US 20250259284A9

(19) United States

(12) Patent Application Publication

MANCHI

(10) Pub. No.: US 2025/0259284 A9

(48) Pub. Date: Aug. 14, 2025

CORRECTED PUBLICATION

(54) **HIGH DYNAMIC RANGE (HDR) IMAGE PROCESSING WITH ADAPTIVE COLOR VOLUME MAPPING**

(71) Applicant: **Synaptics Incorporated**, San Jose, CA (US)

(72) Inventor: **Chandranath MANCHI**, Bangalore (IN)

(73) Assignee: **Synaptics Incorporated**, San Jose, CA (US)

(21) Appl. No.: **18/322,926**

(22) Filed: **May 24, 2023**

Prior Publication Data

(15) Correction of US 2024/0394857 A1 Nov. 28, 2024
See Abstract, Specification, Claims, and Drawings.

(65) US 2024/0394857 A1 Nov. 28, 2024

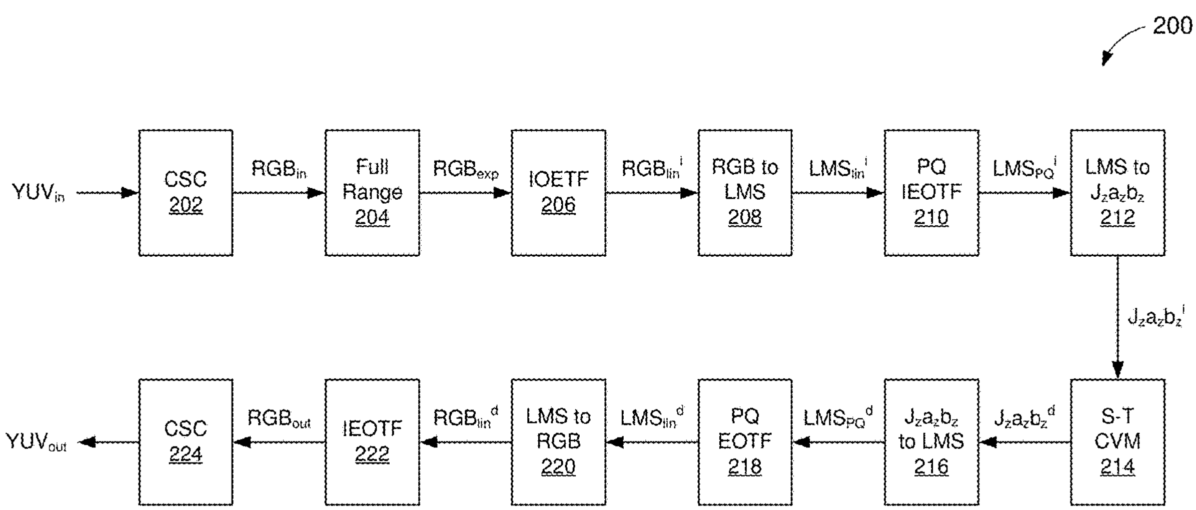
Publication Classification

(51) **Int. Cl.**
G06T 5/00 (2024.01)
G09G 5/06 (2006.01)

(52) **U.S. Cl.**
CPC ***G06T 5/92*** (2024.01); ***G09G 5/06*** (2013.01); *G06T 2207/10024* (2013.01); *G06T 2207/20208* (2013.01); *G09G 2320/0242* (2013.01); *G09G 2340/06* (2013.01); *G09G 2360/16* (2013.01)

(57) **ABSTRACT**

This disclosure provides methods, devices, and systems for color volume mapping (CVM) techniques that operate in the $J_za_zb_z$ color space. In some aspects, an image processor may receive image data having color channels associated with a color space that is not perceptually uniform and may convert the image data to the $J_za_zb_z$ color space. The image processor may perform a global CVM operation which maps a range of J_z, a_z, and b_z values supported by the image source to a range of j_z, a_z, and b_z values supported by the image target. The image processor may further perform a local CVM operation which adaptively tunes the J_z, a_z, and b_z channels of image data based on various properties of the received image. Still further, the image processor may adaptively blend J_z values at the edges of objects and other features to preserve details in low-contrast regions of the received image.



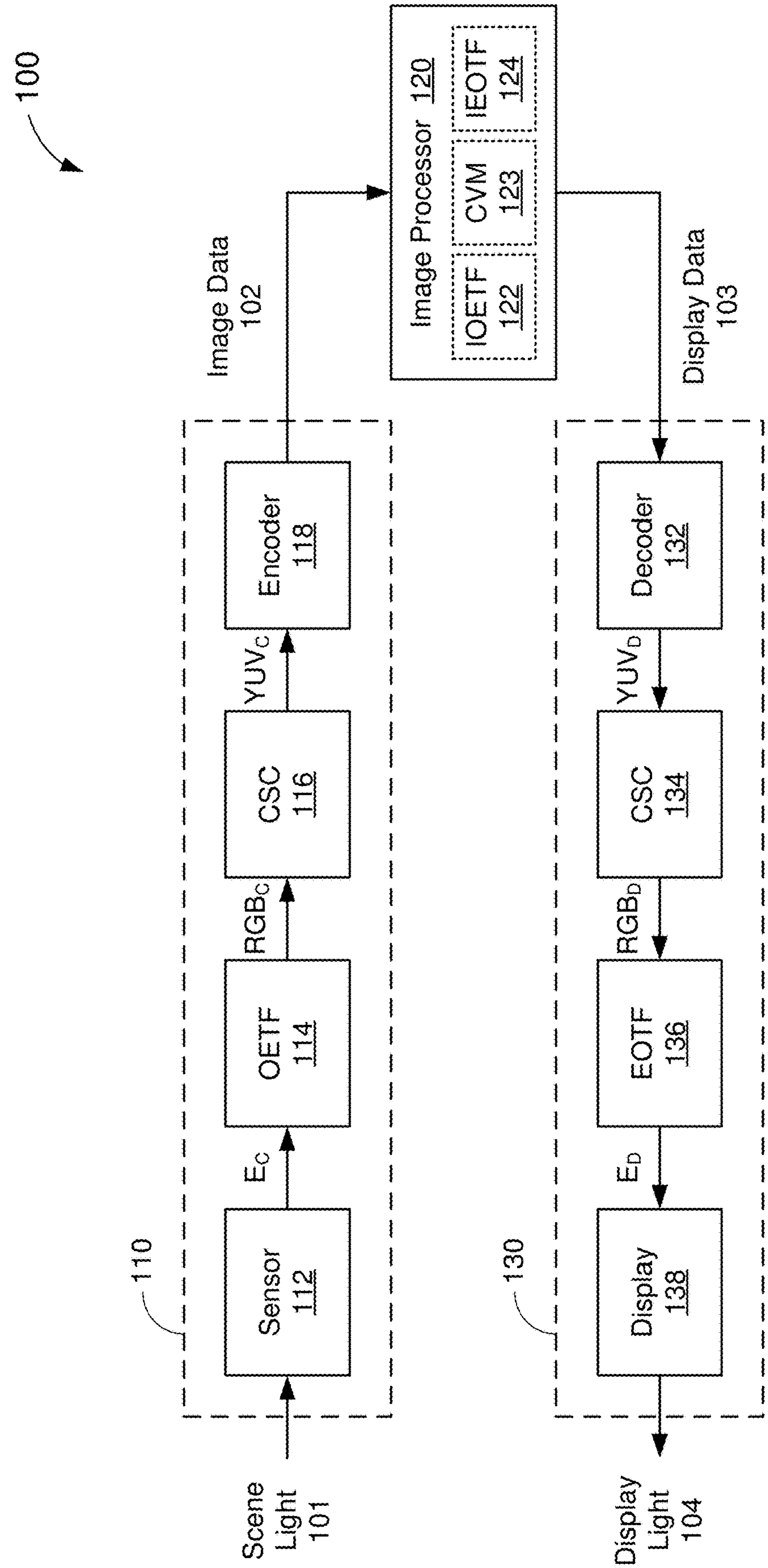

100
Image Data 102
Image Processor 120
IOETF 122
CVM 123
IEOTF 124
Display Data 103
110
Scene Light 101
Sensor 112
E_C
OETF 114
RGB_C
CSC 116
YUV_C
Encoder 118
130
Display Light 104
Display 138
E_D
EOTF 136
RGB_D
CSC 134
YUV_D
Decoder 132

FIG. 1

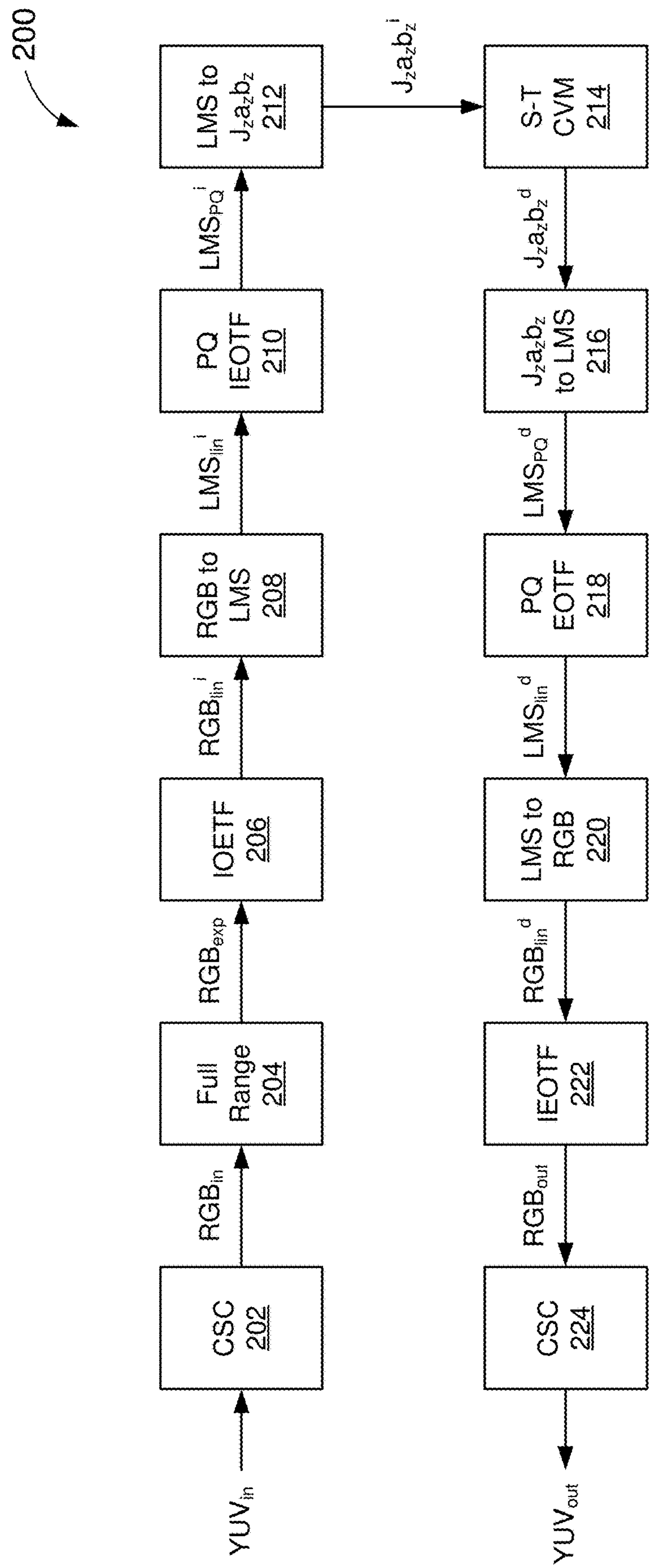

200
YUV_{in}
CSC 202
RGB_{in}
Full Range 204
RGB_{exp}
IOETF 206
$RGB_{lin}{}^{i}$
RGB to LMS 208
$LMS_{lin}{}^{i}$
PQ IEOTF 210
$LMS_{PQ}{}^{i}$
LMS to $J_za_zb_z$ 212
$J_za_zb_z{}^{i}$
S-T CVM 214
$J_za_zb_z{}^{d}$
$J_za_zb_z$ to LMS 216
$LMS_{PQ}{}^{d}$
PQ EOTF 218
$LMS_{lin}{}^{d}$
LMS to RGB 220
$RGB_{lin}{}^{d}$
IEOTF 222
RGB_{out}
CSC 224
YUV_{out}

