A Survey of Tone Mapping Techniques

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Abstract. This paper gives an survey of tone mapping techniques used with global illumination models. Linear and non-linear methods are compared, and drawbacks and strengths of all methods are given according to the authors` opinions. The tone mapping is an important step in the rendering process, and this survey can help potentional users to choose the right mapping technique for a particular purpose.

1 Introduction

In this paper we are going to describe possible solutions for the final step of every rendering process. Once, the radiance values are computed they have to be mapped to values appropriate for displaying. Computed radiance values can vary over a very wide range. The dynamic range or contrast (the ratio of the highest and the lowest radiance) of the computed values is often larger than the available display device contrast. The display device contrast is usually not greater than 100, and computed radiances can have a contrast of several thousands or even more. Therefore some mapping technique should be applied. It is interesting that the human visual system is able to perceive light intensities in the dynamic range of about 10^{10}, but simultaneously we cannot perceive a dynamic range exceeding a few hundreds. This means that our visual system will select a range of perceived luminances when the dynamic range is too large. If you try to look at a person sitting in front of a window on a sunny day you can see the details either of the person's face or of outside. It would be ideal to use exactly the same technique for tone mapping that is used by our visual system. Unfortunately, there are many factors influencing human perception that are not completely understood yet and the model is far too complicated for common use.

We will describe simple, widely used linear scalefactors, improvements of those, and some high end solutions that take into account human perception.

We will not deal with spatially non-uniform methods. This means that all pixels of a certain radiance value will be mapped to the same input value, independently of the pixel position in the image.

In this paper we will also assume that the display device is calibrated, such that it has linear response and input range [0,1]. This input range corresponds to [0,255] for the R, G and B color channels for today's standard devices. Throughout this paper we will use "n" for the device input value, and "L" for the computed radiance value.

2 Linear Scalefactors

Although human vision certainly does not use a linear scaling function, this group of mapping methods renders acceptable results for a wide range of applications. Its strengths are simplicity and speed, and if the right method is chosen, the results can be acceptable for almost all applications.

The first intuitive solution to the mapping problem is the use of a linear scalefactor such that the maximum radiance L_{max} is mapped to 1,

$$n = \frac{L}{L_{max}}$$

This mapping is useless if the light source is visible or the image contrast is too high. In these cases the final image will be too dark. An improvement of this method, especially popular in the radiosity community is the mapping of the largest non-self emiting pixel to 1. Unfortunately, in the case of strong secondary light sources this method still renders very dark images. The second drawback is that pixel self emitance is known only in the first rendering phase, therefore it is not possible to estimate which pixel is and which is not self emitting from the radiance image.

2.1 Mean value mapping

Probably the most widely used mapping method today is the mean value mapping. The idea is to map the average radiance to 0.5 input value, and then clip the values larger than 1 to 1:

$$n = 0.5 \cdot \frac{L}{L_{ave}}$$

where L_{ave} is the average radiance value.

According to (2) value $2*L_{ave}$ will be mapped to 1, and all values larger than $2*L_{ave}$ will be clipped to 1. Obviously the information in the range $[2*L_{ave},L_{max}]$ is lost, although there can be some interesting details. Another problem is the case when few very high radiances increase the average and the final image is too dark in this case. Another drawback arises from the fact that the global illumination solution is linear in source radiance, that means results for any two light source strengths are directly proportional. Therefore the mean value mapping will produce the same image for a scene illuminated with various light sources. To overcome this problem the computed luminances should be computed in absolute units, otherwise it can not be known if the scene is illuminated with a very strong or a very weak light source. Another drawback of the mean value mapping arises when the average scene reflectance is very low or very high. Imagine the image representing a heap of coal. If the average value (which is low) is mapped to 0.5 the whole image will be too bright. On the other hand, an image of snow covered mountains will be too dark.

In spite of all these drawbacks this is still the most widely used method. Most of today's renderers cannot produce absolute value images, and most scenes are not very dark or very bright. These two facts make possible that the mean value mapping is so popular. Of course, when an appropriate lighting atmosphere or an object's correct color should be reproduced, some other tone mapping must be applied.

2.2 Interactive Calibration

To overcome some of the mean value mapping drawbacks interactive calibration of contrast and aperture can be used [MATK96]. This method is based on the photographers approach where a photographer can display different values as medium gray by varying aperture. By choosing different photo papers and developing processes, the final photo contrast can be varied as well. This tone mapping calibrates aperture and contrast and finds a clipping interval [s,e] according to parameter values. The clipping in this method is applied on both sides of the interval: values smaller than s are clipped to s, and values larger than e are clipped to e. The user varies the parameters until the final image looks satisfactory.

