(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 August 2010 (19.08.2010)

PCT

(10) International Publication Number
WO 2010/093433 A1

(51) International Patent Classification: *G09G 3/34* (2006.01)

(21) International Application Number: PCT/US2010/000359

(22) International Filing Date: 9 February 2010 (09.02.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data: 61/151,691 11 February 2009 (11.02.2009) US

(71) Applicant *(for all designated States except US)*: **THOMSON LICENSING** [FR/FR]; 1 rue Jeanne d'Arc, F-92443 Issy-les moulineaux (FR).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **ZHAI, Jiefu** [CN/US]; 3404 Hunters Glen Drive, Plainsboro, New Jersey 08536 (US). **LLACH, Joan** [ES/US]; 101 Castleton Road, Princeton, New Jersey 08540 (US).

(74) Agents: **SHEDD, Robert, D.** et al.; Thomson Licensing LLC, 2 Independence Way, Suite #200, Princeton, New Jersey 08540 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM,

[Continued on next page]

(54) Title: SIGNAL GENERATION FOR LED/LCD-BASED HIGH DYNAMIC RANGE DISPLAYS

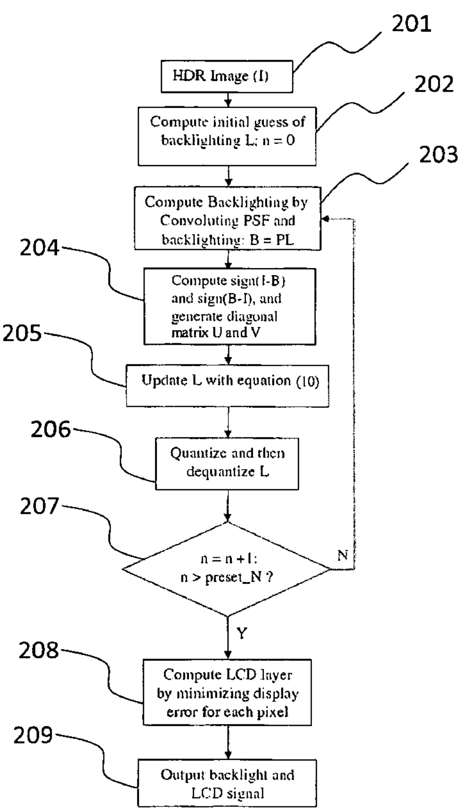


FIG. 2

(57) Abstract: A method of operating a high dynamic range display device comprises the steps of : accessing an image signal (201); generating an intermediate backlighting driver signal for individual backlight elements for a backlighting unit responsive to the image signal (202); convoluting the intermediate backlighting driver signals with a point spread function of the backlighting unit (203); deriving at least one new backlighting driver signal responsive to the convoluting step (204 to 207); determining display error associated with a plurality of available light shutter signals of a front-end unit having individual light shutters and associated with the at least one new backlighting driver signal, the front-end unit having a higher resolution than the backlighting unit (208); driving the display device with a combination of shutter signals and new backlighting driver signals that causes a reduction in the display error with respect to other generated intermediate backlighting driver signals and other available light shutter signals (209).

WO 2010/093433 A1

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

SIGNAL GENERATION FOR LED/LCD-BASED HIGH DYNAMIC RANGE DISPLAYS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 61/151,691, filed February 11, 2009.

Field of the Invention

[0001] The invention is in the field of high dynamic range displays and relates to methods for processing and displaying imagery therein.

Background of the Invention

[0002] High dynamic range (HDR) displays are displays that can display imagery with very high contrast, very deep blacks and very bright whites. Such types of displays can show HDR imagery by using non-uniform backlighting. In particular, one can adjust the intensity of the backlighting on different areas of the screen based on the input image.

[0003] One of the main challenges for such displays is how to convert the input image from three component data (e.g., RGB, YCbCr) to the four component data required by the displays. This is particularly applicable to displays such as those having a light emitting diode backlighting layer (LED layer) which provides one component in the form of intensity information and an LCD layer which provides three components of intensity and color information.

[0004] High dynamic range (HDR) displays have received much attention in the recent years as an alternative format for digital imaging. The traditional Low Dynamic Range (LDR) image format was designed for displays compliant with ITU-R Recommendation BT 709 (a.k.a.

Rec. 709), where only two orders of magnitude of dynamic range can be achieved. However, real world scenes have a much higher dynamic range which are around ten orders of magnitude in daytime. The human visual system (HVS) is capable of perceiving 5 orders of magnitude.

[0005] These HDR displays have been brought to market in recent years and are based on the so-called LED-LCD technology, where the uniform backlighting of conventional LCD displays is replaced by a matrix of individually controlled LEDs, wherein each LED only illuminates a small area of the screen. The number of LEDs in the LED layer is much smaller than the number of pixels in the LCD layer, but the brightness of each LED can be adjusted over a large range of values. As a result, the LED layer provides a very high dynamic range, low resolution backlighting. The front LCD panel is the same as a convention LCD display, wherein the liquid crystal cells control the color of each pixel and fine-tunes the intensity provided by the LED layer.

[0006] In HDR displays, the conversion of three color components of the input image to be converted to four components is not a straightforward process, because there is no simple one-to-one correspondence between the image and the display. Moreover, multiple solutions are possible; as such, finding the optimum solution should be sought, because the various solutions produce various image qualities.

[0007] Because HDR displays which have been introduced recently are mostly prototypes (e.g., BrightSide, BrightSide Technologies Inc., 1310 Kootenay Street, Vancouver, B.C., Canada), there has been very little work on the driving signal generation problem. In the original paper pertaining to HDR displays (Seetzen, H., et al., High dynamic range display systems, ACM Press. p. 760-768. 2004), a simple cross-talking method is proposed to reduce the computational complexity. A follow chart of a simple cross-talking methodology is shown in Fig. 1. In Fig. 1, block 101 corresponds to first obtaining an HRD image having intensity character I, block 102 corresponds to determining the target intensities of the backlighting which relates to the square root of the intensity character I, block 103 corresponds to down-sampling the image to the resolution of the backlighting to obtain the actual backlighting signal to use, and block 104 corresponds to obtaining the LCD signal which uses an LCD response function to compensate for backlighting values and the target intensities. This cross-talking method is considerably fast, but the display error is also quite large. It could also fail under large local contrast. In short, displaying an HDR image on such screens is not straightforward, because the lower resolution of the LED layer and the crosstalk between LEDs makes it not possible to individually control the output of each pixel. Using the wrong backlighting results is low image quality and may even lead to visual artifacts such as false contouring and visible LED patterns.