FIG. 2

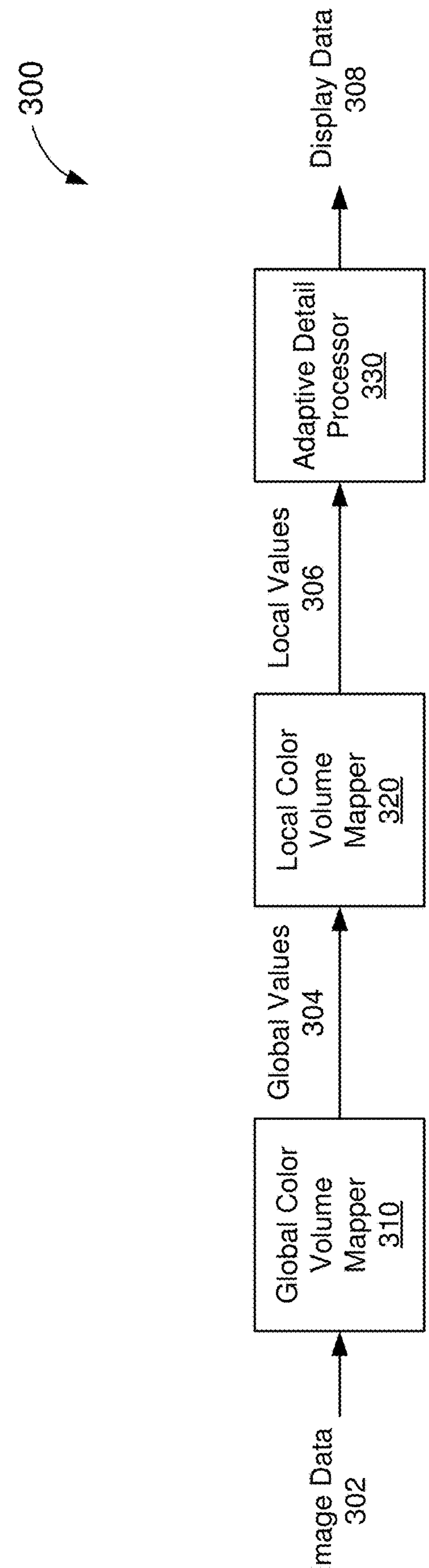
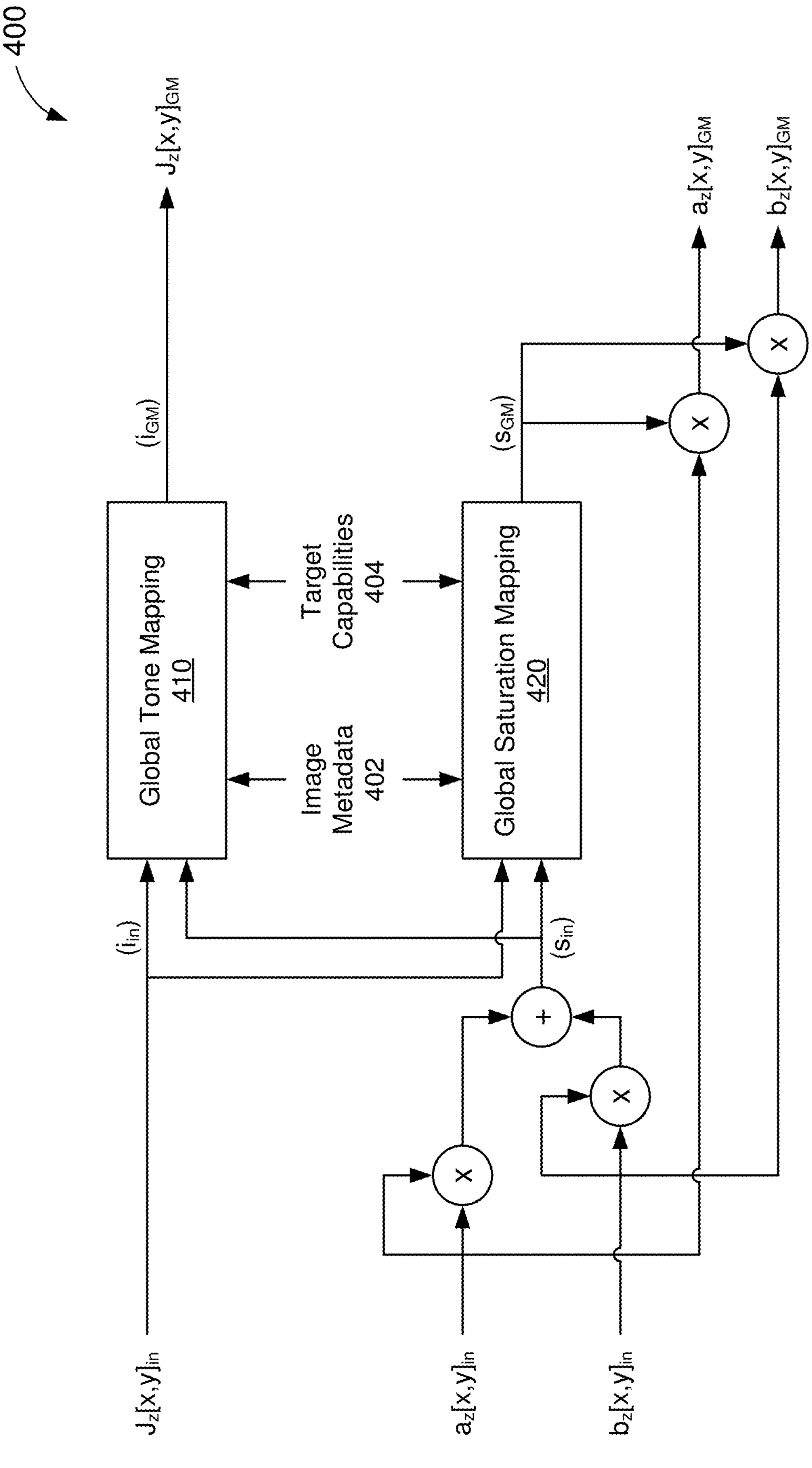

300
Image Data
302
Global Color
Volume
Mapper
310
Global Values
304
Local Color
Volume
Mapper
320
Local Values
306
Adaptive Detail
Processor
330
Display Data
308

FIG. 3



400
$J_z[x,y]_{in}$
$a_z[x,y]_{in}$
$b_z[x,y]_{in}$
(i_{in})
(s_{in})
Global Tone Mapping 410
Global Saturation Mapping 420
Image Metadata 402
Target Capabilities 404
(i_{GM})
(s_{GM})
$J_z[x,y]_{GM}$
$a_z[x,y]_{GM}$
$b_z[x,y]_{GM}$