Aperture is defined different than in photography. Here aperture is 0 iff L_{ave} is mapped to 0.5. Shifting the aperture to +1 means mapping the value L_{+1} which is L_{ave} shifted by 1 on a $\log_2$ scale. Recommended aperture settings are ±0.5, ±1, ±1.5,...,±3. Of course the aperture can be set to larger values or a finer step can be applied but this will rarely be necessary.

The size of the clipping interval depends on the selected contrast. If the selected contrast is large, the number of clipped values will be low, but the final image will be considered low contrasted. On the other hand if the selected contrast is small, the number of clipped values will increase, but the final image will be considered high contrasted.

The clipping interval [s,e] can be estimated knowing L_{ave}, aperture a, and contrast c as:

$$s = \frac{2 \cdot L_{ave} \cdot 2^a}{1+c} = \frac{2^{1+a} \cdot L_{ave}}{1+c}$$

$$e = s \cdot c$$

Now L values outside the [s,e] interval should be clipped to the interval borders, and [s,e] is mapped to [0,1] linearly using the formula: $n = L/e$.

If the selected contrast c is much larger than the display device contrast, it is suggested not to map [s,e] linearly to [0,1] but to use a mapping function of type $n' = n^{0.4}$. In this way the results will be perceptionally more correct.

This method overcomes some of the mean value mapping drawbacks, as the value that will be displayed as 0.5 can be different from L_{ave}. It is possible to reproduce the lighting atmosphere of the scene if it is known. It is also possible to shift the interval so that the shades, or the areas near the light sources on the other hand, can be examined exactly. The method strongly depends on user settings which makes it completely subjective. Another drawback is the lack of automatism in the parameter estimation.

2.3 Minimum Information Loss Methods

Minimum information loss methods were introduced in [NEUM96]. The idea is to find automatically a clipping interval, such that minimum amount of information is lost thereby preserving the contrast ratio of all correctly displayed pixels. Two approaches are introduced. The first considers the color component to be the essential information, and the second considers the pixel as essential information unit. The results do not differ much for most scenes. The idea is to form a logarithmic histogram of the L values and find the clipping interval [a,b] such that b=c*a and the number of clipped histogram entries is minimal. The contrast c is set according to the display device contrast. Figure 1 shows the histogram of the image displayed in Color Plate 1 with the optimum interval of c=50.

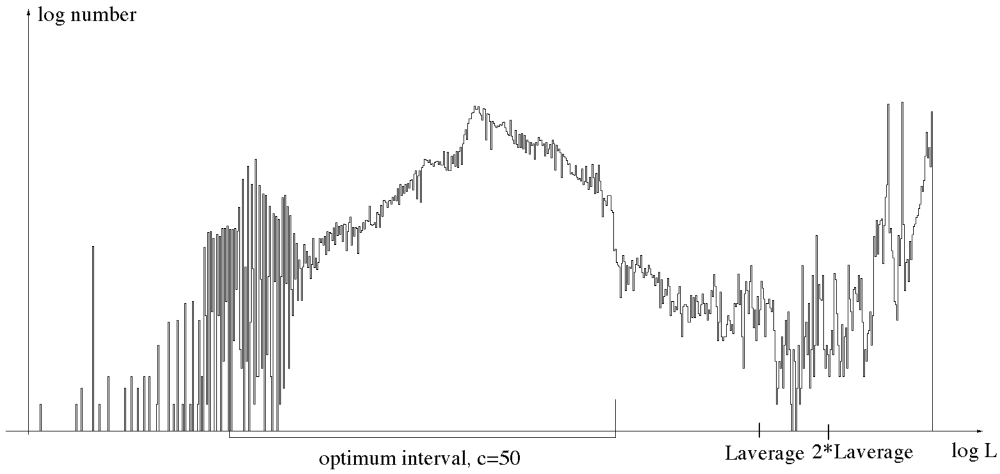

Figure 1. Log histogram and the optimum interval c=50

The interval can be found in linear time. Once the interval is found, L values that are outside are mapped to the interval borders, and the whole interval is linearly mapped to [0,1]. The method showed to work especially well for back lit scenes where the mean value mapping fails.

