A New Time-Dependent Tone Mapping Model

Alessandro Artusi Christian Faisstnauer Alexander Wilkie

Institute of Computer Graphics and Algorithms
Vienna University of Technology

Abstract

In this article we present a new time-dependent tone mapping model which describes the ability of the human vision to adapt to even strong changes in the luminance of the surroundings. This ability depends on time; in fact the human visual system needs a determined amount of time until reaching the final stage of adaptation. Our model accepts the $CIEXYZ$ values of an image as input and converts them into RGB values reproducible on a monitor. This work is based on the retinal model presented by Pattanaik et al [7] , but introducing substantial modifications. In fact, we define a new dynamic model which describes the time dependence of the human visual system, utilizing different filters; the cromatic adaptation is taken into account by introducing the model of von Kries. Furthermore, we introduce new techniques of gamut mapping and conversion between the values of retinal response and luminance of the display. The efficiency of this time-dependent model will be demonstrated on two different types of images, synthetic and real.

Key words: visual adaptation, time-dependence, appearance model, chromatic adaptation, colours.

1 Introduction

The interval of luminance values that can be found in scenes of the real world can be very broad; the human visual system has the ability to adapt to these dynamic intervals, but it needs some time to do so. The cells in our visual system are triggered by a relatively small range of luminance values; large and fast changes in the lighting conditions cause this triggering interval to shrink further, until gradually adapting to the new conditions. The mechanisms which control these time-dependent adaptations are asymetric; it takes more time to adapt to darkness than to bright surroundings [7]. This process which takes place entirely inside the retina [1] is referred to as 'visual adaptation'; it has a substantial impact on the appearance of an image. Continuous adaptations help to keep the visual system sensible towards the different luminance conditions that can be found in real world scenes [7]. But not only the perception of the brightness varies with changing viewing conditions, the perception of the colors is affected as well; if we want to capture the visual appearance of a real image completely, it is necessary to consider the color appearance . The model of cromatic adaptation defined by Von Kries, for example, allows to predict the correct reproduction of colors with respect to varying viewing conditions [3] . Therefore, if we want to visualize a real scene on a monitor we need these models, as the monitor has different visual conditions than the real world. In this paper we present a new time-dependent algorithm which is based on a retinal model [7], but includes substantial modifications. In fact we define a new dynamic model that describes how the human visual system depends on time, utilizing different filters; furthermore the phenomenon of cromatic adaptation is considered by including the model of Von Kries. Our model also introduces a new technique of gamut mapping and of conversion between the values of retinal response and luminance of the display. In Section 2 we discuss related previous work; Section 3 provides an overview about the time-dependent mechanisms and the chromatic adaptation background. The development of our new time-dependent model is described in Section 4, while Section 5 contains the model design. In Section 6 we report some experimental results; conclusions and the future works are finally presented in Section 7.

2 Previous Work

The problem of tone mapping has been researched extensively during the last 10 years, and there is a large number of papers analyzing this topic. The concept of tone mapping has been introduced by Tumblin and Rushmeier [9], who propose a tone reproduction operator that preserves the apparent brightness of scene features. Ward [10] takes a different approach, describing a tone reproduction operator that preserves the apparent contrast and visibility. A model that includes different effects of adaptation has been introduced by Ferwerda et al.[4]. Pattanaik et al.[6] developed a computational model of adaptation and spatial vision for realistic tone reproduction. The model presented by Ward et al.[11] proposed a new histogram adjustment technique and considers glare, visual acuity and color sensitivity. Finally, the time-dependent visual adaptation model has been introduced by Pattanaik et al.[7] and Durand et al. [2].

3 Background

This section provides the background of the time-dependent mechanisms and the chromatic-adaptation phenomenon.

3.1 Retinal model

The mechanisms which control the time-dependent adaptations to varying luminance conditions occur inside the retina of the human eye. The majority of the retinal cells can perceive only a small range of luminance values, compared to the entire luminance interval present in a scene. This range is adjusted continuously in order to adapt to the available light. Equation 1 describes this process (refer also to [7])

$$R(I) = R_{max} * \frac{I^n}{I^n + \sigma^n}. \quad (1)$$

I is the light intensity, R is neural response ($0 < R < R_{max}$), the constant σ is the value that causes the half-maximum response, and n is a sensitivity control.

