Perceptual Reproduction of Wide-dynamic-range Scene based on Local Adaptation of the Human Visual System

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Abstract

Dynamic-range of luminance under standard visual environment, for example among luminance for stars of night sky and for sun-light reaches up to 160 [dB]. Although our visual system can give stable perception against such environment, conventional electronic imaging devices such as digital cameras cannot be able to capture these scenes without lack of information because of the restriction of their dynamic-range. Dynamic-ranges of such conventional electronic imaging devices are only 60 [dB] and lack of dynamic-range yields lacks of information as under exposure or over exposure. Limitation of dynamic-range is crucial problem for wide-dynamic-range image capturing as vehicle video systems, security cameras and so on. Several methods for such problem were proposed in recent studies. For example, the method for using a series of images with different shutter speed is known as 'multiple exposure' can achieve the wide-dynamic-range imaging using pseudo expansion of dynamic-range using conventional electronic imaging device. Recently, this method was implemented as a hardware system combined with a CMOS image sensor to achieve 160 [dB] dynamic-range. The problems for lack of dynamic-range are not only for imaging device but also for image reproduction medium such as displays. Luminance corrections are required to compress the luminance range to fit with image reproduction device's one. This process is known as 'tone mapping' which corresponds to compression of the dynamic-range for multiple exposure image to that of image reproduction devices. Tone mapping method by effective luminance remapping is need to perform the WYSIWYG (What You See Is What You Get) image reproduction. This study aims to propose the tone mapping method to achieve the natural contrast reproduction characteristics and to apply it to video sequences. Proposed tone mapping hypothesized that the local luminance adaption to average luminance around each pixel plays an important role to reproduce the spatially-localized contrast with keeping the global luminance variation by simulating the local adaptation mechanisms for the human visual system. In proposed tone mapping, smoothing by a Bilateral filter was applied to suppress the pseudo edges by halo to calculate the luminance of around pixels for each pixel. Additionally, multi-resolution representation for spatial frequency was introduced to save the calculation cost. Also, a series of subjective evaluation experiment were performed to investigate the dependency of each parameter for reproduced image quality and the dynamic-range dependencies of the proposed tone mapping. Result showed that proposed tone mapping gave highest quality composed image compare to conventional tone mapping or conventional wide-dynamic-range imaging device.

Introduction

Dynamic-range is generally defined as ratio of intensities between weakest and strongest signals. Dynamic-range of luminance under standard visual environment, for example among luminance for stars of night sky and luminance for sun-light, reaches up to 160 [dB] [1]. However, our visual system can give stable perception against such environment, conventional electronic imaging devices such as digital cameras cannot be able to capture these scenes without lack of information because of the restriction of their dynamic-range. Dynamic-ranges of such conventional electronic imaging devices are limited to be only about 60 [dB] which causes the crucial problem for wide-dynamic-range image capturing as vehicle video systems, security cameras and so on. Several methods to support such problem were proposed in recent studies. For example, the method for using a series of images with different shutter speed is known as 'multiple exposure' can achieve the wide-dynamic-range imaging using pseudo expansion of dynamic-range using conventional electronic imaging device as shown in Fig. 1.

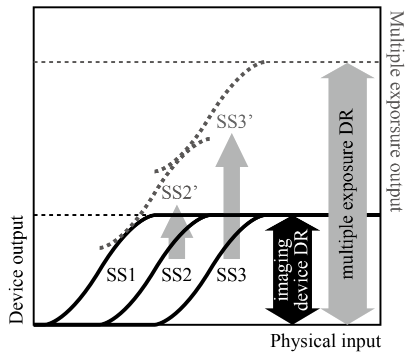

Fig. 1 Dynamic-range expansion by multiple exposure output.

Recently, this method was implemented as a hardware system combined with CMOS image sensor which achieves 160 [dB] dynamic-range [2].

The problems for lack of dynamic-range are not only for imaging device but also for image reproduction medium such as displays. Luminance corrections are needed to compress the luminance range to fit with image reproduction device's one. This process is known as 'tone mapping' which process is corresponds to compress the dynamic-range for multiple exposure image to image reproduction device's one as shown in Fig. 2.

