High Dynamic Range Imaging- A Review

Nayana A. nayana239@gmail.com
Department of Electronics and Communication Engineering
Mar Baselios College of Engineering and Technology
Trivandrum, India.

Anoop K. Johnson anoopkjohnson2340@gmail.com
Department of Electronics and Communication Engineering
Mar Baselios College of Engineering and Technology
Trivandrum, India.

Abstract

The real world scenes have a very wide range of luminance levels. But in the field of photography, the ordinary cameras are not capable of capturing the true dynamic range of a natural scene. To enhance the dynamic range of the captured image, a technique known as High Dynamic Range (HDR) imaging is generally used. HDR imaging is the process of capturing scenes with larger intensity range than what conventional sensors can capture. It can faithfully capture the details in dark and bright part of the scene. In this paper HDR generation method such as multiple exposure fusion in image domain and radiance domain are reviewed. The main issues in HDR imaging using multiple exposure combination technique are Misalignment of input images, Noise in data sets and Ghosting artefacts. The removal of these artefacts is a major step in HDR reconstruction. Methods for removing misalignment and noise are discussed and detailed survey of ghost detection and removal techniques are given in this paper. Single shot HDR imaging is a recent technique in the field of HDR reconstruction. Here instead of taking multiple exposure input images, a single image is used for generating HDR image. Various methods for Single shot HDR imaging are also reviewed.

Keywords: High Dynamic Range Imaging, Multiple Exposure Fusion, Image Registration, Ghosting Artefacts, Single Shot Imaging.

1. INTRODUCTION

Dynamic range (DR) of a scene is defined as the range from the lowest to the highest light intensity occurring in the scene. It is also known as scene contrast. An image is said to be in high dynamic range if it has details in both the bright and dark regions in the image. The dynamic range of real-world scenes can be as high as in the ratio of 100,000:1. Human visual system can process and adapt to a dynamic range of about 50,000:1. The images captured by the cameras can only have dynamic ranges between 300:1 to 1,000:1. These images are therefore considered as low dynamic range (LDR) images. Longer exposures would capture details in the dark areas of a scene while shorter exposures would capture the bright areas of a scene. That is, the details in both the dark and bright areas of a scene are not visible in a single image. Such a type of image is known as LDR image.

High Dynamic Range (HDR) images capture the whole tonal range of real-world scenes, using 32-bit floating-point values to store each colour channel. The use of floating point values gives HDR images several advantages over LDR images. The areas that are too dark are clipped to black and areas that are too bright are clipped to white in an LDR image. Pixel values in an HDR image are normalized between 0.0 and 1.0. Dark and bright areas are assigned different values close to 0.0 and 1.0. Therefore, HDR images can preserve details of a scene having large dynamic range. Another advantage of HDR images is that they preserve optical phenomena such as reflections and refractions. In LDR images, the pixels representing all the bright light sources in a scene are assigned to have the maximum possible integer value and the reflected light should have value less than the light source. In HDR images, the reflected light is assigned with values close but less than 1.0 and the bright source can assume values equal to 1.0. Therefore, HDR images are able to better represent scenes as perceived by human eyes.

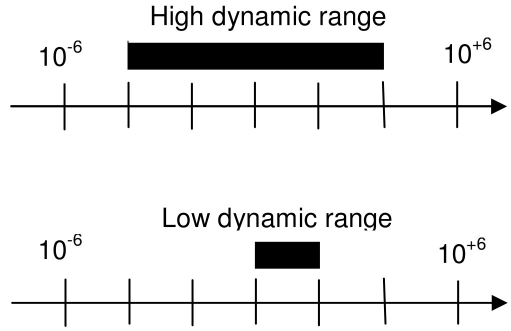

FIGURE1: High Dynamic vs. Low Dynamic Range.

2. HIGH DYNAMIC RANGE IMAGING

High dynamic range (HDR) imaging refers to a set of techniques that allow a greater dynamic range of luminance between the lightest and darkest areas of an image than standard digital imaging techniques. The wide dynamic range of HDR images allows representing the wide range of intensity levels found in real scenes. HDR has the following qualities:

(i) High contrast ratio: Bright and dark regions need to be captured.
(ii) High bit depth: To encode values with quantization levels as small as the just noticeable difference; so that no stepping is visible resulting in a smooth intensity gradient.
(iii) Details are preserved: There is no or little clipping due to over- or under-saturation.