3.2 Chromatic Adaptation

The ability of an organism to change its sensitivity towards determined stimuli in answer to changes of the environmental conditions is referred to as "adaptation". There are three important types of visual adapation: Light, Dark and Chromatic adaption. $Light\ adaptation$ [3] is the decrease in visual sensitivity upon increases in the overall level of illumination. $Dark\ adaptation$ [3] is equivalent to the light adaptation, but in the opposite direction. In fact the dark adaptation is the increase in visual sensitivity experienced upon decreases in the luminance level. $Chromatic\text{-}adaptation$ [3] is the human visual system's capability to adjust to widely varying colors of illumination in order to approximately preserve the appearance of object colors. The adaptation to light or darkness has a substantial impact on the color appearance, but the cromatic adaptation has even bigger importance. In fact, is allows to perceive the color correctly under different viewing conditions. All types of visual adaptation must be included in all models that try to capture the correct color appearance.

The term 'corresponding colors' refers to different stimuli which are perceived under different viewing conditions but appear as the same color, have the same color appearance [3]. For example, one tristimulus value XYZ_1 perceived under determined viewing conditions can appear equal to another stimulus defined by XYZ_2 and a different set of viewing conditions. The tristimulus values of both colors, along with their corresponding viewing conditions, are referred to as 'corresponding colors'. The tristimulus values of two corresponding colors are rarely numerically identical [3]. A general model of cromatic adaptation does not include appearance attributes such as lightness, chroma and hue. But it provides the transformation of tristimulus values from one set of viewing conditions into a different set of viewing conditions [3]. In other words, a model of cromatic adaptation allows to predict the corresponding colors. A generic model of cromatic adaptation starts from the initial LMS values, answers of the cones to the initial viewing conditions, and predicts the new signals L_{new}, M_{new} e S_{new} under the new viewing conditions. In general the colors are espressed using the tristimulus values $CIEXYZ$, but fortunately there exists a 3 x 3 linear transformation between the signals of the LMS cones and the tri-stimuli values $CIEXYZ$. The entire process of chromatic adaptation [3] follows the steps as depicted in Figure 1: transformation of the tristimulus values $(X_1Y_1Z_1)$ into triggering signals of the $L_1M_1S_1$ cones, determinition of the cone signals $L_aM_aS_a$ (adapted to the first set of viewing conditions), transformation to find the corresponding colors defined by the cone signals $L_2M_2S_2$ and the second set of viewing conditions, and finally a transformation into the final tristimulus values $X_2Y_2Z_2$.

4 Development Model

In this section we describe the development of our new time-dependent model. Like the model presented by Pattanaik et al. [7] it is based on four different stages (adaptation, visual appearance, inverse visual appearance and inverse adaptation model), but utilizing different techniques to archieve the final result. In fact we define a new dynamic model that describes how the human visual system depends on time, utilizing different filters. Additionally we consider the phenomenon of chromatic adaptation, using the model of Von Kries, and introduce a new technique of gamut mapping other than an algorithm that transforms the retinal response into luminance values of the display.

4.1 Adaptation Model

The human visual system consists of two photoreceptors behind the retina [8]: rod e $cone$. The rod photoreceptors are responsible for the chromatic vision, given a range of $scotopic$ illumination between 10^{-6} and 10 cd/m^2. The $cone$ photoreceptors are responsible for the color vision, in a range of $photopic$ illumination between 0.01 a 10^8 cd/m^2. Between 0.01 a 10 cd/m^2 both rod and $cone$ photoreceptors are active; this is known as the $mesopic$ range [4]. Our model expects for every image pixel a tristimulus value $CIEXYZ$ as input, and produces the

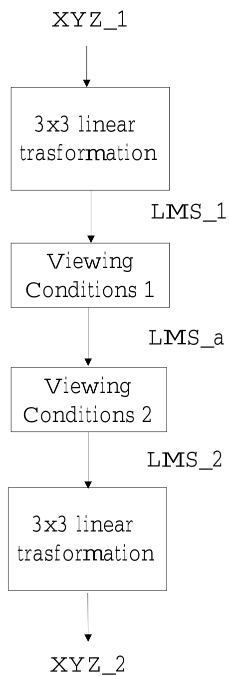

Figure 1: Flow chart Chromatic Adaptation model

RGB values for the display. The goal of the adaptation model is to calcolate the retinal values for both photoreceptors. This is accomplished using the formula 1:

$$R_i = B_i * \frac{L_i^n}{L_i^n + \sigma_i^n}. \quad (2)$$

This formula is identical to the one used in Hunt's model [5] and in the model of Pattanaik et al. [7].

