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Contemplation of Tone Mapping Operators in High Dynamic Range Imaging

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Abstract

The technique of tone mapping has found widespread popularity in the modern era owing to its applications in the digital world. There are a considerable number of tone mapping techniques that have been developed so far. One method may be better than the other in some cases which is determined by the requirement of the user. In this paper, some of the techniques for tone mapping/tone reproduction of high dynamic range images have been contemplated. The classification of tone mapping operators has also been given. However, it has been found that these techniques lack in providing quality of service visualization of high dynamic range images. This paper has tried to highlight the drawbacks in the existing traditional methods so that the tone-mapped techniques can be enhanced.

Keywords: Tone mapping, high dynamic range, tone reproduction operator, local operator, global operator

1. INTRODUCTION

High Dynamic Range Imaging (HDRI) is referred to as a set of techniques in which a large dynamic luminance range is allowed between the darkest and the lightest regions of an image unlike the traditional digital imaging techniques. HDR images allow the representation of a dynamic range of intensities that are present in the real world images. The high dynamic range images reproduced have various characteristics like:

i. Preservation of details: As a result of under-saturation or over-saturation, there may be little or no clipping of images at all.
ii. High level contrast ratio: With the help of HDRI, both the dark and bright regions of a scene can be captured faithfully.
iii. High bit-depth: HDRI result in images with a smooth intensity gradient because there is no visible stepping while encoding values with small quantization levels.

Although there are cameras that have been specialized for capturing HDR images and videos, such devices are pricey. Thus, several approaches have evolved to capture HDR content, the most common being the process of capturing low dynamic range images in succession, each at different exposure settings which are called bracketed exposures. Then, those images are merged or fused into a single high dynamic range image. This process has been named as multiple-exposure technique.

The process of High Dynamic Range Imaging comprises of the following steps:

i. HDR image acquisition: In this step, the real luminance of an image is acquired or captured by means of LDR capturing devices.
ii. Tone reproduction/Tone mapping: This is the next step for the reproduction of quality HDR image where the captured HDR image is mapped onto LDR display device because the traditional display devices are not capable enough to reproduce the wide dynamic range of the real world scenes [1].

Many algorithms have been proposed for tone reproduction of HDR images. In order to compare and test those algorithms, an assessment of the quality of images reproduced is a must e.g., a particular algorithm may be thought of as a better one than the other if it is able to produce similar video quality but with a smaller bit stream. One can easily select a better-looking video clip by mere observation; nevertheless, performing subjective experiments for several parameter variations and video clips is unrealistic. Thus, there arises a requirement for some computational metrics which can be used for predicting the quality of considerable differences between any image and its reference thereby replacing tedious experimentation. Most of the metrics used for image quality reflect on the assessment of quality in a specific medium say, a print or LCD display. But the results obtained from the various substantial graphic approaches are not fixed for a particular device. They may generate images which have linear and radiometric pixel values, unlike the RGB values of devices that are gamma corrected. Also, the radiance values that are associated with the natural scenes have a wide dynamic range that is much greater than the contrast range of traditional display devices. Therefore, a challenge in the form of comparison of the quality of real world images and their corresponding images reproduced by tone mapping arises [2].

1.1 Tone Mapping/Tone Reproduction

The images generated by HDRI have a huge dynamic range spanning a magnitude of more than five orders (65536) whereas traditional display devices cannot visualize magnitude more than two orders (256). Tone mapping has been developed as a solution to this problem [3], [4]. This concept was introduced for the first time in 1993 [5] by Tumblin and Rushmeier [6]. The process of tone mapping involves rendering high contrast images with considerably large color gamut on target medium having limited color reproduction and contrast. In other words, it is a process of transformation of HDR images into pixels that can be produced faithfully on display devices [2]. The main aim of this technique is to perform a compression of the huge dynamic range to a range which can be generated on physical devices that generally have a lesser dynamic range [6]. Furthermore, the goals of tone mapping, the methods employed in tone mapping and some of their applications have been found to be diverse.