2.4 Incident Light Metering

Incident light metering is a well known method in the professional photography and movie industry. The light is not metered at the camera position, instead the incident light is metered at the subject position. The idea to apply a similar principle in computer graphics is introduced in [NEUM97]. This is the only method based on the incident light metering, all others follow, implicitly or explicitly, the reflected light metering principle.

The idea is to place a limited number of diffusors in the scenes, which measure the irradiances. Then the median value m of the irradiance values is found and used as a simple linear scalefactor m:

$$n = m \cdot L$$

The authors described how irradiances can easily be computed with minor changes for all common rendering methods. The largest strength of this method is its ability to reproduce selected object colors correctly. If the scene object colors are dark, the objects will be displayed as dark, independent of average scene reflectivity. The same is true for bright objects. All other mapping methods have problems with reproducing object colors in the scenes with very low or very high average reflectance.

2.5 Ward's Contrast Based Scalefactor

Ward's contrast based scalefactor [WARD94] is based on human vision contrast sensitivity. The idea is to display bright lighting conditions as bright and dark lighting conditions as dark, making the differences just visible in the real world just visible on the display. The scalefactor is derived from the contrast sensitivity studies conducted by Blackwell in the early 1970s. The mapping derived by Ward is:

$$n = \frac{1}{L_{d\,max}} \cdot \left[\frac{1.219 + \frac{L_{d\,max}}{2}}{1.219 + L_{wa}^{0.4}} \right]^{2.5} \cdot L$$

where L_{dmax} is maximum display luminance,
L_{wa} is world adaptation level.

This mapping displays the scene lighting atmosphere properly using a single linear scalefactor. The problem for common users is the use of absolute units. The display device data can be obtained from the manufacturer, but the rendered scene radiances are rarely expressed in absolute units. The scene adaptation level is assumed to be a logarithmic average of radiances (the same as in [TUMB93]), what is certainly not the case in nature, and contrast sensitivity is based on the results for a totally adapted eye, and small viewing angle. When a display is observed, the viewing angle is larger, and since we perceive many colors simultaneously adaptation level cannot be estimated in an easy way. Nevertheless, this method renders great results, and can be used for a wide range of applications where the lighting atmosphere is important.

3 Non Linear Scalefactors

In this section we are going to describe non linear scalefactors. The motivation for using non linear scaling factors is usually found in Weber's law. This law derived at the beginning of the century states that the ratio of brightness discrimination threshold ΔL and corresponding brightness L, $\Delta L/L$ is constant over a wide range of luminances. According to this law a logarithmic mapping can be derived. Schlick [SCHL94] states that appropriate mapping according to more recent experiments should be exponentiation mapping. As these mappings are expensive to compute and always have some free parameters that should be set for each scene separately, Schlick introduced uniform rational quantization [SCHL94] achieving comparable or better results, with much less computational effort.

3.1 Schlick's Mapping

The high computational cost and the need of setting the free parameter for each scene led Schlick [SCHL94] to developing a rational mapping function:

$$n = \frac{p \cdot L}{p \cdot L - L + L_{max}}$$

where $p \in [1,\infty)$.

Schlick also proposed a way of finding the p automatically. The only value that is needed to compute p is M, which represents the input level of the darkest non-black gray. Note that this is almost never 1. The parameter p is then:

$$p = \frac{M \cdot L_{max} - M \cdot L_{min}}{N \cdot L_{min} - M \cdot L_{min}} \approx \frac{M \cdot L_{max}}{N \cdot L_{min}}$$

where N is the number of discrete input values of a particular device.

This method works fine with high contrast images. The method fails when just a few very light pixels increase p too much (or a few very dark pixels, respectively). On the other hand the function is applied to the whole range of radiances, trying to display them all, what is not what the human visual system does. As stated before, in the case of the back light we can see either the object in front of the window, or the landscape outside. We cannot see both at the same time. If the lighting conditions are not extreme and if there are no small high or low intensity areas in the image, this method gives satisfactory results, and due to low computational cost should be used.

3.2 Exponential Mapping

This mapping was introduced by Ferschin et al. in [FERS94]. The main advantage of this mapping is that it reduces an overproportional influence of a few very bright pixels on the average. The used exponential function hardly affects close to average pixels, but suppresses the values of high ones, preventing them to rise above the limit value. The suggested mapping function is:

$$n = 1 - e^{-L/L_{ave}}$$

The influence of the choice of the color system was also studied in [FERS94]. We find this method closer than Schlick's to human perception. This method is not sensitive to the influence of a few extreme radiances. However, the average radiance is used as some sort of reference value, and that is not always the fact in nature. The method is computationally more expensive than Schlick's but it should be used when parameter p is set too large due to few high radiance values.

