Display of HDR Images from Logarithmic CMOS Sensors

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Abstract

The dynamic range of many natural scenes exceeds that of conventional sensors and display devices. Although a sensors' dynamic range can be increased using several techniques, the resulting images cannot be rendered on standard display devices without loss of some details. To display high dynamic range images without losing perceptual quality, several different tone mapping techniques have been proposed. However, these techniques have been developed for use with conventional linear cameras whereas high dynamic range logarithmic cameras are generating an increasing amount of interest for some applications. In this paper, work is reported that shows that tone mapping techniques can be applied to the output from a colour logarithmic camera. The result is that 10 *bit images can be displayed on conventional displays with minimum degradation in perceptual quality.*

Introduction

The dynamic range of most conventional cameras is less than $120dB$. However, the dynamic range of a naturally illuminated scene can be as high as $200dB$, with the result that the images from a conventional camera can sometimes be saturated or under exposed in some areas. This is an inconvenience for some users, but in some potential applications, for example in the automotive market, it is potentially dangerous.

Several approaches to designing cameras with a high dynamic range have been proposed and developed. The resulting cameras can have been either linear or non-linear, the latter usually with a logarithmic response. Any high dynamic range camera will create a high dynamic range image and to match the performance of the human visual system the dynamic range of this image will be too large for conventional display devices. One advantage of the logarithmic cameras is that they compress the dynamic range of the image, whilst retaining the contrast information that is actually detected by the human visual system. For example a logarithmic camera with a dynamic range of $200dB$ can match the best contrast sensitivity of the eye, i.e. it can represent a 1% change in contrast, using only 10 bits. The disadvantage of these cameras is that they tend to suffer from fixed pattern noise which degrades the quality of the resulting image. Techniques have been developed that can be used to remove the effects of this fixed pattern noise so that it is possible to image 1% changes in contrast [1, 2]. The remaining problem is that although the logarithmic response of each pixel significantly reduces the number of bits per pixel, the dynamic range of the image from a logarithmic camera is still larger than that of a conventional display.

In this paper a method of processing the images from a logarithmic sensor is described. This method is based upon a tone mapping algorithm. The paper therefore starts with a description of the previously proposed tone-mapping algorithm. This description is followed by an explanation of how it was adapted to work with images from ideal colour logarithmic cameras that have pixels whose spectral responses correspond to X, Y or Z matching functions. Since cameras usually contain pixels with spectral responses corresponding to red, green or blue, the proposed algorithm is then applied to the simulated output from a logarithmic sensor with the more conventional spectral responses. Finally, results are presented upon the effect of reducing the number of bits per colour from 8 bits to 4 bits.

Tone Mapping

One approach to displaying high dynamic range images on displays with a smaller dynamic range is to employ a tone mapping or tone reproduction algorithm. The aim of these algorithms is to reduce the dynamic range of the image to match that of the display whilst preserving scene features, details or perceptibility. To achieve this, tone mapping algorithms create a mapping between the luminance values in the high dynamic range image and the displayable luminance values. Several tone-mapping algorithms have been proposed [3, 4], of which the one proposed by Ward Larson, Rushmeier and Piatko [5] has been used in this investigation.

Figure 1. An unprocessed wide dynamic range scene used to compare tone mapping algorithms.

Ward Larson, Rushmeier and Piatko proposed a tone-mapping algorithm that includes a histogram adjustment technique for reproducing perceptually accurate tones in high dynamic display images. The starting point for the histogram adjustment was the knowledge that the human visual system is sensitive to relative rather than absolute changes in luminance. This means that the perceptual experience of a scene can be maintained as long as bright areas in the scene are displayed as bright and darker areas appear darker. Since the brightness of an area of an image can be approximated by the logarithm of the luminance the histogram is formed using the logarithm of the luminance. In addition, the eye adapts rapidly to a 1 degree visual field. Hence histogram adjustment is performed on a histogram of the logarithm of the average luminance values, were the average is taken over an area of the image corresponding to a 1 degree field of view. These values are then used to create a cumulative distribution that creates a mapping between the scene luminance values and the corresponding display values.

