HSV-DOMAIN ENHANCEMENT OF HIGH-CONTRAST IMAGES
Power Laws and Unsharp Masking for Bounded and Circular Signals

Alfredo Restrepo (Palacios), Stefano Marsi and Giovanni Ramponi
DEEI, University of Trieste, Via Valerio 10, Trieste, Italy

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Abstract: We present techniques for the amplification of small contrast of bounded signals; one is based on gamma correction and another is of an unsharp-masking type; the one of the unsharp-masking type is suitably modified for its application on circular signals as well. We enhance the saturation and luminance components of high dynamic range images on the basis of a segmentation of the image into light and dark regions.

1 INTRODUCTION

Image contrast results both from *luminance contrast* and from *hue contrast*. By a *High Contrast* (HC) image we mean an image (that typically corresponds to a high radiance range (Debevek and Malik, 1997) scene) with a luminance histogram having modes near 0 and 1, that correspond to very light and very dark regions in the image; such regions usually contain (perhaps unnoticeable) subregions at small contrast. The relatively low dynamic range of visualization devices makes it impossible to literally display HDR images. After rendering the scene radiance to image luminance, large radiance contrast is likely to be observable but *small contrast,* even though present in the resulting image, and probably observable in the original scene, may not be noticeable. Thus, HC images benefit from small contrast amplification that improves their quality and readability.

The luminance and saturation components of an image are normally coded in the interval [0, 1] while the hue is circulary coded in the interval [0, 2P) (we denote the angle pi with the letter P). Increasing maps that fix the points 0 and 1, such as the power law x^g, are appropriate for the modification of the magnitudes of luminance and saturation. In Section 2, we amplify luminance contrast using a variant map related to gamma correction. One other related tool is used for amplifying luminance contrast in Section 3 and, in a circular version, in Section 4, for amplifying hue contrast. The tools apply a variant map that fixes *local value* and has a high gain in the immediate vicinity of this local value. The map respects the bounded and (in the case of the hue) the circular natures of the magnitudes.

A high radiance range scene is typically composed of objects illuminated by direct and reflected or filtered light and, in some cases, radiant objects. We consider that saturation contrast should not be amplified and that the luminance component of an HC image can usually be meaningfully segmented into light and dark regions; we base a correction of luminance and color saturation of HC images on such a segmentation. For scenes where the eye of the observer is likely to be more adapted to the dark region than to the light region (e.g. an observer in a room with a window at daylight), we increase the saturation of the dark pixels using a power law and leave the usually-unsaturated light pixels as such; this gives realism to the resulting image; otherwise, e.g. in the case of an outdoors scene containing shadows, we take the reverse stance increasing the saturation of the light pixels only (the luminance of shadowed pixels is increased).

The lack of *true* or uniform color spaces can be a source of confusion; e.g. RGB functions are different from SLM photoreceptor responses, the psychophysical magnitudes of hue and saturation behave differently from the h and s variables in hsv color space. The Bezold-Brucke effect (Pridmore, 1999) predicts a clustering of (perceived) hues towards yellow (of oranges and cetrines) and blue (of violets and cyans) for large illumination intensities and another towards red (of oranges and violets) and green (of cyans and cetrines) for low illumination intensities; in both cases, the range of perceived hue decreases. On the other hand, it is likely that strong illumination clusters colors near the white corner of the RGB cube and near the black corner for low luminance. Both the hsv and the hsl color systems use the RGB range (i.e.

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the max minus the min) in the numerator of the definitions of the saturation variable; in the denominator, the hsv has min(2midrange, 2(1-midrange)) (the midrange is the average of max and min of RGB) while the hsl system uses the max of RGB. Thus, a decrease of the RGB range is likely to decrease the saturation in both cases. But the effect for light pixels in hsv is to decrease the saturation while increasing it for dark pixels; the hsl system increases the saturation values both cases.

Even though there is no consensus regarding a formula for the conversion of radiance into luminance, there is an agreement that it should be approximately logarithmic. We map the radiance r onto the [0, 1]-coded luminance X by means of the intermediate variable $Y = k.log(r)$ (k is a positive constant), compute its min (which typically is negative) and range (i.e. the max minus the min of Y) and put $X = (Y - min)/range$. For example, consider the use of the formula as applied to *image memorial.hdr* (k=1 and r was calculated as 0.3R+0.6G+0.1B), as shown in Figure 1.

