

Tone-mapping functions and multiple-exposure techniques for high dynamic-range images

Citation for published version (APA):

Cvetkovic, S. D., Klijn, J., & With, de, P. H. N. (2009). Tone-mapping functions and multiple-exposure techniques for high dynamic-range images. *IEEE Transactions on Consumer Electronics*, 54(2), 904-911.
<https://doi.org/10.1109/TCE.2008.4560177>

DOI:

[10.1109/TCE.2008.4560177](https://doi.org/10.1109/TCE.2008.4560177)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Tone-Mapping Functions and Multiple-Exposure Techniques for High Dynamic-Range Images

S. Cvetković, *Member*, IEEE, J. Klijn, P.H.N. de With, *Fellow*, IEEE

Abstract — For real-time imaging with digital video cameras and high-quality with TV display systems, good tonal rendition of video is important to ensure high visual comfort for the user. Except local contrast improvements, High Dynamic Range (HDR) scenes require adaptive gradation correction (tone-mapping function), which should enable good visualization of details at lower brightness. We discuss how to construct and control improved tone-mapping functions that enhance visibility of image details in the dark regions while not excessively compressing the image in the bright image parts. The result of this method is a 21-dB expansion of the dynamic range thanks to improved SNR by using multiple-exposure techniques. This new algorithm was successfully evaluated in HW and outperforms the existing algorithms with 11 dB. The new scheme can be successfully applied to cameras and TV systems to improve their contrast.

Index Terms — Adaptive tone mapping, high dynamic range, video camera, multiple exposure sensors, image fusion.

I. INTRODUCTION

The dynamic range of an image signal generated by an image sensor in CCD or CMOS technology is limited by its noise level on the one hand, and the saturation voltage of the sensor on the other hand. For a CCD-sensor, a dynamic range of 74 dB can be obtained which is sufficient for most applications. However, for applications with a very large contrast ratio, e.g. such as outdoor scenes with bright sunlight, a larger dynamic range is required in order to obtain images with a satisfactory quality. For example, the contrast ratio in a sunny outdoor scene can be as high as 1000 (60dB). For the lowest level in that scene, the SNR needs to be 40 dB in order to achieve an acceptable quality. Therefore, the total dynamic range should be about 100 dB. For a given CCD/CMOS sensor, the saturation voltage (corresponding to maximum image brightness) is fixed, leaving us only with the possibility to reduce the noise level in order to increase the dynamic range.

There were already some solutions proposed in literature to reduce the noise level. A very popular idea known from the state-of-the-art patents [1] is a double-exposure system, where two images are captured with a short time interval. Images are

taken with a short and a long exposure time, where the ratio of the exposure times varies from 4 to 32. The combination of these two images results in a good SNR in the dark parts of the image, due to the long exposure time of the second image. In addition, there is almost no saturation in the bright parts of the image, since the first picture is taken with a short exposure time. In the following stage, two differently exposed images are combined to create an output image having an improved SNR that is necessary for an acceptable image quality.

In a digital camera system, gamma correction is often performed as a compensation of the CRT transfer function. It is observed that the *standard* gamma correction (as in Fig. 1) is often not sufficient to improve visibility of dark image details, due to the compression of the dynamic range of the image sensor to the range of the display device. Simply, a high dynamic range input signal from the sensor (even with the mentioned dynamic range of 74 dB) exceeds the capabilities of display devices with several orders of magnitude (the display has typically a dynamic range of 35-40 dB). This discrepancy poses an interesting challenge. Therefore, in the past, both steeper gamma functions and modified gamma functions with limited amount of compression in the high-brightness regions have been explored (Fig. 1, *extended range*). The problem of these approaches is that they introduce extreme compression of a large portion of the input signal and make the resulting image rather pale, which does not satisfy our requirements.

Several authors studied HDR compression problems [2]-[4]. In our previous work [2], tonal mapping was performed directly on the complementary mosaic sensor signal which creates a difficult problem of non-linear color changes:

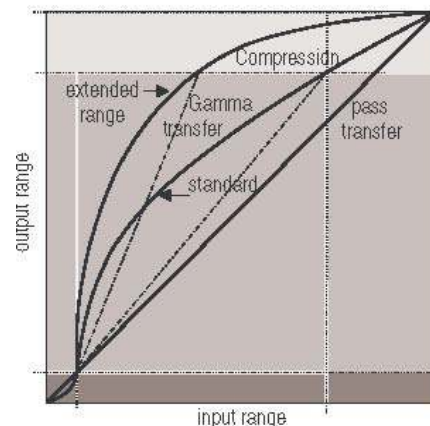


Fig. 1. Various gamma functions, expanding the darker regions, however, at the expense of reduced amplitude range for the largest part of the input range (upper light gray area).

S. Cvetković is with the Bosch Security Systems, Eindhoven, 5616LW NL (e-mail: sacha.cvetkovic@nl.bosch.com).

J. Klijn, is with the Bosch Security Systems, Eindhoven, 5616LW NL (e-mail: jan.klijn@nl.bosch.com).

P.H.N. de With is with University of Technology Eindhoven, EE Dept., 5600MB Eindhoven, and Cyclomedia Technology BV Waardenburg, NL.

preservation of saturation and hue of the colors. Fuzzy logic [3] as well as variable transfer functions in combination with the local contrast enhancement [4] were successfully used, but only up to 10-dB expansion of the dynamic range was achieved. The combination of image fusion and tone reproduction as proposed in [5] looks promising for static digital images, but cannot work well with digital video cameras where large object or camera motion is involved and no recording delays are allowed.