Figure 2. The scene from figure 1 after tone mapping using the histogram equalization mapping function created using the technique proposed by Ward Larson, Rushmeier and Piatko.

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Tone Mapping for Logarithmic Cameras

The predominant feature of existing tone-mapping algorithms is that they have been developed to be used with high dynamic range images in which the pixel value is proportional to the luminance of the corresponding part of the scene. However, tone mapping essentially involves manipulating the human sensation of brightness of a scene so that the same experience is obtained from a display as from the original high dynamic range scene. Considering that brightness can be estimated from the logarithm of the luminance, tone mapping algorithms appear to be ideally suited to use with logarithmic cameras, which create an image containing pixel values proportional to the logarithm of the luminance.

A feature of the algorithm proposed by Ward Larson, Rushmeier and Piatko is that the histogram adjustment to create the important map between the image values and the display values is based upon processing the logarithm of the local average luminance. For a 'conventional' linear high dynamic range image, this is calculated by averaging the pixel responses and then calculating the logarithm of result. When the scene has been captured using a camera with a logarithmic response it is computationally easier to calculate the local average of the logarithm of the pixel luminance rather than the logarithm of the local average pixel luminance. In our experience images tone mapped using histograms of these two different values are indistinguishable. For an image from a logarithmic camera tone mapping can therefore be based upon a local average of areas of the image.

Another important aspect of tone mapping is the way in which colour information is handled to preserve the perception of colour. The tone mapping process is based upon creating a map between image brightness and display brightness. This means that a colour image should be separated into a luminance component, that can be tone-mapped, and chromatic components that are left unaltered. This suggests that the best format for tone-mapping a colour image is one in which the luminance is separated from the chroma.

Most cameras are manufactured with outputs that represent colour information using the RGB format that is most easily displayed. However, the best approximation to luminance that is available is the Y component of the XYZ CIE colour space. This suggests that the best approach to tone mapping is to determine the luminance at each pixel by calculating the Y component at each pixel and then tone mapping this variable. Since tone mapping will involve a transformation between the $logY$ values in the image and that which is displayed it is imperative to create a format in which the RGB values can be displayed correctly after the mapping of the $logY$ value. For a logarithmic camera the simplest means of achieving this is to create the variables

$$
\begin{aligned}
logr &= logR - logY = log\frac{R}{Y} \\
logg &= LogG - logY = log\frac{G}{Y} \\
logb &= logB - logY = log\frac{B}{Y}
\end{aligned}
$$

Once the $logY$ value has been tone-mapped to a corresponding value $log\acute{Y}$ then the three tone-mapped colors $log\acute{R}$, $log\acute{G}$ and $log\acute{B}$ can be calculated using

$$
\begin{aligned}
log\acute{R} &= log\acute{Y} + logr \\
log\acute{G} &= log\acute{Y} + logg \\
log\acute{B} &= log\acute{Y} + logb
\end{aligned}
$$

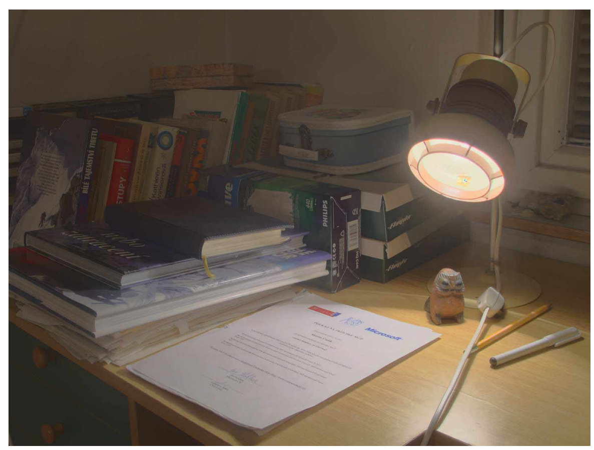

Figure 3. The office image after tone mapping using the response of Y pixels in a logarithmic camera