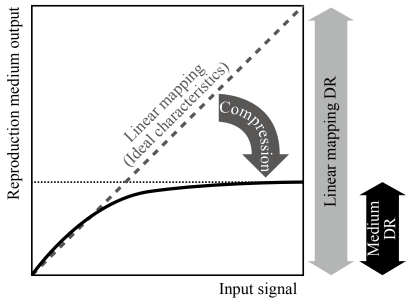

Fig. 2 Abstract of tone mapping.

The linear compression known as the simplest approach for tone mapping method is described as a linear mapping according to the ratio between maximum luminances for multiple exposure image and image reproduction image. However this method often fails to reproduce sufficient images by decreasing of contrast typically for wide dynamic-range images.

Effective tone mapping method have been required to perform the WYSIWYG (What You See Is What You Get) image reproduction. Conventional tone mapping methods are divided into global operator and local operator. Whereas global operator applies unique tone mapping function to every pixels, local operator uses not only each pixel information but also around pixels one of these for tone mapping. The simplest global operator is using the logarithmic [3] or sigmoid function [4], some complex global operator focuses on the changes of lightness or contrast perception between before applying the tone mapping and after applying the tone mapping [5][6][7][8][9] based on Stevens's law [10]. Although global operator can save the amount of calculation, low-contrast images depending in proportion to the dynamic-range are created.

By contrast, there are several local operators, for example, there are focused on the image spatial frequency [12][13], based on Retinex theory [14], color perception model (known as iCam [15]) based on CIECAM02 [16] and so on. Although tone mapping by the local operators can reproduce the high-quality-image, the calculation costs of these methods were too much to apply the video sequence. The wide-dynamic-range image sensor [2], described above, applies global operator (logarithmic function) as tone mapping to processing the video sequences, but low-contract reproductions are observed at the high luminance region in particular.

This study aims to propose the tone mapping method to achieve the natural contrast reproduction characteristics and to apply it to the video sequences. Proposed tone mapping hypothesized the local luminance adaption to average luminance around each pixel plays an important role to reproduce the spatially-localized contrast with keeping the global luminance variation by simulating the local adaptation mechanisms for human visual system. In the proposed tone mapping, smoothing by a Bilateral filter [18] was applied to suppress the pseudo edges by halo to calculate the luminance of around pixels for each pixel. Additionally, multi-resolution representation for spatial frequency was introduced to save the calculation cost. Also, a series of subjective evaluation experiment were performed to investigate the dependency of each parameter for reproduced image quality and the dynamic-range dependencies of proposed tone mapping.

Reproduction method for wide-dynamic-range scene

Adaptation mechanisms for visual system

It is well known that dynamic-range for luminance of the human visual system is quite wide, over than 100 [dB] [17]. The most important mechanism underlying such ability is adaptation of photoreceptor and post-receptor pathway. To capturing the wide-dynamic-range scene, the visual system changes the operation range adaptively depending on the intensity of the input for each sensor independently [19]. Fig. 3 shows the photoreceptor response characteristics against the input luminance. Dotted line shows the response curve for spatially uniform luminance stimulus and it monotonically increase against the luminance. Solid line shows the response curve for the stimulus of round-shaped spot on the spatially uniform luminance background (luminance of spot and background are different). In contrast to the response to spatially uniform luminance stimulus, the responses to the spot stimulus change depending on the background level corresponding to the adaptation luminance determined by depending on the spatially-localized average luminance. Human visual system can capture the wide-dynamic-range scenes due to such shift of the operation range of the sensors.

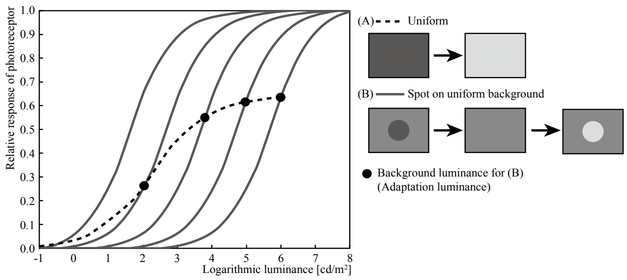

Fig. 3 Response characteristics of photoreceptor.

Tone mapping by simulating the local adaptation mechanisms of human visual system

This study proposes the tone mapping method which is simulating the local adaptation in the human visual system described above. The average luminance around the focused pixel defines as local adaptation luminance shown in Fig. 4, and weighted tone mapping depending on the adaptation luminance are performed.