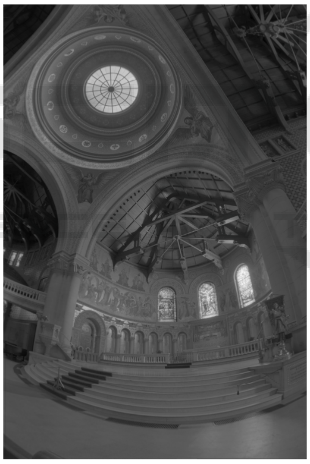

Figure 1: (logR+7.2)/13, applied to the radiance of memorial.hdr.

In addition to logarithmic nonlinearities, other types of nonlinearity have been considered for the rendering of HDR images; in particular, those suspected to play a role in the retina of vertebrates (Meylan et al., 2007). (Naka and Rushton, 1966) proposed the nonlinearity $V = 0.5(1 + tanh(x - x_0))$ (we have added the normalizing factor 0.5) to model the S-potential response to flashes of monochromatic light of (probably bipolar) retinal cells, where the variable x represents the log(I) of the intensity I. In terms of I, the nonlinearity becomes: $V = 0.5(1 + tanh(log(\frac{I}{I_0}))) = \frac{I^2}{I^2+I_0^2}$ which is closely related to the other nonlinearity they propose: $V_0 = \frac{J}{J+1}$, better known in the form $y = \frac{x}{x+x_0}$.

The enhancement of contrast for the visualization of HC images is a topic of actuality. Meylan and Susstrunk (Meylan and Susstrunk, 2006) locally enhance contrast within a retinex framework by computing a *local luminance* using a *mask* resulting from the convolution of the image and a Gaussian *surround function*. (Drago and Chiba, 1997) use a logarithmic law where the base of the logaithm is made dependant on a power law of the pixelwise (rather than local) luminance.

2 ON GAMMA CORRECTION AND CONTRAST ENHANCEMENT

(Unsigned) luminance contrast can be large or small; for [0, 1]-coded luminance, by *small local contrast* we mean a small luminance difference, e.g. less than 0.1; by *large local contrast* we mean neighbor pixels differing in luminance by a large amount, e.g. more than 0.3; we are concerned here with small contrast. We define the *small contrast amplification factor* (SCA) of a tone map as the value of the derivative of the mapping evaluated at the *local luminance* (which is measured using a *location statistic* such as the average, the median, the midrange of the luminances in the window. A [0, 1] $\rightarrow$ [0, 1] luminance map has different effects on small contrast at different luminances. For the power-law technique also known as *gamma correction* the luminance of each pixel is raised to a positive power; by using an exponent g larger (resp. lower) than one an image becomes darker (resp. lighter); this effect has been exploited in the restoration of faded prints (Restrepo and Ramponi, 2008); by looking at the derivative of the mapping it is seen that small contrast is improved where it matters, i.e. at small luminances when $g < 1$ and at large luminances when $g > 1$. Thus, it is conceivable to use an adaptive power law approach to improve the contrast of images; consider choosing an exponent that maximizes the SCA of a power law at the luminance of each pixel; from $\frac{d^2}{dgdL}L^g = 0$ one gets exponent $g(L) = -\frac{1}{log(L)}$. Instead of using it directly as in $l^{g(l)}$ (which gives a constant), we compute the corrected luminance as $A_{L,C}(l) = l^{1+(g(L)-1)C}$ where l is the original (pointwise) luminance and L and C are the *local* (rather than pointwise) luminance and contrast, suitably computed from the data in each window. Here, we use $L = 0.5l + 0.5N$ where N is the median of the data, and C = 0.5R+0.5Q where R is

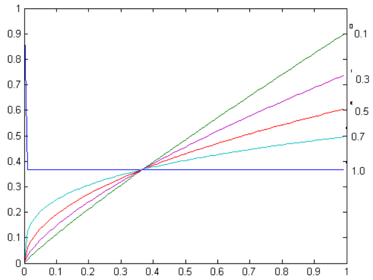

Figure 2: Plot of $A_{L,C}(L)$; for C = 0.1, 0.3, 0.5, 0.7 and 1.0 (indicated on the right). In each case, $A_{L,C}(L) > L$ if $L < \frac{1}{e}$ and viceversa; $\frac{1}{e}$ is a fixed point for each C.