[0008] In the paper by Feng Li, Xiaofan Feng, Ibrahim Sezan, Scott Daly, Deriving LED Driving Signal for Area-Adaptive LED Backlight in HDR, SID Symposium Digest of Technical Papers, 38 #1, 1794-1797 (2007), two methods are designed to address this problem. The first method does not take into account display characterization and the human visual system. The second method requires the backlighting to be always brighter than the desired output level and employs a linear optimizer to solve the problem. It has much higher complexity and the assumptions may not practical.

[0009] In light of the above mentioned problems, a need exists to develop high dynamic range displays and methods related to processing and displaying imagery therein to ensure that HDR displays comply with the ITU-R Recommendation BT 709 standard, are commensurate with HVS, and do not require and/or use overly computational complex signal processing.

Summary of the Invention

[0010] A display device comprises a backlighting unit having a matrix of light generating elements; a front-end unit having a plurality of light shutters grouped into a repeat arrangement which include at least two different shutters that each attenuate different color light; a signal handling system for receiving image signals and having an algorithm to process the image signals and derive final backlight driver signals for the backlighting unit and final front-end driver signals for the front-end unit, wherein the algorithm can be an iterative gradient descent algorithm. The algorithm can employ at least one difference reduction iteration to derive the final driver signals and at least one iteration can be responsive to a display target image brightness values (**I**); at least one projected image brightness values (**O**) correlating to at least one set of intermediate driver signals; and the difference between the brightness values. The algorithm can include: an convolution between a point spread function of the backlighting unit and backlight driver signals, wherein the backlight driver signals can be quantized; can produce or access a backlight matrix **L** of backlight driver signals for the backlighting unit having M rows by N columns that correspond to the light generating elements and a point spread matrix **P** that corresponds to the point spread function; and a product of **L** and **P** that yields a full resolution backlighting brightness matrix **B**; and can be adapted to generate the final front-end driver signals for a color p responsive to a product of the brightness matrix and a normalized front-end driver signal for the color p. At least a term of display output brightness **Op** for a given color p is expressed as a function of the brightness matrix **B**, an input high dynamic range image for the color p **Ip**, and a front-end driver signal for the color p **Dp**, which can be normalized. The display device can optimize the final driver signals by having the algorithm performing least square of the difference calculations between the input high dynamic range image and the display output brightness for the color p and minimizing the least squares. The algorithm can further be adapted such that output error is generated and used in determining the final front-end driver signals for a color p and the output error incorporates at least a term Jp which is a function of an input high dynamic range image brightness **Ip** for the color p, a normalized front-end driver signal for the color p **Dp**, a display output brightness **Op**, and a product of **L** and **P**. The algorithm can further determine and/or be responsive to clipping and quantization errors in optimizing final driver signals. The algorithm can further determine and reduce collective output errors that incorporates at least a term $J = \|\mathbf{I}_r - \mathbf{O}_r\|_2^2 + \|\mathbf{I}_g - \mathbf{O}_g\|_2^2 + \|\mathbf{I}_b - \mathbf{O}_b\|_2^2$ in which the **I**s are an input high dynamic range image brightness for three colors r, g, and b and the **O**s are a display output brightness for the three colors, respectively, and the algorithm can use the collective output errors in determining the final front-end driver signals for at least three colors.

[0011] A method of operating a high dynamic range display device comprises the steps of: accessing an image signal; generating an intermediate backlighting driver signal for individual backlight elements for a backlighting unit responsive to the image signal; convoluting the intermediate backlighting driver signals with a point spread function of the backlighting unit; deriving at least one new backlighting driver signal responsive to the convoluting step; determining display error associated with a plurality of available light shutter signals of a front-end unit having individual light shutters and associated with the at least one new backlighting driver signal, the front-end unit having a higher resolution than the backlighting unit; driving the display device with a combination of shutter signals and new backlighting driver signals that causes a reduction in the display error with respect to other generated intermediate backlighting driver signals and other available light shutter signals. The method can include accessing target display output for the individual shutters from the image signal; using a factor that includes a square root of the target display output, in which the target display output can be normalized, to obtain intermediate backlighting driver signal in the generating step. The method can further include generating a backlight matrix **L** having M rows by N columns that correspond to the backlight elements; producing a full resolution backlighting brightness matrix **B**, at least in part, from the matrix **L** and the matrix **P**; comparing the full resolution backlighting brightness matrix **B** to the image signal; and generating diagonal matrices **U** and **V** having diagonal elements corresponding to sign(**I-PL***) and sign(**PL*-I**), respectively, wherein matrix L* represents iterations of new backlighting driver signals and I represents the target display output of the image signal, wherein the comparing step and generating diagonal matrices steps can be repeated η times, in which η is a predetermined number of iterations. The matrix **L*** can be used after the last iteration to determine a final full resolution backlighting. A final light shutter signal to use can be determined in a manner responsive to the final full resolution backlighting. The method can further include determining clipping error and quantization errors, wherein the clipping error is caused by intermediate driver signals for the backlighting unit correlating to insufficient brightness and is the difference between the insufficient brightness and the target display output, and the quantization error is the difference between a brightness quantization level of the front-end unit and the target display output; and applying the clipping error and/or quantization error into a cost function and using the cost function as a factor in determining the display error. The method can also comprise comparing the full resolution backlighting brightness matrix B to the image signal; and using the comparison in the comparing step in determining the display error and selecting combinations of shutter signals and new backlighting driver signals.