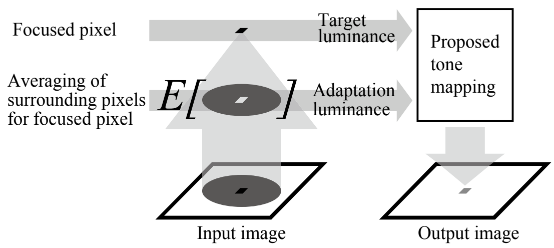

Fig. 4 Tone mapping based on local adaptation mechanisms for human visual system.

The procedure of the proposed tone mapping describes below (see also Fig. 5). To simplify the math expression, input and output luminance describe as I and O, respectively. First, the input luminance I is separated to low frequency component I^L and high frequency component $I^H= (I-I^L)$ by spatial smoothing describes in the following section. Here, I^L represents the local adaptation luminance. Then tone mapping are performed for each component, output luminance O is calculated by adding each processed frequency component described below.

(1) Tone mapping for low frequency component I^L

Tone mapping for I^L is performed by applying the logarithmic function described in Eq.(1) to get output O^L ('Logarithmic mapping' shown in Fig. 5).

$$O^L = \log\left(1 + I^L \times \frac{I^L_{\max}}{\alpha}\right) \Big/ \log\left(1 + \frac{I^L_{\max}}{\alpha}\right) \tag{1}$$

(where $I^L_{\max}$ indicates maximum input of I^L, α indicates the degree of correction)

(2) Tone mapping for high frequency component I^H

Tone mapping for I^H is performed by applying the Eq.(2) ('Adaptive mapping' showed in Fig. 5) to get output O^H. Tone mapping for high frequency component is described as a linear function of the input-output ratio of the low frequency component. This means the gradient of the function changes depending on the low frequency component (i.e. adaptation luminance). For a series of these processes, the spatial local contrast will be kept over the image and keeping the global input-output characteristics as monotone increasing function.

$$O^H = \left(\frac{O^L}{I^L}\right) \times I^H \tag{2}$$

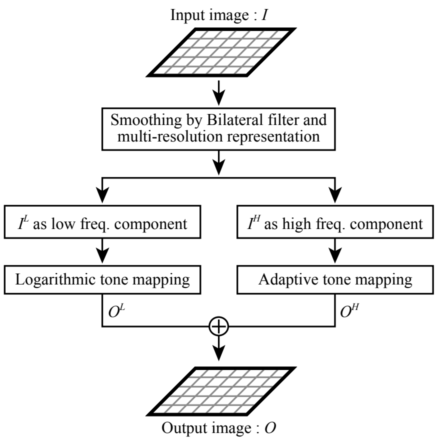

Fig. 5 Process summary of proposed tone mapping.

Input-output characteristics of proposed tone mapping are showed in Fig. 6.

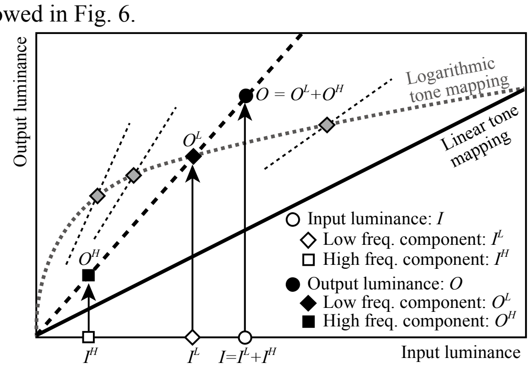

Fig. 6 Input-output characteristics for proposed tone mapping.

Calculation for adaptation luminance

To calculate the adaptation luminance for each pixel, a smoothing filter was applied. Conventional smoothing by simple local average such as moving average filter (shown in Fig. 7(a) as a dashed line) often induces the pseudo edges calls Halo when there is a luminance jump in smoothing area (see Fig. 7(b) as dashed line). To solve this problem, a Bilateral filter was adopted in the proposed tone mapping. Bilateral filter can apply the smoothing process with keeping the luminance edge shown in Fig. 7 (a) as dotted line. Also, multi-resolution representation was applied to separate a number of frequency component, a Bilateral filter is applied for each component. The benefit of applying the multi-resolution representation is reducing the calculation cost compare to same size conventional filter.

