A survey on HDR visualization on mobile devices

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ABSTRACT

There is a vast body of literature concerning the capture, storing, transmission and display of High Dynamic Range (HDR) imaging. Nevertheless, there are few works that try to address the problem of getting HDR on mobile devices. Their hardware limitations, such as processing power, storage space, graphics capabilities and screen characteristics, transform that problem in a big challenge. However, since more and more HDR content is being produced and given that in a few years it can become a standard, it is necessary to provide the means to visualize HDR images and video on mobile devices. The main goal of this paper is to present a survey on HDR visualization approaches and techniques developed specifically for mobile devices. To understand what are the main challenges that need to be addressed in order to visualize HDR on mobile devices, an overview of their main characteristics is given. The very low dynamic range of most of mobile devices' displays implies that a tone mapping operator (TMO) must be applied in order to visualize the HDR content. The current status of the research on TMO will be presented and analyzed, a special attention will be given to the ones that were developed taking in account the limited characteristics of the mobile devices' displays. Another important issue is visualization quality assessment, meaning visualize HDR content without losing the main characteristics of the original HDR content. Thus, evaluation studies of HDR content visualization on mobile devices will be presented and their results analyzed.

Keywords: HDR imaging, mobile devices, Tone Mapping Operator, quality assessment

1. INTRODUCTION

The real world lightning brings to us a wide range of colors and intensities and the Human Visual System (HVS) can adapt itself in order to be able to perceive details in scenes that vary significantly in luminance. A real scene present luminance values that can be higher than 10^5 cd/m^2, in a sunny day, and around 10^{-3} cd/m^2, in a starlight night[1]. The HVS has the capability to capture instantaneously a contrast of around 100000:1 (5 orders of magnitude – log units)[2] and after sometime of adaptation it can achieve 10 orders of magnitude[3]. However, typical cameras and display devices cannot capture or display such a range of luminance. The High Dynamic Range (HDR) imaging has the purpose of capture, store, transmit and deliver real-world lighting in order to overcome the constraints of the conventional imagery technology. In the last years, several techniques have been developed to produce, store and visualize images and video that preserves the whole dynamic range captured by the HVS. Many commercial digital cameras can now produce HDR images and there were defined several formats to store them. In terms of digital devices there are a few that can visualize HDR image in their raw format, but they are too expensive to become available to the public in general. Typical display devices have a quite limited dynamic range of about 2 orders of magnitude, well below the dynamic range perceived by the HVS. Consequently, there is the need to scale-down the dynamic range while preserving the appearance of the HDR image by using a tone mapping operator (TMO). One can find in the literature several TMO proposals and many of them are now available in commercial or open source software that allows visualizing HDR images and video on typical display devices.

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The number of mobile phone users has been increasing over the years, with almost 6 thousand millions of mobile phone subscriptions in 2011[4]. The majority of the mobile devices that are sold nowadays have a built-in digital camera. A study[5] about mobile usage in December 2010, across the U.S, Europe (UK, Germany, France, Spain and Italy) and Japan, revealed that more than 50% of the mobile users take photos with their mobile devices. Moreover, the graphics and processing capabilities of the mobile devices, especially in smartphones, have been increasing. Another fact is that as HDR imaging is becoming a norm there is the need to allow the visualization of HDR images on mobile devices. Given the mobile devices hardware limitations, such as processing power, storage space, graphics capabilities and screen characteristics, HDR visualization on mobile devices deserves a specific study.

Nevertheless, there are few works that address the problem of getting HDR on mobile devices. Most of the work that address HDR on mobile devices are recent[6-8] and their main goal is mainly on capturing HDR image or video using the built-in digital camera. There are some TMO[9] that were developed to take in account different display devices on the generation of the tone mapped image, including the mobile devices displays. However, most of the TMO were developed for visualization on typical CRT or LCD display devices. As was shown recently[10] the visualization of tone mapped images on the mobile devices' small screen deserves a specific study and the development of a devoted TMO.

This paper goal is to present a survey on current HDR visualization approaches and techniques, discussing how those techniques perform on the small screen of the mobile devices and with a very low dynamic range. To understand what are the challenges faced with the HDR visualization on mobile devices, this paper begins with a brief overview about their main characteristics. Hopefully, this review will allow identifying their limitations and provide some knowledge on how to overcome those limitations. Tone mapped image quality assessment will also be addressed because it is important to evaluate to how extent their visualization on mobile devices is perceptual similar to the original scene. This paper ends with some final remarks and points out some possible directions to future research.