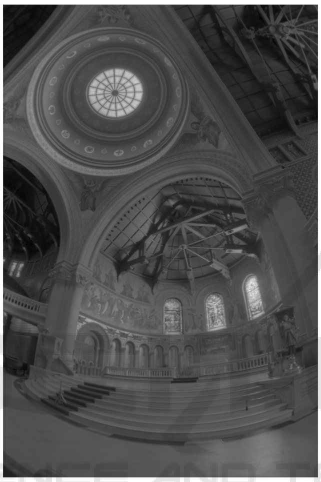

Figure 3: Result of the application of the gamma variant technique $A_{L,C}(l)$ to image in Figure 1.

the range and Q an inner quasirange of the windowed data (A. Restrepo and de la Vega, 1995). The maps shown in the figure darken light pixels (those with luminances above $\frac{1}{e}$,) and viceversa; this type of behavior is apropriate since, in HC images, both dark and light gray levels tend to cluster.

The 1D version of the technique performs as shown in Figure 4.

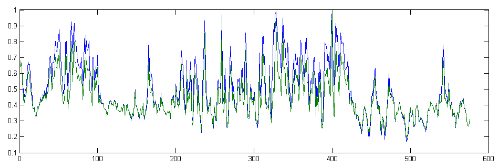

Figure 4: Application of the gamma variant technique to the column number 550 of the McGill-texture image merry-mexico0140.tif; original signal in green and contrast-enhanced signal in blue.

3 A TYPE OF UNSHARP MASKING FOR BOUNDED SIGNALS

A more direct approach to contrast enhancement along the lines of the technique of variant gamma correction described in the previous section is as follows; unlike more standard techniques for contrast enhancement, it explicitly takes into account that the magnitude being processed is bounded. Consider a family of increasing maps $f_l : [0,1] \to [0,1]$ with f(0)=0, f(1)=1. Then, for each pixel luminance l, depending on the local luminance L, one of the maps in the family of tone maps is applied, and the corrected luminance $f_L(l)$ results. The chosen map $f_L(l)$ is such that it has a large slope for pixel luminances l near the local luminance L; in this way, small contrast is amplified. Each map $f_l : [0,1] \to [0,1]$ in the family is a continuous function and moreover $f_L(L) = L$, so that it *fixes* local luminance; also, it has a convex derivative f'_L and $f'_L(l)$ has a maximum at $l = L$, increasing small contrast for luminances l near the local luminance L. The requirement that the functions be strictly increasing ensures that luminances (even those far off the local luminance) do not cluster near 0, 1 or any other intermediate level. The methodology can be catalogued as one of unsharp masking, even if of a special type, specifically designed to be applied to signals that live in the interval [0, 1].

In particular, consider the following family of functions

$$f_L(l) = l + h_1\left(\frac{l-L}{L}\right), l \in [0,L] \quad (1)$$

$$f_L(l) = l + h_2\left(\frac{l-L}{1-L}\right), l \in [L,1] \quad (2)$$

where the functions $h_{1,2}$ and are given by

$$h_1(x) = \frac{-c}{MAX}\frac{l}{3}(-x)^{\frac{1}{2n}}(1+x), x \in [-1,0] \quad (3)$$

$$h_2(x) = \frac{c}{MAX}\frac{1-l}{3}(x)^{\frac{1}{2n}}(1-x), x \in [0,1] \quad (4)$$

the functions h have infinite slope at x=0 (a related but independent approach has been used in (Velde, 1999)); the positive integer n controls the behaviour near the point of infinite slope, for our purposes, n=1 is enough; the constant MAX is given by $\frac{2n}{2n+1}(\frac{1}{2n+1})^{\frac{1}{2n}}$ and $c \in [0,1]$ is a constant that can be used for tuning the desired amount of masking.