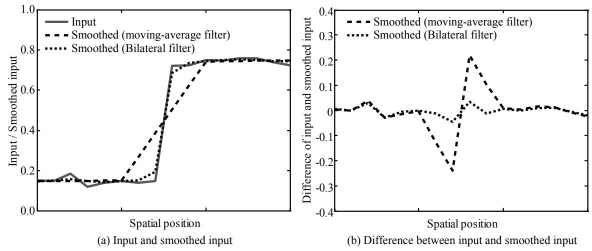

Fig. 7 Spatial luminance distribution of smoothing result by moving-average and Bilateral filter.

(1) Smoothing by a Bilateral filter

Bilateral filter considers both the spatial distance and luminance difference among the focused pixels to determine the smoothing weight as described in Eq.(3). Mainly, Bilateral filter uses for smoothing with keeping the edge information.

$$O^L_{xy} = \frac{\sum_i \sum_j \log I_{i,j} W_d W_v(x,y)}{\sum_i \sum_j W_d W_v(x,y)} \tag{3}$$

Where, x and y indicates the point of pixels. W_d and W_v mean filter kernel about spatial information and luminance information, respectively. i and j is variable about smoothing area. Smoothing area is defined $W*W$ matrix when filter size is w. The center of the filter is the point of pixels (x, y).

The filter kernel W_d for treating the spatial information and its each parameter was referred as Burt's method [20] describe in Eq.(4).

$$Wd = \begin{pmatrix} \cdots & c_3 & \cdots \\ \cdots & c_2 & \cdots \\ \cdots & c_1 & \cdots \\ \cdots & c_2 & \cdots \\ \cdots & c_3 & \cdots \end{pmatrix} \begin{pmatrix} c_3 & 0 & 0 & 0 & 0 \\ 0 & c_2 & 0 & 0 & 0 \\ 0 & 0 & c_1 & 0 & 0 \\ 0 & 0 & 0 & c_2 & 0 \\ 0 & 0 & 0 & 0 & c_3 \end{pmatrix} \tag{4}$$

$$\text{where} \begin{cases} c_1 = 0.4 \\ c_2 = 1/4 \\ c_3 = 1/4 - c_1/2 \end{cases}$$

The filter kernel W_v for treating the luminance information describes as a Gaussian function about logarithmic luminance difference between focused pixels and around the focused pixel as Eq.(5).

$$W_v(x,y) = \exp\left(\frac{-\left(\log I_{xy} - \log I_{ij}\right)^2}{2\sigma_v^2}\right) \tag{5}$$

(2) Smoothing by multi-resolution representation

Smoothing using multi-resolution representation[20] is performed to process the wide-area-smoothing by combining the down sampling and up sampling describe as following procedure (see also Fig. 8).

(a) Generate a smoothed image by applying a Bilateral filter to input image *I*.

(b) Generate a down sampled image by thinning pixels (Resolution will be 1/4 from original).

(c) Apply procedure (a) and (b) with down sampled image.

(d) Continue the procedure (a) to (c) for specified times (number of stages: *L*) to get the down sampled image 1/4, $1/4^2$, ..., $1/4^N$ from input image *I*.

(e) Up sampling the resolution 4 times for each down sampled image.

(f) Apply the Bilateral filter to the up sampled image to smoothing the image. Here, filter kernel $W_v(x, y)$ is determined as difference between up sampled image and same position of up sampled image when input image *I* down sampled with same resolution as up sampled image.

(g) Repeat (e) and (f) until the resolution of proceed image fit to original image *I,* then smoothed image by the Bilateral filter and multi-resolution representation can be generate.

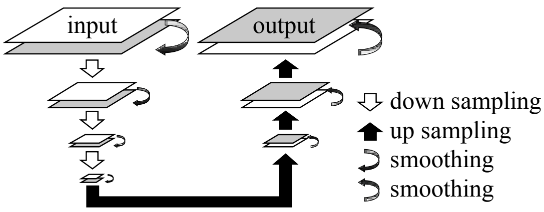

Fig. 8 Smoothing by multi-resolution representation (for number of stages L=4).