2. MOBILE DEVICES CHARACTERISTICS

Between regular cell phones, smartphones and more recently PADs, the number of mobile devices remains steadily increasing in the world. Another recent reality, mainly in smartphones and PADs, is the "always connect" feature that they have gained through flat-rates, which enable cheaper mobile Internet access at an acceptable bandwidth. Having a mobile devices proliferation with affordable internet access means contents: delivering diversified multimedia contents[11-13] to each and every mobile device is an immense market which is only now beginning to be tapped.

However, it is known that mobile devices have hardware limitations which can hinder both supported applications as well as capturing or reproducing multimedia contents. As mobile devices hardware and software rapidly evolve over time and they approach smaller sized pocket computers, delivered multimedia contents may be of better quality. This is where HDR contents visualization gets in.

Presently, mobile devices main hardware limitations regarding graphics are power supply, processing power, physical display size, graphics characteristics, limited memory, floating point operations support and storage size[8, 11, 12, 14]. Next are a few remarks regarding some of the characteristics listed above:

- Power Supply: Being mobile devices battery powered and the graphics display together with constant/heavy processing the main power hoggers, trying to visualize high quality multimedia contents in mobile devices can be a problem[11].
- Processing Power: Despite the steady growth of processing power in mobile devices it still very limited. For example, many of the present processors do not support floating point operations[8, 14]. Some of the high-end recent mobile devices have already a dedicated graphics processing unit which relieves the general purpose CPU for other necessary operations, improves performance and reduces power consumption as it is task optimized[11].
- Physical display size and graphics characteristics: Mobile devices are mostly handheld or pocket size having small display sizes, with the exception of PADs which have larger ones. The detail and quality of multimedia contents that can be presented in such small displays, with less colors available, lower and unusual resolutions, can dispute the need of having HDR visualized on mobile devices. Having new display technologies being introduced in high-end mobile devices, such as the still expensive AMOLED family - which do not need a

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backlight, consume less power and have a superior contrast ratio when regarding regular LCDs - and having better resolutions like the iPhone 4 with 640x960 (the regular resolution is around 480x800)[15], together with more and more HDR contents that are being produced, implies that HDR contents visualization in mobile devices must be thoroughly studied[12].

3. TMO ON MOBILE DEVICES

The tone mapping concept was first introduced, in the computer graphics field, by Tumblin and Rushmeier in 1993[16], which was not a new concept since that for a long time artists and photographers have been using it. The goal of a TMO is to compress the dynamic range of an image to the limited range of the display where it will be seen, while preserving the original perceived contrast. This means that the TMO must take in consideration the display device characteristics, which is particularly important in the case of the mobile devices' displays. In the last years several TMO were proposed that use a mapping function to compute the new image intensities values in order to be possible to visualize it in the display device. There are several ways to do this mapping operation, but always having in mind that the tone mapped image visualization on the display device should provide a similar view experiencing to the real scene visualization. Thus, usually, in the tone mapping process are used visual models which are derived from the HVS study.

Since in the literature one can find a large number of TMO proposals, in this paper are only presented the main characteristics of tone mapping process and based on that are defined some classes of TMO. For each of these classes their advantages and limitations are presented and a special attention will be given to their application on mobile devices. An overview of several TMO algorithms can be found in some books[2, 17] and survey papers[18].

When the TMO maps each pixel based on its intensity and on some global image characteristics, regardless of the pixel's spatial location, the TMO is classified as global (e.g. [19, 20]). If it takes into account the pixel's surroundings in the mapping operation, then the TMO is classified as local (e.g. [21, 22]). This means that a pixel of a given intensity will be mapped to a different value depending on whether it is located in a dark or bright area. The global TMO are simpler and faster than the local ones, which make them a good choice to implement on mobile devices. However, they are not suitable to be applied on very high dynamic range images, in which the intensity change from region to region can be significant. The local TMO deals very well with high dynamic ranges images but it can produce halo artifacts in regions with abrupt change in the luminance values, for instance near light sources. One way to solve this problem is to choose the right dimension of the neighborhood such that there is not an abrupt change in the intensity.

Another important aspect is adaptation to illumination changes over time. If the TMO takes in account the HVS adaptation over time it can be designated as time-dependent (e.g. [23, 24]), otherwise is designated as time-independent (e.g. [25, 26]). The former class of TMO is useful in HDR video visualization. Their implementation in mobile devices can be a challenge since they must be processed at interactive rates.

Most of the TMO compress intensities values but a few work on different representations. Some TMO transform the image to the frequency domain (e.g. [27]) and others to the gradient domain (e.g. [28, 29]). The compression is usually done only in the luminance channel, with no change in the chromatic channels. But in some TMO the compression is done in the three RGB (e.g. [22]) or LMS (e.g. [30]) color channels.