The index i, in the equation 2 indicates the rod or $cone$ receptors; B and σ are adaptation model parameters. The luminance L is equal to the standard CIE value Y' for the rod receptors and to the standard CIE value Y for the cone receptors, see equation 3. The CIE value Y' is obtained from equation 4, using a linear transformation of $CIEXYZ$ tristimulus values as a rough approximation of the rod signal (via linear regression of the color matching function and the $V'(\lambda)$ curve [6]).

$$L_{cone} = Y, \quad (3)$$

and

$$L_{rod} = Y' = -0.702 * X + 1.039 * Y + 0.433 * Z. \quad (4)$$

In the case the result value is negative, it is necessary to clip it to zero. The luminance retinal response is obtained as sum of the retinal response for the rod and the $cone$, see equation 5.

$$R_{Lum} = R_{cone} + R_{rod}. \quad (5)$$

To take account of the color information we use the same equation as used in the model of Pattanaik et al. [7].

$$R_{color} = ((X, Y, Z)/Y)^{S_{color}}, \quad (6)$$

where

$$S_{color} = \frac{n * B_{cone} * L_{cone}^n * \sigma_{cone}^n}{(L_{cone}^n + \sigma_{cone}^n)^2}, \quad (7)$$

where we use the value of n suggest by Hunt (n = 0.73). The parameters σ for rod and cone photoreceptors are computed with the equations used in Hunt's model [5], equations 20 and 18.

4.2 Dynamic Adaptation Model

The model presented in this paper is time dependent, hence it can be defined as a dynamic model (the output depends on time). The model presented by Pattanaik et al. [7] is time-dependent as well, but uses a different strategy with respect to our model.

The scope of the dynamic model is to compute the parameters A_{rod} and A_{cone} that describe fast, symmetric neural effects and are used to compute the σ_{rod} and σ_{cone} values. The model is used to compute the parameters B_{rod} and B_{cone} which describe slower asymmetric effects from pigment bleaching, regeneration and saturation effects; it also sets the response amplitudes R_{max} in equation 1 [7]. For the parameters A we use a exponential filter given by equation 8

$$F = (1 - exp(const)), \quad (8)$$

where for the rod receptors, the $const$ value is:

$$const_{rod} = -T * \frac{10^{-3}}{150 * 10^{-3}}, \quad (9)$$

instead for cone receptors, the $const$ value is:

$$const_{cone} = -T * \frac{10^{-3}}{80 * 10^{-3}}. \quad (10)$$

The value 10^{-3} is used because time is express in millisecond.

The difference with respect to the filter used in the model of Pattanaik et al. [7] is in the update of the parameter A. In our model, the parameter A is updated using the formula 8; for every pixel we use the same value $A = F$. In the model of Pattanaik et al. [7] the value changes for every pixel (with index i) in the following way:

$$A_i = A_{i-1} + (J - K), \tag{11}$$

where the terms J and K are computed using the equation 12

$$J = F * L_i, K = F * A_{i-1}, \tag{12}$$

in the case $i = 1$, A is equal to L_{cone} for the cone receptors and L_{rod} for the rod receptors. The parameters B for each pixel are computed with the equation 13

$$B_i = const + (K - J). \tag{13}$$

If the value of the term B is negative, it has to be clipped to zero. The parameters K and J for the rod receptors are computed according to

$$K_{rod} = T * \frac{10^{-3} * (1 - const)}{400}, \tag{14}$$

$$J_{rod} = T * 10^{-3} * (const/16) * L_{rod}, \tag{15}$$

and for the cone receptors according to

$$K_{cone} = T * \frac{10^{-3} * (1 - const)}{110}, \tag{16}$$

$$J_{cone} = T * 10^{-3} * (const/2.2 * 10^8) * L_{cone}. \tag{17}$$

The term $const$ is taken as one-fifth of the paper white reflectance patch in the Macbeth chart, about 20 cd/m^2. The Pattanaik model [7] uses a different strategy to update the parameters B and to compute the terms K and J. The parameters B and A are used to calculate the parameters σ_{cone} (equation 18) and σ_{rod} (equation 20), which are used in the retinal model, equation 2.