An effect for employing the multi-resolution representation for saving calculation cost

Although, it seems to increase the calculation cost to apply the multi-resolution representation because of the complexity of this method, calculation cost of this method is much smaller than compare to same size filter without multi-resolution representation. For example, applying the filter with 5*5 size with Multi-resolution representation (*L*=4) is equivalent to with 40*40 size without multi-resolution representation. Here, a number of pixels assumed as *N*, and then numbers of multiplication times for with multi-resolution representation and without multi-resolution representation are about 66*N* times and 1600*N* times, respectively. However, down sampling and up sampling are necessary for multi-resolution representation, the calculation cost for multi-resolution representation is much smaller than conventional filter.

Controlling the contrast enhancement in proposed tone mapping

In addition, to control the degree of contrast enhancement, proposed tone mapping was extended by introducing the parameter *R* which control the contrast enhancement described as Eq.(6).

$$O^R = R \times O + (1 - R) \times \log(I) \qquad (6)$$

log(*I*)in the Eq.(6) indicates the tone mapping by logarithmic function, this is equivalent to the output which replace the input luminance *I* with I^L in Eq.(1). The range of parameter *R* is 0 to 1.0. As showed in Fig. 9, when the parameter *R* is 0, tone mapping by proposed tone mapping is equivalent to the tone mapping by logarithmic function, *R*=1.0 causes the maximum contrast enhancement by proposed tone mapping.

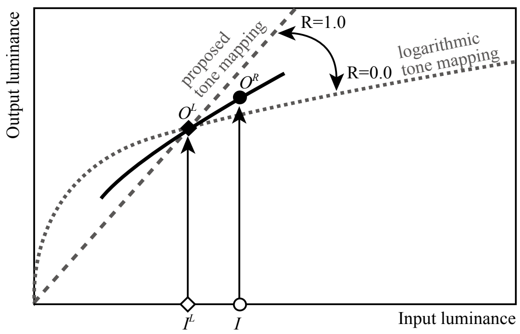

Fig. 9 Contrast enhancement control for proposed tone mapping by introducing parameter 'R'.

Apparatus & Result

Apparatus

Wide-dynamic-rage imaging device (YWD-001, YAMAHA corporation) was used for evaluate the proposed tone mapping. YWD-001 captures four images (VGA size, 640*480 [px]) differ in shutter speed with every 1/20 [sec] or multiple exposure image with 20 [fps] in Bayer format. To simplify the expression, these four images call here, L0, S1, S2 and S3 in shutter speed order (L0 < S1 < S2 < S3), respectively.

Results

Fig. 10 shows the captured images using YWD-001. Shutter speed ratio for L0, S1, S2, S3 were 1, 1/9, 1/36 and 1/144, respectively. These four images were combined into one multiple exposure image to expand the dynamic-range.

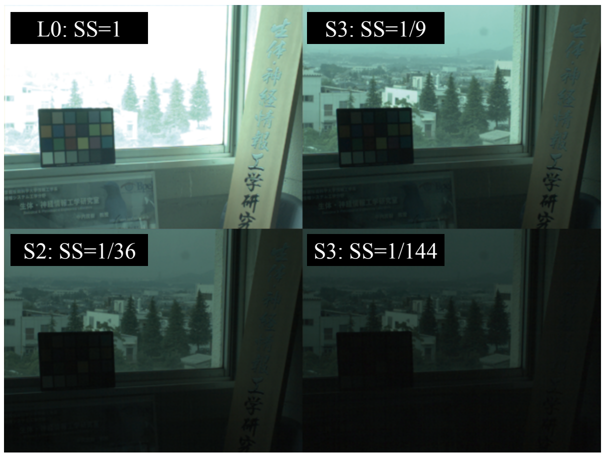

Fig. 10 Original images with different shutter speed.

Application result for conventional logarithmic tone mapping and proposed tone mapping are showed in Fig. 11 and 12, respectively. Here, the filter size of the Bilateral filter was set to 5*5, each parameter, a, L, s_v, R, for proposed tone mapping were set to 50, 4, $\log_{10}2.5$, 0.6, respectively. In Fig. 13, each symbols indicate the input-output characteristics of each pixel in the region framed by colored solid line in Fig. 12, curved line indicates input-output characteristics by logarithmic tone mapping which is also equivalent to local adaptation luminance O^L in proposed tone mapping. In each regions, luminance is distributed around the each local adaptation luminance O^L calculated by smoothing. To compare the difference of tone mapping, luminance profiles on the dashed line in Fig. 13 and Fig. 12 are showed in Fig. 14. Comparing these luminance profiles, it is clear that proposed tone mapping gives effective and superior contrast enhancement.