To improve HDR imaging for moving video signals, we propose a new segmented luminance tone-mapping function based on splines, in which we control individual segments, together with a control algorithm for their selection. In this paper, it will be clarified that the applicability of our technique is increasing with the new multiple-exposure-time sensors. This is explained by the fact that multi-exposure sensors improve the SNR in the dark areas where the signal is weak, which is exactly the area where expansion is required. In our case, the expansion will be realized with a set of spline functions which enable flexibility in the optimization process.

The sequel of this paper is organized as follows. Section II describes an improved tone-mapping method. Section III discusses the noise improvement with the focus on multi-exposure-time techniques. Section IV provides experimental results, and in Section V conclusions are presented.

II. AN IMPROVED TONE-MAPPING METHOD

A. Knee tone-mapping function

At the start, we split the *extended-range* gamma transfer function into two functions: the so-called knee and regular gamma function. The *knee* transfer function is stretching the black interval to enhance visibility in darker parts of the scene. It is especially useful for the HDR scenes with sufficient SNR.

As the optimal amount of stretching is scene, light and sensor dependent, a flexible circuit was designed using quadratic splines. The basic spline function we used is shown in Fig. 2, consisting of three sub-functions:

$$f(y) = \begin{cases} c_1(y+1)^2 & \text{for } -1 < y \leq 0, \\ c_2(1-2y(y-1)) & \text{for } 0 < y \leq 1, \\ c_3(y-2)^2 & \text{for } 1 < y \leq 2. \end{cases} \quad (1)$$

In the example, the basic spline function is depicted with a solid (red) line, for a $c_1 = c_2 = c_3 = 1$. Section $0 < y \leq 1$ is the 'core' part of the function, while the tails extend in the neighboring sections. Tone mapping starts with splitting the luminance input range into n sections, where in each section a spline function is used. Each section has its own core part while the two spline tails extend to the neighboring sections. When looking at one section, the parameter c_2 can be set freely, while the left and right neighbors give the tails with amplitudes c_1 and c_3 . The shape of the function guarantees a smooth transition for all combinations of c_1 , c_2 and c_3 , when going from one section to the next (continuous first derivative). To calculate the overall function for one section with boundaries $0 < y \leq 1$, we have to add the right part of the left-shifted function (blue, dotted) and the left part of the right-shifted

function (brown, dashed) to the central part of the central function (red, solid line), in order to find the function: $f(y) = c_1(y-1)^2 + c_2(1-2y(y-1)) + c_3y^2$, which can also be rewritten to the following second-order function:

$$f(y) = (c_1 + c_2) + 2(c_2 - c_1)y + (c_1 - 2c_2 + c_3)y^2. \quad (2)$$

Accordingly, each knee section is constituted from the functions (2), with c_2 being the core section parameter. The adjacent future section has its own c_2 parameter, which also represents the c_3 parameter of the actual section. Similarly, the c_2 parameter of the previous section is used as the c_1 parameter of the current section.

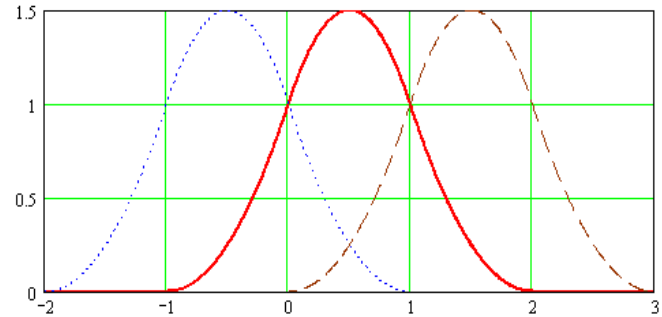


Fig. 2. Two shifted versions of the basic spline function in the middle.

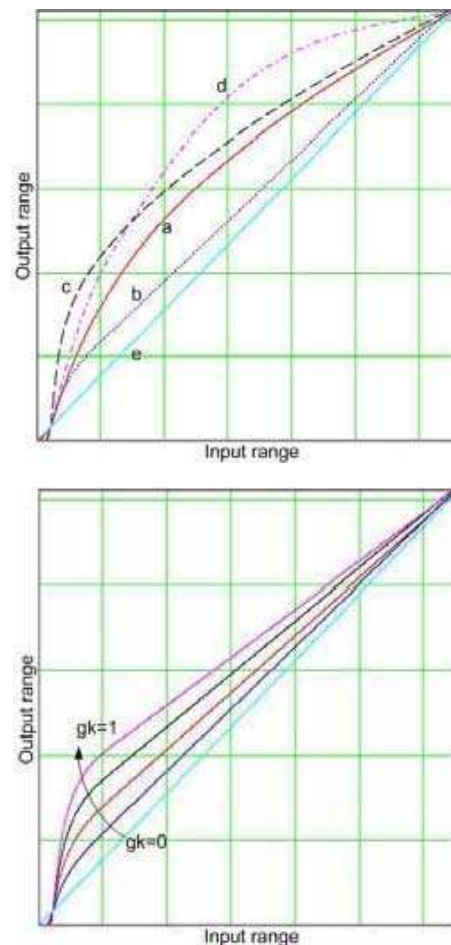


Fig. 3. (top): Tone-mapping functions: a) Gamma; b) Knee; c) Gamma and Knee together; d) smart extended range Gamma; e) linear transfer function. Figure 3 (bottom): Example set of knee transfer functions for several values of g_k , ranging from 0 to 1.