The technique is of the unsharp masking type whenever the computation of the local luminance l involves an operation of the smoothing type, as it is usually the case (location estimators are usually considered as smoothers even though this is discussable).

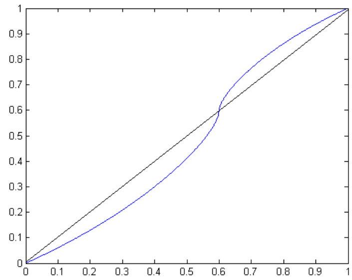

Figure 5: c=0.5, n=5, l=0.6.

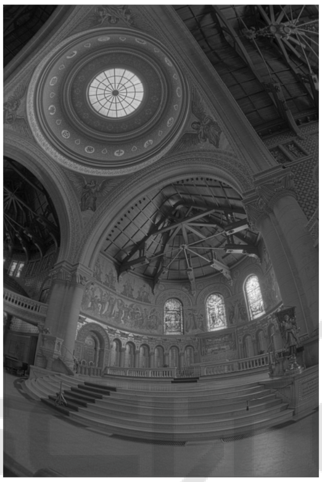

Figure 6: The image in Figure 1, after the application of bounded unsharp masking; c=0.3, n=1.

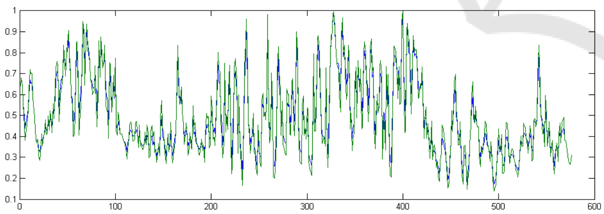

Figure 7: Application of the unsharp masking technique to the column number 550 of the McGill-texture image merry-mexico0140.tif; original signal in green and contrast-enhanced signal in blue.

The difference between the signal and the smoothed version is amplified accordingly. Figure 6 shows an example of the application of the technique to the image in Figure 1.

4 UNSHARP MASKING FOR CIRCULAR SIGNALS

The angular hue variable h of the hsv color system measures 0 degrees for RGB = 100, 120 degrees for RGB = 010 and 240 degrees for and RGB = 001; nevertheless, for better uniformity, yellow not being a *binary color* (it is possible to talk of *unique yellow,*) the perceptual difference between red and yellow and that between yellow and green, are the same as those between green and blue, and blue and red. Thus, we transform the hue variable h of the hsv and hsl systems to a *modified hue* H, also circular, as follows. For angles h between 0 and (2/3)P, put H=(3/2)h while for angles h between (2/3)P and 2P, put H=(3/4)h + (1/4)2P. It is also convenient to denote each angle x with the complex number e^{jx}, where $e^{j0}, e^{j2P\frac{1}{4}}, e^{j2P\frac{1}{2}}, e^{j2P\frac{3}{4}}$ represent the *basic hues* red, yellow, green and blue, respectively, and where the *binary hues* are correspondingly in between, e.g. the oranges are of the form e^{jw} with $0 < w < \frac{P}{2}$.

For the enhancing of hue contrast, the hue H of each pixel is mapped to a hue $m_t(H)$; the function m_t depends on the *local hue* t, which is computed using e.g. the *circular average* or a *circular median,* (when they exist, see (Mardia and Jupp, 2000) and (Restrepo et al., 2007)) of the hues in the window. Here, we use the circular mean. The map $m_t(H)$ has infinite "slope" at the local hue t; in this way, the variations of hue near the local hue are amplified. m_t is defined on the basis of a continuous, increasing function $f : [0,2P] \to [0,2P]$ with $f(0) = 0$, $f(2P) = 2P$, $f(P) = P$ such that the derivative of f is maximal at P. with infinite slope at P given by

$$f(x) = x - cx(P-x)^{\frac{1}{2n}}, x \in [0,P] \tag{5}$$

$$f(x) = x + c(2P-x)(x-P)^{\frac{1}{2n}}, x \in [P,2P] \tag{6}$$

where the constant c ensures that f' is positive everywhere.