To directly capture HDR content, specialized cameras are proposed but these devices are expensive. The approach commonly used is to take sequential LDR images at different exposure levels (known as bracketed exposures) and then merge them into an HDR image. This method is known as multiple exposure technique.

High dynamic range (HDR) imaging consists of:

(i) HDR recovery or acquisition: In HDR acquisition the true luminance of a scene is captured with a low dynamic range capturing device.
(ii) Tone mapping: To faithfully represent HDR information on a low dynamic range display device that is incapable of reproducing the actual luminance and the true colours.

2.1 Tone Mapping

One of the problems associated with high dynamic range imaging is the display of high dynamic range radiance maps on conventional reproduction media such as CRT or LCD monitors, and projectors. The dynamic range of the generated HDR image often spans more than five orders of magnitude (2^{16} = 65536). But a conventional display is able to visualize a maximum of two orders of magnitude (2^8 = 256). A solution to this problem is to compress the dynamic range of the radiance maps such that the mapped image can be fitted into the dynamic range of the display devices. This method is called tone mapping [1,2]. Here one set of colors are mapped to another to approximate the appearance of high dynamic range images in a medium that has a limited dynamic range. Tone mapping operator reduces the scene radiance contrast to the displayable range while preserving the image details and color appearance.

There are several tone mapping methods and these methods can be divided into two broad categories. The global tone mapping techniques use a single spatially invariant mapping function for all pixels in the image. It is much simpler to implement but tend to lose details. The local mapping techniques adapt the mapping functions to local pixel statistics. It is much more computationally intensive as there are a number of parameters which have to be set empirically. Depending on the particular requirements, one method will be better suited than others in some cases, or a combination of methods will be necessary in some other cases.

3. MULTIPLE EXPOSURE FUSION TECHNIQUE

The most common method of HDR generation is to take multiple images of the same scene with different exposure times, and combine them into a single HDR image. The basic concept is that each pixel will be properly exposed in at least one image. A single photo is insufficient to record all the details in the scene because, some areas in the photo may be over-exposed and other portions may appear under-exposed ie, details can hardly be seen (Figure 2). These limitations motivate the development of fusion techniques for multi-exposure images. The fusion of a set of LDR images can be classified into two main approaches: fusion in the radiance domain and fusion in the image domain.

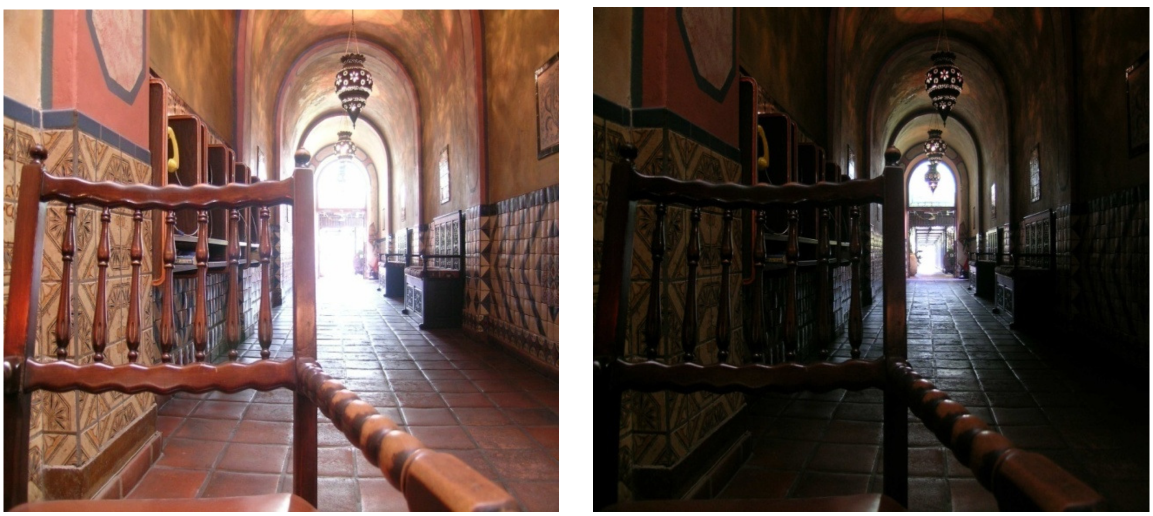

FIGURE 2: Multiple Exposure Images.