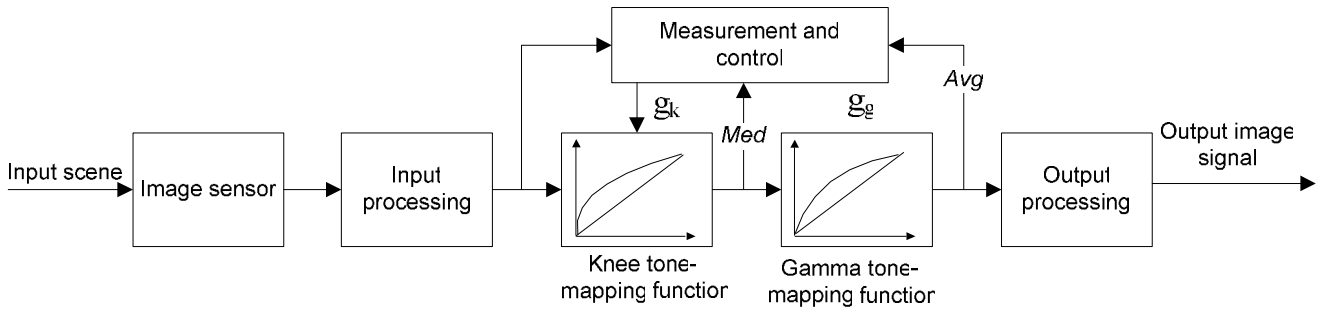


Fig. 4. Dynamic control of knee function to optimize the displayed image.

Additionally, we have found a relationship between n section parameters c_1, c_2, \dots, c_n , which ensures a desirable shape of the overall knee tone-mapping function. It relates all section parameters c_i to one control parameter g_k with which the overall knee function can be controlled to a desired shape. As a result, when y is the input-range variable and h_i (for $i=1..n$) is a set of functions, the overall knee function is specified by:

$$\begin{aligned} f_{knee}(y) &= f_{knee}(y, c_i | i = 1..n) \\ &= f_{knee}(y, g_k | c_i = h_i(g_k), i = 1..n), \end{aligned} \quad (3)$$

where the individual functions and their parameters c_i comply with the overall knee function specified by parameter g_k (see Fig. 3 bottom). As noted in Fig. 3 top, the knee transfer function (as well as the overall transfer function knee + gamma) can be steeper than the standard gamma function in the beginning of the input range, while introducing less compression in the last part of the input interval. As a final result, we can reproduce the objects with a dynamic range that emulates an expanded range which is better than that of the standard display, while not significantly deteriorating the gradation in the bright area.

We should comment at this point that using tone-mapping functions that have very high gain in the lowest part of the luminance range, is beneficial for perception of details in that region, but this process is very much limited by the available SNR. The SNR is the worst in low-brightness regions where even small signal gains bring visibility of the noise to a disturbing level. To cope with this problem, multi-exposure sensors are used in which the darkest luminance parts are substituted with longer exposure parts having better SNR. This principle will be further explained in Section III.

B. Control algorithm to determine the optimal knee tone-mapping function

A preferred control strategy is to relate the image median value after the knee tone-mapping function to the mean video level after the gamma output (see Fig. 4, *Med* and *Avg*). We achieve this by controlling parameter g_k of the f_{knee} function. Hence, we couple the knee transfer-function gain to the output video level. Increasing parameter g_k leads to a non-linear growth in the output video level and the *Med* value. Because of the chosen knee shape, the *Med* increase is larger than the *Avg* increase for the majority of the images. By such an action, the image histogram is redistributed to an improved version. The idea behind this control is that when the customer sets a certain

Wanted Video Level (WVL) from the camera, we will only optimize the output video image around that level and not change it too much. In this way, we do not over-compensate the video signal, especially at low WVL. To control the extent of the knee function, min/max knee values are introduced which limit the range in which g_k can change. Hence, images are not drastically changed.

An example of such a control is realized by modifying g_k to achieve that $Med = a * Avg$, with $a < 1$. The setting of coefficient a depends on the input image and user preferences. When designing such a control, one has to anticipate on the change of the image histogram that occurs as a result of the gamma transfer function, and to pre-compensate for it. To this end, we introduce a new parameter g_g that controls the extent of the gamma function and that depends on the user setting and the system itself. We can create versatility of the gamma functions from a linear one to those that are much steeper than the standard gamma function by employing a power exponent:

$$f_{gamma}(y) = C \cdot (y + off)^{g_g}, \text{ where } g_g \in [0.2, \dots, 1.0]. \quad (4)$$

Here, y and $f_{gamma}(y)$ are input and output signals, respectively, parameter *off* is offset and C represents normalization constant.

We calculate the *Med* value from the differentiated image histogram after the knee transfer function. For this, we only consider pixels that belong to the detailed regions in the image. Hence, we ensure that expansion of the dynamic range occurs only if there are visually interesting details in the darker image parts. A simple implementation of this action is to start at the beginning of each line and to consider only pixels which are different from the *previously selected* pixel for a given threshold.