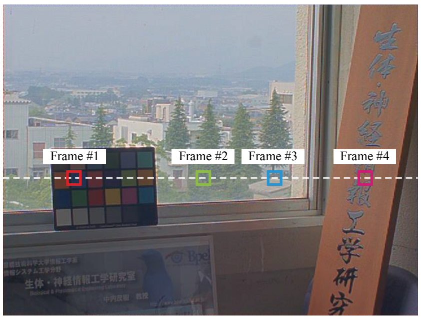

Fig. 11 Result by logarithmic tone mapping.

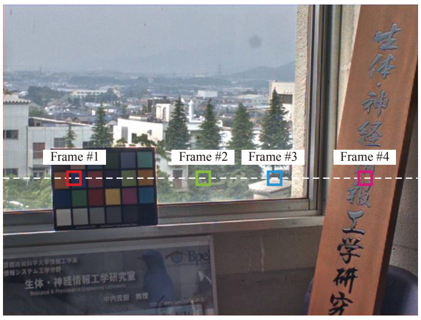

Fig. 12 Result by proposed tone mapping.

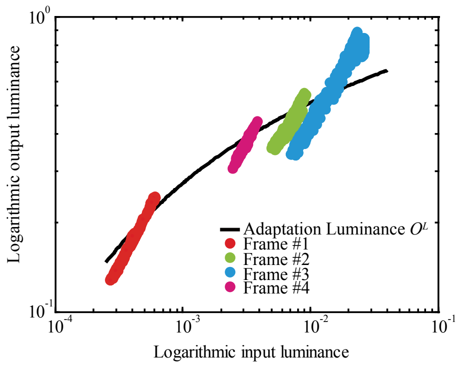

Fig. 13 Input-output characteristics of frame showed in Fig. 12.

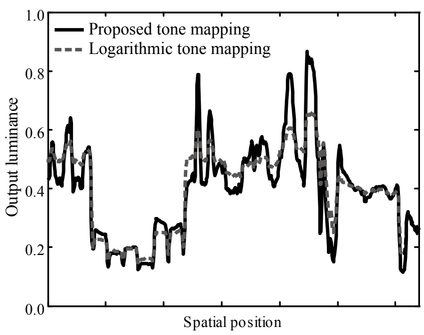

Fig. 14 Luminance profile on the dashed line showed in Fig. 12 for each tone mapping.

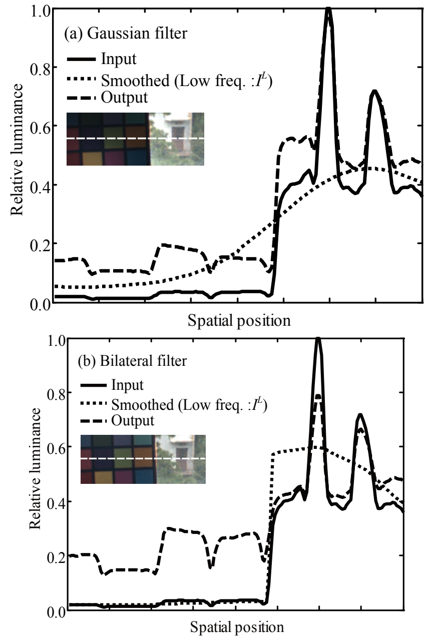

Fig. 15 Difference of luminance profile by types of smoothing method.

Luminance profile of reproduced image using Gaussian filter and Bilateral filter for smoothing were compared to evaluate an availability of the Bilateral filter. Fig. 15 (a) shows result for smoothing by Gaussian filter with size of 40*50, s was 40/3, respectively, Fig. 15 (b) shows result for smoothing by the Bilateral filter.

