiple exposures directly without the knowledge of the camera response function. These methods take only the best parts of each exposure. The resulting HDR image is obtained as a weighted average of pixel values across exposures. Methods that combine exposures in the image domain are more efficient than the previously mentioned technique since they avoid the estimation of the camera response function and do not require tone mapping. These methods directly produce HDR images which can be displayed on LDR monitors.

Most of already developed de-ghosting methods consists of two steps: a ghost detection, the detection of regions where ghosts appeared, and a ghost removal.

2.1 Ghost Detection

Ghost detection methods detect motion in a sequence of exposures where a moving object can appear on a static background or on a moving background with static or dynamic objects. The following methods, mostly taken from [1], can detect both or only the first mentioned type of motion.

Variance Based

Variance based ghost detection method published by Reinhard et al. [4] detects regions with moving objects based on weighted variance measure. First, the camera response function and the radiance maps for each LDR are computed. Then a Variance Image (VI) is generated by evaluating the variance of radiance values at each spatial location and the calculated VI is used as a likelihood measure for intra-image movements because regions inclusive motion exhibit high variance.

Regions, where the local variance measure is above a defined threshold, are detected as ghost regions.

This method has weak results and cannot be used if the moving objects have similar colors as the background. Therefore, Jacobs et al. [5] proposed another measure derived from entropy.

Entropy Based

First, a local neighbourhood based entropy map is computed for each LDR image. For each pixel (u,v) in L_k, the entropy is calculated from a local histogram computed in the window of size $r \times r$ around (u,v), where r is an odd number bigger than 1. Then, an Uncertainty Image (UI) is derived from the weighted difference of the precomputed entropy image and is used to find ghost regions based on thresholding.

Prediction Based

Grosch [6] uses in his method the deviation between the predicted intensity value of a pixel and the actual intensity as a measure to find ghost pixels. The deviation is calculated from two images L_k and L_l using the estimated camera response function f:

$$Z^l_{uv} = f\left(\frac{\Delta t_l}{\Delta t_k} f^{-1}(Z^k_{uv})\right), \quad (1)$$

where Δt_l and Δt_k are the exposure times of L_k and L_l, respectively.

Pixels which show a significant difference between the predicted and the actual value for each pair of consecutive input LDR images, are marked as ghost pixels.

This method seems to be applicable for the given project as well as the previously presented entropy based method.

Pixel Order Relation

It is possible to relate pixel values to radiance values using the camera response function f as published by Sidibé et al. [7]:

$$Z^k_{uv} = f(E^k_{uv} \Delta t_k). \quad (2)$$

An increase in radiance values always produces an increased or equal recorded pixel values. The pixel order relation method uses this evidence to assume that f is monotonic. Then, the intensity values for each pixel location (u,v) in different exposures must satisfy:

$$Z^k_{uv} \le Z^l_{uv}, \text{ if } \Delta t_k < \Delta t_l. \quad (3)$$

The creation of ghost map ensues from the previous Equation (3) as:

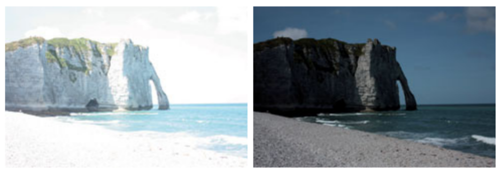
$$G_{uv} = \begin{cases} 0 & \text{if } Z^1_{uv} \le Z^2_{uv} \le \ldots \le Z^N_{uv} \\ 1 & \text{otherwise} \end{cases} . \quad (4)$$

This method completely removes the moving objects from the final HDR image and thus it is not appropriate for the given issue.

Bitmap Based

This method uses the median threshold bitmap (MTB) algorithm which was introduced by Ward et al. [8] for the purpose of image alignment and taken over by Pece and Kautz [9] to detect ghost artefacts in dynamic scenes. The MTB technique helps the comparison of images that are taken under different exposures by effectively removing most of the illumination differences between images. This method relies on the fact that if a pixel is not affected by ghost, then its relation to the median intensity of the image must be the same in all taken LDR images.

A binary bitmap B_k is computed by applying a threshold to the image L_k based on its median intensity pixels value. If the values in the image L_k are less than or equal to its median intensity pixels value, pixels of B_k are black. On the other hand white regions of B_k indicate the pixels whose values are greater then the median intensity pixels value. The obtained bitmap B_k reveals image features while removing intensity differences between different exposures (see Figure 2).



(a) Original Exposures: +2 and -2 stops respectively.

(b) Bitmaps generated by MTB.