The table 1 presents a taxonomy for the TMOs analyzed on this work. This taxonomy classifies each TMO according to three dimensions, the spatial, time and domain dimensions.

One simple way to perform the dynamic range compression is using a linear mapping, which is equivalent to multiply the world luminance values by a scale factor to obtain the display luminance values. There are some TMO that follows this strategy (e.g. [23, 31]). However, a linear mapping may result on the loss of detail in brighter and darker areas, which for very high dynamic range images can be a problem. The HVS response curves have a non-linear nature which points out to the necessity of using non-linear mapping functions on the TMO design. Actually, most of the TMO proposals are based on the knowledge of the HVS mechanisms and follow a visual adaptation model. Some of the TMO use a visual model derived from the photoreceptor adaptation model (e.g. [19, 32]) and others from the threshold-versus-intensity (TVI) model (e.g. [23]), which are equivalent [2]. Nowadays, the interest on the use of color appearance models in TMO design have been increasing, which resulted on several TMO proposals (e.g. [33, 34]). Another set of TMO use perception or engineering-based approaches (e.g. [20, 35]).

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Table 1. A TMO taxonomy. It classifies the TMOs according to the spatial, time and domain dimension.

TMO	Spatial	Time	Domain
Brightness-preserving operator[16] – Tumblin1993	Global	Independent	Intensity
Spatially nonuniform scalling[21] – Chiu1993	Local	Independent	Intensity
Uniform Rational Quantization[19] – Schlik1994	Global	Independent	Intensity
Ferwerda visual adptation model[23] – Ferwerda1996	Global	Dependent	Intensity
Retinex TMO[22] – Rahman1996	Local	Independent	Intensity (log)
Histogram adjustment[20] – Ward1997	Global	Independent	Intensity (log)
Multiscale observer model[30] – Pattanaik1998	Local	Independent	Intensity
Low Curvature Image Simplifier[28] – Tumblin1999	Local	Independent	Gradient
Time-dependent visual adaptation[24] - Pattanaik2000	Global	Dependent	Intensity
Photografic Tone Reprodution[36] - Reinhard2002	Local	Independent	Intensity
TMO Algorithm for High Contrast Scenes[26] - Ashikmin2002	Local	Independent	Intensity
Adaptive Gain Control[25] - Pattanaik2002	Local	Independent	Intensity
iCAM[33] - Fairchild2002	Local	Independent	Intensity
Fast Bilateral Filtering[27] - Durand2002	Local	Independent	Frequency
Gradient Domain Compression[29] - Fattal2002	Local	Independent	Gradient
Drago Logarithmic Mapping[37] – Drago2003	Global	Independent	Intensity
Segmentation-based approach[38] - Yee2003	Local (Segmentation)	Independent	Intensity
Reinhard and Devlin photoreceptor model[32] – Reinhard2005	Global	Dependent	Intensity
Subband encoding[39] - Li2005	Local	Independent	Frequency
Lightness Perception[35] - Krawczyk2005	Local (Segmentation)	Independent	Intensity
Model of human cones[40] - Van Hateren2006	Global	Dependent	Intensity
A Retinex-Based Operator[41] - Meylan2006	Local	Independent	Intensity
iCAM06[34] - Kuang2007	Local	Independent	Intensity
Exposure Fusion[42] - Mertens2007	Local (Segmentation)	Independent	Intensity
Display-adaptive tone reproduction[9] - Mantiuk2008	Local	Independent	Intensity

In fact the HVS performs, with success, a dynamic range compression since the signal-to-noise ratio of the individual channels of the visual pathway is of 32 to 1, which is less than 2 orders of magnitude. Thus, if a TMO uses a visual model to convert to perceived values, then the observer will perform a second conversion too, which can lead to undesired results. Therefore, some authors[2] argue that the tone mapping process must be done in two steps: a forward

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adaptation and an inverse adaptation. In the forward adaptation it is determined how the HVS will perceive the real scene based on the scene luminance values, the scene attributes and on a visual adaptation model. The inverse adaptation step will map the output of the first step to display luminance values using an inverse adaptation model and taking in consideration the display attributes. The goal is to obtain a set of display luminance values that will be perceived by the HVS as the real scene luminance values. Several TMO (e.g. [16, 34]) follow this approach, including all the ones that use color appearance models. This approach is particularly important for the mobile devices since it uses an inverse display model, where can be included the limited characteristics of the mobile devices' display. This way, hopefully, one can have TMO that works well on several types of display devices. Actually, in practice this is not true. In Reinhard et al.[2] it is shown that apply an inverse display model after a forward visual model do not give always a good result, indeed it can result on images with too much contrast for the output display. Mantiuk et al.[9] presented a solution to this problem by proposing a TMO that uses a slight different two-step approach. Instead of stating that the perceived responses from the real world and the perceived responses from the display devices are equal and then use an inverse display model to compute the displayable image values, it changes the tone mapping parameters values in order to minimize the difference between the two perceived responses. This minimization problem is defined as a quadratic program and simplified to guarantee that it have a unique solution. The display model accounts for the limited capabilities of the display devices as well as the viewing conditions, such as the ambient light that is reflected by the display surface. The behavior of the TMO was simulated for the visualization of HDR images on a mobile display under different illumination conditions. However, the TMO was not tested on real mobile devices.