In Fig. 15 (a), high luminance region calls Halo was observed at edges of color chart, because Gaussian filter do not consider the bumps of the luminance difference. Although this edge is bound of inside or outside of the room which causes precipitous luminance changes physically, the luminance profile after smoothing by Gaussian filter is gradual compare to physical one. This is the reason why occur the Halo. In contrast to the result for Gaussian filter, Bilateral filter can keep such precipitous luminance changes as shown in Fig. 15 (b).

Result

A series of subjective evaluation experiment were performed to investigate generality of proposed tone mapping. These experiments mainly focused on as follows.

(a) Find the optimized value for parameter R.
(b) Investigate the dependency about dynamic-range of captured scene.

In addition, conventional wide-dynamic-range imaging device for security purpose was also used to compare the reproduced image quality.

Stimulus sets for subjective evaluation experiment

Stimuli were prepared with 8 scenes which differ in dynamic-range. The dynamic-range of each scene was calculated with Eq.(7) using the photometric data captured by spectral radiometer (Photo Research Inc, PR-650). The darkest point (L_{min}) and brightest point (L_{max}) were considered as black panel in color chart and sky respectively. Table. 1 shows the dynamic-range for each scene.

$$DR = 20\log\frac{L_{max}}{L_{min}} \quad (7)$$

Table. 1 Dynamic-range of scenes which used in subjective evaluation experiment.

Scene #	DR [dB]	Scene #	DR [dB]
1	35.28	5	50.76
2	38.45	6	53.80
3	48.13	7	54.96
4	49.88	8	65.10

For each scene, a series of reproduced images were generated which parameter R was varied 0.0 to 1.0 in 0.2 steps (i.e. 1 logarithmic tone mapping image and 5 proposed tone mapping images) In addition, 2 image which captured by conventional wide-dynamic-range imaging device with different parameters were prepared. Then 8 images for each scene were prepared. Fig. 16 shows the example of scene (scene #8).

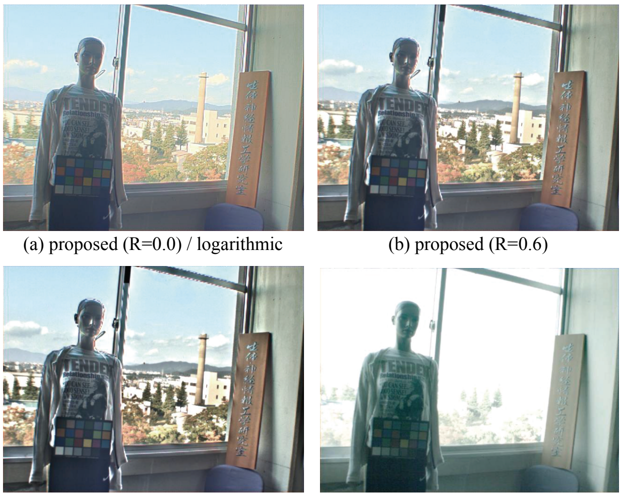
(a) proposed (R=0.0) / logarithmic
(b) proposed (R=0.6)
(c) proposed (R=1.0)
(d) conventional WDR imaging device

Fig. 16 Example of experiment stimulus (scene #8).

Stimulus sets for subjective evaluation experiment

Experiments were conducted under the general office environment. The luminance on the desk was varied within 340 to 370 [lx]. In the experiment, paired comparison tasks were performed. Two stimulus were randomly presented on the uniform gray (75.39 [cd/m^2]) using LCD (SONY, SDM-HS92PB). The sizes of presented stimulus were 10.5*14 [cm] in landscape, view distance was 70 [cm]. 11 subjects were participated to the experiment. They were instructed to choose the 'more natural and clear image' by two alternative forced choice (2AFC) paradigm. Z-score were calculated from choice probability which were obtained by a series of experiments.

Results

Results of a series of experiment were analyzed for two point described above.

Find optimized value for parameter R

Result focused on dependency between image quality and contrast enhancement parameter 'R' is showed in Fig. 17. Horizontal axis shows the value for parameter R, vertical axis shows the normalized interval scale. Each z-score was normalized to average of z-score should be zero as normalized interval scale. Higher score indicates the image quality is higher. Dashed line shows the interval scale for each scene, and solid line shows averaged interval scale calculated with each parameter. Error bar indicates standard deviation among subjects. Although each scale was relatively varied for each scene, most suitable parameter R was 0.4 for all scenes. In addition, there were no drastic scale variances depending on little change of parameter R. This indicates the robustness of proposed tone mapping.