Displaying a logarithmic image directly leads to a disappointing result in which many colors appear to be less saturated than expected. However, in normal tone mapping, and other techniques such as homomorphic filtering, the logarithmic representation is only an intermediate stage and the image is converted to a linear representation before it is displayed. This suggests that the image should be converted to a linear format $\acute{R}\acute{G}\acute{B}$. In some applications, notably display of computer generated scenes that must be as realistic as possible, it would be appropriate to modify this image to mimic the changes in the performance of the human visual system at different luminance levels. However, when displaying the image from a camera it is more appropriate to display the image as captured, even if the result is better than could be achieved by the unaided human visual system. The parts of the algorithm proposed by Ward Larson, Rushmeier and Piatko aimed at matching the subjective experience of viewing the image, including models for human contrast sensitivity, glare, spatial acuity, and color sensitivity, have not been implemented.

Figure 3 shows the effects of tone mapping the simulated output of a logarithmic response camera. As expected the resulting image is very similar to the result of tone mapping the conventional image of the same scene, shown in figure 2.

Tone Mapping using Green

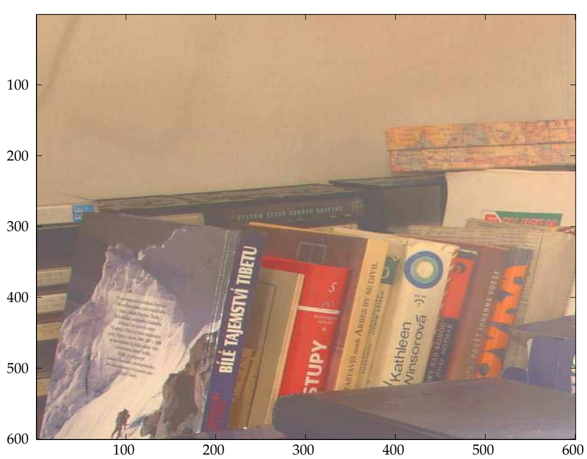

Figure 4. The office image after tone mapping using the response of Y pixels in a logarithmic camera.

Figure 3 shows that a tone mapping algorithm can be applied to the image from a logarithmic camera. However, as in the original algorithm tone mapping was performed using the variable luminance channel Y. In a linear camera calculating Y from the RGB values is relatively simple. However, in a logarithmic camera the response of each pixel has to be converted to the linear domain, before the Y value is calculated so that the average of the logarithm of Y is used in tone mapping. Since green is more than 70% of the luminance Y, it appears that there is an opportunity to avoid the complexity of transforming between different representations by simply tone mapping using the local average responses of the green pixels in an image from a logarithmic sensor since it approximates the brightness of an area.

In order to investigate the possible compromise in the quality of an image resulting from tone mapping using green several images have been tone mapped using green channel rather than the Y luminance channel. Results from these images suggest that almost all areas of the images are indistinguishable when tone mapped using the two different variables. However, there is the occasional object in each image whose appearance is noticeably changed. One example of this effect is the red book at the left of the office image. This difference can be clearly seen by comparing figure 4 and figure 5. Comparison with the original image suggests that, as would be expected, the results obtained using tone mapping of $logY$ are more similar to the original scene than tone mapping using $logG$. However, the zoomed and equally brightened views of parts of the scene in figures 4and 5 show that there are some small differences that are only detectable if the tone mapped image is compared directly to the original. Our experience suggests that tone mapping using $logG$ leads to comparatively good results.

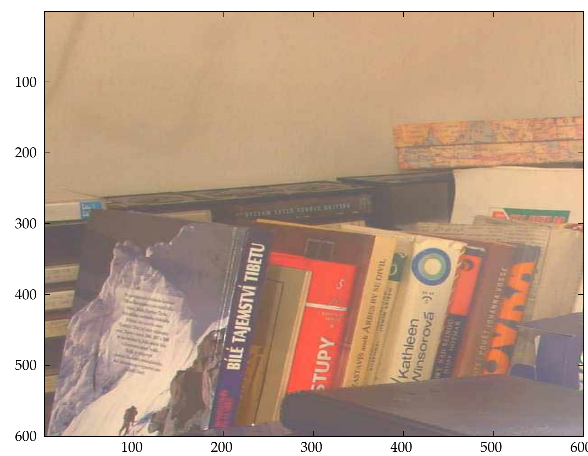

Figure 5. The office image after tone mapping using the responses of the green pixels in a logarithmic camera.