The table 2 presents for each TMO their main characteristics.

4. TMO EVALUATION

Tone mapped image quality assessment can be done using subjective or objective evaluation. The former is human perception based and the latter is physical measurement based.

4.1 Subjective evaluation

In recent years some TMO evaluation and comparisons have been done using psychophysical experiments. In these experiments the participants compared tone mapped images obtained by different TMO. These studies differ from each other in many aspects. It follows a brief description of the most often referred in the literature.

In 2003, Drago et al.[43] defined a methodology to compare existing TMO in order to better understand their strengths and weaknesses. They applied the methodology in a psychophysical experiment where it were evaluated 6 TMOs using a pairwise comparison. The 24 images, corresponding to 4 different scenes, were displayed in two CRT displays and evaluated by the 11 participants with relation to three attributes: detail, naturalness and contrast.

Yoshida et al. conducted a psychophysical experiment that compared directly the tone mapped image displayed on a LCD monitor with the real-world scenes[44]. Besides to evaluate the differences in how the tone mapped images were perceived the experiment aimed to find out which attributes of image appearance account for these differences when tone mapped images are compared directly with their corresponding real-world scenes rather than with each other. For each of the 2 scenes were created tone mapped images by applying 7 different TMO, being one of them a linear TMO. The participants evaluated the 14 tone mapped images by comparing the image with the corresponding real scene according to contrast, brightness, naturalness and detail attributes.

Ledda et al. used, for the first time, an HDR display device for TMOs evaluation[45]. The main purpose of this study was to determine which is the best TMO and to propose an experimental methodology to evaluate such operators using a HDR display. In this methodology, the participant must choose between two tone-mapped images, using a pairwise comparison, having as reference the HDR image shown in the HDR display. According to the authors, the use of the HDR image as an alternative to the real scene has the advantage of use a controlled environment, which allows testing with a large set of images including outdoor scenes. In these experiments the participants evaluated 138 images, resulting from the application of 6 TMO to 23 HDR images of different real scenes, in two rounds. In the first round the participants evaluate the similarity with the reference image and in the second one they judged the images based on the detail reproduction.

Table 2. TMO main characteristics.

TMO	Approach	Adaptation steps	Goal
Tumblin1993[16]	Brightness perception model	Two-step	Preserve brightness
Chiu1993[21]	Spatially Nonuniform Scaling Transformation	Forward adaptation	Preserve local contrast
Schlik1994[19]	Photoreceptor adaptation model	Forward adaptation	Preserve contrast
Ferwerda1996[23]	TVI model	Two-step	illumination changes adaptation
Rahman1996[22]	Multiscale Retinex model	Forward adaptation	Preserve the visual acuity;
Ward1997[20]	Histogram adjustment	Forward adaptation	Illumination changes adaptation"
Pattanaik1998[30]	Color appearance model	Two-step	Preserve local contrast
Tumblin1999[28]	Painting Techniques / low curvature image simplifier	Forward adaptation	Preserves visibility and contrast
Pattanaik2000[24]	Photoreceptor adaptation model	Forward adaptation	Preserve Color appearance
Reinhard2002[36]	Photographic Techniques Principles	Forward adaptation	Preserving local contrast
Ashikmin2002[26]	perserve local contrast / TVI model	Two-step	Illumination changes adaptation
Pattanaik2002[25]	Visual adaptation model + Adaptive gain control to decide the size of the neighborhound	Forward adaptation	Contrast and detail preservation
Fairchild2002[33]	Color appearance model	Two-step	Preserving local contrast
Durand2002[27]	Bilateral Filtering	Forward adaptation	Preserve detail in lighted and darker areas
Fattal2002[29]	Apply a compressive function to the gradient field	Forward adaptation	Preserve Color appearance
Drago2003[37]	Adaptive logarithmic response curve	Forward adaptation	Preserving local contrast
Yee2003[38]	Local visual adaptation	Forward adaptation	Preserving local contrast
Reinhard2005[32]	Photoreceptor adaptation model	Forward adaptation	Contrast and detail preservation
Li2005[39]	Band-pass filtering	Forward adaptation	Contrast and detail preservation
Krawczyk2005[35]	Lightness Perception	Forward adaptation	Light and chromatic adaptation
Van Hateren2006[40]	Human Cone model	Forward adaptation	Range compression and noise reduction
Meylan2006[41]	Surrond Retinex model	Forward adaptation	Reproduce the lightness perception
Kuang2007[34]	Color appearance model	Two-step	Illumination changes adaptation
Mertens2007[42]	Blends multiple exposures	Forward adaptation	Preserves local contrast and prevents halo artifacts
Mantiuk2008[9]	Contrast transducer function	Two-step	Preserve Color appearance