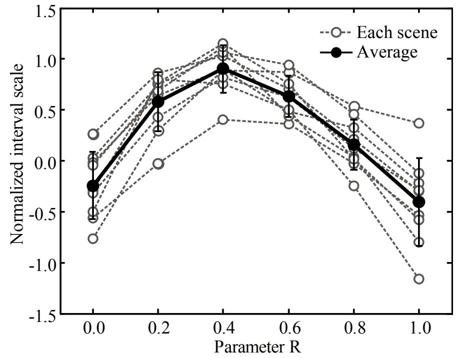

Fig. 17 The effect of contrast enhancement control parameter 'R' to image quality.

Investigate the dependency about dynamic-range of captured scene

Next, dynamic-range dependencies about each tone mapping method were investigated. Here, Reproduced images for logarithmic tone mapping (i.e. R=0.0), proposed tone mapping and conventional wide-dynamic-range imaging device were compared. The parameter R for proposed tone mapping was set to 0.4 because maximum image qualities were observed at its value described above. Fig. 18 shows the comparison for each method about dynamic-range dependency. Horizontal axis shows the dynamic-range for each scene, vertical axis shows the normalized interval scale. Open circle symbol, cross symbol and open square symbol indicate proposed tone mapping, logarithmic tone mapping, and conventional wide-dynamic-range imaging device, respectively. As shown in Fig. 18, scale for conventional wide-dynamic-range imaging device was degraded around 50 to 55 [dB]. This is considered that under exposure or over exposure like shown in Fig. 10 were occurred when dynamic-range of scene was wider than wide-dynamic-range imaging device's one. In contrast, proposed tone mapping showed highest scale independently to dynamic-range for each scene. This tendency indicates that proposed tone mapping can apply to the narrow-dynamic-range scene.

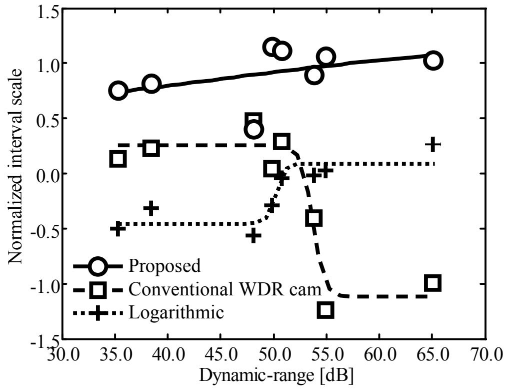

Fig. 18 Dynamic-range dependencies for each method.

Conclusion

As described above, human visual system dynamically changes the operation range of each photoreceptor depending on the adaptation luminance to realize the stable perception. At first, this study proposed the new local operator tone mapping method based on local adaptation mechanisms in human visual system. In the proposed tone mapping, multi-resolution representation was adopted to decrease the calculation cost. In addition, Bilateral filter was applied to suppress the incidence of Halo. Also parameter 'R' was introduced to control the degree of contrast enhancement, then contrast enhancement of proposed tone mapping can be control between conventional logarithmic tone mapping (R=0) to maximum contrast enhancement (R=1.0). Second, a series of subjective evaluation experiment was performed to investigate the performance of proposed tone mapping. Paired comparison tasks were developed using a series of reproduced image with logarithmic tone mapping which is conventionally used, proposed method with several different parameter R and conventional wide-dynamic-range imaging device. Result showed that proposed tone mapping gave highest quality composed image compare to logarithmic tone mapping or conventional wide-dynamic-range imaging device.

Calculation cost for proposed tone mapping can save compare to the other local operator tone mapping, because, proposed tone mapping can realize combining the simple digital filters. For example, proposed tone mapping was implemented to a real time processing system which used a wide-dynamic-range image sensor (YWD-001) and conventional personal computer (CPU 2.66GHz, Memory 3.25GB) by programming with C++ language. Then processing speed of this system was about 3 [fps] in VGA size.

Optimized mathematical description or hardware implementations are necessary to reach applicative processing performance for applying the real time processing system. To solve this problem, proposed tone mapping could be a key technology for reproducing the wide-dynamic-range information.

Acknowledgement

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