Bit Length per colour

The results in the previous sections show that it is possible to tone map the output from a high dynamic range logarithmic camera into a conventional display format with 8 bits per colour per pixel. This format is suitable for many conventional display devices. However, an increasing number of low cost display devices, such as viewfinders for digital cameras and displays on mobile phones have fewer bits per colour per pixel.

The impact of reducing the number of bits per colour has been investigated by using the tone mapping algorithm to convert input images into displayable images with between 4 and 8 bits per colour per pixel. The typical results in figure 6 show that as expected reducing the number of bits per colour reduces the quality of the displayed image. The degradation with only 4 bits per colour is quite severe. However, the images 7 bits per colour are indistinguishable from the results with 8 bits per colour. The effect of reducing from 7 bits per colour to 6 bits per colour is an acceptable quality image over most of the scene, but a loss of detail in some areas, such as the box resting on the top of the row of books at the right hand side of the scene in figure 6 is questionable. The final decision concerning the acceptable quality of the final image and hence the number of bits per colour that must be used ultimately depends upon the application. However, these results suggest that tone mapping can be used to display the output of a high dynamic range logarithmic camera on displays with less than 8 bits per colour.

Figure 6. The effects of reducing the number of bits used to display the image. The image in the top left is the starting image. The other two images on the top row are quantized to 8 and 7 bits. The bottom row is 6, 5 and 4 bits from left to right.

Conclusion

Logarithmic cameras can be used to image high dynamic range scenes. After fixed pattern noise correction, the images can cover a range of 5 decades and match the contrast sensitivity of the human visual system using 10 bits per colour or 30 bits per pixel. This is significantly fewer bits than a conventional camera with the same dynamic range and contrast sensitivity. However, the dynamic range of the image is still larger than that of conventional display devices.

Preliminary results have been presented that show that a modified form of a tone mapping algorithm can be used to display the images from a logarithmic camera using a conventional display with 8 bits per colour. In particular the results suggest that tone mapping can be based upon brightness estimated from the local average of the image of a logarithmic camera rather than the logarithm of the local average colour. In a colour image tone mapping should be undertaken using the colour component that most closely approximates the luminance of an area of the scene. This suggests that the best results will be obtained with a colour logarithmic camera in which the spectral responses of each pixel correspond to either X,Y or Z. Our simulations suggest that in this case the image from a logarithmic camera is indistinguishable from the original image after conventional tone-mapping. However, simulation results have also been presented that show that using the green component of a logarithmic camera with red, green or blue pixels leads to good results, containing only the occasional noticeable different between the original image and the result of tone mapping. Finally, results have been represented that show that the proposed method of displaying the images from logarithmic cameras can be used to display images on displays with as few as 5 or 6 bits per colour.

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Author Biography

Stephen O. Otim received a BSc. degree in Electrical Engineering from Makerere University, Uganda in 2001 before embarking on a D.Phil in the Engineering Science department of Oxford University. Since September 2002, he has been studying logarithmic CMOS sensor fixed pattern noise calibration and quality image reproduction on low range displays. His interests include visual imaging, colour science and image processing.

Steve Collins received a B.Sc. degree in Theoretical Physics from the University of York, York, U.K. in 1982 and the Ph.D. degree from the University of Warwick, Warwick, U.K., in 1986. From 1985 until 1997, he worked in the Defense Research Agency on various topics including the origins of $1/f$ noise in MOSFETs, CMOS cameras and analog information processing. Since 1997 he has been working at the University of Oxford, Oxford,U.K. where he has continued his interest in CMOS camera with particular emphasis on high dynamic range logarithmic cameras.