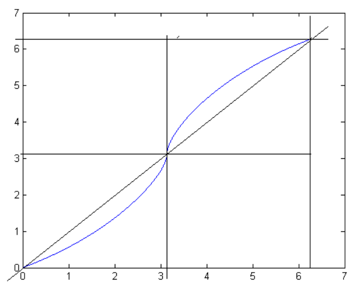

Figure 8: n=1, c=.3; consider the rectangle [0, 2P]×[0, 2P] as a torus split along a meridian and a longitude.

Figure 9: Image of a faded tapestry.

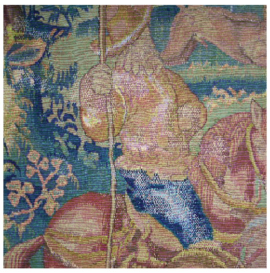

Figure 10: Chroma processing of the image in Figure 9; saturation processing with $g = 0.7$ and hue processing with c=0.3, n=1.

Now, for each t, let $m_t : S^1 \to S^1$ ($S^1 := \{z \in \mathbf{C} : |z| = 1\}$ is the unit circle) be the function given by $m_t(H) = -e^{jt} e^{jf(\angle \frac{e^{jH}}{-e^{jt}})}$ where $\angle z$ stands for the angle of the complex number z. This effectively implements a circular map,whose *graph* lives on the *torus* $S^1 \times S^1$, that has infinite *derivative* at t. It *fixes* local hue: $m_t(t) = t$ and has a convex derivative m_t'; $m_t'(H)$ is maximal at $H = t$, and minimal and smaller than one, at the opposed hue. As in the previous section, the methodology presented is of the unsharp masking type, circular in this case; the technique compares well with that in (Restrepo et al., 2008).

5 POWER-LAW LUMINANCE AND SATURATION ENHANCEMENT OF HC IMAGES

Consider the enhancement of the HC image shown in Figure 11.

Since it can be argued that the corrections needed depend on the level of radiance coming from each part in the 3D scene, rather than making corrections to the image on the basis of pointwise luminance, we

Figure 11: An image of high contrast, resulting from a high dynamic radiance scene.

Figure 12: The image is segmented into light and dark regions.

Figure 13: The image in Figure 11, after adaptive saturation and value enhancement.

segment the image using a standard region-growing routine (Kroon, 2008) into light and dark regions and apply a correction that depends on the region. See Figure 12.

We use power laws on the saturation and value components of the image. For saturation enhancement, we used the exponents 0.95 (a slight adjustment) and 0.7 for the clear and dark regions, respectively. For the luminance component V, we applied no correction in the light region and the exponent 0.5 in the dark regions. See the result in Figure 13. There seems to be no reason to decrease the saturation at any part of the image.

6 CONCLUSIONS

It is of value to have tools for increasing the contrast of signals with bounded range such as luminance and saturation signals, and of signals with a circular range such as hue and phase signals. The presented tools leave room for the choice of the location (luminance) and dispersion (contrast) estimators involved; likewise, several parameters are tuned here in an ad hoc fashion. For aesthetic reasons it may be convenient to let an experienced user choose the parameters; nevertheless, for the processing of large image databases, it is convenient to use heuristics that automatically determine the values of the parameters. We are preparing a set of guidelines for automatic parameter selection but this is not a clear cut subject. In (Restrepo and Ramponi, 2008) gamma is chosen so that the correlation coefficient between luminance and contrast is minimized. Regarding unsharp masking, if both the V and the H components are sharpened the image may become too crispy. The readability of an HC image is usually improved manipulating the luminance of the image; this nevertheless usually also leads to a loss of *depth* (in the perceived 3D scene): a compromise must be made.

Many continuous magnitudes in the physical world are unbounded and linearly ordered and are typically modeled on the real line or on the positive real line. Transducers give bounded electrical readings normally using a saturating nonlinearity. Both bounded and circular magnitudes play an important roles in image processing.

It is usually a fruitful strategy to simulate the known mechanisms present in biological vision systems for their implementation in cameras and in image processing software; nevertheless, it must not be forgotten that, when seen, the image will again, in some sense, be processed by the Human Visual System and there is a risk of overdoing things.

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