3.3 Tumblin and Rushmeier's Mapping

This method is generally considered to be the state-of-the-art among tone mapping methods. It was introduced by Tumblin and Rushmeier in [TUMB93]. It solves the problem of displaying the same scenes that are lit by light sources of various strengths. It is clear that we would see different a room illuminated by a firefly (3.18×10^{-4} cd/m^2) or by a searchlight (3.18×10^{6} cd/m^2) (examples according to [TUMB93]). The idea is to find a tone mapping factor such that the display observer perceives the same brightness as a real world observer would perceive. To apply this method radiances in absolute units are required. The mapping method is based on an observer model derived by Stevens and Stevens [STEV63]. The device input value n is:

$$n = \left[\left(\frac{L_{rw}^{\left(\frac{\alpha_{rw}}{\alpha_d}\right)}}{L_{d\,max}} \right) \cdot 10^{\left[\frac{(\beta_{rw} - \beta_d)}{\alpha_d}\right]} - \left(\frac{1}{C_{max}} \right) \right]^{\left(\frac{1}{\gamma_d}\right)}$$

where α and β are complex expressions depending on L.

This model was developed for grayscale images only. To apply it on color images we follow Ward's approach, and apply it on each color channel separately what certainly is not the best way. Just as Ward's model this model is based on the observations made in a laboratory where the observer is adopted to constant brightness, what is not the case in real life. We find the images mapped using this model a little to dark. The reason is the model functions over such a great range (firefly to search light). Note that they illuminated a test room with a search light (3.18×10^{6} cd/m^2), and just for comparison snow cowered ground in full sunlight emits 1.6×10^{4} cd/m^2 or horizon sky emits 3.0×10^{4} cd/m^2 at a day with sunlit clouds [GLAS95]. If such extreme lighting conditions are needed this model should be used. On the other hand for every day illumination of interiors images will be a little too dark, as other vision characteristics were not taken into account.

3.4 Model of Visual Adaptation

A model of visual adaptation was introduced by Ferwerda et al. in [FERW96]. This model is based on Ward's contrast based scalefactor, but in addition to Ward's model it captures the changes in threshold visibility, color appearance, visual acuity, and sensitivity over time that are caused by the visual system's adaptation mechanism. If changes over the adaptation period are important for some application, this method is the right choice since it is the only model that takes these changes into account. We did not implement this rather complicated model, but it is mentioned here for the sake of completeness.

4 Visual Comparison

The results are shown in color plates 1 to 3. All images were rendered using the RADIANCE [WARD94a] software because of its ability to render raw images. Raw images were mapped using various mapping techniques described in this paper. Tumblin and Rushmeier's mapping originally developed for gray scale images was applied to color images as suggested by Ward in the RADIANCE package, namely the mapping was applied to each color channel separately. The results are shown in color plates 1 to 3. Color plate 1 shows a back lit scene. It is obvious that max to 1 and the mean value mapping mappings produce unacceptable results. Schlick's solution is interesting, as it shows the details outside the window, and in the room as well. In spate of this fact, the image does not look natural. Humans simply do not see that way. Color plate 2 shows the same scene but without window. The wall color was changed as well, and walls are supposed to be brighter now. Again Schlicks solution is interesting. Due to a high intensity highlight on the red ball, the solution does not look natural again. Color plate 3 shows another simple scene. Two raw images were rendered for plate 3. The only difference is the wall color. Originally selected object colors are displayed in the color bar below each image. The incident light metering method shows its strengths here. Schlick's method functions well, but if we introduce a small black box in the bright scene, parameter p explodes, and result is unacceptable. The same change would hardly affect other methods as the average value remains almost unchanged. Methods not included in plate 3 also fail to reproduce originally selected colors.

5 Conclusion

We have tested various tone mapping methods and we cannot recommend one method that should be used generally. If a lighting atmosphere under extreme lighting conditions is important, then the clear winner is Tumblin and Rushmeier's mapping. If the selected object colors reproduction is crucial, incident light metering seems as a good choice. Ward's method is much simpler than Tumblin and Rushmeier's and gives nice results for various adaptation levels. The minimum information loss methods could be the right choice for back lit scenes. The model of visual adaptation is the only method that takes adaptation into account. It is up to users to choose the right method for their purposes. We recommend to users not to use one method exclusively, but to experiment and find the most appropriate mapping for themselves.

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