FIGURE 3: HDR Image.

4. HDR RECONSTRUCTION IN RADIANCE DOMAIN

HDR image generation process in radiance domain consists of three steps.

(i) Recover the camera response function to bring the pixel brightness values into radiance values. This function models the effect of non-linearities introduced in the image acquisition process. Different methods can be used for its estimation.
(ii) Then all radiance maps are combined into an HDR image.
(iii) To make the HDR image displayable on LDR monitors a tone mapping operator is used.

HDR image is computed as the weighted average of pixels values across exposures using the camera response function.

$$I_m^{hdr} = \frac{\sum_{n=1}^{N} w(I_m^n)[g^{-1}(I_m^n)/t_n]}{\sum_{n=1}^{N} w(I_m^n)}$$

where I_m^n is value of pixel *m* of the *n*-th exposure image, *N* is the number of images, t_n is the exposure time of the *n*-th image, and *w* is a weighting function. *w(.)* is assigned to reduce the influence of unreliable pixels. In order to display the obtained HDR image on a low dynamic range device, a tone mapping operator is applied. Tone mapping techniques can be classified into global and local methods.

In [3], an image with extended dynamic range is obtained from a sequence of exposures using the function

$$M = \alpha + \beta I^{\gamma}$$

to model the response curve *g* of the imaging system. α is the bias parameter and β is the scaling factor. α is obtained by taking an image with the lens covered and then performing a regression operation. Consider two images taken under different exposures with known ratio $R = e_l/e_2$. The measurement *M (I)* in the first image *(I* is unknown) produces the measurement *M(RI)* in the second. A pixel with brightness *M (R I)* is sought in the first image that would then produce the brightness $M(R^2 I)$ in the second image. This search process is repeated to obtain the measurement series *M (I)* , *M (RI)*, ..., $M(R^n I)$. To these samples regression is applied to estimate the parameter y. In [4] also the radiometric response function is computed from a sequence of differently exposed images. This algorithm does not require precise estimates of the exposures used. Rough estimates of the ratios of the exposures are sufficient for accurate recovery of the response function as well as the actual exposure ratios. They improved [3] by assuming f^{-1} to be a polynomial and its coefficients are determined through a regression model. This response function is then used to fuse the multiple images into a single HDR radiance image. The response function of the imaging system is estimated using the principle of reciprocity in [5]. Using the recovered response function the multiple LDR images are fused into HDR radiance. They worked with logarithmic data and did not impose any restrictive analytic form to f^{-1}, yet they required it to be smooth by adding a penalization term proportional to the second derivative of f^{-1} to the optimization problem. This work is applicable in many areas of computer graphics and has become the de-facto standard in the field of HDR imaging with static conditions.

5. HDR RECONSTRUCTION IN IMAGE DOMAIN

In this category multiple exposures are combined directly without computing camera response function. These methods combine LDR images by preserving only the best parts of each exposure. Final HDR image is obtained as a weighted average of pixel values across exposures:

$$I_{ij}^c = \sum_{k=1}^{N} w(Z_{ij,k}) Z_{ij,k}$$

where I^C is the composite image.