Figure 2. Bitmap similarity using MTB (taken from [9])

By summing up all computed bitmaps into image M, the pixels affected by movement are detected because each pixel to preserve its bit value across all B_k in the static scene. The morphological operations (dilation and erosion) are applied on the image M to reduce noise. Then, any pixel in the M that is neither 0 nor N (N is a number of exposures) is classified as a movement. M is converted into a cluster map where each identified cluster has a different label which is computed using connected component labelling [10]. An overview of this technique is illustrated in Figure 3.

This method uses a fusion in an image domain but it is possible to integrate it also into a radiance domain

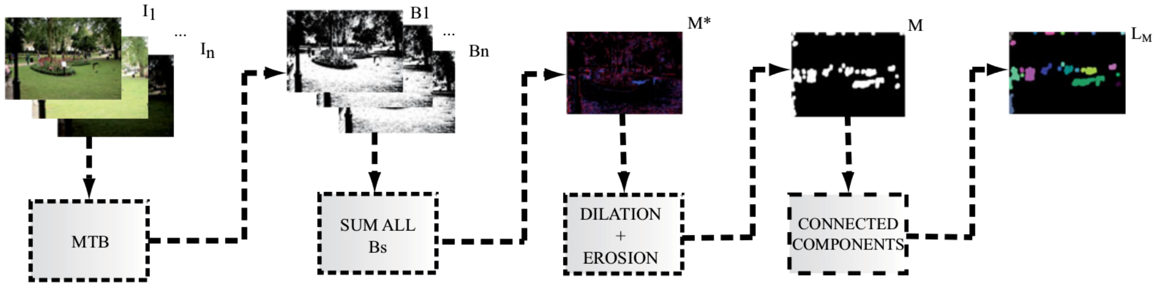


Figure 3. Bitmap movement detection algorithm overview (taken from [9])

fusion. The algorithm works well on a large variety of movement configurations. Moreover, the method is faster than other de-ghosting algorithms, relies only on simple binary operations and thus it can be easily implemented directly on a camera hardware [9].

Histogram Based

This method proposed by Min et al. [11] calculates ghost maps based on multi-level threshold maps which are extended from the MTB. It takes advantage of the condition that the grey levels at a particular pixel location must exhibit an increasing or equal property when the images are captured from lowest to highest exposures. First, each image z_j is divided into N levels which gives a set of N threshold values $T_{j,k}$, where each level has the same number of pixels. Then, the multi-level threshold maps L_j are computed by classifying the intensity value of z_j into N levels using these thresholds. Figure 4b shows the multi-level threshold maps L_j, $1 \leq j \leq 3$, $N = 8$, extracted from LDRIs in Figure 4a. The ghost maps are estimated using the computed multi-level threshold maps for each LDRI excluding the mid-exposure LDR which is taken as the reference image:

$$G_{i,j} = \begin{cases} 1 & \text{if } |L_{i,ref} - L_{i,j}| \geq 1, j \neq ref \\ 0 & \text{otherwise} \end{cases} . \quad (5)$$

Therefore, the method produces $j-1$ ghost maps, where j is a number of input exposures. This method generates the radiance map based on Debevec et al. [2] and incorporates computed ghost maps into their weighting factor.

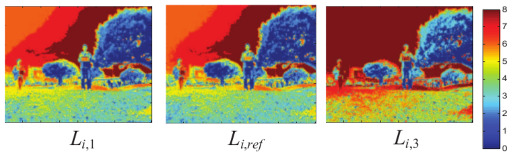
Lee et al. [12] proposed an improvement of this algorithm and later on Ahirwal et al. [13] also built on this method.

Patch Based

This method [14] is based on the fact that the intensity values at any location (u,v) in any two input images L_k and L_l satisfy the following condition:

$$\frac{Z^k_{uv}}{\Delta t_k} = \frac{Z^l_{uv}}{\Delta t_l}. \quad (6)$$

(a) LDRI sequence with three different exposures



(b) Multi-level threshold maps

Figure 4. Histogram based method (taken from [11])

Besides saturated pixels, the above rule is broken only at locations affected by ghost. The processing is performed on a patch level in order to be robust to noise. At first, the least saturated image is selected as the reference L_{ref}. Then, log intensities of an $r \times r$ patch in L_k are plotted against the log intensities of the corresponding patch in the reference image L_{ref} in order to find patches of L_k affected by ghost. A best fit line through the plot is obtained by the RANSAC procedure [15] and the percentage number of outliers is calculated using a distance threshold. If the percentage is greater than the threshold, the tested patch includes a ghost.

A patch-based algorithm which uses energy-minimization formulation was proposed by Sen et al. [16]. Hu et al. [17] present another patch-based algorithm uses an iterative approach to register LDR images to a reference image.