FIG. 4

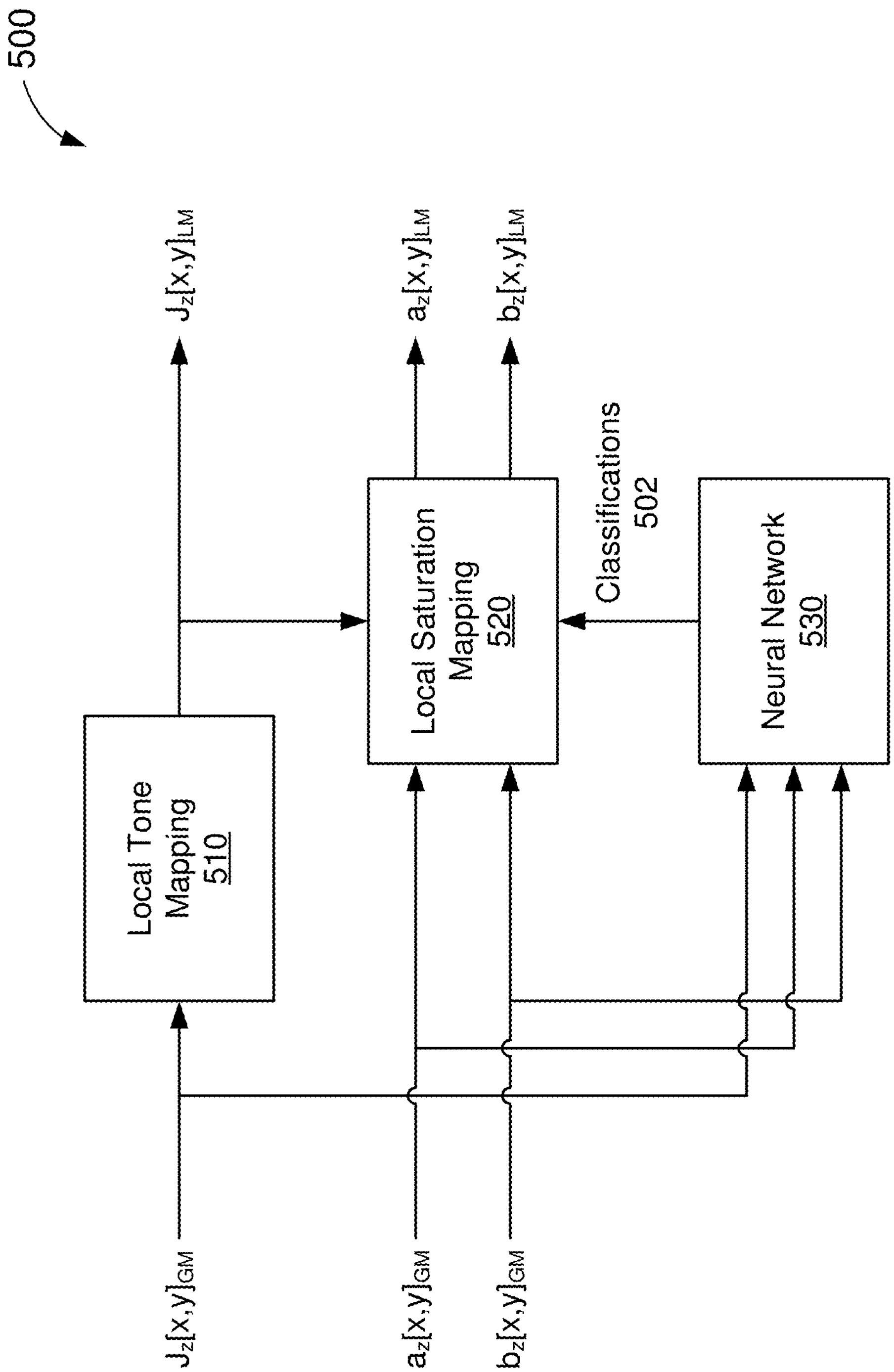

500
$J_z[x,y]_{GM}$
$a_z[x,y]_{GM}$
$b_z[x,y]_{GM}$
Local Tone Mapping 510
Local Saturation Mapping 520
Neural Network 530
Classifications 502
$J_z[x,y]_{LM}$
$a_z[x,y]_{LM}$
$b_z[x,y]_{LM}$

FIG. 5

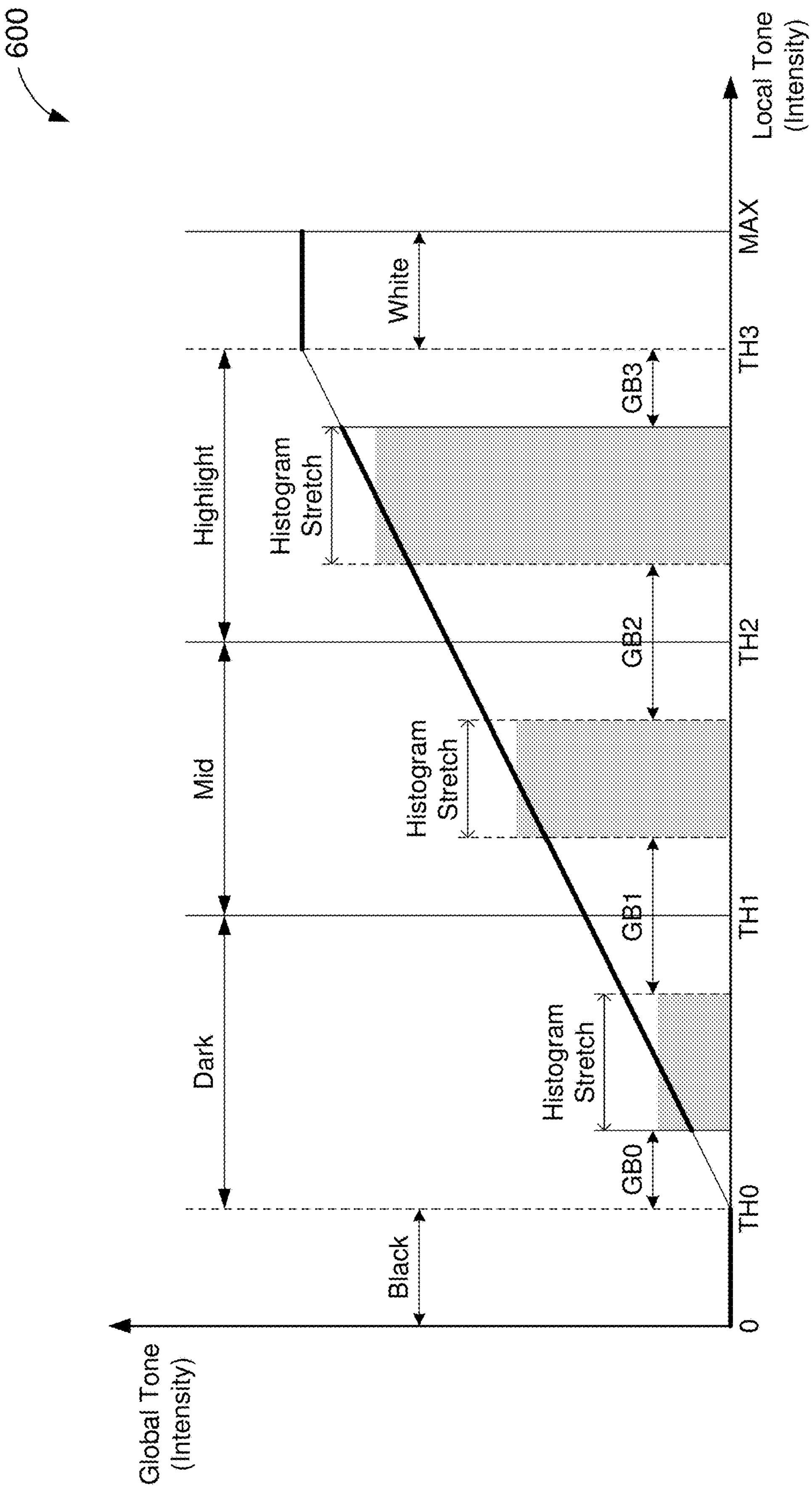

600
Global Tone (Intensity)
Local Tone (Intensity)
Black
Dark
Mid
Highlight
White
Histogram Stretch
Histogram Stretch
Histogram Stretch
GB0
GB1
GB2
GB3
0
TH0
TH1
TH2
TH3
MAX

FIG. 6

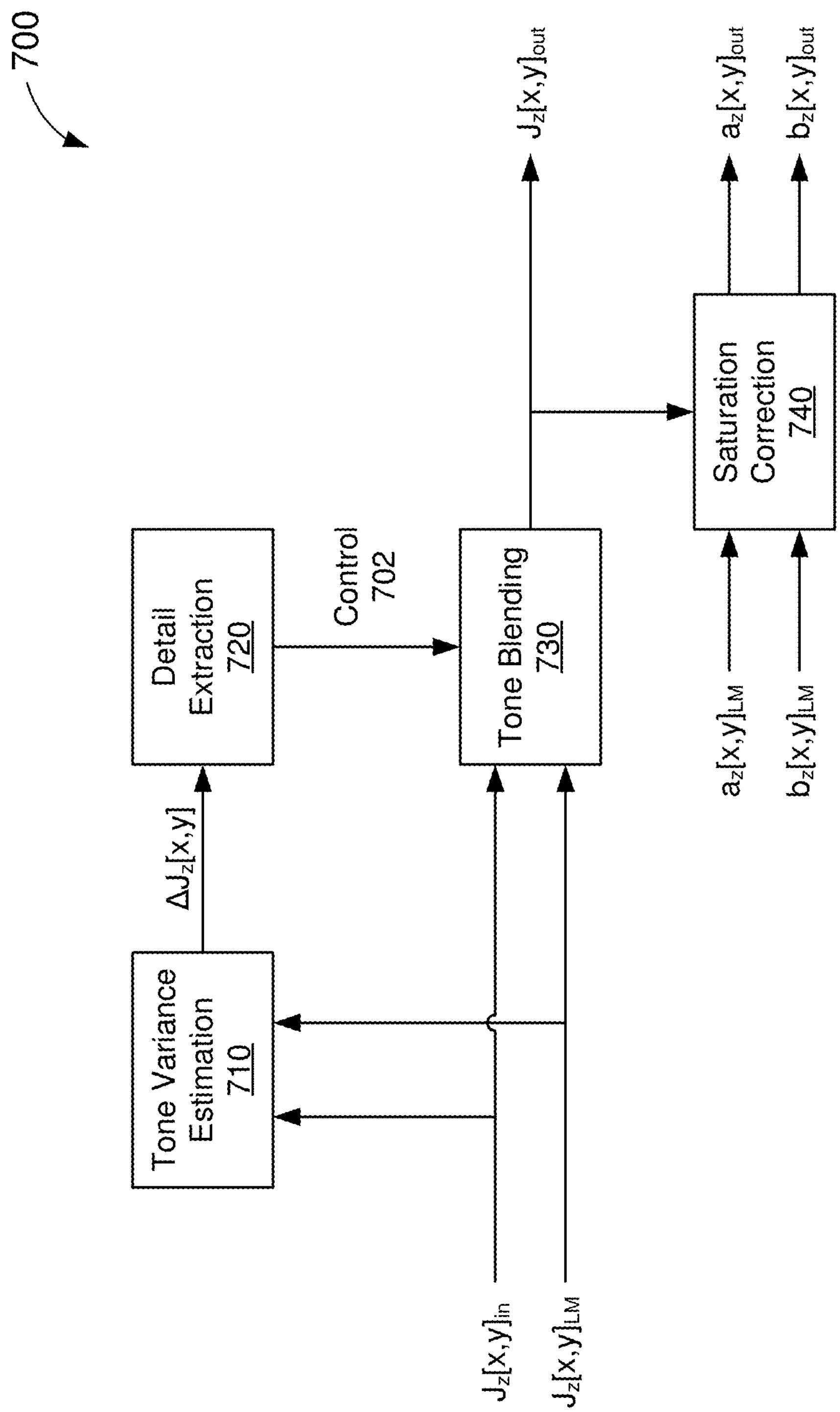

700
Tone Variance Estimation 710
$\Delta J_z[x,y]$
Detail Extraction 720
Control 702
Tone Blending 730
Saturation Correction 740
$J_z[x,y]_{in}$
$J_z[x,y]_{LM}$
$J_z[x,y]_{out}$
$a_z[x,y]_{LM}$
$b_z[x,y]_{LM}$
$a_z[x,y]_{out}$
$b_z[x,y]_{out}$