1.2 Objectives of Tone Mapping

The objective of tone mapping is determined by the application and the field where it is to be applied. There is a need to categorize those objectives clearly so that there is no misconception or confusion regarding tone mapping. On the basis of the goal or objectives of tone mapping, the tone mapping operators have been classified [7] as:

- Scene Reproduction Operator: When a device with reduced contrast, peak luminance and color gamut is used for representing an image, these operators try to preserve the actual appearance of the image such as, sharpness, color and contrast. However, these make no attempt to simulate the changes in appearance of images resulting from perceptual effect like, loss of color vision or acuity in dark. These operators only concentrate on removing the drawbacks in the display device in order to obtain the real image in the given dynamic range with limited color gamut.
- Visual System Simulator: These are used for simulating the characteristics and limitations of visual systems e.g., such a tone-mapping operator can be used to reduce contrast as well as color in dark regions of an image or it may enhance glare in images. These can also be used to adjust the images to accommodate the differences in viewing conditions and real world adaptation conditions.
- Best Subjective Quality Operators: These have been developed for producing ideal images and videos in terms of artistic goals and subjective preference. These involve parameters that can be easily adjusted or customized as per the artistic goals. Photo-editing softwares e.g., Adobe Photoshop Lightroom is one such example.

The objectives that have been mentioned above might not be able to encompass all the aspects of tone reproduction/tone mapping and there are still some applications that have not found their place in any of those categories. Nevertheless, these objectives help us in outlining the differences in the expectations and basic assumptions in tone mapping and also attempt to elucidate the reason that no single best algorithm for tone mapping has been found. The goal or objective of tone mapping is particularly important for performing a comparison of the various tone mapping algorithms so that the algorithms with diverse goals are not put together [2].

1.3 Tone Reproduction Operators

The tone mapping operators are used for reduction of scene radiance contrast to the range that can be displayed on physical devices without any loss in colour appearance and details of the image. Numerous tone mapping methods have been developed for this purpose and have been classified broadly as: Global operators and Local operators [1].

- Global Operator (Spatially Uniform): These operators make use of a single mapping function that is spatially varying for all the pixels in the scene i.e., these apply the same transforming function to every pixel. These operators are easy to implement but at the same time there is loss in details of an image. The methods proposed by Ward, Pattanaik, Drago and linear mapping exemplify global operators [6].
- Local Operator (Spatially Varying): These operators make adjustments in the mapping function as per local pixel statistics i.e., their scales are customized to different regions within an image. Since sufficient number of parameters have to be modified experimentally, these are expensive computationally. The approaches given by Reinhard, Durand and Dorsey, and Ashikhmin are examples of local operators [2], [6].

The method to be selected for tone mapping depends on the requirements of the user as has been discussed earlier in this section. In certain cases, one approach may serve well than the other or the two approaches can be used in combination as well [1].

2. LITERATURE REVIEW

A variety of researches have been conducted on the tone-mapping techniques employed for generation of high dynamic range images. All have had the same motive i.e., determination of an algorithm that produces optimal quality images. In this section, advantages and limitations of some of the techniques have been conferred.

A novel approach based on non-linear Successive Mean Quantization Transform (SMQT) has been introduced for reliable conversion of HDRI to LDR images [8]. In this paper, the authors have proposed two methods, the first approach being carried out on the luminance channel and the other model has been applied on the RGB-colour space directly. These two methods have been compared to the existing standard methods and have produced visually analogous results. The proposed methods have been found to have the fastest processing speeds as observed on the single

CPU. The fastest reported processing speed in the said model has been found to be of the order of 12 FPS on VGA loaded with a 2.13 GHz processor in default mode. The investigation of the two methods have led to the conclusion that the model operated on the entire RGB channel has proven to have better properties in comparison to the one operated on the luminance channel in terms of reduced processing speed and the associated degradation of image. However, there is loss of information in terms of the actual tones of every color. Further enhancement in terms of processing speed and its effect on the quality of the image have been explored.

The authors in [9] have presented tone mapping technique for displaying HDR images on LDR display devices that is easy to use and is computationally efficient as well. The proposed method has been called Hierarchical Non-linear Linear (HNL) tone reproduction operator that is responsible for mapping pixels in two successive steps in a hierarchy. The first step is responsible for allocating suitable number of LDR display levels to diverse high dynamic intensity intervals based on the pixel density of the intervals. In the second step, HDR intensity intervals are linearly mapped to their respective LDR display levels. A single adjustable parameter having a linear relationship with the tone-mapped images is responsible for handling the allocation of LDR display levels to HDR intensity intervals. In this paper, it has been demonstrated that the results of the proposed methods result in good variety of HDR images with possible image enhancement.