The median is chosen as a control measurement for the algorithm as it provides a simple central tendency description of the pixel distribution in the image histogram. Instead of the median, we could also use other percentile measurements or other kinds of measurements like mode, skewness or kurtosis. The guideline is to measure where the majority of pixels are, how many low-brightness pixels are left after $f_{knee}(y)$ and how many high-brightness pixels are compressed, due to the overall transfer function. Up to this point, we have defined a special knee tone-mapping function and a control algorithm. These techniques are now combined with the multi-exposure sensor technique to provide a better SNR and enable a low-noise output image. This is particularly important when significant black stretching is performed.

III. MULTIPLE-EXPOSURE TECHNIQUE

To improve the SNR performance, images taken with at least two exposure time settings should be available at the same time for the camera processing. This is possible by means of the special CCD which physically stores images taken with two exposure times on one CCD. An image taken with long exposure time has a good SNR but it is over-exposed in bright parts of a scene. An image taken with a shorter exposure time is a standard image which has a lower SNR, and is under-exposed in dark parts. The long and the short exposed images have to be combined into a single image for further processing.

The simplest way to derive this combination is to bring them to the same base by weighing them to retain the luminance relations occurring in the real scene (see examples in Figs. 5 and 6). For example, if the long exposure time equals four times the short exposure time, then we would give the short-exposed image relatively four times more gain than the long-exposed image, to retain the luminance relation. In this particular example, when the ratio of exposure times equals four, after recombining those two images into one image, the first quarter of the input luminance range is derived from the long-exposure image and the other three quarters are derived from the short-exposure image (Fig. 6 top), where one can also notice differences in SNR between short and long exposed parts (Fig. 6 bottom).

In cases when evident changes between long and short exposed images pixels occur (for instance when motion is present in the image) a problem of miss-registration appears and linear relationship between exposed images is no longer valid. Easiest way to solve for this problem is to discard the long exposed image part with motion and use only short exposed image for those problematic pixels.

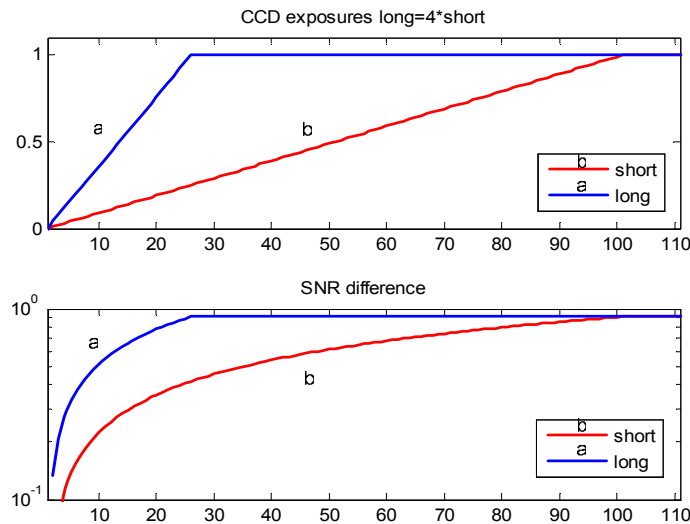


Fig. 5. Example of dual exposure action where long exposure equals 4 times short exposure.

An additional important consideration is the detailed mixing or combining short- and long-exposed images into one image. We will discuss two options. At the top part of Fig. 7, a *hard switch* is presented: if the input level is lower that a threshold th , a pixel from the long-exposed image is used, and vice

versa. Fig. 7 (bottom) depicts a *soft switch* between long- and short-exposure images, where two images are mixed in a transition region with weights proportional to their value. According to the example from Figs. 5 and 6, in which an exposure ratio of 4 was used, the setting of threshold parameter $th = (th_1 + th_2) / 2 = Y_{in\ max} / 4$.

It is a well-known phenomenon that saturation effects occur for over-exposed areas in a long-exposed image, since too many electrons are captured in one memory cell (pixel). The effect originates from the self-induced electrical field and results in a distortion in the potential bucket of a sensor integration cell for high input levels. This effect has to be compensated, so that both exposure parts become collinear. Most critical is the cross-over point of the transition between

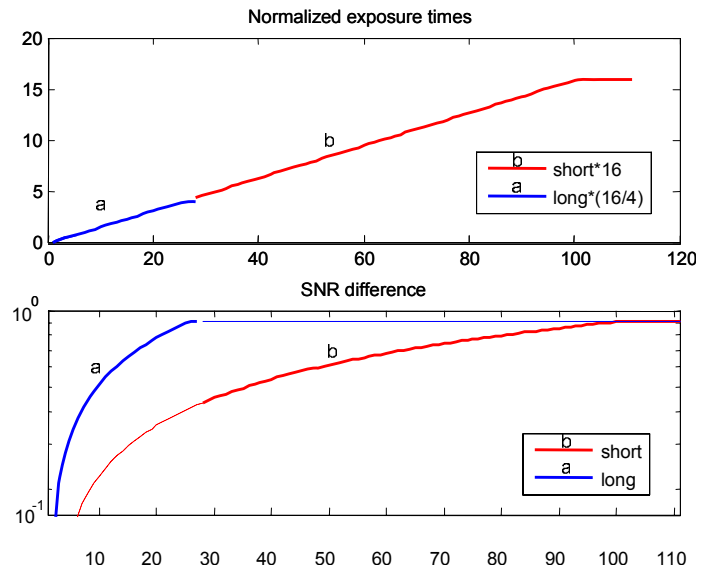


Fig. 6. Images originating from two exposure times after correction to the same base.