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In 2006, Cadik et al., presented an overview of image quality attributes of different TMOs and proposed a schema of relationship between these attributes leading to the definition of an overall image quality measure[46]. They conducted subjective psychophysical tests to prove the proposed relationship scheme and the results were used also to evaluate existing tone mapping methods with regard to these attributes. In each test the participants evaluate the tone mapped images in terms of the overall image quality, and four basic attributes – brightness, contrast, reproduction of detail and reproduction of colours. A total of 14 tone mapped images of an indoor real scene, resulted from the application of 14 different TMOs, were used in the two experiments. In the first experiment the images were evaluated with respect to the real scene. In the second one they ranked the 14 images according to the same set of attributes. In 2008, Cadik et al, extended their previous work with 2 new scenes (an outdoor scene and a night scene) using an identical design setup[47].

The work done by Ashikhmin and Goyal, in 2006, showed the importance of using the real scene as a reference to meaningfully judge and compare relative performance of tone mapping techniques[48]. There were conducted three psychophysical tests, where only in the last one the real scene was used as a reference. In this last experiment, for each one of the 20 tone mapped images, corresponding to 4 scenes and 5 different TMO, its similarity with the real scene was evaluated. In the first two experiments the participants evaluated the images without using any reference, and identified, respectively, the preferred one and the most natural one.

In 2007, Kuang et al, also made an evaluation of tone mapping algorithms trying to find out the "best" TMO currently available[49]. They proposed a new generic psychophysics based evaluation framework for testing TMOs. They conducted a total of four psychophysical tests which evaluate the TMO taking in consideration the participant's preference or the similarity with the real scene. In the first two experiments there were used 12 synthetic HDR images and applied 6 TMO, obtaining a total of 72 images, that were evaluated using a pairwise comparison method. In the last two experiments tone mapped images of 3 real scenes, after being applied 7 different TMO, were evaluated. In the third experiment the 21 images were evaluated using a pairwise comparison method, without a reference, and in the fourth one the images were compared with the real scene.

None of the above experiments evaluated the visualization of tone mapped images on mobile devices. Urbano et al. performed an evaluation study of currently used TMOs using different types of displays, including mobile displays[10]. Their main goal was to verify whether or not the development of TMOs specifically to small screen devices (SSD), like the mobile displays, needs a special and different approach comparing with the existing ones. The idea was not to obtain a new ranking of TMOs but to show that the ranking is different for SSD. The images were shown on three types of displays, a 17'' CRT, a 17'' LCD and a 2.8'' PDA display. For each type of display were presented 7 tone mapped images resulting from 7 TMO and evaluated using a pairwise comparison method but having the real scene as a reference. For each pair they evaluate 4 attributes: colour, detail, contrast and naturalness. The results show that the limited size, resolution and colour depth of SSDs require a different approaching when tone mapping HDR images for display on such a device. From this work it is also point out that, based on the experiment results, some image characteristics need to be emphasized by the TMO to SSD, such as stronger detail reproduction, more saturated colours and overall brighter image appearance.

In the subjective TMO evaluation studies it is used a comparison method. This comparison can be made comparing the tone mapped images with each other, resulting only a preference ranking. Another way is to compare the tone mapped images with a reference, which can be the real scene or the HDR image visualized on a HDR display. Both approaches possess advantages and disadvantages. The use of the real scene as a reference allow a more truth comparison but in the case of an outdoor scene and even in some indoor scenes, if there is no control on the illumination, for instance in the presence of a window, the comparison task can be difficult. The use of a HDR image visualized on a HDR display as a reference gives more control over the visualization conditions, and allows to testing more types of scenes. However, the HDR image does not completely represent the real scene. In the case of TMO evaluation on mobile devices we suggest the use of the real scene as reference and the experiment must be conducted under controlled illumination conditions. If we want to evaluate the behaviour of the TMO under different illuminations conditions, for instance view the image in the mobile display under sunlight, then it is not used any reference. The use of a HDR display can be very difficult because there is not any HDR display for mobile devices. Of course, that we can display a smaller image in the HDR display and simulate the visualization of the HDR image on a mobile device but it is not a simple process neither guarantees good results.