In this paper [10], the authors have examined eight algorithms for rendering HDR images. An extensive comparison psychophysical experiment was designed which comprises of two sections capable of general rendering and grayscale mapping performances correspondingly. Evaluation of results was done by introducing an interval scale for preferences. The authors have found results indicating uniformity of tone mapping performances with the general rendering results. Further illustration of Dorsey and Durand’s bilateral fast filtering technique along with Reinhard’s photographic tone reduction has led to the conclusion that these methods show the best rendering performance. The main aim of this paper was to perform a thorough testing followed by assessment methodology based on the results obtained from the psychophysical experiment so as to provide a way to lead future researches in this field. In the future, the authors have decided to perform a performance testing based on the ability of reproduction accuracy for high dynamic range images together with chances to provide an integrated robust model having capabilities to render HDR images.

For successful reproduction of high dynamic images on low dynamic display devices, the authors in [11] have proposed a number of tone mapping operators capable to perform contrast compression. A number of fields were studied viz., image processing, photography and human visualization model to design an operator that will be able to tackle problems related to reproduction of HDR images on LDR displays. A vast number of researches conducted so far desire some evaluation to estimate their performances, which could be obtained no better than by the systematic perceptual evaluation. In the proposed paper, a psychophysical evaluation was done which compared real world scenes and HDR images on low dynamic display devices by their appearances. Seven tone mapping operators were used to tone map HDR images. The main focus of this paper was to evaluate, through psychophysical experiment, the differences that humans can perceive so as to determine the attributes which contribute to such differences when toned HDR images and corresponding real world scenes are compared to each other. Naturalness of the image, overall contrast, brightness and capability to reproduce details in bright and dark regions of the image with the corresponding real world scene was observed by the human subjects. Considerable differences have been observed in image perception resulting from distinct tone mapping techniques. The paper has successfully been able to produce clear distinction among local and global operators based on appearance and naturalness attributes. Analysis results have shown that the seven mapping operators used are having varying qualitative differences which affect the perception of scenes by humans thus enabling proper selection of algorithms for a specific application or evaluation of new approaches of tone mapping methods.

The proposed paper [12] has examined the effects of tone mapping algorithms on contrast brightness, reproduction of colors as well as details and the various artifacts affecting the HDR images. The authors were not able to obtain differences among the two methodologies, reason being evaluation of real world scenes as references. The general image quality was estimated by developing a relationship between the various attributes available, which showed that the contrast, brightness, artifacts and colour of an image are the major contributing factors which must be undertaken to evaluate perceptual quality analysis. However, it has also been revealed that the brightness attribute is assimilated through other attributes. Further, the authors also observed that there exists an agreement among rating any real world scene and ranking both the tone methods.

The authors [13] have proposed an algorithm which is time dependent, having the capability to map both the dynamic and static images, either rendered or photographed. The proposed algorithm is based on the perceptual model presented by Tumblin and Rushmeier [6]. Further, an eye adaptation model has also been included that is able to characterize colour as well as lightness. The proposed tone mapping operator was able to accept a diverse range of luminance levels and scenes with the property to take various adaptation factors into account. The operator was found to be ideal for dynamic scenes as human eye properties and various past psychology literature were taken into account. However, the only limitation that the operator was found to have was that it fails to contain the local eye adaptation methodology which is a key property for faithful visual appearance.

In the proposed paper [14], the authors have put forward an algorithm based on objective quality assessment for tone mapping of HDR images by taking a combination of two things: i) multi-scale measure of signal fidelity based on revised structural similarity index, ii) a measure of naturalness of image based on intensity values of real-world images. The authors have confirmed that there is a good correlation of the tone mapped quality index (TMQI) of the image with the subjective ranking score that was ascertained by subject-rated, independent databases of images. Further, the paper also demonstrates various applications of tone mapped quality index with the help of two examples viz., adaptive fusion of multiple tone-mapped images and parameter tuning of tone mapping operators. But it also has some limitations which the authors intend to resolve in future attempts like, only grayscale images can be evaluated using TMQI although most of the high dynamic range images are rich in color. An easier approach for the evaluation of the images produced by tone mapping is the application of TMQI to every channel independently and to combine them later. There should be enhancement in quality of images obtained by trying to improve color naturalness and color fidelity. Another drawback is the use of simple averaging in the pooling technique used for structural fidelity map. Thus, for the improvement in predicting the quality of images reproduced, visual attention replica should be incorporated in advanced pooling technique. Yet another limitation is the basis of the statistical naturalness measure on intensity values only. In order to enhance the statistical naturalness measure, advanced statistical approach should be included that displays the regularities in space, orientation and scale in real world images [15]. The next limitation has been found to be the usage of TMQI as the novel optimization objective by which most traditional tone mapping operators can acquire better quality of images. New tone mapping operators might be proposed by making use of the assessment of quality approach. Lastly, the proposed method has been tested and applied to real world images only.