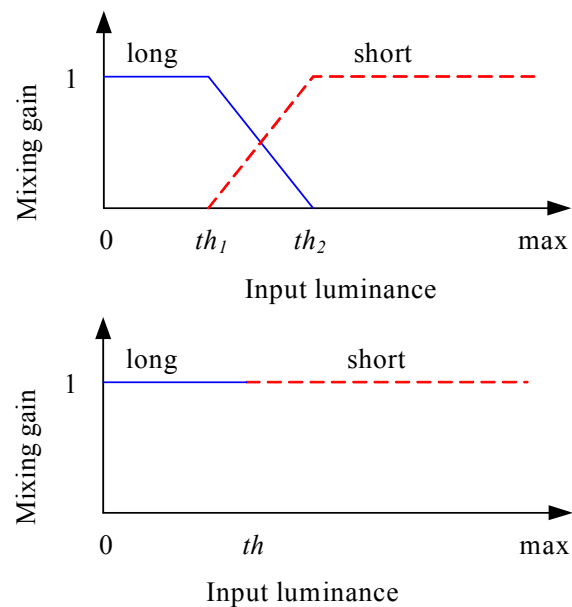


Fig. 7. Merging long- and short- exposure images into one image: top) mixing; bottom) hard switching.

long and short exposure time, since any discrepancy or mismatch at that point would introduce unacceptable color errors and even the occurrence of colors in the gray images or colorless image parts.

In case when soft switching is used between long- and short-exposed images (Fig. 7 top), due to the mixing in the transition region, the color-error problem is minimized. A disadvantage of mixing is that a short-exposure signal with much lower SNR will corrupt a long-exposure signal with higher SNR and thereby lower the point from which SNR is improved ($th_l < th$).

It is more advantageous to use a hard-switch threshold (bottom of Fig. 7.), since a corruption of the SNR does not occur. In this case, an additional correction circuit has to be used to cope with the saturation problem. For this purpose, we have already proposed a second-order correction function [6].

Let us now explain the image combining problem and the related color error problem in more detail.

A. Combining long and short exposed images

The line graph shown in Fig. 8 (top) shows the functional relation between light level (x-axis) and output signal (y-axis) of an image pickup sensor, especially a CCD-sensor, both of them in arbitrary units. We can observe the functional relations from the short and long exposure times (*Short, Long*). Both

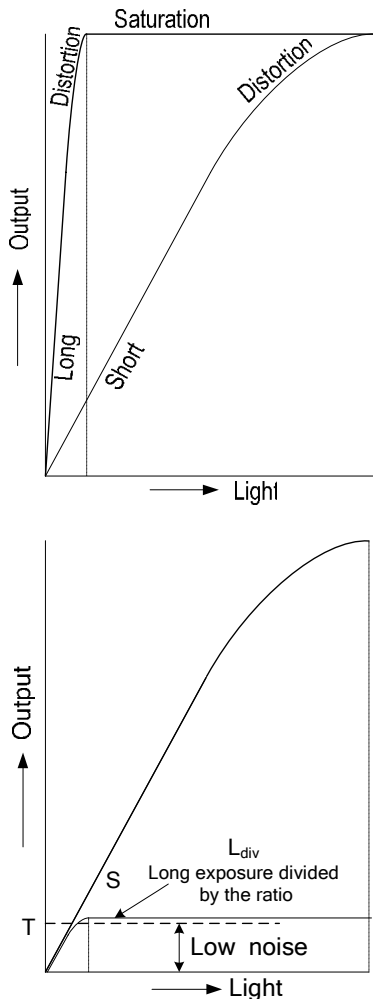


Fig. 8. Basic principle of combining long and short exposed images.

curves show a linear part and a part with non-linear distortion when going into saturation. Fig. 8 (bottom) shows a similar graph after a combination processing step.

During this process the values of the *Long* transfer function are divided by the ratio of the exposure times applied. This results in the curve that goes into saturation at rather low values of the light level. The *Short* transfer function representing the functional relation between light level and output signal due to a short exposure time remains unchanged. The combination of the two images *L* (signal of the long exposed image) and *S* (signal of the short exposed image), is performed making use of the following relations:

$$Out = L_{div} \text{ if } (S < T) \text{ else } Out = S, \text{ where } L_{div} = L / R \text{ with } R = T_L / T_S. \tag{5}$$

Here *T* stands for threshold, T_L is a long exposure time, T_S is a short exposure time and *Out* represents the combined output signal.

The major problem combining the two images in this way is to avoid irregularities at or near the cross-over point. The CCDs use color filters in order to create a color image. In the output signal of such a CCD, the consecutive pixels can have different values as they are filtered with a different color filter. Around the threshold level *T* this results in a signal *Out* which originates from pixels based on a different input *S* or *L*. As the color decoding process may use the differences between consecutive or nearby pixels, irregularities will create color errors.

