Signal Processing: Image Communication 63 (2018) 100–112

Contents lists available at ScienceDirect

Signal Processing: Image Communication

journal homepage: www.elsevier.com/locate/image

Automatic saturation correction for dynamic range management algorithms

Alessandro Artusi [a,*], Tania Pouli [b], Francesco Banterle [c], Ahmet Oğuz Akyüz [d]

[a] KIOS Center of Excellence University of Cyprus, Cyprus
[b] Technicolor, Cesson-Sévigné, France
[c] Visual Computing Laboratory, ISTI-CNR, Pisa, Italy
[d] Middle East Technical University, Ankara, Turkey

ARTICLE INFO

Keywords:
High dynamic range imaging
Color correction
Gamut mapping
Tonemapping
Inverse/reverse tonemapping

ABSTRACT

High dynamic range (HDR) images require tone reproduction to match the range of values to the capabilities of a display. For computational reasons and given the absence of fully calibrated imagery, rudimentary color reproduction is often added as a post-processing step rather than integrated into tone reproduction algorithms. In the general case, this currently requires manual parameter tuning, and can be automated only for some global tone reproduction operators by inferring parameters from the tone curve. We present a novel and fully automatic saturation correction technique, suitable for any tone reproduction operator (including inverse tone reproduction), which exhibits fewer distortions in hue and luminance reproduction than the current state-of-the-art. We validated its comparative effectiveness through subjective experiments and objective metrics. Our experiments confirm that saturation correction significantly contributes toward the perceptually plausible color reproduction of tonemapped content and would, therefore, be useful in any color-critical application.

1. Introduction

Recent advances in both capture and display technologies allow images of a much wider dynamic range to be photographed, manipulated, and displayed; better capturing the light of natural scenes and giving artists unparalleled freedom. Although HDR standards and workflows are being defined and have begun to be adopted, they are not yet mainstream. As such, HDR technologies currently coexist with more prevalent consumer imaging pipelines [1]. HDR data often needs to be compressed for display on most current displays, a process known as tonemapping or tone reproduction. In contrast, existing low dynamic range (LDR) data may need to be expanded or reconstructed in order to fit the capabilities of emerging HDR display devices, a process known as inverse/reverse tonemapping (ITM) [2]. In both cases, the aim is to preserve the appearance and information content of an image as much as possible while ensuring that it can be displayed on the chosen display device. To achieve that, tonemapping and inverse tonemapping algorithms typically operate on the luminance of the image with little to no consideration for the color information present, leading to noticeable changes in the color appearance of the image, as shown in Fig. 1.

Commonly, luminance-compressed images acquire an over-saturated appearance when only the luminance channel is processed [6,7]. Image appearance models, which can be seen as tone reproduction operators with integrated color appearance management [4], are designed to reproduce color appearance, but they require calibrated images, precise knowledge of the scene in which the image was taken as well as measurements of the viewing environment and the display device itself. This makes these algorithms very useful in color-critical applications, but their requirement for measurements coupled with high computational complexity due to spatially varying processing limits their general applicability.

Some solutions exist for correcting saturation mismatches after tonemapping [7]. This leads to a computationally efficient correction, although hue and luminance shifts may be introduced. Moreover, they require manual parameter selection which is strongly image and tone reproduction operator dependent. Recently, a subjective study was conducted for defining an automatic model to derive the parameters necessary for such corrections, but only allows parameters to be predicted when the tone compression or expansion function is global [6]. In this paper, we therefore, present an efficient and effective color post-processing technique with the aim to relieve the user from having to set parameters, while being applicable to any form of image processing, whether spatially varying or not. This has the additional benefit that our post-processing can be applied even if the input image was manually touched-up, including but not limited to manual dodging and burning. Our work offers the following contributions and advantages: (1) Our novel algorithm is based on recent advances in perceptually linear

* Corresponding author.
E-mail address: artusialessandro4@gmail.com (A. Artusi).

https://doi.org/10.1016/j.image.2018.01.011
Received 10 August 2017; Received in revised form 30 January 2018; Accepted 31 January 2018
Available online 8 February 2018

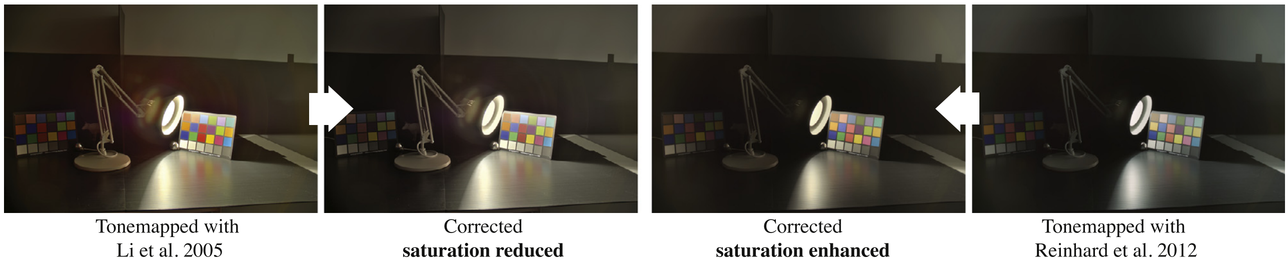

Fig. 1. The same HDR image was tonemapped with different operators (left — [3], right — [4]). The left tonemapped image is overly saturated, while the right image has reduced the saturation too far. With our method, both images are automatically corrected to have a similar appearance.
Source: Image from [5].