$$\sigma_{cone} = \frac{12.9223 * A_{cone}}{par_{cone}^4 * A_{cone} + \gamma}, \tag{18}$$

where γ is:

$$\gamma = 0.171 * (1 - par_{cone}^4)^2 * A_{cone}^{1/3}, \tag{19}$$

$$\sigma_{rod} = \frac{2.5874 * A_{rod}}{19000 * par_{rod}^2 * A_{rod} + \gamma 1}, \tag{20}$$

where $\gamma 1$ is:

$$\gamma 1 = 0.2615 * (1 - par_{rod}^2)^4 * A_{rod}^{1/6}, \tag{21}$$

and where par_{cone} and par_{rod} are:

$$par_{cone} = \frac{1}{5 * A_{cone} + 1}, \tag{22}$$

$$par_{rod} = \frac{1}{5 * 10^5 * A_{rod} + 1}. \tag{23}$$

4.3 Visual Appearance Model

In the model presented by Pattanaik et al. [7] the visual appearance does not include the chromatic adaptation. In effect, it uses a simple linear mapping for the color appearance, as it equals the value Q_{color}, which represents the color appearance, to the value R_{color}, representing the color of the scene. In this way it is not possible to represent two colors under different viewing conditions. But as the scene and the display provide different viewing conditions, we need a model of chromatic adaptation. When we first determine the values describing the appearance of the scene (Q_{Lum}, Q_{span}, Q_{mid} e Q_{color}) we use the same techniques as described in the model [7]. Only in a second time, when we considier the different viewing conditions of scene and display, we utilize the model of chromatic adapation as described in section 4.6.

4.4 Inverse Visual Appearance Model

We have implemented a new model of inverse visual appearance, using the maximum and minimum luminance reproducible by the display as white and black reference values, denominated $REF_{white_{display}}$ and $REF_{black_{display}}$. Both values are within the range $[0.0, 1.0]$. The model presented by Pattanaik et al. [7] uses a different strategy, where these values are computed using the retinal model described in Section 4.1. $REF_{white_{display}}$ and $REF_{black_{display}}$ are used to calculate the values of visual appearance for the display: $Q_{span_{display}}$ and $Q_{mid_{display}}$. Now it is necessary to determine the retinal answer adapted to the display, called reference luminance R_{Lum}, using a mapping between the real world and the display. We consider two different possibilities:

- The value of the reference luminance of the scene is contained in the range of luminance of the display. In this case it is not necessary to perform any operation and the value R_{Lum} is not modified.

- The value of the reference luminance of the scene lies outside the range of luminance of the display.

In the latter case we distinguish three subcases:

- The range of luminance of the scene is large compared to the range of luminance of the display. This can be determined by checking $Q_{span} > Q_{span_{display}}$; the new value of R_{Lum} can then be determined by mapping into the luminance range of the display $[0.0, 1.0]$.

- The middle range of luminance of the scene is large compared to the range of luminance of the display. This can be determined by checking $Q_{mid} > Q_{mid_{display}}$; the new value of R_{Lum} is determined using the equation 24;

- In all other cases we apply the equation 25.

$$R_{Lum_{new}} = R_{Lum} - REF_{white_{scene}} + REF_{white_{display}}. \tag{24}$$

In other words, the luminance value of the scene is reduced by $REF_{white_{scene}}$ for every pixel.

$$R_{Lum_{new}} = R_{Lum} + REF_{black_{display}} - REF_{black_{scene}}. \tag{25}$$

In this second case, the luminance value of the scene is reduced by $REF_{black_{scene}}$ for every pixel.