Due to the non-linearity of the CCD output, the transfer is non-continuous at the threshold *T* when using exactly *R* to calculate the L_{div} signal. However, even when the ratio *R* is adapted to exactly match *S* and L_{div} at the threshold *T*, the first

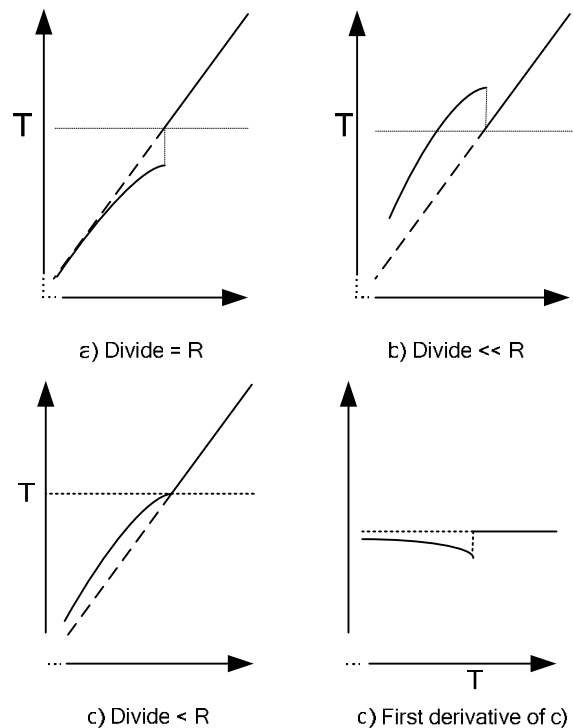


Fig. 9. Matching problems at the cross-over point.

derivative remains non-continuous (see Fig. 9). This creates severe color errors.

B. Sensor non-linearity correction

One of the possible approaches to cope with the sensor's non-linearity is to use minimum AGC setting [7]. The idea is to calibrate the image sensor such that it operates only in the linear mode (part) of the Opto-Electronic Conversion Function (OECF) by multiplying the signal with a gain. Likewise, we shift the non-linear part of the OECF to the clipping range. However, we noticed that the OECF non-linearity starts at an early stage, so that this approach can severely reduce the applicable dynamic range of the sensor.

Other approaches [8],[9] try to overcome this problem by making a gradual transition over a certain range when going over from L_{div} to S , and vice versa (mixer), instead of switching. This has serious drawbacks. Firstly, the noise in S is much higher (by a factor R) than in L_{div} . When using a mixer L_{div} , nearly the whole mixing range would be dominated by the noise of S . Secondly, the range of the mixer would need to be large to really annihilate distortion. This sacrifices much of the precious low noise L_{div} range. Thirdly, the involved distortion influences 2 sensor lines due to the different signal amplitudes coming from different optical filters. A mixer would need to be a vertical- or 2D-mixer to be effective.

For these reasons, we propose a novel correction function that is applied to L_{div} prior to switching. The curve of this function is exactly compensating the non-linear CCD output such that the resulting transfer (after division) is linear and exactly matches the transfer of S . Many functions are applicable for correction, for example, the non-linear function

$$y = x + k_1 \cdot x^2 + k_2 \cdot u(x-p)(x-p)^2. \quad (6)$$

The term $k_1 x^2$ compensates the charge distortion in the CCD and term $k_2(x-p)^2_{x>p}$ (only valid for $x>p$ due to unit-step function u) is compensating the saturation of the output stage.

The solution proposed above only solves half the problem: the factors k_1 , k_2 and p in the correction function need to be found and dynamically adapted, as the non-linearity of the CCD is temperature dependent. To find those, the signals S and L_{div} (or L) are measured at defined levels and after some curve-fitting calculations, the parameters for the non-linear correction function can be computed.

We measure S and L_{div} and close a feedback control loop such that the differences between those signals become zero when a perfect match is achieved. It is also possible to measure L and S and make an equally good feed-forward control.

In a practical implementation, a software feedback loop is made using 4 measurement bins with a width of $1/64^{\text{th}}$ of the L_{div} range (Fig. 10). The values of the pixels falling in the bins are summed over a frame time. The first bin is set at 50 % of the range while $p>50$ % of the range. From this, k_1 can be optimized. The second bin is positioned just below, the 3rd at and the 4th just above the threshold level. When k_1 is found and p is fixed, k_2 can easily be optimized with the use of the 3rd bin. Instead of calculations, also a simple hill-climbing strategy can be used, as the final results should be such that the contents of the corresponding bins are the same.

The 2nd and 4th bin can be used to check if the optimization is correct or if the threshold should be changed, because of a higher /lower distortion than expected.

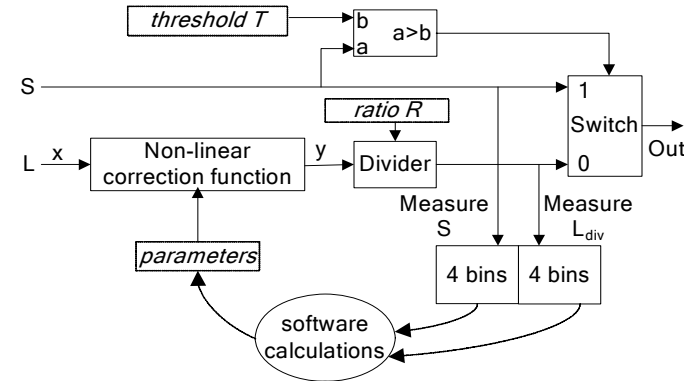


Fig. 10. Correction of the non-linearity of OECF and image combination.