Brief Description of the Drawings

[0012] The invention will now be described by way of example with reference to the accompanying figures of which:

Figure 1 is a block diagram of a method of processing HDR signal for an HDR display according to the prior art;

Figure 2 is a block diagram of a method according to the invention; and

Figure 3 is a block diagram of an HDR system according to the invention.

Detailed Description of the Invention

[0013] An approach is disclosed to generate the video signal required to drive HDR displays based on LED-LCD (light emitting diode and liquid crystal display) technology. The proposed approach relies on a mathematical model that characterizes the HDR image and display. For each input HDR image, LED and LCD values are jointly optimized using a display characterization model in order to minimize the difference between the input image (i.e., the ideal output) and the display output. The human visual system (HVS) can also be taken into account in the optimization problem. In an illustrative first embodiment, the optimization is solved by using an iterative method.

[0014] In another illustrative embodiment, a simplified scheme with reduced complexity and similar quality is proposed.

[0015] In accordance with the principles of the invention, an iterative method is proposed to resolve the LED/LCD optimization problem. The response curve of an LCD can be modeled as an exponential function and the response curve of an LED can be modeled as a linear function. The output of the LED layer of the display can be modeled as the convolution of LED values and a point spread function. A distortion function can defined to provide a measure of the difference between desired output and the actual output, where characteristics of the HVS can be taken into account in this distortion function. By minimizing, the distortion function (e.g., with an iterative gradient descent algorithm), the LED and LCD signals can be obtained.

[0016] A simplified version of the proposed algorithm contains only a couple of iterations to reduce the complexity, while maintaining a similar level of quality.

[0017] Regarding the HDR device according to the invention, it is important to point out that the display has a pixelated LCD front end panel. Each pixel of the front LCD panel can block light according to its driving signal. In the case of an HDR display, the front LCD panel can be the same as the one in a typical LCD display. The backlighting, however, is non-uniform and of high contrast and high brightness. The backlighting is provided by a regularly arranged matrix of LEDs. The response of a LED can be experimentally obtained by turning on a single LED and measuring the light intensity around it with a photometer. The measured intensity matrix is usually called point spread function in imaging applications. A general model for the backlighting as the convolution between the LED values (quantized values driving the LED layer) and the point spread function of the LEDs. For convenience, this model can be written in matrix form as:

$$\mathbf{B} = \mathbf{P}\mathbf{L} \quad (1)$$

[0018] The pixel arrangement of the LCD panel is M rows by N columns, where **B** and **L** are

vectors of size $MN \times 1$. **P** is the point spread function matrix of size $MN \times MN$. **L** is the LED matrix, where each element of **L** equals the normalized LED value, if it corresponds to an LED position or 0 otherwise. Matrix **B** is the backlighting intensity at each pixel location. Note that these matrices are built for easier formulation; in practice there is no need to construct them. As will be shown later, the matrices of only screen size M×N are used for a more efficient computation.

[0019] Once the backlighting is calculated, the LCD layer has to be adjusted so that the output is as close as possible to the input HDR image. To achieve that, a formulation to describe the display output from the previously computed backlighting and the input HDR image is generated and presented as follows:

$$\begin{aligned}\mathbf{O}_g &= \mathbf{B}\otimes\mathbf{D}_g \\ &= \operatorname{sign}(\mathbf{I}_g-\mathbf{B})\otimes\mathbf{B}+\operatorname{sign}(\mathbf{B}-\mathbf{I}_g)\otimes(\mathbf{B}\otimes\mathbf{D}_g)\end{aligned} \quad (2)$$

[0020] Here, $\mathbf{O}_g$, $\mathbf{I}_g$ and $\mathbf{D}_g$ are display output (green channel), input HDR image (green channel) and normalized LCD signal (green channel), respectively. (Note that the LCD panels according to the invention may have red, green and blue channels for color display. However, for convenience, the green 'g' component is used, but the same formulation can be used for red and blue.) These are all lexicographically ordered vectors of size $MN\times 1$. Note that both input and output signals are linear, not gamma corrected. "⊗" denotes element-wise multiplication. The sign() function denotes the element-wise sign function, defined as follows:

$$\operatorname{sign}(\mathbf{A})=\mathbf{B},\text{ where } b_{ij}=\begin{cases}1 & \text{if } a_{ij}>0,\\ 0 & \text{otherwise.}\end{cases} \quad (3)$$

[0021] Next, an output error is generated. It measures the difference between the ideal output (i.e. the input image) and the actual output (i.e. the displayed image). Based on the previous LED and LCD output models, the following formulation is proposed to compute the square of the difference between the input HDR image and the display output:

$$\begin{aligned}J_g(\mathbf{L},\mathbf{D}_g) &= \left\|\mathbf{I}_g-\mathbf{O}_g\right\|_2^2 \\ &= \left(\operatorname{sign}(\mathbf{I}_g-\mathbf{PL})\otimes(\mathbf{I}_g-\mathbf{PL})+\operatorname{sign}(\mathbf{PL}-\mathbf{I}_g)\otimes(\mathbf{PL}\otimes\mathbf{D}_g-\mathbf{I}_g)\right)^T \\ &\quad\times\left(\operatorname{sign}(\mathbf{I}_g-\mathbf{PL})\otimes(\mathbf{I}_g-\mathbf{PL})+\operatorname{sign}(\mathbf{PL}-\mathbf{I}_g)\otimes(\mathbf{PL}\otimes\mathbf{D}_g-\mathbf{I}_g)\right)\end{aligned} \quad (4)$$

[0022] This equation can be read as follows: for each pixel, if the backlighting is higher than the desired output value (i.e., **PL** > **Ig** for a particular pixel), then the error for that pixel is the LCD layer quantization error (i.e. **Ig-PL_Dg**). (T is in this equation and other equations is the symbol for transposing a matrix.) . If the backlighting is lower than the desired output value (i.e. **PL** < **Ig**), then the output image is clipped and the LCD cannot increase brightness. In this case, the error is the difference between the ideal output and the clipped value (i.e., **Ig -PL**).