4.5 Inverse Adaptation Model

Once obtained the new retinal answer $R_{Lum_{new}}$ apt for the display, this value is used to determine L_{cone}, the luminance value for the display derived from the *cone* photoreceptors. It can be obtained by inverting the equation 5 and consists in solving a second-degree equation (the model of Pattanaik et al. [7] follows a different strategy). But before calculating the luminance value, it in necessary to determine the coefficients $B_{cone_{display}}$ (using equation 26) and $B_{rod_{display}}$ (using equation 27) for the display. In this case the inverse adaptation model is considered which is static, hence not depending upon time. The coefficients for the display, $A_{cone_{display}}$ e $A_{rod_{display}}$, are equalized to the work luminance value of the display ld, in the range $[0.0, 1.0]$.

$$B_{cone_{display}} = \frac{2 * 10^6}{2 * 10^6 + A_{cone_{display}}}, \tag{26}$$

$$B_{rod_{display}} = \frac{0.04}{0.04 + A_{rod_{display}}}. \tag{27}$$

The coefficients $\sigma_{cone_{display}}$ and $\sigma_{rod_{display}}$ are calculated using equations 18 and 20, with the parameters $A_{cone_{display}}$ and $A_{rod_{display}}$.

The form of the second degree equation is:

$$L_{cone}^{2n} * a + L_{cone}^{n} * b + c = 0, \tag{28}$$

where a is given by equation 29, b by equation 30 and c by equation 33:

$$a = B_{cone_{display}} + B_{rod_{display}} - R_{Lum_{new}}, \tag{29}$$

$$b = B_{cone_{display}} * \sigma_{rod_{display}}^{n} * ratio^{n} + \epsilon - \epsilon 1, \tag{30}$$

where ϵ is:

$$\epsilon = B_{rod_{display}} * \sigma_{cone_{display}}^{n}, \tag{31}$$

and $\epsilon 1$ is:

$$\epsilon 1 = R_{Lum_{new}} * (\sigma_{cone_{display}}^{n} + \sigma_{rod_{display}}^{n} * ratio^{n}), \tag{32}$$

$$c = -R_{Lum_{new}} * \sigma_{cone_{display}}^{n} * \sigma_{rod_{display}}^{n} * ratio^{n}. \tag{33}$$

The coefficient $ratio$ is the rapport between the cone luminance value L_{cone} and the rod luminance value L_{rod}. Only in second instance we take into account the L_{rod} luminance value applying the equation 34.

$$X, Y, Z = R_{color}^{1/S_{color}} * L_{cone} + L_{rod}, \tag{34}$$

where S_{color} is obtained with the display parameters (inverse adaptation model) and R_{color} is computed with the equation 6; for every tristimulus values $CIEXYZ$, L_{cone} and L_{rod} are the new luminance value for the cone and the rod receptors adapted to the display.

4.6 Chromatic Adaptation

All models of chromatic adaptation allow to compute the corresponding colors, but they do not allow to predict the values of the appearance attributes such as lightness, chroma or hue. In other words, with these models it is possible to predict the color matches across changes in viewing conditions. Any physiologically plausible model of chromatic adaptation must act on the cone responses [3]. Thus, in applications that use the CIE colorimetry values, tristimulus values $CIEXYZ$ are transformed into cone responses LMS with a linear transformation 35.

$$\begin{aligned} L &= 0.400 * X + 0.708 * Y - 0.081 * Z \\ M &= -0.226 * X + 1.165 * Y + 0.046 * Z \\ S &= 0.000 * X + 0.000 * Y + 0.918 * Z \end{aligned} \tag{35}$$

In related literature we find different chromatic adaptation models: Von Kries, Naytani,Guth's, Fairchild's etc. In this paper is presented the Von Kries model for several motivation: is a simple model, every chromatic-adaptation models follow the hypothesis of Jhoan Von Kries. The modern interpretation of the Von Kries hypothesis in terms of a chromatic-adaptation model is expressed by the formula 36:

$$XYZ_2 = M^{-1} * LMS_{max2} * \frac{1}{LMS_{max1}} * M * XYZ_1, \quad (36)$$

where M is the matrix that describe the linear relation between tristimulus values $CIEXYZ$ and the cone responses LMS, equation 35. The values LMS_{max} represent the cone responses of the white point, and $CIEXYZ$ represent the pixel tristimulus values. The indexes 1 and 2 represent the different viewer: real word and display system.