This type of methods could be suitable for the given issue, however, only some of these methods which do not use an iterative approach and which do not completely remove ghosting objects from the final HDR image.

Graph-Cuts Based

Heo et al. [18] use joint probability density functions between exposure images to get global intensity transfer functions to roughly detect ghost regions. These regions are further refined using energy minimization based on graph-cuts methods. This algorithm does not require accurate ghost detection and not suffer from the color artefact problem. This method is possibly suitable for the given project.

Optical Flow Based

Optical flow algorithms are recognized as one of the most successful algorithms in aligning differently exposed LDR images by motion compensation. There are already a lot of optical flow algorithms for HDR image acquisition such as Kang et al. [19], Mangiat and Gibson [20], Zimmer et al. [21]. They perform image alignment by applying energy-based or gradient-based optical flow approach. These methods are computationally challenging and therefore not suitable for a usage in the FPGA architecture.

Markov Random Field

Jinno and Okuda [22] use detection based on the Markov random field (MRF) model and estimate displacements, occlusion and saturated regions simultaneously by using Maximum a Posteriori (MAP) estimation instead of a ghost map creation. They do not estimate accurate motion vectors but compute displacement to the pixel with the closest irradiance. Unfortunately, MRF model and MAP estimation are not easily implementable techniques for FPGA architecture.

Singular Value Decomposition Based

This method [23] uses singular value decomposition (SVD) to resolve the ghosting problem. The method is based on extracting local spatio-temporal neighbourhoods and using the second biggest singular value of the matrix formed by values within the neighbourhoods as a measure for ghost detection. This method is computationally challenging and not suitable for the FPGA architecture as well as the previously mentioned techniques.

2.2 Ghost Removal

Ghost removal methods can be divided into two main categories - removing ghost artefacts while keeping a single occurrence of the moving object and completely removing the moving object from the final image.

Keeping a single occurrence of the moving object

The simplest approach to keep a single occurrence of moving object in the final HDR image, is to apply the standard multiple exposure fusion method in ghost-free regions while selecting a single reference exposure in ghost affected areas. This approach requires a computed ghost map. The reference exposure is typically the image which is least saturated [4, 5] or the image whose ghost regions are best kept in range [6]. Another approach is to determine the correct number of exposures to use in different ghost affected areas [14]. However, using a single reference exposure introduces new artefacts in the resultant HDR image. These new artefacts are created at ghost regions boundaries. For the better result without new ghost artefacts in the final image it is possible to use a Laplacian pyramid blending framework [9, 3] or a gradient domain approach [14]. Zhang and Cham [24, 25] use gradient information to generate ghost-free HDR images directly without a ghost detection.

Complete removing of the moving object

Some methods completely remove all moving objects from the final HDR image. The most simple approach to achieve this goal, is to discard exposures effected by ghost regions during the combination step of HDR acquisition process. This idea is used by Sidibé et al [7] and Gallo et al [14]. Methods proposed by Khan et al. [26] and by Pedone and Heikkilä [27] directly remove ghost artefacts without a ghost detection by adjusting the weighting function when the combined radiance map is calculated.

These algorithms assume that moving objects appear in a small number of images at each pixel location. Moreover, these methods require a sufficiently large number of images and can be computationally expensive since they require a number of iterations to produce good results [1]. It makes them inappropriate for a use in the FPGA implementation.

3. Summary of De-ghosting Methods

The classification of the reviewed methods from Section 2 is shown in Figure 5. This classification is based on the following parameters:

- Fusion domain - radiance or image
- Number of exposures needed for good results of the algorithm
- Ghost map detection - if ghost map detection is first computed and number of ghost maps - one or more using one exposure as a reference image
- Thresholds tuning - some input parameters such as a threshold value has to be set automatically or manually, respectively
- Reference image selection - if one of the input images is used as a reference
- Final result with an occurrence of moving object at fixed position or removal of all moving objects

The methods marked by a star seem to follow all desired requirements for the given project.