[0023] In the above formulation, vectors **L** and **D** are normalized, which means each one of their elements is a real number between 0 and 1. However, in digital systems, **L** and **D** have to be quantized. **L*** and **D*** and can be defined as the result of applying linear quantization and inverse quantization to **L** and **D**. Equation (4) then becomes:

$$\begin{aligned} J_g(\mathbf{L}^*,\mathbf{D}_g^*) &= \|\mathbf{I}_g-\mathbf{O}_g\|_2^2 \\ &= \left(\text{sign}(\mathbf{I}_g-\mathbf{PL}^*)\otimes(\mathbf{I}_g-\mathbf{PL}^*)+\text{sign}(\mathbf{PL}^*-\mathbf{I}_g)\otimes(\mathbf{PL}^*\otimes\mathbf{D}_g^*-\mathbf{I}_g)\right)^T \\ &\quad\times\left(\text{sign}(\mathbf{I}_g-\mathbf{PL}^*)\otimes(\mathbf{I}_g-\mathbf{PL}^*)+\text{sign}(\mathbf{PL}^*-\mathbf{I}_g)\otimes(\mathbf{PL}^*\otimes\mathbf{D}_g^*-\mathbf{I}_g)\right) \end{aligned} \quad (5)$$

[0024] As in for equation (2), equations (4) and (5) can be applied to the red 'r' and blue 'b' color components.

[0025] The optimization problem is defined as the matrices $\mathbf{L}^*$ and $\mathbf{D}^*$, which stand for quantized LED and LCD vectors, respectively. These need to be optimized to minimize the square of difference between the input HDR image and the display output. Solving this optimization problem directly is very difficult. A simplified approach begins by first reducing the number of variables. Considering sign(($\mathbf{PL}^*$- $\mathbf{I}_g$) and sign(($\mathbf{I}_g$.$\mathbf{PL}^*$) are complementary to each other, equation (5) can be rewritten as:

$$\begin{aligned} J_g(\mathbf{L}^*,\mathbf{D}_g^*) &= \|\mathbf{I}_g-\mathbf{O}_g\|_2^2 \\ &= \left(\text{sign}(\mathbf{I}_g-\mathbf{PL}^*)\otimes(\mathbf{I}_g-\mathbf{PL}^*)+\text{sign}(\mathbf{PL}^*-\mathbf{I}_g)\otimes\left|\mathbf{PL}^*\otimes\mathbf{D}_g^*-\mathbf{I}_g\right|\right)^T \\ &\quad\times\left(\text{sign}(\mathbf{I}_g-\mathbf{PL}^*)\otimes(\mathbf{I}_g-\mathbf{PL}^*)+\text{sign}(\mathbf{PL}^*-\mathbf{I}_g)\otimes\left|\mathbf{PL}^*\otimes\mathbf{D}_g^*-\mathbf{I}_g\right|\right) \end{aligned} \quad (6)$$

Here $|\cdot|$ defines element wise absolute function. In equation (5) the quantization error $|\mathbf{PL}^* \otimes \mathbf{D}_g - \mathbf{I}_g|$ could be approximated by $\mathbf{PL}^*/4q$ if the quantization error is uniformly distributed, where q is the number of quantization levels of the LCD panel. It has been found that this assumption holds fairly well for natural HDR images. Then, it can be seen that the objective function now depends only on $\mathbf{L}^*$ in the following equation:

$$\begin{aligned} J_g(\mathbf{L}^*) = &\left(\text{sign}(\mathbf{I}_g - \mathbf{PL}^*) \otimes (\mathbf{I}_g - \mathbf{PL}^*) + \text{sign}(\mathbf{PL}^* - \mathbf{I}_g) \otimes \mathbf{PL}^* / 4q\right)^T \\ &\times \left(\text{sign}(\mathbf{I}_g - \mathbf{PL}^*) \otimes (\mathbf{I}_g - \mathbf{PL}^*) + \text{sign}(\mathbf{PL}^* - \mathbf{I}_g) \otimes \mathbf{PL}^* / 4q\right) \end{aligned} \quad (7)$$

[0026] To optimize J, the partial derivative of J over **L*** can be obtained and used in a gradient descent method to solve the optimization in an iterative manner in the following equation. (The color component will not be indicated in the following to reflect that the equations are applicable to all color components.)

$$L^{*(n+1)} = L^{*(n)} - \lambda \left(\frac{\partial J}{\partial L} \right) \Bigg|_{L=L^{*(n)}} \quad (8)$$

The right side of equation (7) is non-continuous function, thus the derivative of J can be undefined in some places. To solve the issue, a small λ is chosen such that during one iteration sign($\mathbf{I}$-$\mathbf{PL}^*$) and sign($\mathbf{PL}^*$- I) do not change or only changes slightly. Thus, $\mathbf{L}^{*(n)}$ can be changed to sign($\mathbf{I}$-$\mathbf{PL}^*$) and sign($\mathbf{PL}^*$-$\mathbf{I}$) to get a constant vector and simplify the problem. The equation (7) then becomes:

$$J_{n+1}(\mathbf{L}^*) = \left(\mathbf{U}(\mathbf{I} - \mathbf{PL}^*) + \mathbf{VPL}^* / 4q\right)^T \left(\mathbf{U}(\mathbf{I} - \mathbf{PL}^*) + \mathbf{VPL}^* / 4q\right) \quad (9)$$

Here, **U** and **V** are diagonal matrices with their diagonal elements equal to sign($\mathbf{I}$-$\mathbf{PL}^*$) and sign($\mathbf{PL}^*$-$\mathbf{I}$), respectively. This helps to eliminate the element-wise multiplication and makes it easier to compute the partial derivative. In each iteration, the object function is updated, and then partial derivatives are computed according to equation (8). The extended form of equation (8) can be written as follows:

$$\mathbf{L}^{*(n+1)} = \mathbf{L}^{*(n)} - \lambda\left(\left(\left(\frac{\mathbf{V}}{4q} - \mathbf{U}\right)\mathbf{P}\right)^{T}\left(\left(\frac{\mathbf{V}}{4q} - \mathbf{U}\right)\mathbf{P}\mathbf{L}^{*(n)} + \mathbf{U}\mathbf{I}\right)\right) \quad (10)$$

[0027] The above equation describes how to update **L*** on each iteration. The procedure to compute **L*** and **D*** is shown Fig. 2 and is as follows:

Step 1. In block 201, an HDR image having intensity character **I** is first obtained.