The image domain technique of merging is mentioned in [6] which is based on image partitioning and merging. Differently exposed input images are firstly divided into some sub regions and a gradient method is implemented to judge the well exposed one. In another technique [7], an image with extended dynamic range is obtained simply by using quality measures like saturation, contrast and well exposedness. Input images in the stack may contain under- and overexposed regions. These regions should receive less weight while areas which contain color and brightness details should be preserved. Three quality measures are used to achieve this. To obtain the contrast measure C a Laplacian filter is applied to the gray scale version of each image and the absolute value of the filter response is taken. A saturation measure S is computed as the standard deviation within the R, G and B channel, at each pixel. To obtain the well exposed pixels E the intensities that are not near zero (underexposed) or one (overexposed) must be kept. Each intensity is weighted based on how close it is to 0.5 using a Gauss curve. There is no need for the estimation of camera response function. The quality of resulting image is comparable to existing tone mapping operators. As in [8] differently exposed raw images can also be used for HDR generation. The effective dynamic range can be extended to 256 times if five differently exposed raw images are fused. Edge detection iterations are used to extract the image details.

5.1 Comparison between Fusion in Radiance and Image domain

The two different HDR image generation processes are depicted in Figure 4. Methods that combine images in the radiance domain are highly relied on accurate estimation of the camera response function, which is sensitive to image noise and misalignment. These methods require tone mapping operators for HDR image reproduction. A true HDR radiance map is obtained in the combination step which contains the whole dynamic range of the captured scene. Methods that combine exposures in the image domain are more efficient since they avoid the estimation of the camera response function and do not require tone mapping. They directly produce a tonemapped-like HDR image.

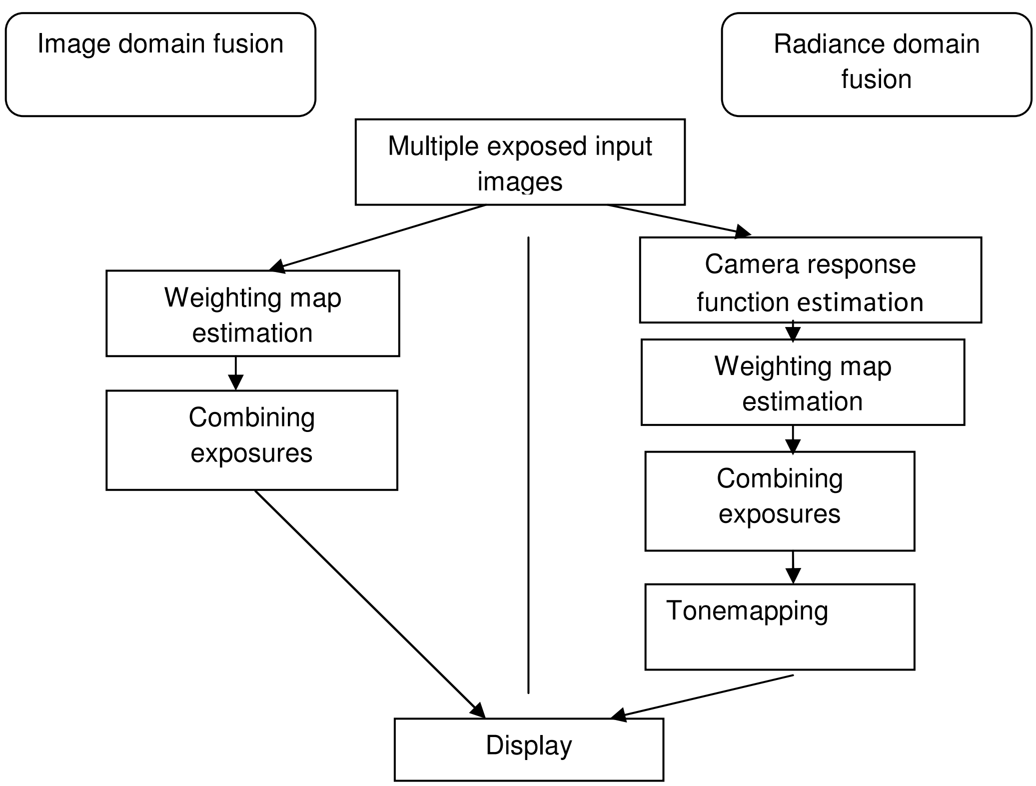

FIGURE 4: Comparison of Image and Radiance Domain Fusion.

