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Tone expansion using lighting style aesthetics

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ABSTRACT

High Dynamic Range (HDR) is the latest video format for display technology and there is a strong industrial effort in deploying an HDR capable ecosystem in the near future. However, most existing video content today are in Standard Dynamic Range (SDR) format and there is a growing necessity to upscale this content for HDR displays. Tone expansion, also known as inverse tone mapping, converts an SDR content into an HDR format using Expansion Operators (EOs). In this paper, we show that current state-of-the-art EOs do not preserve artistic intent when dealing with content of various lighting style aesthetics. Furthermore, we present a series of subjective user studies evaluating user preference for various lighting styles as seen on HDR displays. This study shows that tone expansion of stylized content takes the form of gamma correction and we propose a novel EO that adapts the gamma value to the intended style of the video. However, we also observe that a power function-based expansion technique causes changes in terms of color appearance. To solve this problem, we propose a simple color correction method that can be applied after tone expansion to emulate the intended colors in HDR. We validate our method through a perceptual evaluation against existing methods. In addition to this, our work targets 1000 nits HDR displays and we present a framework aligning our method in conformance with existing SDR standards and the latest HDR TV standards.

1. Introduction

High Dynamic Range (HDR) displays [1] are the latest advancement in commercial display technology. These HDR displays are characterized by a high peak brightness and contrast levels that increase perceptual details in dark and bright regions. This new generation of displays also have a Wide Color Gamut (WCG) [2] which provides a range of colors exceeding the gamut of current television. The combination of HDR and WCG on modern displays gives the viewer an unprecedented closeness to reality never seen on traditional Standard Dynamic Range (SDR) displays. In order to support this migration towards HDR television, an SDR to HDR conversion technique is essential at different stages of the video transmission pipeline. This would be beneficial especially in view of existing video libraries and infrastructure is mostly SDR.

Research refers to this conversion problem as *inverse/reverse tone mapping* or alternatively termed as tone expansion [3]. These tone *expansion operators* (EOs) attempt to process the SDR content in the best possible way so as to be displayed on an HDR monitor. As a result, they attempt to solve a typical ill-posed inverse problem where the additional dynamic range available in HDR displays is missing in SDR format. This information is often lost during acquisition when using an SDR camera in the form of sensor saturation. For content captured natively in HDR, this information has to be tone mapped in post-production as most professional displays are SDR. Most EOs attempt to solve this problem on strong a priori assumptions that lead to positive or negative results based on specific conditions.

In a recent study, De Simone et al. [4] presented a detailed user study suggesting that out of the many EOs in the literature, a simple linear operator gives the best results. However, as shown later on, such an approach does not preserve artistic intent particularly for complex lighting styles (extreme variation in luminance and contrast).

In this work, we extend upon the EO proposed by Bist et al. [5] based on lighting style for tone expansion by using mathematical models derived from user studies. We further improve this method by applying a color correction process after tone expansion. Our main aim is to display SDR content on an HDR monitor exploiting the available dynamic range and color gamut while fully preserving the artistic intent. Furthermore, unlike other EOs, our experiments have been implemented on a professional 1000 nits HDR display instead of prototype displays. We kept in mind that initial commercial HDR displays in the market are limited to 1000 nits and have oriented our work towards it. The main contributions of this paper are:

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- Lighting styles aesthetics for tone reproduction,
- User studies giving insights into human preference on viewing HDR content,
- A tone expansion technique that preserves artistic intent and is also faithful to reality,
- HDR color reproduction and correction for tone expansion,
- Industrial framework for tone expansion on commercial HDR displays compliant with emerging standards for HDR video.

This paper is structured as follows. Section 2 reviews the related work on tone expansion, HDR color reproduction, lighting styles, and gives an overview of current HDR television systems. Section 3 provides details of our tone expansion method with detailed user studies. In Section 4, we propose a color correction method specific to our EO. Section 5 shows our methods applied to an industrial framework. We present our results in Section 6 and conclude the paper in Section 7.

2. Background and related works

In this section we position our approach with respect to the current state-of-the-art tone expansion models. We explore some color correction techniques used in tone reproduction and also define lighting style aesthetics. Finally, we discuss the present day industrial scenario related to HDR technology.