Method	Final result: Remove all moving objects	Final result: Keep moving object at fixed location	Ghost detection and removal: Reference image selection	Ghost detection and removal: Thresholds tuning – Automatic	Ghost detection and removal: Thresholds tuning – Manual	Ghost detection and removal: More ghost maps	Ghost detection and removal: Ghost map detection	Ghost detection and removal: Number of exposures – Large (> 5)	Ghost detection and removal: Number of exposures – Small (≤ 3)	Fusion: Image domain	Fusion: Radiance domain
Variance – *Reinhard et al. [4]*		X	X		X		X		X		X
*Entropy – *Jacobs et al. [5]*		X	X		X		X		X		X
*Prediction – *Grosch [6]*		X	X		X	X	X		X		X
Pixel Order Relation – *Sidibé et al. [7]*	X			X			X	X			X
*Bitmap – *Pece and Kautz [9]*		X			X		X		X	X	
*Histogram – *Min et al. [11]*		X	X	X		X	X		X		X
*Patch – *Gallo et al. [14], etc.*	X	X	X		X	X	X		X		X
*Graph-Cuts – *Heo et al. [18]*		X	X		X	X	X		X		X
Optical Flow – *Kang et al. [19], etc.*		X	X		X		X		X		X
Markov Random Field – *Jinno and Okuda [22]*		X	X		X				X		X
SVD – *Srikantha et al. [23]*		X		X		X	X		X		X
Density Estimation – *Khan et al. [26]*	X				X			X			X
Constraint Propagation – *Pedone and Heikkilä [27]*	X				X			X			X
Gradient – *Zhang and Cham [24, 25]*	X	X	X	X					X	X	

Figure 5. Classification of ghost detection methods (inspired by [1])

4. Suggested Methods

The required methods have to keep a single occurrence of moving objects in the final image. Moreover, the requirements based on the assumption of an FPGA implementation discussed in Section 1.1 have to be met. Based on the review in Figure 5 and results presented by various researchers, the bitmap movement detection [9] and histogram based ghost removal [11] methods are selected as appropriate solutions for the given issue. These methods were implemented in C++ as prototypes for testing. The following section shows the results of the tests. Figure 6 shows the sequence of input images which were used for testing.

4.1 Bitmap Movement Detection

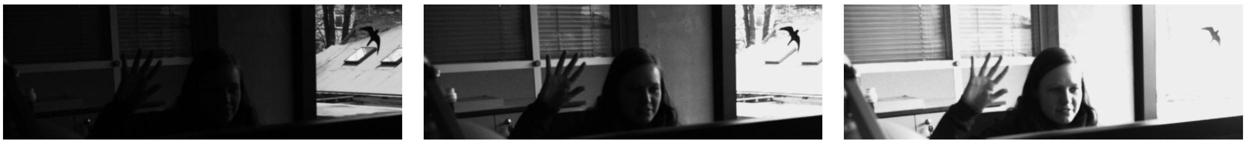
Figure 7 shows the resultant HDR image using the bitmap movement detection with simple exposure fusion in the image domain. To compare the final result, Figure 8 shows the HDR image using the fusion in the image domain without any artifact compensation method. The computational time for both HDR images were around 0.12 seconds.

Figure 7. Final HDR image without ghost artifacts using the bitmap movement detection method

Figure 8. HDR image with ghost artifacts using the fusion in the image domain

4.2 Histogram Based Ghost Removal

Figure 9 shows the resultant HDR image using the histogram based ghost removal method with the fusion in the radiance domain. For comparison, the HDR image in Figure 10 with ghost artifacts is brought together in the radiance domain as well.



(a) Under-exposed **(b)** Mid-exposed **(c)** Over-exposed

Figure 6. Input LDR exposures sequence

Figure 9. Final HDR image without ghost artifacts using the histogram based ghost detection method

Figure 10. HDR image with ghost artifacts using the fusion in the radiance domain

A logarithmic tone-mapping is used to display final images on common LDR monitors. The computational time for both HDR images were around 0.21 seconds.

The histogram based ghost removal method has better results in the ghost regions than the bitmap movement detection method. However, the tone-mapping operator has to be implemented. The bitmap movement detection method has some artifacts on the boundaries of removed ghost regions. However, these artifacts could be removed by using a Laplacian pyramid blending.

5. Conclusion

This paper deals with the ghost problem in HDR imaging and includes a review of the recently existing methods to solve this issue. Methods which combine exposures in the image domain are time-efficient as they avoid the camera response function estimation and tone-mapping. On the other hand, methods using radiance domain fusion give a true HDR radiance map which might be useful for later processing or display applications. Generally speaking, there is a huge amount of de-ghosting methods but no single best technique. The results depend on the particular input sequence - a contrast of colors, a size of movement, a number of exposures etc.

Moreover, the bitmap movement detection and histogram based ghost removal methods are suggested as appropriate solutions for the FPGA HDR real-time video camera. The results of these methods depends on a few implementation details. However, as the Section 4 shows, these techniques aim to solve the given issue.

As a further work on this topic some other methods will be implemented to compare them with suggested techniques in the sense of suitability for the FPGA architecture implementation and a real-time video use.

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