FIG. 7

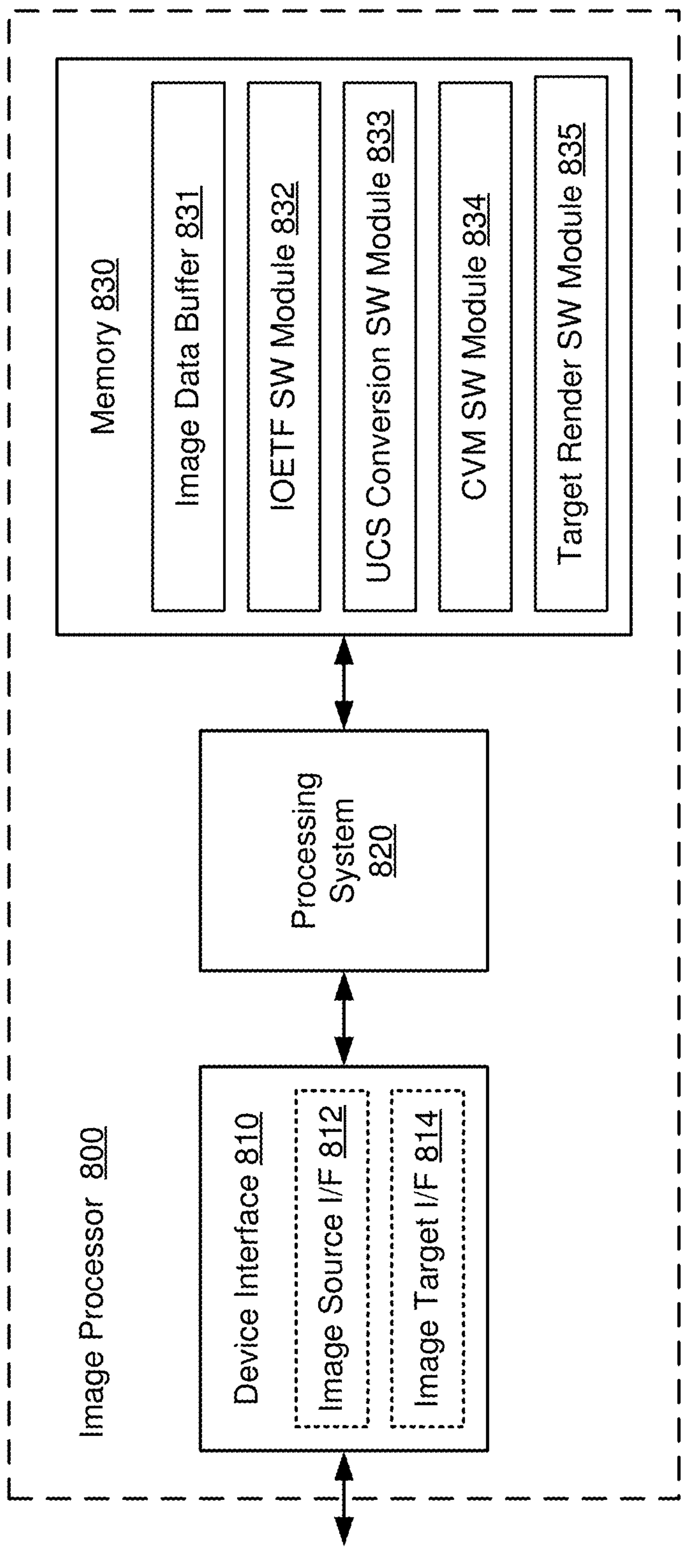


Image Processor 800
Device Interface 810
Image Source I/F 812
Image Target I/F 814
Processing System 820
Memory 830
Image Data Buffer 831
IOETF SW Module 832
UCS Conversion SW Module 833
CVM SW Module 834
Target Render SW Module 835

FIG. 8

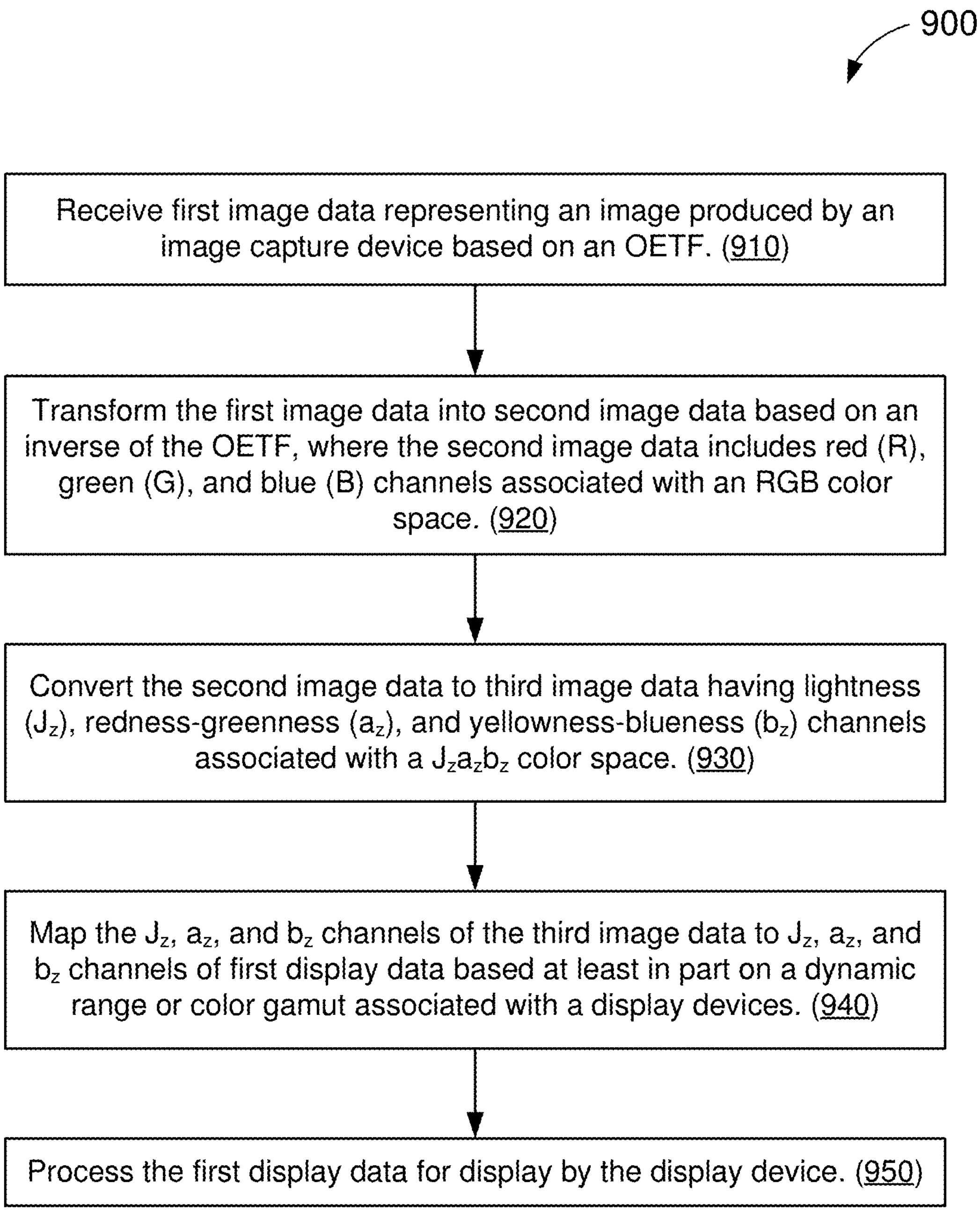

900
Receive first image data representing an image produced by an image capture device based on an OETF. (910)
Transform the first image data into second image data based on an inverse of the OETF, where the second image data includes red (R), green (G), and blue (B) channels associated with an RGB color space. (920)
Convert the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_z a_z b_z$ color space. (930)
Map the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display devices. (940)
Process the first display data for display by the display device. (950)

FIG. 9

HIGH DYNAMIC RANGE (HDR) IMAGE PROCESSING WITH ADAPTIVE COLOR VOLUME MAPPING

TECHNICAL FIELD

[0001] The present implementations relate generally to image processing, and specifically to high dynamic range (HDR) image processing with adaptive tone and color volume mapping.

BACKGROUND OF RELATED ART

[0002] Display devices (such as televisions, set-top boxes, computers, and mobile phones) may use different imaging technologies than those used by image capture devices (such as cameras and video recorders). Advancements in display technologies have resulted in improved capabilities such as high dynamic range, wider color gamut and migration from high definition (HD) display to ultra-high definition (UHD) display technologies. As a result, image processing may be used to properly render, on a given display, images captured by devices with different system capabilities and standards. For example, a display device that is capable of displaying only standard dynamic range (SDR) content may be unable to reproduce the full range of color, brightness, or contrast of images captured in a high dynamic range (HDR) format. An image processor may modify the raw image data produced by an image capture device so that the image can be reproduced more accurately or realistically on the display device (such as to utilize the full dynamic range of the display).

[0003] Some image processing techniques (also referred to as "tone mapping") may reduce the color, brightness, or contrast of an HDR image to be rendered on an SDR display. Some other image processing techniques (also referred to as "inverse tone mapping") may increase the color, brightness, or contrast of an SDR image to be rendered on an HDR display. Even when the image capture and display devices both support HDR, image processing can further enhance the quality of the displayed image due to differences between the display environment (such as a television with electronically-limited brightness, color, contrast, and resolution) and the image capture environment (such as a natural environment with unlimited brightness, color, contrast, and resolution). As image capture and display technologies continue to evolve, new image processing techniques are needed to bridge the capabilities (such as dynamic range or color gamut) between image capture and display devices.

SUMMARY

[0004] This Summary is provided to introduce in a simplified form a selection of concepts that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to limit the scope of the claimed subject matter.

[0005] One innovative aspect of the subject matter of this disclosure can be implemented in a method of image processing. The method includes receiving first image data representing an image produced by an image capture device based on an opto-electrical transfer function (OETF); transforming the first image data into second image data based on an inverse of the OETF, where the second image data includes red (R), green (G), and blue (B) channels associated with an RGB color space; converting the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space; mapping the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of display data based at least in part on a dynamic range or color gamut associated with a display device; and processing the display data for display by the display device.

[0006] Another innovative aspect of the subject matter of this disclosure can be implemented in an image processor including a processing system, comprising a hardware process and software process, which cause the image processor to receive first image data representing an image produced by an image capture device based on an OETF; transform the first image data into second image data based on an inverse of the OETF, where the second image data includes red (R), green (G), and blue (B) channels associated with an RGB color space; convert the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space; map the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of display data based at least in part on a dynamic range or color gamut associated with a display device; and process the display data for display by the display device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The present implementations are illustrated by way of example and are not intended to be limited by the figures of the accompanying drawings.

[0008] FIG. **1** shows a block diagram of an example image capture and display system, according to some implementations.

[0009] FIG. **2** shows a block diagram of an example image processing system, according to some implementations.

[0010] FIG. **3** shows a block diagram of an example color volume mapping (CVM) system, according to some implementations.

[0011] FIG. **4** shows a block diagram of an example system for global CVM, according to some implementations.

[0012] FIG. **5** shows a block diagram of an example system for local CVM, according to some implementations.

[0013] FIG. **6** shows an example mapping of global pixel tone values to local pixel tone values with adaptive histogram equalization.

[0014] FIG. **7** shows a block diagram of an example adaptive detail processor, according to some implementations.

[0015] FIG. **8** shows another block diagram of an example image processing system, according to some implementations.