Step 2. In block 202, an initial guess or estimate for backlight or LED values L^* is obtained. The method for obtaining the initial estimate is to first consider the intensity of light that would be needed for the closest backlight element or LED element or the like for the give front-end element (pixel). In sum, this estimate could be the method in Fig. 1. Here, this can be setting the estimate to a value that corresponds to the square root of the normalized output image intensity or the like.

Step 3. In block 203, a convolution of the backlight or LED values with a point spread function characteristic of the backlighting unit is performed to get the full resolution backlighting, $\mathbf{B}=\mathbf{P}\mathbf{L}^{*(n)}$.

Step 4. In block 204, the full resolution backlighting is compared to the input HDR image and matrices **U** and **V** are computed.

Step 5. In block 205, the backlight or LED values **L** are determined with equation (10).

Step 6. In block 206, the backlight or LED values $\mathbf{L}^*$ are obtained by quantizing **L**. Dequantization in the chart is the process of going from discrete or digitized values to continuous values.

Step 7. In block 207, n is set to n +1. If (n > preset_η), then the process advances to step 8. If preset value of η is not yet reached, then further processing is performed in blocks 203 through 207 until the preset value is reached.

Step 8. In block 208, with $\mathbf{L}^*$ being known and fixed, the final full resolution backlighting $\mathbf{PL}^*$ is computed. For each pixel i, if the backlighting $\mathbf{PL}^*_i$ is larger than input HDR image $\mathbf{I}_i$, the $\mathbf{D}^*_i$ for the LCD front-end is set to its maximum value. If the backlighting $\mathbf{PL}^*_i$ is not larger than input HDR image $\mathbf{I}_i$, the best $\mathbf{D}^*_i$ is chosen to minimize the difference. Note that this applies to all color components.

Step 9. In block 209, the resultant $\mathbf{D}^*_i$ and backlighting are employed.

[0028] Some of the key features of the invention include the cost function (i.e. equation 4). Here the pixels are categorized into two groups depending on whether backlighting is larger than input image. Quantization error and clipping error are both taken into account in the cost function. Further, there is simplification of the cost function by using the approximation of quantization (i.e. equation 6). The simplification of the cost function is assumed by providing that the sign vectors remain constant during one iteration (i.e. equation 9).

[0029] Embodiments of the invention include optimizing LED values for more than one color component. If the three color components are used, equation (4) would become:

$$J(\mathbf{L},\mathbf{D}) = \|\mathbf{I}_r - \mathbf{O}_r\|_2^2 + \|\mathbf{I}_g - \mathbf{O}_g\|_2^2 + \|\mathbf{I}_b - \mathbf{O}_b\|_2^2 \quad (11)$$

In the cost function, L_p norm can be used instead of L_2 norm:

$$J(\mathbf{L},\mathbf{D}) = \|\mathbf{I} - \mathbf{O}\|_p^p \quad (12)$$

Here, the L_p norm is defined as:

$$\| A \|_p = \sqrt[1/p]{\sum_i A_i^p} \quad (13)$$

The L_1 norm is of special interest because it has a close-form solution and usually more stable and can be expressed as:

$$J(\mathbf{L},\mathbf{D}) = \left\| \mathbf{I} - \mathbf{O} \right\|_1^1 = \left| \mathbf{I} - \mathbf{O} \right| \quad (14)$$

In this case, $\mathbf{L}^*$ is updated as follows:

$$\mathbf{L}^{*(n+1)} = \mathbf{L}^{*(n)} - \lambda \left(\left(\left(\frac{\mathbf{V}}{4q} - \mathbf{U} \right) \mathbf{P} \right)^T \operatorname{sign}\left(\left(\frac{\mathbf{V}}{4q} - \mathbf{U} \right) \mathbf{P}\mathbf{L}^{*(n)} + \mathbf{U}\mathbf{I} \right) \right) \quad (15)$$

[0030] In the cost function, the human vision system can be taken into account by considering the relative error rather than absolute error. One can define diagonal matrix **F** of size MNxMN, whose diagonal elements equal to the inverse of elements of vector **I**, as:

$$\mathbf{F}_{i,j} = \frac{1}{\mathbf{I}_i}$$

$$\mathbf{F}_{i,j} = 0 \qquad \text{for } i \neq j \quad (16)$$

[0031] Then the cost function could be rewritten as follows:

$$J_g(\mathbf{L}^*) = \left(\mathbf{FU}(\mathbf{I} - \mathbf{PL}^*) + \mathbf{FVPL}^* / 4q \right)^T \left(\mathbf{FU}(\mathbf{I} - \mathbf{PL}^*) + \mathbf{FVPL}^* / 4q \right) \quad (16)$$

This cost function could be optimized in a similar way as equation (9).

[0032] In accordance with the principles of the invention, an HDR display system is herein disclosed. This is generally shown in Fig. 3, wherein the system includes a video signal generator 301 that receives input images and generates video or driver signals 302 as described above for driving an HDR display 303. The HDR display can include an LED backlighting unit; however, the invention does include and is applicable for displays having backlighting units with arrays of other types light generating sources. Furthermore, the HDR display can include an LCD front-end; however, the invention does include and is applicable for displays having front-end units with arrays of other types light shuttering or attenuating elements.

[0033] In view of the above, the foregoing merely illustrates the principles of the invention and it will thus be appreciated by those skilled in the art to devise numerous alternative arrangements which, although not explicitly described herein, embody the principles of the invention and are within its spirit and scope.