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4.2 Objective evaluation

The most widely used method to assess TMOs is subjective evaluation. Although these techniques provide useful information in studying the performance of TMO, they have some important drawbacks. First of all, subjective experiments are often very extensive and time-consuming. Secondly, the results from these evaluations are difficult to be included into the optimization of the TMO. Third, subjective experiments may not be able to provide a complete evaluation because some details of HDR images are invisible to human subjects[50].

Although typical objective image quality metrics cannot be directly applied to HDR images because they assume that the dynamic range of compared images is the same[51], few objective methods to assess TMOs have been very recently developed. Mantiuk et al.[52] proposed an HDR version of the visible difference predictor (VDP) that can predict the difference between two HDR images taking into account the full luminance masking. Kung et al [53] developed the iCAM framework, which is capable to model HDR images appearance and predict difference statistics. Smith et al.[54] presented a TMO evaluation tool to measure threshold contrast distortions between the original HDR image and its tone mapped LDR image. As a drawback, this metric have limited sensitivity to high frequency details and is excessively sensitive to small near threshold distortions. Aydın et al.[55] proposed a method to compare HDR-LDR images based on an advanced visual model of the human visual system (HVS). When comparing the two images, their algorithm produces quality maps, which showed good correlations with subjective classifications of image degradation (blur, no distortion, contrast, sharpening). Yet, this method does not provide a single overall quality score for an entire image because no spatial pooling is realized. Finally, based on the structural similarity index metric (SSIM)[51] and multi-scale SSIM[56], Yeganeh and Wang[50] developed an image quality metric that use the original HDR image to measure the quality of a given LDR image. Since SSIM cannot be applied directly to HDR images due to the fact that luminance and contrast comparisons are invalid across different dynamic ranges, they modified the multi-scale SSIM method to allow contrast comparisons. This method gives an overall quality score of the image and a quality map that indicate the local quality variations across scale and space. This model was recently improved with a naturalness assessment component[57].

5. CONCLUSIONS AND FUTURE WORK

This paper presented a survey on several aspects related with HDR visualization on mobile devices, including the identification of the mobile devices' main characteristics, a discussion on the tone mapping process and the analysis of TMOs evaluation.

Most of the TMO proposals were not designed specifically for mobile devices. Although, a few possess characteristics that make them suitable to be applied on mobile devices they were not yet fully evaluated on mobile devices. The use of a two-step approach seems to be the right direction to follow in order to get a TMO suitable for mobile devices. Though, the definition of the display model is critical and deserves a special attention. An in-depth study must be done to identify the best way to plug-in the two steps in order to get the desired effect.

The rankings obtained in the TMO evaluation studies are different and sometimes even contradictory. Moreover, only one of these studies has evaluated TMO on mobile devices, which was not designed with the objective of getting a ranking. Thus, there is the need to perform a thorough study to evaluate TMO on mobile devices. This study will help to understand the challenges facing HDR visualization on mobile devices.

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REFERENCES

[1] B. Wandell, [Foundations of Vision], Sinauer Associates, Inc., Sunderland, MA(1995).

[2] E. Reinhard, W. Heidrich, P. Debevec *et al.*, [High Dynamic Range Imaging, Second Edition: Acquisition, Display, and Image-Based Lighting], Morgan Kaufmann, Burlington, MA(2010).

[3] A. F. James, "Elements of Early Vision for Computer Graphics," 21, 22-33 (2001).

[4] www.itu.int/ITU-D/ict/facts/2011/material/ICTFactsFigures2011.pdf

[5] http://www.comscoredatamine.com/2011/02/top-mobile-activities-in-the-u-s-eu5-an-japan/

[6] T. K. Castro, A. Chapiro, M. Cicconet *et al.*, "Towards Mobile HDR Video," Eurographics, 30(2), 1-2 (2011).

[7] R. Mantiuk, J. Cybularczyk, M. Cichowicz *et al.*, "HDR Photographic Pipeline for Camera Modules in Mobile Devices," 77-78 (2011).

[8] R. C. Bilcu, A. Burian, A. Knuutila *et al.*, "High dynamic range imaging on mobile devices." 1312-1315.

[9] R. Mantiuk, S. Daly, and L. Kerofsky, "Display adaptive tone mapping," ACM Trans. Graph., 27(3), 1-10 (2008).