[0016] FIG. **9** shows an illustrative flowchart depicting an example operation for image processing, according to some implementations.

DETAILED DESCRIPTION

[0017] In the following description, numerous specific details are set forth such as examples of specific components, circuits, and processes to provide a thorough understanding of the present disclosure. The term "coupled" as used herein means connected directly to or connected through one or more intervening components or circuits. The terms "electronic system" and "electronic device" may be used interchangeably to refer to any system capable of electronically processing information. Also, in the following description and for purposes of explanation, specific nomenclature is set forth to provide a thorough understanding of the aspects of the disclosure. However, it will be apparent to one skilled in the art that these specific details may not be required to practice the example embodiments. In other instances, well-known circuits and devices are shown in block diagram form to avoid obscuring the present disclosure. Some portions of the detailed descriptions which follow are presented in terms of procedures, logic blocks, processing and other symbolic representations of operations on data bits within a computer memory.

[0018] These descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. In the present disclosure, a procedure, logic block, process, or the like, is conceived to be a self-consistent sequence of steps or instructions leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, although not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated in a computer system. It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities.

[0019] Unless specifically stated otherwise as apparent from the following discussions, it is appreciated that throughout the present application, discussions utilizing the terms such as "accessing," "receiving," "sending," "using," "selecting," "determining," "normalizing," "multiplying," "averaging," "monitoring," "comparing," "applying," "updating," "measuring," "deriving" or the like, refer to the actions and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0020] In the figures, a single block may be described as performing a function or functions; however, in actual practice, the function or functions performed by that block may be performed in a single component or across multiple components, and/or may be performed using hardware, using software, or using a combination of hardware and software. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described below generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure. Also, the example input devices may include components other than those shown, including well-known components such as a processor, memory and the like.

[0021] The techniques described herein may be implemented in hardware, software, firmware, or any combination thereof, unless specifically described as being implemented in a specific manner. Any features described as modules or components may also be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a non-transitory processor-readable storage medium including instructions that, when executed, performs one or more of the methods described above. The non-transitory processor-readable data storage medium may form part of a computer program product, which may include packaging materials.

[0022] The non-transitory processor-readable storage medium may comprise random access memory (RAM) such as synchronous dynamic random-access memory (SDRAM), read only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), FLASH memory, other known storage media, and the like. The techniques additionally, or alternatively, may be realized at least in part by a processor-readable communication medium that carries or communicates code in the form of instructions or data structures and that can be accessed, read, and/or executed by a computer or other processor.

[0023] The various illustrative logical blocks, modules, circuits and instructions described in connection with the embodiments disclosed herein may be executed by one or more processors (or a processing system). The term "processor," as used herein may refer to any general-purpose processor, special-purpose processor, conventional processor, controller, microcontroller, and/or state machine capable of executing scripts or instructions of one or more software programs stored in memory.

[0024] As described above, image processing may be used to properly render, on a given display, images captured by devices with different system capabilities and standards. More specifically, an image processor may modify the raw image data produced by an image capture device so that the image can be reproduced more accurately or realistically on the display device (such as to utilize the full dynamic range of the display). Many existing image capture and display devices are configured to process image data having luma (Y) and chrominance (UV) color channels. As such, many existing image processors are designed to perform tone mapping or inverse tone mapping operations in a YUV color space. However, the Y and UV color channels are not perfectly orthogonal. In other words, changing the dynamic range of the Y component of a given image also changes the saturation of any distinguishable hue by a variable amount. Thus, performing tone mapping or inverse tone mapping in the YUV color space may impose a significant penalty on quality, latency, memory, and processing resources, which may not be suitable for many image processing applications (such as for processing video or for implementation in battery-powered devices or other edge devices with limited resources).

[0025] Aspects of the present disclosure recognize that image processing overhead can be significantly reduced, without loss of accuracy, by performing tone mapping and inverse tone mapping operations in a perceptually uniform color space (UCS). A UCS is any color space in which the geometric distance between any two points in the color space reflects an equal amount of change in perceived color.

An example suitable UCS for tone mapping and inverse tone mapping is the $J_za_zb_z$ color space, which is defined by lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) color components.

[0026] Various aspects relate generally to image processing, and more particularly, to color volume mapping (CVM) techniques that operate in the $J_za_zb_z$ color space. In some aspects, an image processing system may receive image data having color channels associated with a color space that is not perceptually uniform (such as RGB or YUV) and may convert the image data to the $J_za_zb_z$ color space. In some implementations, the image processing system may perform a global CVM operation which maps a range of J_z, a_z, and b_z values supported by the image source (such as an image capture device) to a range of j_z, a_z, and b_z values supported by the image target (such as a display device). In some other implementations, the image processing system may further perform a local CVM operation which adaptively tunes the J_z, a_z, and b_z channels of image data based on various properties of the received image. Still further, in some implementations, the image processing system may adaptively blend J_z values at the edges of objects and other features to preserve high-frequency details in low-contrast regions of the received image.

[0027] Particular implementations of the subject matter described in this disclosure can be implemented to realize one or more of the following potential advantages. By processing image data in a perceptually uniform color space (such as $J_za_zb_z$), aspects of the present disclosure may substantially reduce the latency and computational load of CVM operations (such as tone mapping and inverse tone mapping) without loss of accuracy. For example, unlike the YUV color space, the $J_za_zb_z$ color space is a perceptually uniform color space. As such, tone mapping and inverse tone mapping operations can be performed using two-dimensional (2D) lookup tables (LUTs) in the $J_za_zb_z$ color space (compared to 3D LUTs which are generally used for tone mapping and inverse tone mapping operations in the YUV color space). Additionally, aspects of the present disclosure support high data precision for video processing and provide a wide range of programming options and hardware flexibility. Thus, the CVM techniques of the present implementations may be suitable for limited-area, low-latency applications (such as set-top boxes, digital televisions, streaming devices, and other video applications) or devices with limited memory or processing resources (such as low-power edge devices).

[0028] FIG. **1** shows a block diagram of an example image capture and display system **100**, according to some implementations. The system **100** includes an image capture device **110** (also referred to as an "image source"), an image processor **120**, and a display device **130** (also referred to as an "image target"). The image capture device **110** captures a pattern of light **101** (also referred to as "scene light") and converts the captured light to a digital image. For example, the image capture device **110** may be a camera. The display device **130** displays the digital image by reproducing the pattern of light, as display light **104**, on a corresponding display surface. Example suitable display devices include televisions, computer monitors, laptops, tablets, and smartphones, among other examples.

[0029] The image capture device **110** includes a sensor **112**, an opto-electrical transfer function (OETF) **114**, a color-space converter (CSC) **116**, and an encoder **118**. The sensor **112** converts the scene light **101** to an electrical signal (E_C). In some implementations, the sensor **112** may include an array of optical sensing elements (such as charge-coupled device (CCD) cells or complementary metal-oxide-semiconductor (CMOS) cells), each configured to sample a respective pixel of the scene light **101**. The OETF **114** transforms the electrical signal E_C to coded image data (RGBc) having red (R), green (G), and blue (B) color channels associated with an RGB color space. More specifically, the OETF **114** converts RGB information from an analog domain to a digital domain. For example, the OETF **114** may convert the analog electrical signals E_C to digital R, G, and B values representing the primary color components associated with the sensor **112**.

[0030] The CSC **116** changes the color space associated with the coded image data RGB_C. In some aspects, the CSC **116** may convert the coded image data RGB_C from the RGB color space to another color space that may be easier for the encoder **118** to compress or otherwise encode for transmission to the display device **130** (such as a YUV color space). In some implementations, the CSC **116** may convert the coded image data RGBc to image data (YUV_C) having luma (Y) and chrominance (UV) channels associated with a YUV color space. The encoder **118** encodes the converted image data YUV_C, as image capture data **102**, for transmission to the image processor **120** or the display device **130**. For example, the encoder **118** may apply data compression or signal modulation to the converted image data YUV_C based, at least in part, on various communication standards or protocols supported by the communication medium (not shown for simplicity) or the display device **130**.

[0031] The image processor **120** processes the image capture data **102** to produce display data **103** that can be used to more accurately or realistically reproduce the original scene light **101** on the display device **130** (given the differences in dynamic range or color gamut supported by the image capture device **110** and the display device **130**). For example, display devices that are capable of displaying only standard dynamic range (SDR) content may be unable to reproduce the full range of color, brightness, or contrast of images captured in a high dynamic range (HDR) format. On the other hand, images captured in an SDR format may not utilize the full range of color, brightness, or contrast supported by display devices that are capable of displaying HDR content. Accordingly, the image processor **120** may bridge the image capture capabilities of the image capture device **110** and the image display capabilities of the display device **130**. In some aspects, the image processor **120** may be incorporated in the image capture device **110**. In some other aspects, the image processor **120** may be incorporated in the image display device **130**.

[0032] The display device **130** includes a decoder **132**, a CSC **134**, an electro-optical transfer function (EOTF) **136**, and a display **138**. The decoder **132** receives the display data **103** from the image processor **120** and decodes the received data to recover display data (YUV_D) having Y, U, and V channels associated with a YUV color space. In some implementations, the decoder **132** may reverse the encoding performed by the encoder **118** of the image capture device **110**. The CSC **134** changes the color space associated with the recovered image data YUV_D. In some aspects, the CSC **134** may convert the recovered image data YUV_D from the YUV color space to another color space that is used by the display **138** for rendering and displaying images (such as an

RGB color space). In some implementations, the CSC **134** may convert the image data YUV_D to image data (RGBD) having R, G, and B color channels associated with an RGB color space.

[0033] The EOTF **136** transforms the converted image data RGBD to an electrical signal (E_D) that can be used to illuminate the pixels of the display **138**. More specifically, the EOTF **136** converts RGB information from a digital domain to an analog domain. For example, the EOTF **136** may convert the digital image data RGB_D to analog brightness values (or "nits") associated with the display **138**. The display **138** converts the electrical signal E_D to the display light **104**. For example, the display **138** may include an array of pixel elements each configured to display a respective pixel of the corresponding image (such as using cathode ray tube (CRT), liquid crystal display (LCD), organic light emitting diode (OLED), or other display technologies). More specifically, the color and brightness of light output by each pixel element may be defined or otherwise indicated by the characteristics of the electrical signal E_D.

[0034] The OETF **114** of the image capture device **110** performs a nonlinear transformation on the electrical signal E_C. More specifically, the OETF **114** transfers the electrical signal E_C from a linear domain to a nonlinear domain. As a result, the image capture data **102** received by the image processor **120** is nonlinear. Aspects of the present disclosure recognize that many image processing operations are more complex to perform on nonlinear image data than on linear image data. Thus, in some aspects, the image processor **120** may include an inverse opto-electrical transfer function (IOETF) **122**, a color volume mapping (CVM) component **123**, and an inverse electro-optical transfer function (IEOTF) **124**. The IOETF **122** transfers the image capture data **102** back to the linear domain for processing as display data **103**. Thus, the IOETF **122** may be the inverse of the OETF **114**. The IEOTF **124** transfers the display data **103** back to the nonlinear domain for display by the display device **130**. Thus, the IEOTF **124** may be the inverse of the EOTF **136**.