5 Model Design

Our model follow the scheme in fig. 2, receive in input the tristimulus values $CIEXYZ$, for every image pixel, and the first step is obtain the luminance for both photoreceptors, cone and rod, and compute the coefficient ratio between them (conversion). The second step is apply the dynamic adaptation model to obtain the parameters of the scene A_{cone}, A_{rod}, B_{cone}, B_{rod}, σ_{cone}, and σ_{rod}. These parameters are necessary to compute the luminance retinal response for both photoreceptors. With these two values is possible obtain the luminance retinal response for the scene, equation 5, and the color information, equation 6 (Retinal model). The next step is compute the visual appearance values for the scene and for the display, visual appearance model, and used them to obtain the new value of the luminance retinal response adapted at the display $Rlum_{dsplay}$. This is obtained using a mapping operation, inverse visual appearance model. With the inversion of the equation 5, is possible to obtain the new value of the luminance adapted to te display, for cone photoreceptors, resolution second degree equation, $Lcone_{display}$. With the coefficient ratio we obtain the luminance value for rod photoreceptors adapted at the display. With the equation 7, using the parameters for the display obtained from inverse adaptation model, and the inversion of the equation 6 are obtain the amount colors for tristimulus values. The finally tristimulus values, $XYZ_{display}$, are obtained with the multiplication between the luminance value for cone receptors and the amount colors for tristimulus values (conversion1). Is possible to add to them the luminance value for the rod receptors (conversion1). In second instance we apply the Von Kries model, on the tristimulus values $XYZ_{display}$, to predict the colors data under the display viewing conditions. We need this last operation because, how explained in the section 4, the visual appearance model in the Pattanaik et al. [7], does not make a chromatic-adaptation. To make this operation is necessary to normalize the tristimulus values in the range $[0.0, 1.0]$. The final output of our model are the new tristimulus values $XYZ_{new_{display}}$, after data denormalization, of the image. The last step is to transform the tristimulus values $CIEXYZ$ in RGB display values, with a linear transformation.

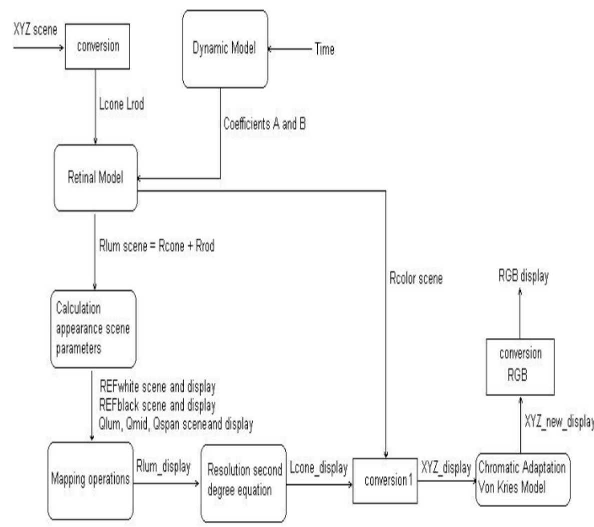

Figure 2: Flow chart of our model

6 Results

In this section we report the results of our research. The software has been implemented in C++ as library of the ART software (Advanced Rendering Toolkit). This software has been development in the Institute of Computer Graphics and Algorithms University of Technology (TU Vienna). We tested our model on different images shown in fig.3, fig.4, fig.5 and fig. 6, fig. 7 for both real world and synthetically generated scene intensity data. The first experiment is to simulate what happens in the human visual system during the adaptation time. In fact we have

Figure 3: Road: real world image obtained with our time-dependent tone mapping model. Simulation Time -Dependent Visual Adaptation system.

Figure 4: Window: real world image obtained with our time-dependent tone mapping model. Is possible to observe the correct reproduction of the visibility objects, contrast, overall brightness, chromatic-adaptation.