This paper [16] presents a new metric for image quality that is capable to operate on a pair of images, both having arbitrary or subjective dynamic ranges. The proposed metric makes use of a human visual system model and its fundamental objective is a novel description of visible distortion on the basis of the categorization and detection of changes visible in the structure of the image. The authors have standardized the proposed metric carefully and have also validated its performance by means of perceptual experiments. The authors have also exhibited various applications of the proposed metric to evaluate inverse as well as direct tone-mapping operators. Also, the appearance of images on the display devices having several characteristics has been analyzed.

In this paper [17], authors have proposed an approach to remove ghost artifacts present in HDR images with no need to estimate motion of object/camera or detection of objects explicitly. The weights that are operated on pixels are worked out iteratively in order to determine the contribution of each weight on the resulting image. A non-parametric approach is used for the static region in a scene and its weight is determined by the membership of the pixel in the model. Therefore, no restrictions have been imposed on the background. The authors have made only one assumption i.e., the predominance of exposure sequence capturing the background in order that the pixels capturing the background are considerably large in number than the ones capturing the object. Thus, it is the pixel neighborhood that acts as a realistic background representation while the pixel’s membership probability acts as the weight for the pixel. Contrary to the prior techniques, this approach is independent of tracking, pixel-wise motion estimation or explicit object detection. Moreover, the effectiveness of this technique has been demonstrated through the ghost free images of various scenes.

In this paper [18], authors present an estimation of optical flow field among the various exposures and then deform those exposures independently so as to align the entire features of the scene accurately. In the same way, the paper presented by [19] makes use of optical flow based on gradient between consecutive frames so as to figure out a dense motion field. This is later utilized to deform the pixels in several exposures in order to produce ghost free image after averaging together the suitable values. Such techniques that depend on motion estimation have proved to fail in images with effects like, specularities, translucency and inter-reflections [19].

The author in [20] has addressed the issue of ghost artifacts in certain cases when the background and the object are of the same color. The author has applied the threshold on a metric derived from entropy that does not vary with the level of contrast in the given data. The portions of an image possible to be detected as ghost regions are then replaced with single exposure values. Although this solution works for many images, it fails when ghost artifacts are present in regions where there is high dynamic range.

In the proposed paper [21], the authors have conducted experiments in tone mapped images that concentrate on contrast perception only. They have made use of HDR images generated artificially so as to manage various other complex factors present in the natural HDR image.

Six tone-mapping algorithms were perceptually evaluated in terms of preference and similarity by authors in [22]. In this paper, a set of four high dynamic range images were compared pair-wise with six tone-mapping operators and then subjects were told to assess the difference between the two when displayed on the screen. About eleven subjects performed multi-dimensional perceptual scaling of the data which showed the two most significant stimulus dimensions in space. Those dimensions were found to be detail and naturalness of images. Also, the best preference point was identified in the stimulus space.

The authors in [23] have evaluated six tone reproduction methods after making a comparison of the images generated on HDR display devices. The display devices permitted authors to involve a number of input images (about 23). Three images i.e., two tone-mapped scenes and their corresponding reference were simultaneously put forward before the subjects who had to select the scene closely resembling the reference. The subjective data were processed using statistical methods and the six tone-mapping methods were examined in terms of the overall quality of images and the reproduction of details and features.

In [24], authors have put forward a tone reproduction operator for high dynamic range images on the basis of a perceptual constancy model. Although the proposed approach was capable of generating attractive images, it had some limitations. Since it was not a quantitative model, it could not be predicted if the tone-mapped image would be visually similar to the real world scene.

Another tone reproduction operator was introduced by [25] that was capable of preserving visibility in the high dynamic range images. However, this method was based on a technique of histogram adjustment which makes use of local adaptation luminance of an image, as a result of which some regions of the images generated have highly enhanced contrast while other regions are intensively compressed.

Authors in [26] have conducted a review on many tone-mapping algorithms proposed for the conversion of HDR images into a dynamic range that is capable of matching the appearance of real world images. The authors have categorized those algorithms into Tone Reproduction Operators and Tone Reproduction Curves. In this paper, two important results have been obtained. Firstly, it was realized that algorithms based on TRCs are quite efficient besides being simple. This was because these are applied to the image data point-wise. Secondly, it was found that TROs attempt the preservation of the local contrast in an image since they make use of spatial structures of data.

The findings of the review work have been presented in a tabulated form in Table 1.