2.1. Expansion operators (EOs)

The most basic EO is a global model where a single global expansion function is applied to every pixel of a SDR video. Akyuz et al. [6] have presented a series of psychophysical experiments to conclude that a trivial linear operation is sufficient to provide good HDR tone expansion. The paper further argues that a mean luminance is preferred over contrast. This method works well in optimum conditions such as for uncompressed well-exposed images. For the special case of over-exposed content, Masia et al. [7] have found that a nonlinear tone expansion, in the form of an adaptive gamma (γ) correction, is sufficient for HDR displays. In real-world scenarios, particularly in the case of live broadcasting, these global methods are practical for real time applications. They are also the least complex and avoid temporal artifacts due to their frame-based nature [4]. However, when applied to video broadcast, a simple scaling tends to amplify the compression artifacts along with the camera noise. Furthermore, Masia et al.'s [7] adaptive γ correction method works very well for a specific test set of images but gives an artificial appearance when tested with different images.

More advanced tone expansion models are based on image segmentation. This family of EOs segments the SDR image into different regions (such as diffuse and specular highlights) and expands the segments accordingly. Meylan et al.'s [8] work detects specular highlights and diffuse parts of the image and applies a separate linear tone curve to both regions. Didyk et al. [9] and Wang et al. [10] also use EOs based on segmentation but require manual assistance. In a practical system, an automated approach would be more appropriate. The expansion map model is another approach that has been investigated in various works [11–13]. In these techniques, the expansion process is guided by an expansion map which gives the magnitude of expansion per pixel.

These tone expansion techniques provide credible insight into requirements for subjective visual quality and computational performance. The evaluation by De Simone et al. [4] clearly identifies the linear EO by Akyuz et al. [6] as the one giving best subjective results and also the least complex. Thus, we base our approach on a global model especially as local methods do not offer substantial gains in terms of video quality or reduced complexity. A general global model is based on the equation below:

$$Y_{HDR} = L_{max} \times Y_{SDR}^{\gamma} \tag{1}$$

where Y_{HDR} is the HDR luminance, L_{max} is the maximum luminance that can be supported by the display, Y_{SDR} is the SDR luminance and γ is an adaptive parameter that varies per frame. The work by Akyuz et al. [6] proposes a similar global expansion model with $\gamma = 1$ while Masia et al.'s [7] EO adapts the γ using the key which a statistic that measures the lightness or darkness of an image [14]. Masia et al.'s [7] method is based on user study of over-exposed content which shows that γ increases as content gets brighter. We align our work on similar user studies that model the choice of γ [15–17] considering not only well-exposed or over-exposed images but a variety of lighting style aesthetics.

2.2. Color appearance and reproduction in HDR

Color reproduction has been extensively studied on devices of limited dynamic range and color gamut in the context of tone mapping and gamut mapping [18–20]. However, very little is known on correctly expanding tone and gamut of legacy content on to next generation displays. From color appearance studies we know that a number of factors affect our color perception such as image size [21], luminance and color of background and viewing environment [22,23]. Perhaps the most important study for our work is the hunt effect which states that an increase in luminance level results in an increase in perceived colorfulness [24]. Factors such as the Stevens effect explain that we perceive a contrast change when adapting to different luminance levels [25] also have to be considered in tone expansion. Therefore, these appearance effects play an important role in accurate expansion of tones and color.

A new study by Abebe et al. [26] combines EOs with HDR color appearance models and evaluates them through psychophysical tests. Their work suggests that global expansion leads to better results and reproduction of contrast and luminance is more important than color in tone expansion. It also indicates that HDR color appearance models such as works by Kim et al. [27] and Reinhard et al. [23] are not always suitable for tone expansion. Thus in this paper, we refrain from using appearance models as they are used to predict perceived colors of a given stimulus under different viewing environments [28]. In our case, we attempt to reproduce cinematic colors [29] which are colors mastered by a professional color grading suite. This is later explained in Section 2.3.

Discarding appearance models as a possible color reproduction solution we seek inspiration from methods used in tone mapping for color correction. In tone mapping, the basic approach for color processing was introduced by Schlick [30] by replacing color channels as shown below:

$$R_{out} = \left(\frac{R_{in}}{L_{in}}\right)^{s} L_{out} \tag{2}$$

where R represents a color channel (red, green, or blue), L is the luminance channel, s is a color saturation parameter, and in/out indicates the channel before and after tone reproduction. It is known that mapping using only the luminance channel in the RGB color space with saturation at $s = 1$, often results in over-saturated images in tone mapping. The case when $s \neq 1$, may also lead to shifts in luminance. To avoid this effect, an alternative saturation adjustment was proposed by Mantiuk et al. [20]:

$$R_{out} = \left(\left(\frac{R_{in}}{L_{in}} - 1\right)s + 1\right)L_{out}. \tag{3}$$

This formulation preserves luminance however it creates slight