6. ARTEFACTS IN HDR IMAGE

Multiple exposure technique suffers from three main problems:

(i) Misalignment: Global camera motion, from hand-held camera for instance, results in misaligned input images that cause the combined HDR image to look blurry. This problem can be solved by placing the camera on a tripod or by using an image registration method. Image registration is the process of transforming different sets of data into one coordinate system. In particular, the median threshold bitmap (MTB) technique [9,10] is an efficient solution. The translation alignment based on median threshold bitmaps [10] is extended with an additional rotation [9].This method is fast and can accurately recover the small displacements between images. Other registration methods based on key points extraction and matching can also be used. The most commonly used key points detectors are Harris corners and SIFT features.

(ii) Noise: The irradiance estimation that is used in multiple exposure technique is generally performed on a per-pixel basis. That is, for a given pixel, the estimation only relies on the observed values at the same location for all the available exposures. This estimation scheme does not take advantage of the redundancy present in most images. This problem can be solved by making use of a bilateral filtering during the frame fusion step [11]. However, such a local filtering cannot cope with large motions. A patch-based approach [12] is used in case of large motions, to find similar pixels that are then combined for the irradiance estimation thus making use of redundancy present in the input images.

(iii) Ghosting: Moving objects in the scene will appear in different locations in the combined HDR image, creating what are called ghosts or ghosting artefacts. Ghosting artefacts are the most severe limitation of the multiple exposures technique since moving object is unavoidable.

The Figure 5 denotes three level exposures of the scene with moving object [13]. Those exposures are captured in different time and using different shutter speed. In each image the sun (moving object) is located at a different location leading to ghosting artefact in the resultant HDR image.

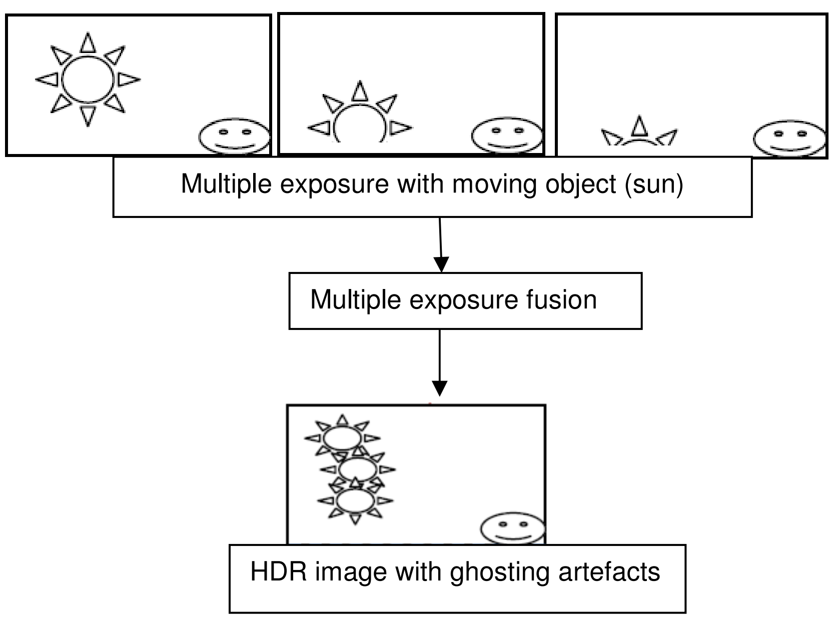

FIGURE 5: Framework for HDRI with Ghost Artefact.

FIGURE 6: An Example for Ghosting Artefact.