CLAIMS:

1. A display device comprising:

a backlighting unit having a matrix of light generating elements;

a front-end unit having a plurality of light shutters grouped into a repeat arrangement which include at least two different shutters that each attenuate different color light;

a signal handling system for receiving image signals and having an algorithm to process the image signals and derive final backlight driver signals for the backlighting unit and final front-end driver signals for the front-end unit, wherein

the algorithm employing at least one difference reduction iteration to derive the final driver signals, the at least one iteration being responsive to a display target image brightness values (I); at least one projected image brightness values (O) correlating to at least one set of intermediate driver signals; and the difference between the brightness values.

2. The display device of claim 1, wherein the algorithm is an iterative gradient descent algorithm.

3. The display device of claim 1, wherein the algorithm employs a convolution between a point spread function of the backlighting unit and quantized backlight driver signals.

4. The display device of claim 3, wherein the algorithm is adapted to produce or access:

a backlight matrix L of the quantized backlight driver signals for the backlighting unit having M rows by N columns that correspond to the light generating elements and a point spread matrix P that corresponds to the point spread function; and

a product of L and P to yields a full resolution backlighting brightness matrix B.

5. The display device of claim 4, wherein the algorithm is adapted to generate the final front-end driver signals for a color p responsive to a product of the brightness matrix and a normalized front-end driver signal for the color p.

6. The display device of claim 5, wherein at least a term of display output brightness O_p for a given the color p is expressed as

$$\begin{aligned}\mathbf{O}_p &= \mathbf{B} \otimes \mathbf{D}_p \\ &= \text{sign}(\mathbf{I}_p - \mathbf{B}) \otimes \mathbf{B} + \text{sign}(\mathbf{B} - \mathbf{I}_p) \otimes (\mathbf{B} \otimes \mathbf{D}_p)\end{aligned}$$

where I_p and D_p are an input high dynamic range image for the color p and the normalized front-end driver signal for the color p, respectively.

7. The display device of claim 6, wherein the algorithm is adapted to produce a least square of the difference between the input high dynamic range image and the display output brightness for the color p and the algorithm reduces the least square.

8. The display device of claim 4 , wherein the algorithm is adapted such that output error is generated and used in determining the final front-end driver signals for a color p, the output error incorporates at least a term expressed as:

$$\begin{aligned}J_p(\mathbf{L}, \mathbf{D}_p) &= \|\mathbf{I}_p - \mathbf{O}_p\|_2^2 \\ &= \left(\text{sign}(\mathbf{I}_p - \mathbf{PL}) \otimes (\mathbf{I}_p - \mathbf{PL}) + \text{sign}(\mathbf{PL} - \mathbf{I}_p) \otimes (\mathbf{PL} \otimes \mathbf{D}_p - \mathbf{I}_p)\right)^T \\ &\quad \times \left(\text{sign}(\mathbf{I}_p - \mathbf{PL}) \otimes (\mathbf{I}_p - \mathbf{PL}) + \text{sign}(\mathbf{PL} - \mathbf{I}_p) \otimes (\mathbf{PL} \otimes \mathbf{D}_p - \mathbf{I}_p)\right)\end{aligned}$$

where I_p,D_p , and O_p are an input high dynamic range image brightness for the color p, a normalized front-end driver signal for the color p, and a display output brightness, respectively.

9. The display device of claim 5, wherein the algorithm is adapted to be responsive to clipping error and quantization error, wherein:

the clipping error is caused by some intermediate driver signals for the backlighting unit correlating to insufficient brightness and is the difference between the insufficient brightness and the display target image brightness value, and

the quantization error is the difference between a brightness quantization level of the front-end unit and the display target image brightness value.

10. The display device of claim 4, wherein the algorithm is adapted such that a collective output error J is generated and used in determining the final front-end driver signals for at least three colors, the collective output error is reduced by the algorithm and incorporates at least a term expressed as:

$$J = \|\mathbf{I}_r - \mathbf{O}_r\|_2^2 + \|\mathbf{I}_g - \mathbf{O}_g\|_2^2 + \|\mathbf{I}_b - \mathbf{O}_b\|_2^2$$

where the Is are an input high dynamic range image brightness for three colors r, g, and b and Os are a display output brightness for the three colors, respectively.

11. A method comprising the steps of:

accessing an image signal;

generating an intermediate backlighting driver signal for individual backlight elements for a backlighting unit responsive to the image signal;

convoluting the intermediate backlighting driver signals with a point spread function of the backlighting unit;

deriving at least one new backlighting driver signal responsive to the convoluting step;

determining display error associated with a plurality of available light shutter signals of a front-end unit having individual light shutters and associated with the at least one new backlighting driver signal, the front-end unit having a higher resolution than the backlighting unit;

driving a display device with a combination of shutter signals and new backlighting driver signals that causes a reduction in the display error with respect to other generated intermediate backlighting driver signals and other available light shutter signals.

12. The method of claim 11 further comprising:

accessing target display output for the individual shutters from the image signal;

using a factor that includes a square root of the target display output to obtain intermediate backlighting driver signal in the generating step.

13. The method of claim 11 further comprising:

generating a backlight matrix L having M rows by N columns that correspond to the backlight elements; and

producing a full resolution backlighting brightness matrix B, at least in part , from the matrix L and the matrix P.

14. The method of claim 13 further comprising:

comparing the full resolution backlighting brightness matrix B to the image signal; and

generating diagonal matrices U and V having diagonal elements corresponding to sign($\mathbf{I}$-$\mathbf{PL}^*$) and sign($\mathbf{PL}^*$-$\mathbf{I}$), respectively, wherein matrix $\mathbf{L}^*$ represents iterations of new backlighting driver signals and I represents the target display output of the image signal.

15. The method of claim 14 further comprising:

repeating the comparing step and generating diagonal matrices steps η times, wherein η is a predetermined number of iterations.