[10] C. Urbano, L. Magalhães, J. Moura *et al.*, "Tone Mapping Operators on Small Screen Devices: An Evaluation Study," Computer Graphics Forum, 29(8), 2469-2478 (2010).

[11] T. Capin, K. Pulli, and T. Akenine-Möller, "The State of the Art in Mobile Graphics Research," IEEE Comput. Graph. Appl., 28(4), 74-84 (2008).

[12] L. Chittaro, "Visualizing Information on Mobile Devices," Computer, 39(3), 40-45 (2006).

[13] C. Lindsay, E. Agu, and F. Wu, "Dynamic correction of color appearance on mobile displays," Proceedings of graphics interface 2008, 25-31.(2008).

[14] K. Choi, K.-A. Toh, and H. Byun, "Realtime training on mobile devices for face recognition applications," Pattern Recognition, 44(2), 386-400 (2011).

[15] http://beta.techradar.com/news/phone-and-communications/mobile-phones/best-phone-screen-display-tech-explained-951855

[16] J. Tumblin, and H. Rushmeier, "Tone Reproduction for Computer Generated images," IEEE Computer graphics and Applications, Vol. 13 (6):42-48.(1993).

[17] E. Reinhard, G. Ward, S. Pattanaik *et al.*, [High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting], Morgan Kaufmann, (2005).

[18] K. Devlin, "A review of tone reproduction techniques," Department of Computer Science, University of Bristol, Tech. Rep. CSTR-02-005, (2002).

[19] C. Schlick, "Quantization Techniques for Visualization of High Dynamic Range Pictures," 5th Eurographics Workshop on Rendering.(1994).

[20] G. Ward-Larson, H. Rushmeier, and C. Piatko, "A Visibility Matching Tone Reproduction Operator for High Dynamic range Scene."

[21] K. Chiu, M. Herf, P. Shirley *et al.*, "Spatially Nonuniform Scaling Functions for High Contrast Images." p. 245–253.

[22] Z.-u. Rahman, D. J. Jobson, and G. A. Woodell, "Multi-Scale Retinex for Color Image Enhancement," International Conference of Image Processing, 1003-1006.(1996).

[23] J. A. Ferwerda, S. N. Pattanaik, P. Shirley *et al.*, "A Model of Visual Adaptation for Realistic Image Synthesis," ACM Computer Graphics (Proc. of SIGGRAPH)'96, pp. 249-258.(1996).

[24] S. N. Pattanaik, J. Tumblin, H. Yee *et al.*, "Time-Dependent Visual Adaptation For Fast Realistic Image Display," ACM Computer Graphics (Proc. of SIGGRAPH)'00, 47-53.(2000).

[25] S. Pattanaik, and H. Yee, "Adaptive gain control for high dynamic range image display," 18th Spring Conference on Computer graphics, 83-87.(2002).

[26] M. Ashikhmin, "A Tone Mapping Algorithm for High Contrast Images," Thirteenth Eurographics Workshop on Rendering.(2002).

[27] F. Durand, and J. Dorsey, "Fast Bilateral Filtering for the Display of High-Dynamic-Range Images," ACM Computer Graphics (Proc. of SIGGRAPH)'2002, pp. 257-266.(2002).

[28] J. Tumblin, and G. Turk, "LCIS: A Boundary Hierarchy For Detail-Preserving Contrast Reduction," Proceedings ACM SIGGRAPH Conference 1999 Los Angeles, pp.83-90.(1999).

[29] R. Fattal, D. Lischinski, and M. Werman, "Gradient Domain High Dynamic Range Compression," ACM Computer Graphics (Proc. of SIGGRAPH)'2002, pp. 249-256.(2002).

Optics, Photonics, and Digital Technologies for Multimedia Applications II, edited by
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Proc. of SPIE Vol. 8436, 2012 SPIE CCC code: 0277-786X/13/$18 doi: 10.1117/12.924068