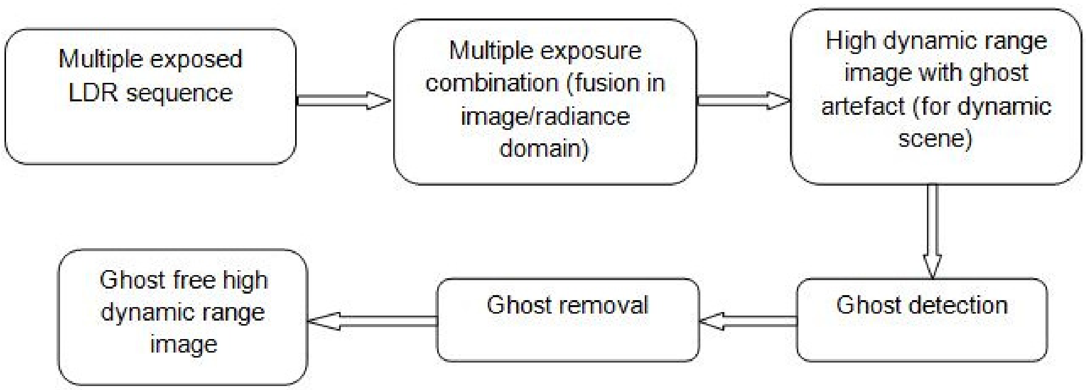

FIGURE 7: The Overall Process of HDRI.

7. GHOST DETECTION METHODS

Most of the HDR generation methods employ a two-step strategy: ghost detection and ghost removal. Ghost detection methods are based on motion detection. There are two types of motions in a dynamic scene:

(i) a moving object on a static background.
(ii) a moving background with static or dynamic objects. Some of the methods can detect only the first type of motion while others can detect both.

Weighted variance measure [14,15] can be used to detect ghost regions. The camera response function is first estimated using which the radiance maps are computed. By evaluating the variance of the radiance values a variance image (*VI*) is generated. In the *VI* image regions affected by movement exhibit high variance.

A high contrast movement occurs when the moving object is different from the background, can be detected using variance measure. While a low contrast movement occurs when the dynamic object and the background are similar in color and this type of motion can be detected using entropy measure [15]. For each input image an entropy map is computed. An Uncertainty Image (*UI*) is then derived from the weighted difference of the entropy images. This uncertainty image is used to find ghost regions based on thresholding. In another method, the deviation between the predicted intensity value of a pixel in first image and the actual intensity value in second image is used to decide whether that pixel is a ghost pixel using camera response function [9]. If there is significant difference between predicted and the actual value then that pixel is a ghost pixel. Order relation [16] between pixel values in differently exposed images can be used to find ghost areas. Moving areas in the scene can also be detected based on multi-level threshold maps [17]. The multi-level threshold maps are computed by classifying the intensity values of the images into P levels using P thresholds. Then the ghost map estimate is generated using the multi-threshold maps. In [18], ghost regions are detected based on median bitmaps which impose relations between pixels in each single exposure. If a pixel is not affected by ghost, then its relation to the median intensity of the image must be the same in all LDR images. The ghost map is recovered from the median bitmaps. Patches of ghost regions can be detected using RANSAC method [19]. In this method the intensity values at any location (*u, v*) in any two input images *Lk* and *Ll* are related by:

$$\frac{Z_{uv}^{k}}{\Delta t_k} = \frac{Z_{uv}^{l}}{\Delta t_l}$$

The above equation deviates only at locations affected by ghosts, apart from saturated pixels. In another method of ghost detection [20], the second biggest singular values extracted over local spatio-temporal neighbourhoods can be used for ghost region detection. The second biggest singular value should be small or approximately equal to zero for a ghost free region. This is the best ghost detection method since it gives higher sensitivity and specificity values, i.e. it correctly detects almost all ghost pixels with very few false positives.

8. GHOST REMOVAL METHODS

Ghost removal methods can be classified into two. The first category is to remove ghosting artefacts while keeping a single occurrence of the moving object. The second method will completely remove the moving object in the image.

a) Keeping Single Occurrence of Moving Object

If the moving object is of interest, then it is desirable to keep it at a fixed location in the final HDR image rather than completely removing it.