IV. EXPERIMENTAL RESULTS

We have tested our HDR expansion scheme and compared it to other approaches using both LDR (low dynamic range) and HDR video sequences. In Fig. 11, one can observe loss of details either in dark or bright areas when using the other methods, and the clear improvement with our proposal of dark objects while keeping a good gradation in bright areas.

We also show snap-shot results of an HDR video sequence in Fig. 12. The right side of the image, placed against the light box, is covered with the dark foil to create a larger dynamic-range scene while the left side simply shows dark background. As can be observed, the SNR performance is poor when the multi-exposure technique is not incorporated. Since perception of details is also poor, we applied the local contrast-enhancing technique from our previous work [10]. Likewise, in Fig. 13 we show the original HDR image followed by the contrast-improved images. We observe that use of the multi-exposure technique is necessary to improve otherwise unacceptable SNR performance.

For other scenarios, similar improvement results are obtained. In cases when the input image has LDR, no or small black stretching occurs, which is then advantageous for the image contrast. Otherwise, for HDR images, the system performs the black stretch depending on the image parameters and user preferences.

V. CONCLUSION

We have presented a new technique for the expansion of HDR images that uses spline functions. For simplicity, the system controls the spline function with only one parameter. At the same time, we also presented the control algorithm for the spline function that uses the image statistics and performs dynamic-range expansion to the extent that is needed. The result of this method is a 21-dB expansion of the dynamic range in which an acceptable amount of compression is introduced. We use this HDR expansion technique in combination with a multiple-exposure time technique. This approach provides the desired improved SNR needed for



Fig. 11. Results: (a) standard camera image, (b) smart extended range Gamma, (c) method from the [4], (d) our method ($\alpha=0.5$).

the dark areas within the usage of dynamic-range expansion. We have observed that the multiple-exposure technique is particularly important in cases where local contrast enhancement is applied to improve otherwise unacceptable SNR performance.

Additionally, we have increased the operating range of the sensor's OECF by applying a non-linear correction function to the distorted sensor signal and make a good dynamically-controlled match in the transition region from long to short exposed image used for creating combined larger dynamic range image. With a 16-bit AD converter and an exposure ratio between long and short image of 16 times, we effectively obtained a 20-bit accuracy of the sensor signal. If spatial/temporal dynamic noise reduction is used, the noise floor is further lowered and this provides 6-12 dB additional dynamic range.

It is beyond discussion that the complete presented solution is attractive for both consumer cameras (camcorders, etc.) and professional equipment. However, the tuning should be adapted to the application. Also, with the introduction of newer multiple-exposure sensors that provide an even better SNR in dark areas, the applicability of our technique becomes more attractive.

REFERENCES

- [1] Alston L. E.; Levinstone D. S.; Plummer W. T., "Exposure control system for electronic imaging camera - has information signals stored in memory with controller selecting to provide image output of subject," US patent number US 4 647 975 A1 from 03.03.1987.
- [2] S. Cvetkovic and P.H.N. de With, "Image enhancement circuit using nonlinear processing curve and constrained histogram range equalization," Proc. of SPIE-IS&T, Electronic Imaging, Vol. 5308, pp. 1106-1116 (2004).
- [3] Sakaue, S.; Nakayama, M.; Tamura, A.; Maruno, S., "Adaptive gamma processing of the video cameras for the expansion of the dynamic range", *IEEE Trans. on Consume .Electronics*, vol.41, no. 3, p.p: 555 - 562, Aug. 1995.
- [4] Y. Monobe, H. Yamashita, T. Kurosawa, H.Kotera, "Dynamic Range Compression Preserving Local Image Contrast for Digital Video Camera," *IEEE Trans. on Consume .Electronics*, vol. 51, no. 1, p.p. 1 -10, Feb. 2005.
- [5] Wen-Chung Kao, "High Dynamic Range Imaging by Fusing Multiple Raw Images and Tone Reproduction," *IEEE Trans. on Consume .Electronics*, vol. 55, no. 1, pp. 10-15, Feb. 2008.
- [6] J. Klijn, J. Schirris, P. Dielhof, "Image pickup apparatus has non-linear correction unit that corrects anyone of image signals acquired at small and large exposure times to obtain smooth transition between image signals at transition point," patent application number WO-2007038977 from 12.04.2007.
- [7] Wen-Chung Kao, Chin-Ming Hong, and Sheng-Yuan Lin, "Automatic sensor and mechanical shutter calibration for digital still cameras," *IEEE Trans. on Consume .Electronics*, vol. 51, no. 4, pp. 1060-1066, Nov. 2005.
- [8] E. Ikeda, , "Image processing method of digital video camera - by combing digital data of different images of equal signal levels," patent application number US 5 801 773 A from 1.09.1998.
- [9] E. Ikeda, K. Kondo, "Image composition apparatus for video cameras - uses brightness level adjustment unit to unit brightness level of non-standard image signal from multiple image signals," patent application number US 6 204 881 B1 from 20.03.2001.
- [10] Sascha D. Cvetkovic, Johan Schirris and Peter H. N. de With, "Non-Linear Locally-Adaptive Video Contrast Enhancement Algorithm Without Artifacts," *IEEE Trans. on Consume .Electronics*, vol. 54, no 1,pp.1-9,.Feb. 2008.