applied our model to the image shown in fig.3, with different slice times. We start with $T = 0$, which obviously produces a black image, as this is equivalent to be in a dark room in the first adaptation time. The second image is the result of the adaptation after $T = 300mS$, equivalent of coming out from from the dark room; it is necessary to adapt to the new luminance level. The image in fig.3 corresponds to the final adaptation state. The images in fig.4, fig.5 and fig. 6 are the final results after the adaptation time. The goals of every tone mapping operator are to reproduce visibility and reproduce the overall impression of brightness, contrast and color. Reproducing the visibility means to have the option to see an object on the display only if that object is also visible in the real scene. In this way the objects are not obscured in the over- or underexposed regions which have a high or low brightness value, and the characteristics of the object are not lost in the other regions [11]. Reproducing the overall impression of brightness, contrast and color means that the user has a similar perceptual experience in seing the image on the display and in the real scene [11]. The images presented in this Sections show that these two goals have been met; objects are not obscured in under- or overexposed regions, and there is no loss of features in the middle. It is possible to see how the user's subjective perception of an object can be reproduced, especially fine details such as the window of the bulb (see fig. 4), the lights (see fig. 5), the overall impression of brightness in fig. 3, and finally the correct reproduction of the contrast in fig. 4, 5, 3 6. Another point must also be considered, the correct prediction of the corresponding color. The phenomenon of chromatic-adaptation, which allows to predict two colors under different viewing conditions, is part of the color appearance model. In all images (real word and synthetically, fig. 4, 5, 3 6, 7) it is possible to observe that the chromatic-adaptation model allows a realistic reproduction of the colors.

Figure 5: Christmas Tree: real world image obtained with our time-dependent tone mapping model. Is possible to observe the correct reproduction of the visibility objects, contrast, overall brightness, chromatic-adaptation.

Figure 6: Church: real world image obtained with our time-dependent tone mapping model. Is possible to observe the correct reproduction of the visibility objects, contrast, overall brightness, chromatic-adaptation.

7 Conclusion and Future Works

In this paper we have presented a new time-dependent tone mapping operator that not only describes the time-dependent adaptation mechanism of the human visual system, but also considers other aspects, as the visibility of objects or the subjective experience when viewing a real scene (such as the overall impression of brightness, contrast and colors). To reproduce the appearance of the colors we use a chromatic-adaptation model that allows to 'capture' the colors under different viewing conditions (real world and display system). In order to improve the performances of this algorithm, the next step in our research is to investigate the defects of the human visual system, in order to improve the realism of the displayed images and develop a real-time tone mapping algorithm apt for different real applications.

Acknowledgements

As usual, we would like The Master for his spiritual guidance.

References

[1] J. E. Dowling. The Retina: An Approachable Part of the Brain. Cambridge:Belknap, 1987.

[2] F. Durand, J. Dorsey. Interactive Tone Mapping. *Proceedings Eurographics Workshop on Rendering*, **2**000.

[3] M. D. Fairchild. *Color Appearance Models*. Addison Wesley, 1998.

[4] J. A. Ferwerda, S. N. Pattanaik, P. Shirley, D. P. Greenberg. A Model of Visual Adaptation for Realistic Image Synthesis. *ACM Computer Graphics (Proc. of SIGGRAPH)'96*, **2**49–258, 1996.

Figure 7: Airplane: synthetically image obtained with our time-dependent tone mapping model. Is possible to observe the correct reproduction chromatic-adaptation.

[5] R. W. G. Hunt. The Reproduction Color. Chapter, Fountain Press, England, 1995.

[6] S. N. Pattanaik, J. A. Ferwerda, M. Fairchild, D. P. Greenberg. A Multiscale Model of Adaptation and Spatial Vision for Realistic Image Display. *ACM Computer Graphics (Proc. of SIGGRAPH)'98*, **2**87–298, 1998.

[7] S. N. Pattanaik, J. Tumblin, H. Yee, D. P. Greenberg. Time-Dependent Visual Adaptation For Fast Realistic Image Display. *ACM Computer Graphics (Proc. of SIGGRAPH)'00*, **4**7–53, 2000.

[8] D. Travis. Effective Color Displays. **A**cademic Press, 1991.

[9] J. Tumblin, H. Rushmeier. Tone Reproduction for Realistic images. *IEEE Computer graphics and Applications*, **13**(6):42–48, 1993.

[10] G. Ward. A Contrast-based Scale Factor for Luminance Display. *In P.S. Heckbert (Ed.), Graphic gems IV, Boston: Accademic Press Professional*, **1**994.

[11] G. Ward-Larson, H. Rushmeier, C. Piatko. A Visibility Matching Tone Reproduction Operator for High Dynamic range Scene. *IEEE Transaction on Visualization and Computer Graphics*, **3**(4):291–306, 1997.