Ghost removal techniques are based on the detected ghost map. The approach is to apply the standard multiple exposure fusion method in ghost-free regions while selecting a single reference exposure in ghost affected areas [14,15,9]. Another approach [19] is to determine the correct number of exposures to use in different ghost affected areas. This number is obtained as the number of images in which the patch does not deviate from the patch in the reference image. Then HDR image is built using different number of exposures on each detected ghost region. For a seamless composition of exposures, Pece and Kautz [18] and Mertens et al. [21] use a Laplacian pyramid blending at multiple resolutions [22]. To avoid boundary effects in the final HDR image [19] uses a gradient domain approach. Laplacian pyramid blending and Poisson editing frameworks are used to avoid boundary effects introduced by using a single reference exposure in ghost affected regions. A simpler method which produces good results is based on weights adaptation [17,14, 18, 11]. Another ghost-free HDR image generation method using gradient information is proposed in [23]. The gradient direction in stationary regions remains stable in different exposures and varies if the content changes due to object movement.

b) Completely Removing Moving Objects

To achieve this goal, the approach is to discard exposures that are affected by ghosting at each pixel location in the combination step. This idea is used in [16] where for each pixel location two sets of exposures are created. First exposure set contains ghosting at location (u, v), while the second represents exposures that do not contain ghosting. Combining only exposures in second set leads to a ghost-free HDR image. A similar algorithm proposed in [19] is based on image patch processing rather than working with pixels individually. Other methods [24, 25] directly remove ghosting by adjusting the weighting function used in the HDR image generation equation. These methods iteratively change pixels weights to minimize the number of visible artefacts. In [24] a kernel density estimation method is used that iteratively estimates the probability that a pixel belongs to the static part of the scene. In [25] bandwidth matrices are estimated for computing the accurate probability that a pixel belongs to the background. The final probabilities are used as weights in the HDR generation.

9. SINGLE SHOT HIGH DYNAMIC RANGE IMAGING

Multiple exposure technique of HDR generation has several drawbacks, such as the need for alignment and motion estimation to avoid artefacts. In order to avoid these limitations, another technique where a large range of exposures are captured in only one shot (single shot) using spatially varying pixel exposures (SVE) is proposed in [26]. For controlling the amount of light that reaches each pixel an optical mask with spatially varying transmittance is used. This gives different exposure levels to the pixels according to the given transmittance pattern. The main drawback of the SVE acquisition is that the under and over exposed pixels are unknown. For the reconstruction of these unknown pixels the aggregation or the interpolation approaches can be performed [26]. Aggregation approach consists in averaging the local irradiance values produced by the correctly exposed pixels. The interpolation approach is based on bi-cubic interpolation [27]. To avoid aliasing problems spatially varying exposures in a non-regular (random) pattern is used [28]. The irradiance image is then reconstructed using a frequency selective extrapolation algorithm [29]. To reconstruct the unknown pixels and denoise the known ones another method using Gaussian Mixture Model (GMM) is proposed in [30]. Another method [31] utilizes weighted histogram separation (WHS) to estimate the threshold for histogram separation. Then it divides the histogram into two sub-histograms and generates differently exposed (over and under) LDR images from a single image. The drawback of this method is that utilizes a fixed weighting factor for histogram separation which is not suitable for images displaying different characteristics. In a recent method [32] over- and under-exposed images are generated from a single input image by making use of adaptive histogram separation. HDR image is constructed from the generated differently exposed LDR images by making use of a fuzzy based fusion approach.

10. CONCLUSION

In this paper various methods of high dynamic range image generation such as multiple exposure technique and single shot imaging are reviewed. Several limitations of multiple exposure technique such as misalignment of input images and ghosting artefacts are discussed. Detailed study of various fusion techniques in multiple exposure technique like fusion in image and radiance domain is performed. It is concluded that true radiance map can be obtained using fusion in radiance domain methods. Methods using fusion in image domain technique are more efficient since they avoid estimation of the camera response function and do not require tone mapping. Then a detailed survey of different artefacts found in HDR image obtained from multiple exposures are performed. The reason of occurrence of these artefacts, the various methods of detection and removal of these artefacts are also discussed. Ghosting artefact is the most severe limitation among other artefacts and it is concluded that SVD method of ghost detection is the best ghost detection method. The several limitations of multiple exposure technique can be avoided by using single shot method of HDR generation. Existing HDR generation methods in image domain can be extended to single shot method by generating multiple exposed images from single shot image using histogram separation or gamma correction. As a suggestion the performance of ghost detection can be improved by combining singular value decomposition and maximum a posterior probability (MAP) parameters.

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