[0035] The CVM component **123** is configured to map the linear image capture data **102** to the linear display data **103**. In some implementations, the CVM component **123** may reduce the color, brightness, or contrast of an HDR image for display on an SDR display device (also referred to as "tone mapping"). In some other implementations, the CVM component **123** may increase the color, brightness, or contrast of an SDR image for display on an HDR display device (also referred to as "inverse tone mapping"). Still further, in some implementations, the CVM component **123** may adjust the color, brightness, or contrast of an HDR image data for display on an HDR display device (such as to compensate for differences in dynamic range or color gamut supported by the image source and the image target).

[0036] As described above, the image capture data **102** is encoded based on the converted image data YUV_C having Y, U, and V color channels. As such, the image capture data **102** is also associated with the YUV color space. However, the YUV color space is not a perceptually uniform color space. As such, the brightness, saturation and hue planes are not orthogonal to each other. In other words, changing the luminance range will result in varied amounts of changes in saturation for different hue colors. Similarly, changing the saturation range will result in varied amounts of changes in luminance level for different colors. Thus, performing tone mapping or inverse tone mapping in the YUV color space is more prone to artifacts and may impose a significant penalty on latency, memory, and processing resources, which may not be suitable for many image processing applications (such as for processing video or for implementation in battery-powered devices or other edge devices with limited resources).

[0037] Aspects of the present disclosure recognize that image processing overhead can be significantly reduced, without loss of accuracy, by performing tone mapping and inverse tone mapping operations in a perceptually uniform color space (UCS) such as, for example, the $J_za_zb_z$ color space which is defined by lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) color components. In some aspects, the image processor **120** may convert the image capture data **102** to the $J_za_zb_z$ color space for image processing. More specifically, the image processor **120** may convert the Y, U, and V channels of the image capture data **102** to J_z, a_z, and b_z channels associated with the $J_za_zb_z$ color space. The CVM component **123** may further map the J_z, a_z, and b_z channels of the image capture data **102** to J_z, a_z, and b_z channels of the display data **103** based on the dynamic range or color gamut supported by each of the image capture device **110** and the display device **130**.

[0038] FIG. **2** shows a block diagram of an example image processing system **200**, according to some implementations. The image processing system **200** is configured to convert image data (YUV_{in}) captured by a source device (such as an image capture device) to display data (YUV_{out}) for display by a target device (such as a display device). In some implementations, the image processing system **200** may be one example of the CVM component **123** of FIG. **1**. With reference for example to FIG. **1**, the image data YUV_{in} may be one example of the image capture data **102** and the display data YUV_{out} may be one example of the display data **103**.

[0039] The image processing system **200** includes a color-space converter (CSC) **202**, a full-range expander **204**, an IOETF **206**, an RGB to long, medium, short (LMS) CSC **208**, a perceptual quantizer (PQ) IEOTF **210**, an LMS to $J_za_zb_z$ CSC **212**, a source-to-target (S-T) color volume mapper (CVM) **214**, a $J_za_zb_z$ to LMS CSC **216**, a PQ EOTF **218**, an LMS to RGB CSC **220**, an IEOTF **222**, and a CSC **224**. The CSC **202** converts the received image data YUV_{in} to image data (RGB_{in}) having R, G, and B color channels associated with an RGB color space. In some implementations, the CSC **202** may convert the received image data YUV_{in} from a YUV color space to the RGB color space. In some other implementations, the image processing system **200** may directly receive the image data RGB_{in} in the RGB color space. In such implementations, the CSC **202** may be bypassed or omitted from the image processing system **200**.

[0040] The full-range expander **204** expands the maximum range of the converted image data RGB_{in} to produce expanded image data (RGB_{exp}). For example, the range of digital YUV values may be limited between an artificial minimum ("min") and an artificial maximum ("max") in order to reserve some codes for timing reference purposes. Thus, if the received image data YUV_{in} has been limited (such as between **256** and **3760**, in the 12-bit range), then a full-range expansion may cause the expanded image data RGB_{exp} to fall within a predetermined maximum range (such as between 0 and 4095) associated with the RGB color space. When the received image data YUV_{in} is converted to the RGB color space, the range of values associated with the converted image data RGB_{in} may remain the same. Thus, each of the R, G, and B components may be expanded using only a limited set of parameters.

[0041] The IOETF **206** transforms the expanded image data RGB_{exp} into linearly-interpolated image data (RGB_{lin}^{i}). In some implementations, the IOETF **206** may be the inverse of an OETF implemented by the source device. With reference for example to FIG. **1**, the IOETF **206** may be one example of the IOETF **122** of the image processor **120**. Thus, the IOETF **206** may be the inverse of the OETF **114** of the image capture device **110**. To achieve a high precision IOETF curve while reducing the memory requirements for lookup table (LUT) storage, the IOETF **206** may use a **128** segmented piecewise linear interpolation technique to convert 16-bit RGB components to 32-bit RGB components in the linear domain.

[0042] The RGB to LMS CSC **208** converts the linear image data RGB_{lin}^{i} to image data (LMS_{lin}^{i}) having long (L), medium (M), and short(S) channels associated with an LMS color space. The L, M, and S channels represent the responses of the three types of cones in the human eye. Thus, the converted image data LMS_{lin}^{i} also may be referred to herein as "perceptual image data." In some implementations, the RGB to LMS CSC **208** may convert the linear image data RGB_{lin}^{i} to the perceptual image data LMS_{lin}^{i} through intermediate conversion to a tristimulus (XYZ) space defined by the Commission Internationale de l'Éclairage (CIE):

$$\begin{bmatrix} X'_{D65} \\ Y'_{D65} \end{bmatrix} = \begin{bmatrix} bX_{D65} \\ gY_{D65} \end{bmatrix} - \begin{bmatrix} (b-1)Z_{D65} \\ (g-1)X_{D65} \end{bmatrix}$$

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.41478972 & 0.579999 & 0.0146480 \\ -0.2015100 & 1.120649 & 0.0531008 \\ -0.0166008 & 0.264800 & 0.6684799 \end{bmatrix} \begin{bmatrix} X'_{D65} \\ Y'_{D65} \\ Z_{D65} \end{bmatrix}$$

where X_{D65}, Y_{D65}, and Z_{D65} belong to the CIE XYZ tristimulus space with CIE standard illuminant D65 as white point, b=1.15, and g=0.66. Aspects of the present disclosure recognize that any RGB color space can be transformed to the CIE XYZ tristimulus space. Thus, the transformation matrix that is used to transform the image data from the RGB color space to the XYZ color space may depend on the RGB color space implemented by the image processing system **200**.

[0043] The PQ IEOTF **210** transforms the perceptual image data LMS_{lin}^{i} from the linear domain to the PQ domain. The PQ IEOTF **210** is a nonlinear transfer function adopted by Society of Motion Picture and Television Engineers (SMPTE) and International Telecommunication Union (ITU) standards for HDR display. For example, the PQ domain supports luminance levels in the range of 0.0001 to 10000 nits. Thus, the PQ IEOTF **210** may transform the L, M, and S channels of the perceptual image data LMS_{lin}^{i} into L', M', and S' channels of PQ image data (LMS_{PQ}^{i}):

$$\{L', M', S'\} = \left(\frac{c_1 + c_2\left(\frac{\{L,M,S\}}{10000}\right)^n}{1 + c_3\left(\frac{\{L,M,S\}}{10000}\right)^n} \right)^p$$

where $c_1=3424/2^{12}$, $c_2=2413/2^7$, $c_3=2392/2^7$, $n=2610/2^{14}$, and $p=1.7\times2523/2^5$.

[0044] The LMS to $J_za_zb_z$ CSC **212** converts the PQ image data LMS_{PQ}^{i} to image data ($J_za_zb_z^{\ i}$) having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space. As described with reference to FIG. **1**, the $J_za_zb_z$ color space is a perceptually uniform. Thus, the converted image data $J_za_zb_z^{\ i}$ also may be referred to herein as "perceptually uniform image data." In some implementations, the LMS to $J_za_zb_z$ CSC **212** may convert the PQ image data LMS_{PQ}^{i} to the perceptually uniform image data $J_za_zb_z^{\ i}$ according to Equations 1 and 2, below:

$$\begin{bmatrix} I_z \\ a_z \\ b_z \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 & 0 \\ 3.524000 & -4.066708 & 0.542708 \\ 0.199076 & 1.096799 & 1.295875 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} \quad (1)$$

$$J_z = \frac{(1+d)I_z}{1+dI_z} - d_0 \quad (2)$$

where d=–0.56 and $d_0=1.6295499532821566\times10^{-11}$.

[0045] The S-T CVM **214** is configured to map the perceptually uniform image data $J_za_zb_z^{\ i}$ to perceptually uniform display data ($J_za_zb_z^{\ d}$) that is better suited for presentation on the target device. More specifically, the S-T CVM **214** may map the range of J_z, a_z, and b_z values supported by the source device to a range of J_z, a_z, and b_z values supported by the target device. In some implementations, the S-T CVM **214** may reduce the dynamic range associated with the perceptually uniform image data $J_za_zb_z^{\ i}$ by mapping the J_z channel of $J_za_zb_z^{\ i}$ to a narrower range of J_z values (also referred to as "tone mapping"). In some other implementations, the S-T CVM **214** may increase the dynamic range associated with the perceptually uniform image data $J_za_zb_z^{\ i}$ by mapping the J_z channel of $J_za_zb_z^{\ i}$ to a wider range of J_z values (also referred to as "inverse tone mapping").

[0046] In some implementations, the S-T CVM **214** may reduce the color gamut associated with the perceptually uniform image data $J_za_zb_z^{\ i}$ by mapping the a_z and b_z channels of $J_za_zb_z^{\ i}$ to a narrower range of a_z and b_z values (also referred to as "saturation mapping"). In some implementations, the S-T CVM **214** may increase the color gamut associated with the perceptually uniform image data $J_za_zb_z^{\ i}$ by mapping the a_z and b_z channels of $J_za_zb_z^{\ i}$ to a wider range of a_z and b_z values (also referred to as "inverse saturation mapping"). Because the J_z channel is orthogonal to the a_z and b_z channels, the S-T CVM **214** can adjust the tone (or J_z channel) of the perceptually uniform image data $J_za_zb_z^{\ i}$ without affecting the saturation of the image. The S-T CVM **214** can also adjust the saturation (or a_z and b_z channels) of the perceptually unform image data $J_za_zb_z^{\ i}$ without affecting the image tone.