16. The method of claim 15 further comprising:

quantizing the backlight driver signals in the matrix L.

17. The method of claim 16 further comprising the steps of:

using the matrix $\mathbf{L}^*$ after the last iteration to determine a final full resolution backlighting; and

selecting final light shutter signals responsive to the final full resolution backlighting to use in the driving step.

18. The method of claim 17 comprising:

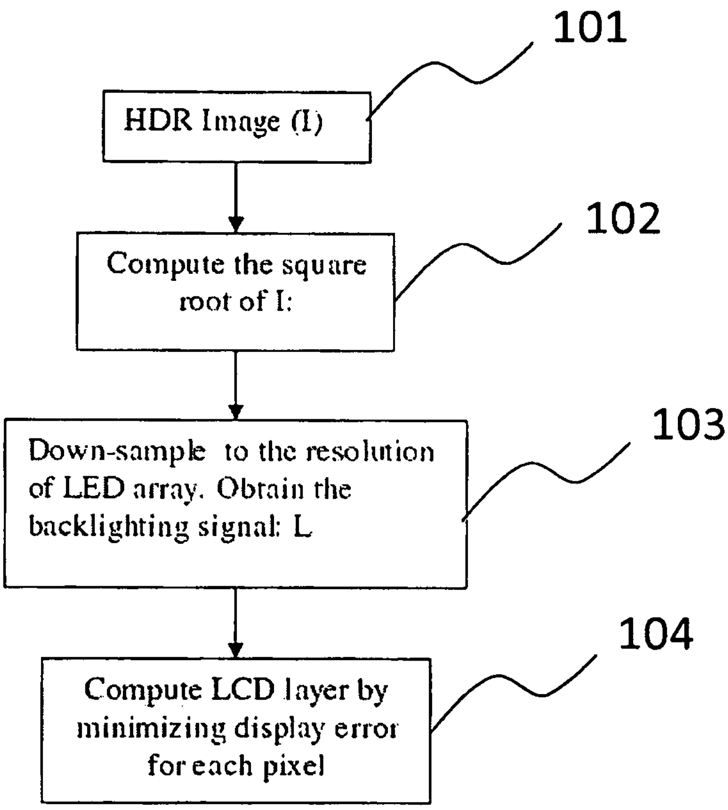
determining clipping error and quantization error, wherein the clipping error is caused by intermediate driver signals for the backlighting unit correlating to insufficient brightness and is the difference between the insufficient brightness and the target display output, and the quantization error is the difference between a brightness quantization level of the front-end unit and the target display output;

applying the clipping error or quantization error into a cost function and using the cost function as a factor in determining the display error.

19. The method of claim 13 further comprising:

comparing the full resolution backlighting brightness matrix B to the image signal; and

using the comparison in the comparing step in determining the display error and selecting combinations of shutter signals and new backlighting driver signals.