Table 1: Literature Survey

Author	Contribution	Result Obtained	Limitations
(Tumblin et al., 1997)	Developed tone mapping operator for HDR images based on the model of perceptual constancy	• Generates images that are attractive to the human eye	• Not a quantitative model thus cannot predict if the image produced matches the scene visually
(Larson et al., 1997)	Presented visibility matching tone reproduction operator for HDR scenes	• Computationally simple therefore beneficial in real-time applications	• Loss of image features visible to human eye • Low contrast images generated • Unable to fine-tune visualization appearance flexibility in accordance with diverse user's preferences
(Pattanaik et al., 1998)	Developed a computational, multiple-scale adaptation model and spatial vision for tone reproduction of realistic images	• Images displayed match scene perception at threshold as well as supra-threshold levels to the possible degree for a given device • Applicable to image compression methods, image quality metrics and perceptually-based image synthesis algorithms	• Static vision model as it doesn't take into account illumination levels varying dynamically • Generation of inverse gradients besides appearance of halo at the proximity of high levels of luminance gradients
(DiCarlo and Wandell, 2000)	Classified tone mapping algorithms as Tone Reproduction Curve and Tone Reproduction Operator based	• TRO based algorithms preserve local contrast in the scenes to be displayed • TRC based methods are simple as well as efficient	• Tone Reproduction Operator based algorithm proves to be computationally expensive • Reduced spatial sharpness in images generated by Tone Reproduction Curve
(Qiu and Duan, 2005)	Presented computationally efficient hierarchical non-linear tone mapping technique that is easy to use realistically	• Adaptable and simple technique that makes use of only one parameter that is to be adjusted • Can be utilized to enhance the ordinary images effectively	• Can lead to loss of contrast in images produced
(Aydin et al., 2008)	Developed a new metric for quality assessment that is	• Reveals supplementary facts regarding nature of images in	• Profound penalization of global amplification error

	proficient in dealing with pair of images having randomly diverse dynamic ranges	contrast to prior approaches • Successfully applied to evaluate TMO and iTMO operators	• Meagerly castigates artifacts that are particularly bothersome to a common viewer
(Nilson, 2013)	Proposed two new non-linear SMQT based tone mapping operators	• Fast processing speed than all the traditional techniques • Images generated are visually similar to other existing TMOs	• Loss of information in terms of actual color tones of the image
(Yeganeh and Wang, 2013)	Put forward an objective for assessing quality of images using a combination of statistical naturalness measure and multiple scale structural fidelity measure	• Produces quality images in general • Generates multiple scale quality maps which reveal structural fidelity changes across space and scale • Practical correlation of TMQI with subjective image quality evaluation	• Evaluates only grayscale images • Simple averaging employed in the present pooling method of the structural fidelity map • Operated and experimented only on natural images • Basis of existing measure of statistical naturalness only on intensity statistics

3.OPEN ISSUES

The number of techniques developed for tone mapping high dynamic range images is enormous and are broadly categorized as Tone Reproduction Operator and Tone Reproduction Curve based methods. However, both these techniques have their drawbacks and advantages. After an analysis of these approaches, several challenges were imposed that need to be tackled.

- A number of parameters have to be set by the user for high dynamic image range reproduction in most of the techniques. This makes those methods somewhat difficult to be used. Also, setting those parameters involves several trial and errors since it is relatively ad hoc [2], [6], [7], [11].
- TRO based reproduction methods are found to be expensive computationally as they are based on multi-resolution spatial processing [26].
- TRC based reproduction approach cause considerable loss in the spatial sharpness of the reproduced images [26].
- These approaches, as discussed in the literature, have been found to have their own pros and cons when image quality, implementation, ease-of-use and computational complexity are taken into consideration. Thus, these tone mapping approaches might co-exist in near future [2], [13], [14], [18], [20], [24], [25].

4. CONCLUSION

Numerous tone mapping operators have been proposed till date. In this paper, some of the approaches used for tone mapping have been reviewed with a view to find out the pros and cons in the various methods. The sole aim of this analysis was to point out the shortcomings in the tone reproduction algorithms proposed so that new algorithms can be devised that are much better in visualizing high dynamic range (HDR) images on low dynamic range devices. The base for the new algorithm designed should be improved quality of service in terms of brightness, image contrast, color reproduction, apparent naturalness, reproduction of artifacts and details, etc. but at the same time, there should not be compromise with the ease of use in terms of the number of parameters that are to be set to obtain HDR images.

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