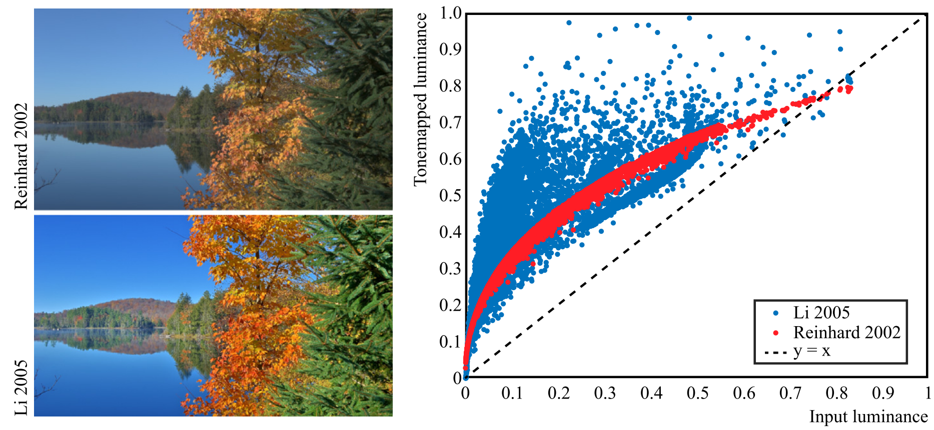

Fig. 2. Normalized input versus output luminance for two tonemapping operators. The parameters used are the one specified in their original work [8] and [3]. Note that each operator changes the relationship between input and output luminance in different ways leading to different types of saturation and hue shifts.

color-space and saturation computation. (2) Irrespective of the applied image processing technique or tonemapping operator, our algorithm is fully automatic and able to recover an accurate reconstruction of image saturation. (3) We take the gamut boundary of the output color space into consideration, leading to lower hue shifts and significantly lower luminance distortion. (4) We evaluate our algorithm by means of a subjective experiment and objective metrics, revealing that our algorithm reproduces saturation significantly better, as well as significantly reduces luminance distortions than the current state-of-the-art.

2. Hue and saturation correction

Tonemapping aims to compress the dynamic range of images and prepare them for display. Typically, this happens through a non-linear transformation of the luminance channel. The aim of tonemapping is then two-fold; images need to be processed so that their absolute luminance range is compressed, but pixel relations also need to be altered to maximize visible detail, therefore changing the contrast in the image. Changes to contrast and luminance, however, often lead to changes in the appearance of colors in the image and specifically in their saturation and hue. Furthermore, different tonemapping algorithms alter luminance and contrast in vastly different ways (Fig. 2), preventing a simple correction parameter to work for all cases. Thus, our algorithm is designed to correct the image's appearance while minimizing luminance and contrast modifications without requiring the user to set any parameter [9].

2.1. Algorithm overview

The input to the algorithm consists of two images given in a linear RGB color space: the tone compressed image $\mathbf{M}_t$ and the original, unprocessed HDR image $\mathbf{M}_o$ as it contains the original saturation and hue values that we aim to reproduce. In case the input tonemapped image is gamma corrected, an inverse gamma correction is performed to linearize its RGB values. The goal of our algorithm is to modify $\mathbf{M}_t$ such that it matches $\mathbf{M}_o$ in terms of hue and saturation, while preserving luminance values from the tonemapped image $\mathbf{M}_t$. Note that matching the *appearance* of saturation requires active non-linear management of saturation values to account for the Hunt effect [10]. Although HDR images are given in linear units, since in most cases accurate radiometric data is not available, their luminance values are inherently inaccurate. As such, we focus on contrast changes between the two input images and therefore normalize both $\mathbf{M}_t$ and $\mathbf{M}_o$ before converting them to the IPT color space, which has better hue uniformity than CIE $L^*a^*b^*$ and HSV color spaces [11]. Recently, a variant of the IPT space for HDR images, known as $hdr-IPT$ space, has been proposed. In this new space, the power function in IPT has been replaced with the Michaelis–Menten function to improve the behavior of the color space for very low and very high luminance levels [10]. We decided to not use this color space to avoid using different color spaces for tonemapped and HDR images.

As we need separate access to lightness, hue and colorfulness, we then convert to a cylindrical color space akin to CIE $L^*C^*h^*$. This space is based on IPT and therefore we refer to it as the ICh space, where I encodes lightness, C represents colorfulness and h is a measure of hue. The lightness channel I is not further processed because this was the main purpose of the preceding tonemapping operator. The hue in the tonemapped image h_t is subsequently set to the hue h_o of the original image, restoring any hue distortions that may have arisen due to gamut clipping during tonemapping. The quantity that needs to be matched between the HDR and tonemapped images is saturation (s). However, the aforementioned cylindrical color space produces colorfulness (C). Saturation is defined as colorfulness relative to lightness, i.e. $s = C/I$. However, a recent proposal to define saturation as colorfulness relative to the full magnitude of the stimulus, i.e. $s = C/\sqrt{C^2 + I^2}$ [12], provides more accurate results for our application.