[0047] The $J_za_zb_z$ to LMS CSC **216** converts the perceptually uniform display data $J_za_zb_z^{\ d}$ to perceptual display data (LMSPod) having L', M', and S' channels associated with the LMS color space. More specifically, the $J_za_zb_z$ to LMS CSC **216** may reverse the color-space conversion performed by the LMS to $J_za_zb_z$ CSC **212**. In some implementations, the $J_za_zb_z$ to LMS CSC **216** may convert the perceptually uniform display data $J_za_zb_z^{\ d}$ to the perceptual display data LMS_{PQ}^{d} according to equations 3 and 4, below:

$$I_z = \frac{J_z + d_0}{1 + d - d(J_z + d_0)} \tag{3}$$

$$\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 & 0 \\ 3.524000 & -4.0.66708 & 0.542708 \\ 0.199076 & 1.096799 & -1.295875 \end{bmatrix}^{-1} \begin{bmatrix} I_z \\ a_z \\ b_z \end{bmatrix} \tag{4}$$

where d=–0.56 and d_0=1.6295499532821566–10^{-11}.

[0048] The PQ EOTF **218** transforms the perceptual display data LMS_{PQ}^{d} from the PQ domain back to the linear domain. More specifically, the PQ EOTF **218** may be the inverse of the PQ IEOTF **210**. Thus, the PQ EOTF **218** may transform the L', M', and S' channels of the perceptual display data LMS_{PQ}^{d} into L, M, and S channels of linear display data (LMS_{lin}^{d}):

$$\{L, M, S\} = 10000 * \left(\frac{c_1 - (\{L', M', S'\})^{\frac{1}{p}}}{c_3(\{L', M', S'\})^{\frac{1}{p}} - c_2} \right)^{\frac{1}{n}}$$

where $c_1=3424/2^{12}$, $c_2=2413/2^7$, $c_3=2392/2^7$, $n=2610/2^{14}$, and $p=1.7\times2523/2^5$.

[0049] The LMS to RGB CSC **220** converts the linear display data LMS_{lin}^{d} to display data (RGB_{lin}^{d}) having R, G, and B channels associated with the RGB color space. More specifically, the LMS to RGB CSC **220** may reverse the color-space conversion performed by the RGB to LMS CSC **208**. In some implementations, the LMS to RGB CSC **220** may convert the linear display data LMS_{lin}^{d} to the display data RGB_{lin}^{d}through intermediate conversion to the CIE XYZ tristimulus space:

$$\begin{bmatrix} X'_{D65} \\ Y'_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 0.41478972 & 0.579999 & 0.0146480 \\ -0.2015100 & 1.120649 & 0.0531008 \\ -0.0166008 & 0.264800 & 0.6684799 \end{bmatrix}^{-1} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

$$X_{D65} = \frac{X'_{D65} + (b-1)Z_{D65}}{b}$$

$$Y_{D65} = \frac{Y'_{D65} + (g-1)X_{D65}}{g}$$

where b=1.15 and g=0.66. Aspects of the present disclosure recognize that the CIE XYZ tristimulus space can be transformed to any RGB color space. Thus, the transformation matrix that is used to transform the display data from the XYZ color space to the RGB color space may depend on the RGB color space implemented by the image processing system **200**.

[0050] The IEOTF **222** transforms the converted display data RGB_{lin}^{d}into nonlinear display data (RGB_{out}). In some implementations, the IEOTF **222** may be the inverse of an EOTF implemented by the target device. With reference for example to FIG. **1**, the IEOTF **222** may be one example of the IEOTF **124** of the image processor **120**. Thus, the IEOTF **222** may be the inverse of the EOTF **136** of the image capture device **130**. To achieve a high precision IEOTF curve while reducing the memory requirements for LUT storage, the IEOTF **222** may use a **128** segmented piecewise linear interpolation technique to convert 32-bit RGB components to 16-bit RGB components in the nonlinear domain.

[0051] The CSC **224** converts the nonlinear display data $RGB_{out}$to the display data (YUV_{out}) for output to the target device. More specifically, the CSC **224** may reverse the color-space conversion performed by the CSC **202**. In some implementations, the CSC **224** may convert the display data RGB^{out} from the RGB color space to the YUV color space. In some other implementations, the image processing system **200** may directly output the nonlinear display data RGB_{out} in the RGB color space. In such implementations, the CSC **224** may be bypassed or omitted from the image processing system **200**.

[0052] FIG. **3** shows a block diagram of an example CVM system **300**, according to some implementations. The CVM system **300** is configured to transform image data **302** representing an image captured by a source device into display data **308** that can be used to reproduce the image at a display device. In some implementations, the CVM system **300** may be one example of the CVM component **123** of FIG. **1** or the S-T CVM **214** of FIG. **2**. With reference for example to FIG. **2**, the image data **302** may be one example of the perceptually uniform image data $J_za_zb_z{}^{i}$ and the display data **308** may be one example of the perceptually uniform display data $J_za_zb_z{}^{d}$. Thus, each of the image data **302** and the display data **308** includes J_z, a_z, and b_z channels associated with the $_za_zb_z$ color space.

[0053] The CVM system **300** includes a global color volume mapper **310**, a local color volume mapper **320**, and an adaptive detail processor **330**. The global color volume mapper **310** is configured to map the received image data **302** to a set of global color values **304** associated with the $J_za_zb_z$ color space based on the dynamic range and color gamut supported by each of the source device and the target device. For example, the range of J_z values that can be included in the image data **302** is bounded or limited by the dynamic range of the source device and the range of a_z and b_z values that can be included in the image data **302** is bounded or limited by the color gamut of the source device. By contrast, the range of J_z values that can be included among the global color values **304** is bounded or limited by the dynamic range of the target device and the range of a_z and b_z values that can be included among the global color values **304** is bounded or limited by the color gamut supported of target device.

[0054] In some aspects, the global color volume mapper **310** may map the range of J_z, a_z, and b_z values supported by the source device to the range of J_z, a_z, and b_z values supported by the target device (such as through expansion or compaction of each range of values) and may determine the set of global color values **304** based on the "global" mapping between the source device and the target device. In some implementations, the global color volume mapper **310** may map the J_z channels of the image data **302** to the J_z channels of the global color values **304** based on a tone mapping operation or an inverse tone mapping operation. In some other implementations, the global color volume mapper **310** may map the a_z and b_z channels of the image data **302** to the a_z and b_z channels of the global color values **304** based on a saturation mapping operation or an inverse saturation mapping operation.

[0055] The local color volume mapper **320** is configured to remap the set of global color values **304** to a set of local color values **306** based on various properties of the corresponding image. Aspects of the present disclosure recognize that the human visual system can perceive more details in darker and brighter regions of an image compared to the mid-tones. However, some image details may fade in the darker or brighter regions of the image as a result of mapping the J_z channel of the image data **302** to the J_z channel of the global color values **304** through global expansion (or compaction) of the dynamic range. In some aspects, the local color volume mapper **320** may dynamically tune the global color values **304** so that details are preserved in the darker and brighter regions of the image. For example, the J_z channel of the local color values **306** may span a wider range of dark tones than mid-tones and may span the widest range of bright (or "highlight") tones.

[0056] Aspects of the present disclosure also recognize that a global expansion of saturation values may not produce optimized colors for various objects in any given scene. More specifically, different levels of saturation may be more aesthetically pleasing to the human eye for different types of content. For example, bluer skies and greener grass may be visually appealing in the context of an outdoor sports scene but may be distracting in the context of a movie scene (for at least some genres of film). In some aspects, the local color volume mapper **320** may dynamically tune the global color values **304** based on contextual information about the image. For example, the local color volume mapper **320** may determine a classification associated with various objects or features in the image and may remap the a_z and b_z channels of the global color values **304** to a_z and b_z channels of the local color values based on the determined classifications.

[0057] The adaptive detail processor **330** may further remap the local color values **306** to the display data **308** based on details detected in the corresponding image. Aspects of the present disclosure recognize that, as a result of expanding the dark and highlight tones, high-frequency details may become lost in low-contrast regions of the image depicted by the local color values **306**. For example, individual blades of grass on a football field may be difficult to discern due to the stretching of tones at the edges of the grass. In some aspects, the adaptive detail processor **330** may adaptively tune the local color values **306** so that high-frequency details are preserved in low-contrast regions of the image depicted by the display data **308**. More specifically, the adaptive detail processor **330** may detect the edges of objects or features in the image and adaptively blend the J_z channel of the local color values **306** at the detected edges based on the contrast of the surrounding region.

[0058] FIG. **4** shows a block diagram of an example system **400** for global CVM, according to some implementations. The system **400** is configured to map J_z, a_z, and b_z channels of image data ($\{J_z[x,y]_{in}, a_z[x,y]_{in}, b_z[x,y]_{in}\}$, where x and y denote horizontal and vertical pixel coordinates) to J_z, a_z, and $b_z$channels of global display data ($\{J_z[x,y]_{GM}, a_z[x,y]_{GM}, b_z[x,y]_{GM}\}$). In some implementations, the system **400** may be one example of the global color volume mapper **310** of FIG. **3**. With reference for example to FIG. **3**, the image data $\{J_z[x,y]_{in}, a_z[x,y]_{in}, b_z[x,y]_{in}\}$ may be one example of the image data **302** and the display data $\{J_z[x,y]_{GM}, a_z[x,y]_{GM}, b_z[x,y]_{GM}\}$ may be one example of the global color values **304**.

[0059] The system **400** includes a global tone mapping component **410** and a global saturation mapping component **420**. In some aspects, the system **400** may convert the image data $\{J_z[x,y]_{in}, a_z[x,y]_{in}, b_z[x,y]_{in}\}$ to intensity (i_{in}) and saturation (s_{in}) values, where $i_{in}=J_z[x,y]_{in}$ and $s_{in}=a_z[xy]_{in}*b_z[x,y]_{in}$. The global tone mapping component **410** is configured to map the i_{in} and s_{in} values to a global intensity value (i_{GM}) based on source image metadata **402** associated with the received image data and target capabilities **404** associated with the target device. The global saturation mapping component **420** is configured to map the i_{in} and s_{in} values to a global saturation value (s_{GM}) based on the image metadata **402** and the target capabilities **404**.

[0060] The target capabilities **404** may include any known capabilities of the target device such as, for example, a dynamic range or color gamut supported by the target device. By contrast, the source image metadata **402** may be received with the image data and may indicate a dynamic range or color gamut of a mastering display (used to author or "master" the image data). Example suitable metadata may include color calibration data associated with the mastering display, a maximum frame average light level (MaxFALL), a maximum content light level (MaxCLL), RGB primaries, white point, or display maximum and minimum light levels, among other examples. In some implementations, the source image metadata **402** may include static metadata that is broadly applicable to a series of images (or multiple frames of video). In some other implementations, the source image metadata **402** may include dynamic metadata that is specific to the received image data.