Fig. 12. top) HDR image after proposed tone mapping and without Local contrast enhancement still shows unacceptable SNR; bottom) Improved SNR image using multiple exposure technique as proposed.



Sascha D. Cvetković received his University degree in EE in 2000 from the Fac. of Electrical Engineering, Belgrade, Serbia. Since 2001 he is a senior research engineer at Bosch Security Systems. He develops various algorithms in the field of image and video signal processing, digital loop control and video content analysis. Since 2003, he is working part-time

towards a PhD degree in the EE Dept. at the Technical Univ. of Eindhoven, the Netherlands. He is the recipient of the Nikola Tesla award and as a part of the team he won 2005 NSCA Innovations in Technology Award for contributing to the design of the Dinion^{XF} Day/Night Camera.



Jan Klijn received his degree on the technical university of Delft the Netherlands in 1981. He started to work at Philips Ela, first in Breda later in Eindhoven on the development of security cameras using the early CCDs from Philips. One of his later products was the worlds' first, award winning, day / night camera with switchable IR filter. Since 1999 he

is employed at Philips VCM, after 2001 part of Bosch security systems. His work as camera architect has resulted in a number of patents and IC developments applied in a range of cameras.



Peter H.N. de With, Fellow of the IEEE, obtained the MSc and PhD degree from University of Technology Eindhoven and Delft, Netherlands. He has worked on video coding for recording at Philips Research Labs Eindhoven from 1984 till 1993. Between 1994 and 1997 he headed programmable TV architecture research at the same Lab. From 1997- 2000 he was

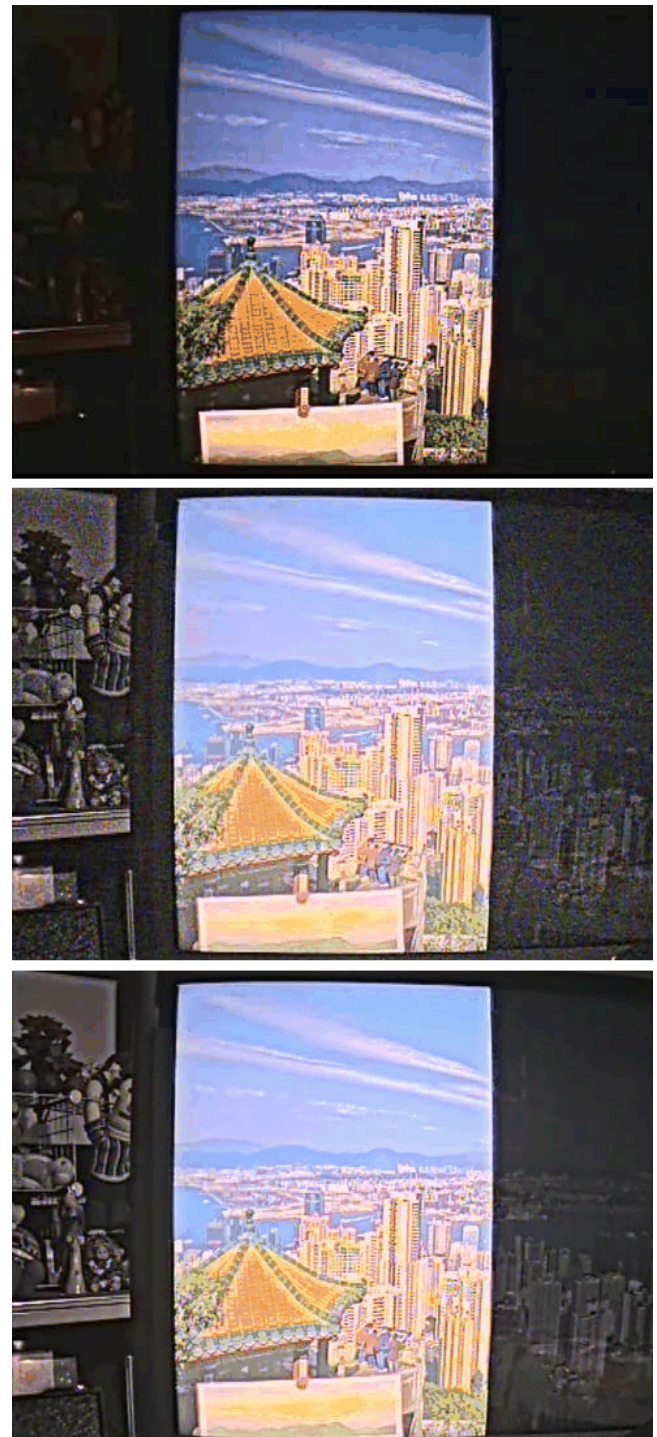


Fig. 13. From top to bottom: a) Original HDR image; b) HDR image after proposed tone mapping and Local contrast enhancement shows unacceptable SNR; c) Improved SNR image using multiple exposure technique as proposed.

full professor at the University of Mannheim, Germany. From 2001-2007, he was principal consultant at LogicaCMG and professor at the University of Technol. Eindhoven. He is now with CycloMedia Technology. He has written and co-authored over 200 papers and received paper awards at ICCE, SPIE and ISCE conferences. He is committee member in ICIP, VCIP, IISCE, ICCE conferences and chaired multiple working groups. He is advisor to Philips Research, VDG and various other companies.