PRIOR ART

FIG. 1

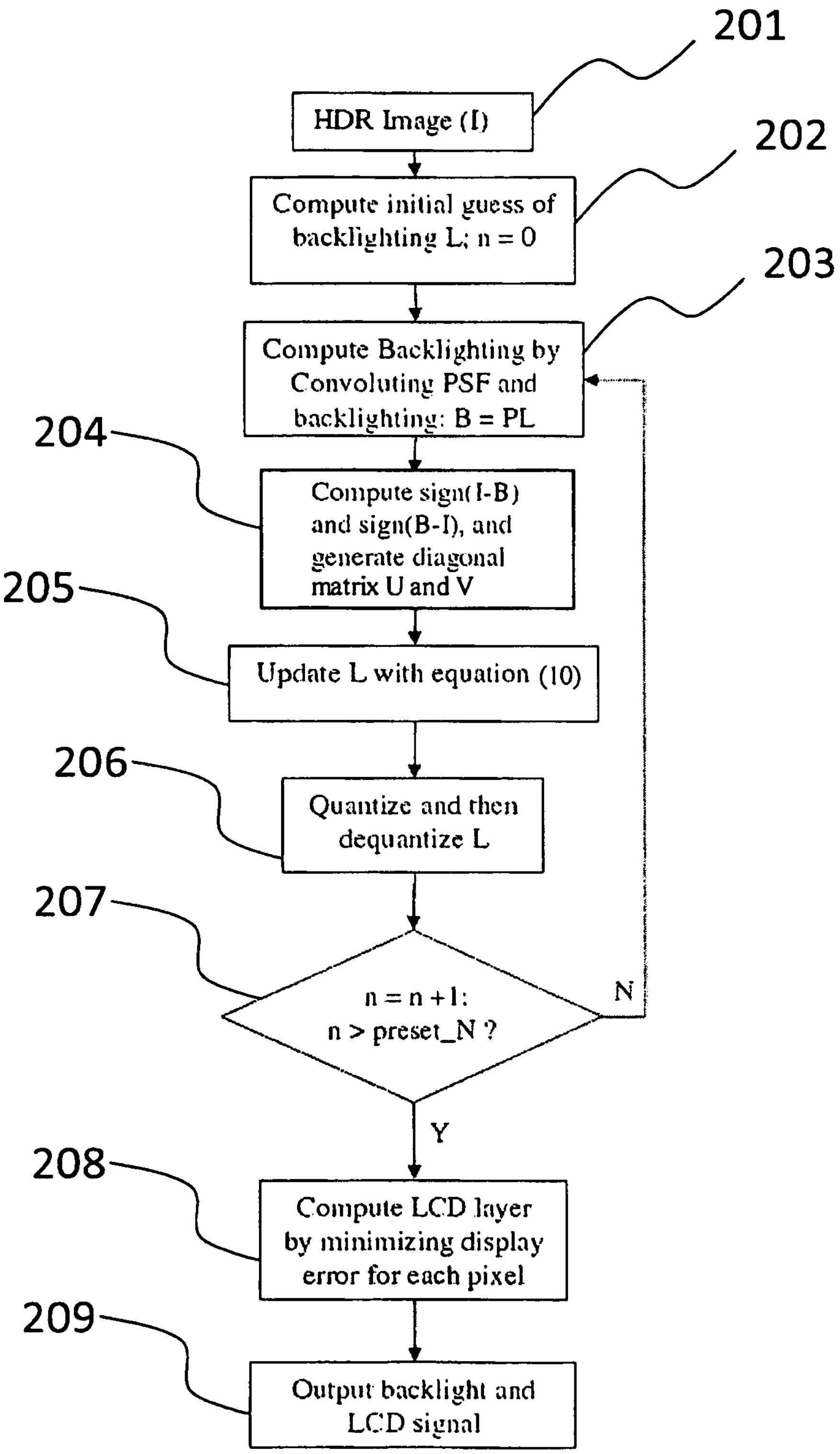

201
202
203
204
205
206
207
208
209
HDR Image (I)
Compute initial guess of backlighting L; n = 0
Compute Backlighting by Convoluting PSF and backlighting: B = PL
Compute sign(I-B) and sign(B-I), and generate diagonal matrix U and V
Update L with equation (10)
Quantize and then dequantize L
n = n + 1;
n > preset_N ?
N
Y
Compute LCD layer by minimizing display error for each pixel
Output backlight and LCD signal

FIG. 2

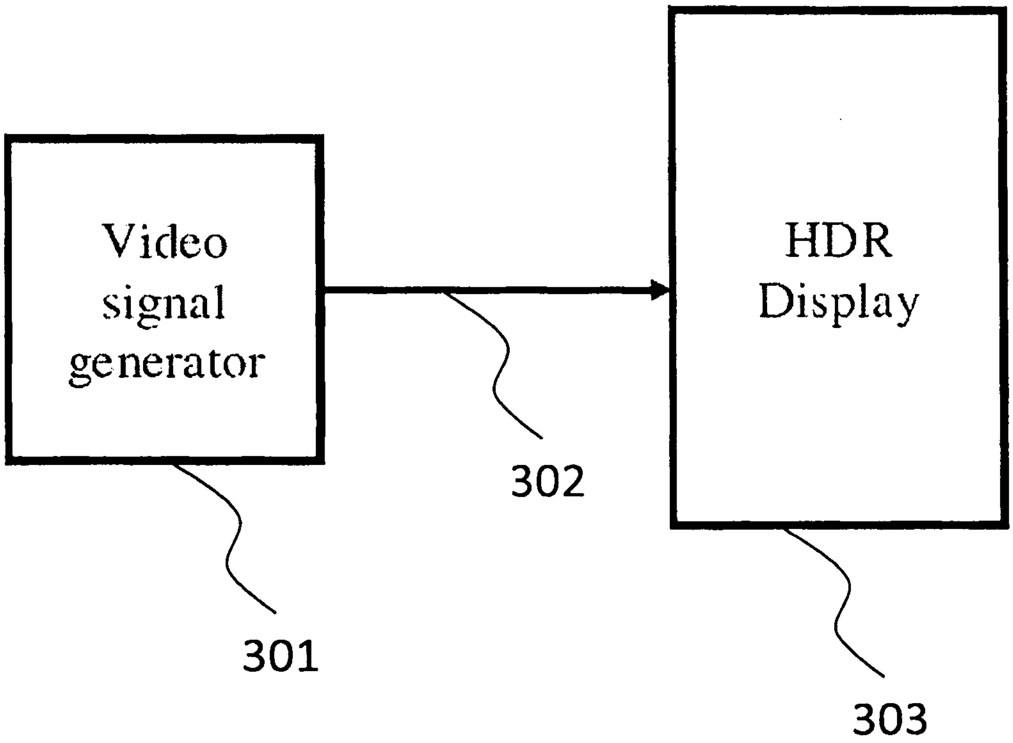


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/000359

A. CLASSIFICATION OF SUBJECT MATTER
INV. G09G3/34
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G09G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FENG LI CHESTER F CARLSON CENTER FOR IMAGING SCIENCE ET AL: "66.1: Distinguished Student Paper: Deriving LED Driving Signal for Area-Adaptive LED Backlight in High Dynamic Range LCD Displays" SID 2007, 2007 SID INTERNATIONAL SYMPOSIUM, SOCIETY FOR INFORMATION DISPLAY, LOS ANGELES, USA, vol. XXXVIII, 20 May 2007 (2007-05-20), pages 1794-1797, XP007013384 ISSN: 0007-966X cited in the application	1,3-8, 10,11, 13,19
Y	page 1794 - page 1797 from chapter 1 to chapter 3 and chapter 5figure 1	2

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 May 2010	20/05/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Ley, Théodore

2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 927 974 A2 (SHARP KK [JP]) 4 June 2008 (2008-06-04)	1,3-6, 11, 13-17,19
Y	paragraphs [0028], [0032], [0049], [0055] - [0074] figures 3,12,13-15	2
X	TRENTACOSTE ET AL: "Photometric image processing for high dynamic range displays" JOURNAL OF VISUAL COMMUNICATION AND IMAGE REPRESENTATION, ACADEMIC PRESS, INC, US LNKD- DOI:10.1016/J.JVCIR.2007.06.006, vol. 18, no. 5, 5 September 2007 (2007-09-05), pages 439-451, XP022231050 ISSN: 1047-3203	1,3-7,9, 11-13,19
Y	page 439 - page 440; figure 1 page 442 - page 445; figure 3	2
Y	BIEMOND J ET AL: "Iterative methods for image deblurring" PROCEEDINGS OF THE IEEE, IEEE. NEW YORK, US LNKD- DOI:10.1109/5.53403, vol. 78, no. 5, 1 May 1990 (1990-05-01), pages 856-883, XP002361158 ISSN: 0018-9219 chapter IV-B and IV-C; page 863 - page 868 chapter IX; page 877 - page 878	2

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2010/000359

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 1927974 A2	04-06-2008	CN 101202023 A	18-06-2008
		JP 2008139871 A	19-06-2008
		US 2008129677 A1	05-06-2008