[30] S. N. Pattanaik, J. A. Ferwerda, M. Fairchild *et al.*, "A Multiscale Model of Adaptation and Spatial Vision for Realistic Image Display," ACM Computer Graphics (Proc. of SIGGRAPH)'98, 287-298.(1998).
[31] G. Ward, "A contrast-based scalefactor for luminance display," Academic Press Professional, Inc. 415-421 (1994).
[32] E. Reinhard, and K. Devlin, "Dynamic Range Reduction Inspired by Photoreceptor Physiology," IEEE Transactions on Visualization and Computer Graphics.(2005).
[33] M. D. Fairchild, and G. M. Johnson, "Meet iCAM: A next-generation color appearance model," 10th Color Imaging Conference, 33-38.(2002).
[34] J. Kuang, G. M. Johnson, and M. D. Fairchild, "iCAM06: A refined image appearance model for HDR image rendering," J. Vis. Comun. Image Represent., 18, 406-414 (2007).
[35] G. Krawczyk, K. Myszkowski, and Hans-PeterSeidel, "Lightness Perception in Tone Reproduction for High Dynamic Range Images," The European Association for Computer Graphics 26th Annual Conference EUROGRAPHICS 2005.(2005).
[36] E. Reinhard, M. Stark, P. Shirley *et al.*, "Photographic tone reproduction for digital images," Proceedings of the 29th annual conference on Computer graphics and interactive techniques.(2002).
[37] F. Drago, K. Myszkowski, T. Annen *et al.*, "Adaptive Logarithmic Mapping For Displaying High Contrast Scenes," Eurographics EG2003.(2003).
[38] H. Yee, and S. N. Pattanaik, "Segmentation and Adaptive Assimilation for Detail-Preserving Display of High-Dynamic Range Images," Visual Computers, 19, 7-8 (2003).
[39] Y. Li, L. Sharan, and E. H. Adelson, "Compressing and Companding High Dynamic Range Images with Subband Architectures," SIGGRAPH 2005, 24, 836-844 (2005).
[40] J. H. V. Hateren, "Encoding of high dynamic range video with a model of human cones," ACM Trans. Graph., 25, 1380-1399 (2006).
[41] L. Meylan, and S. Süsstrunk, "High Dynamic Range Image Rendering With a Retinex-Based Adaptive Filter," IEEE TRANSACTIONS ON IMAGE PROCESSING, 15, 2820-2830 (2006).
[42] T. Mertens, J. Kautz, and F. V. Reeth, "Exposure Fusion," 15th Pacific Conference on Computer Graphics and Applications, 382-390.(2007).
[43] F. Drago, W. L. Martens, K. Myszkowski *et al.*, "Perceptual evaluation of tone mapping operators," ACM SIGGRAPH 2003 Sketches & Applications.(2003).
[44] A. Yoshida, V. Blanz, K. Myszkowski *et al.*, "Perceptual evaluation of tone mapping operators with real-world scenes," SPIE.(2005).
[45] P. Ledda, A. Chalmers, T. Troscianko *et al.*, "Evaluation of tone mapping operators using a High Dynamic Range display," ACM SIGGRAPH 2005 Papers, 640-648.(2005).
[46] M. Cadik, M. Wimmer, L. Neumann *et al.*, "Image Attributes and Quality for Evaluation of Tone Mapping Operators." pages 35-44.
[47] M. Cadik, M. Wimmer, L. Neumann *et al.*, "Evaluation of HDR Tone Mapping Methods Using Essential Perceptual Attributes," Comput. Graph., 32, 330-349 (2008).
[48] M. Ashikhmin, and J. Goyal, "A reality check for tone-mapping operators," ACM Trans. Appl. Percept., 3(4), 399-411 (2006).
[49] J. Kuang, H. Yamaguchi, C. Liu *et al.*, "Evaluating HDR rendering algorithms," ACM Trans. Appl. Percept., 4(2), 9 (2007).
[50] H. Yeganeh, and W. Zhou, "Objective assessment of tone mapping algorithms." 2477-2480.
[51] W. Zhou, and A. C. Bovik, "A universal image quality index," Signal Processing Letters, IEEE, 9(3), 81-84 (2002).
[52] R. Mantiuk, S. J. Daly, K. Myszkowski *et al.*, "Predicting visible differences in high dynamic range images: model and its calibration." 5666, 204-214.
[53] J. Kuang, G. M. Johnson, and M. D. Fairchild, "iCAM06: A refined image appearance model for HDR image rendering," Journal of Visual Communication and Image Representation, 18(5), 406-414 (2007).
[54] K. Smith, G. Krawczyk, K. Myszkowski *et al.*, "Beyond Tone Mapping: Enhanced Depiction of Tone Mapped HDR Images," Computer Graphics Forum, 25(3), 427-438 (2006).
[55] T. O. Aydin, R. Mantiuk, K. Myszkowski *et al.*, "Dynamic range independent image quality assessment," ACM SIGGRAPH 2008 papers, 1-10.(2008).
[56] http://www.cgg.cvut.cz/members/cadikm/tmo

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Proc. of SPIE Vol. 8436, 2012 SPIE CCC code: 0277-786X/13/$18 doi: 10.1117/12.924068

[57] H. Yeganeh, and Z. Wang, "Structural fidelity vs. naturalness - objective assessment of tone mapped images," Proceedings of the 8th international conference on Image analysis and recognition - Volume Part I, 111-121.(2011).

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