[0061] In some implementations, the global tone mapping component **410** may map the i_{in} and s_{in} values to an i_{GM} value based on a source to target tone mapping operator in intensity axis (TI) lookup table (LUT) and a source to target tone mapping operator in saturation axis (TS) LUT. Because the $J_za_zb_z$ color space is a perceptually uniform color space and the J_z channel is perfectly orthogonal to the a_z and b_z channels, the color volume mapping operation is isotropic and can be implemented by one-dimensional (1D) LUTs associated with each tone and saturation axis. For example, the global tone mapping component **410** may look up the tone map for the intensity value i_{in} in the TI LUT and may look up the tone map for the saturation value s_{in} in the TS LUT, where the TI and TS LUTs are 1D LUTs and where $i_{GM}=TI[i_{in}]*TS[s_{in}]$. In some implementations, the global tone mapping component **410** may determine or generate the TI LUT and the TS LUT based on the source image metadata **402**, the target capabilities **404**, or any combination thereof. In some aspects, the system **400** may further convert the global intensity value i_{GM} to the J_z channel of the global display data, where $J_z[x,y]_{GM}=i_{GM}$.

[0062] In some implementations, the global saturation mapping component **420** may map the i_{in} and s_{in} values to an SGM value based on a source to target color saturation mapping operator in intensity axis (SI) LUT and a source to target color saturation mapping operator in saturation axis (SS) LUT. Because the $J_za_zb_z$ color space is a perceptually uniform color space, the global saturation mapping operation is isotropic in nature, and requires only 1D operators associated with each intensity and saturation axis. For example, the global saturation mapping component **420** may look up the saturation mapping for the intensity value i_{in} in the SI LUT and may look up the saturation mapping for the saturation value sin in the SS LUT, where the SI and SS LUTs are 2D LUTs and where $s_{GM}=SI[i_{in}]*SS[s_{in}]$. In some implementations, the global saturation mapping component **420** may determine or generate the SI LUT and the SS LUT based on the source image metadata **402**, the target capabilities **404**, or any combination thereof. In some aspects, the system **400** may further convert the global saturation value s_{GM} to the a_z and b_z channels of the global display data, where $a_z[xy]_{GM}=a_z[xy]_{in}*s_{GM}$ and $b_z[x,y]_{GM}=b_z[x,y]_{in}*s_{GM}$.

[0063] FIG. **5** shows a block diagram of an example system **500** for local CVM, according to some implementations. The system **500** is configured to map J_z, a_z, and b_z channels of global display data ($\{J_z[x,y]_{GM}, a_z[x,y]_{GM}, b_z[x,y]_{GM}\}$) to J_z, a_z, and b_z channels of local display data ($\{J_z[x,y]_{LM}, a_z[x,y]_{LM}, b_z[x,y]_{LM}\}$). In some implementations, the system **500** may be one example of the local color volume mapper **320** of FIG. **3**. With reference for example to FIG. **3**, the global display data $\{J_z[x,y]_{GM}, a_z[x,y]_{GM}, b_z[x,y]_{GM}\}$ may be one example of the global color values **304** and the local display data $\{J_z[x,y]_{LM}, a_z[x, y]_{LM}, b_z[x,y]_{LM}\}$ may be one example of the local color values **306**.

[0064] The system **500** includes a local tone mapping component **510** and a local saturation mapping component **520**. The local tone mapping component **510** is configured to map the J_z channel of the global display data $J_z[x, y]_{GM}$ to the J_z channel of the local display data $J_z[x,y]_{LM}$. In some aspects, the local tone mapping component **510** may perform the mapping based, at least in part, on a distribution of the values of $J_z[x,y]_{GM}$. More specifically, the mapping may improve the contrast of the image while preserving details in the darker and brighter regions of the image. In some implementations, the local tone mapping component **510** may perform histogram equalization on the J_z channel of the global display data $J_z[x,y]_{GM}$. Histogram equalization is a technique for increasing the contrast of an image by spreading out or redistributing a relatively narrow range of tone values over a wider range.

[0065] Aspects of the present disclosure recognize that the human visual system can perceive more details in darker and brighter regions of an image compared to the mid-tones. Thus, in some implementations, the local tone mapping component **510** may perform histogram equalization on independent bands of tones. As used herein, a "band" refers to a range of tones that does not overlap with any other band. For example, each tone value associated with the J_z channel of the global display data $J_z[x,y]_{GM}$ may fall within a spectrum that is partitioned or subdivided into "dark," "mid," and "highlight" bands. The local tone mapping component **510** may perform a separate histogram equalization operation on the tone values within each of the dark, mid, and highlight bands so that the tone values in a given band do not cross over to another band as a result of the histogram equalization.

[0066] The local saturation mapping component **520** is configured to map the a_z and b_z channels of the global display data $a_z[x,y]_{GM}$ and $b_z[x,y]_{GM}$ to the a_z and b_z channels of the local display data $a_z[x,y]_{LM}$ and $b_z[x,y]_{LM}$. Aspects of the present disclosure recognize that the brightness of an image may affect the perception of colors in the image. Thus, in some implementations, the local saturation mapping component **520** may perform the mapping based, at least in part, on the J_z channel of the local display data $J_z[x,y]_{LM}$. For example, the local saturation mapping component **520** may adjust the hue (h_z) or chroma (C_z) of a given pixel based on the value of $J_z[x,y]_{LM}$, where:

$$h_z = \arctan\left(\frac{b_z}{a_z}\right) \tag{5}$$

$$C_z = \sqrt{a_z^2 + b_z^2} \tag{6}$$

[0067] In some implementations, the local saturation mapping component **520** may further map the a_z and b_z channels of the global display data $a_z[x,y]_{GM}$ and $b_z[x,y]_{GM}$ to the a_z and b_z channels of the local display data $a_z[x,y]_{LM}$ and $b_z[x,y]_{LM}$ based, at least in part, on classifications **502** of one or more objects or features in the image. The classifications **502** provide contextual information about the objects or features that can be used to determine optimal colors for displaying such objects or features on the target device. For example, if the classification **502** associated with a particular object indicates that the object is a human face, the local saturation mapping component **520** may tune the hue h_z and chroma C_z of the object (using Equations 5 and 6) to match a skin tone that is known to appear more natural on the target device.

[0068] In some aspects, the classifications **502** may be inferred by a neural network **530**. Example suitable neural networks may include various types of deep neural networks (DNNs), such as convolutional neural networks (CNNs) or recurrent neural networks (RNNs), among other examples. In some implementations, the neural network **530** may infer the classifications **502** based on one or more channels of the global display data $\{J_z[x,y]_{GM}, a_z[x,y]_{GM}, b_z[x,y]_{GM}\}$ (such as shown in FIG. **5**). In some other implementations, the neural network **530** may infer the classifications **502** based on other data associated with the image (not shown for simplicity). Example suitable data may include metadata (such as the image metadata **402** of FIG. **4**) or image data from which the global display data is derived (such as the image data **302** of FIG. **3**).

[0069] FIG. **6** shows an example mapping **600** of global pixel tone (or intensity) values to local pixel tone (or intensity) values with adaptive histogram equalization. In some implementations, the mapping **600** may be performed by the local tone mapping component **510** of FIG. **5**. With reference for example to FIG. **5**, the global pixel tone values may be one example of the J_z channel of the global display data $J_z[x,y]_{GM}$ and the local pixel tone values may be one example of the J_z channel of the local display data $J_z[x,y]_{LM}$.

[0070] In the example of FIG. **6**, global pixel tone values (such as the values of $J_z[x,y]_{GM}$) are depicted along a vertical axis and local pixel tone values (such as the values of $J_z[x,y]_{LM}$) are depicted along on a horizontal axis. The mapping **600** is represented by a curve that extends, along the horizontal axis, between a minimum intensity threshold (TH0) and a maximum intensity threshold (TH**3**). As shown in FIG. **6**, the range of intensity values between TH0 and TH3 represents a spectrum that is subdivided into "dark," "mid," and "highlight" bands. More specifically, the dark band is bounded by the minimum intensity threshold THO and a first intensity threshold (TH1), the mid band is bounded by the first intensity threshold TH1 and a second intensity threshold (TH2), and the highlight band is bounded by the second intensity threshold TH2and the maximum intensity threshold TH3.

[0071] As described with reference to FIG. **5**, the local tone mapping component **510** may perform histogram equalization on the global pixel tone values within each of the dark, mid, and highlight bands. In other words, the mapping **600** may redistribute or "stretch" the pixel tone values within each band. For example, within the dark band, the local tone mapping component **510** may remap the values of $J_z[x,y]_{GM}$ so that the resulting values of $J_z[x,y]_{LM}$ are more evenly distributed but remain bounded by the thresholds TH0 and TH1. Similarly, within the mid band, the local tone mapping component **510** may remap the values of $J_z[x,y]_{GM}$ so that the resulting values of $J_z[x,y]_{LM}$ are more evenly distributed but remain bounded by the thresholds TH1 and TH2. Also, within the highlight band, the local tone mapping component **510** may remap the values of $J_z[x,y]_{GM}$ so that the resulting values of $J_z[x,y]_{LM}$ are more evenly distributed but remain bounded by the thresholds TH2 and TH3.

[0072] In some implementations, guard bands may be used to maintain a sufficient amount of separation between the local pixel tone values in each of the dark, mid, and highlight bands (such as to avoid crushing pixel intensities as a result of histogram stretching). For example, a first guard band (GB0) provides a buffer between black pixel values and the next-darkest local pixel tone values; a second guard band (GB1) provides a buffer between the local pixel tone values in the dark band and the local pixel tone values in the mid band; a third guard band (GB2) provides a buffer between the local pixel tone values in the mid band and the local pixel tone values in the highlight band; and a fourth guard band (GB3) provides a buffer between white pixel values and the next-highest local pixel tone values.

[0073] Aspects of the present disclosure recognize that the human visual system can perceive more details in dark regions of an image compared to the mid-tones. Thus, in some implementations, the dark band may span a wider range of pixel intensities than the mid band (such that TH0−TH1>TH1−TH2). As such, the dark band may support greater amounts of histogram stretching than in the mid band. Aspects of the present disclosure further recognize that the human visual system can perceive even more details in bright regions of an image compared to the dark regions. Thus, in some implementations, the highlight band may span a wider range of pixel intensities than the dark band (such that TH2−TH3>TH0−TH1). As such, the highlight band may support greater amounts of histogram stretching than the dark band and the mid band.

[0074] FIG. **7** shows a block diagram of an example system **700** for adaptive detail processing, according to some implementations. The system **700** is configured to map J_z, a_z, and b_z channels of local display data $(\{J_z[x,y]_{LM}, a_z[x,y]_{LM}, b_z[x,y]_{LM}\})$ to J_z, a_z, and b_z channels of output display data $(\{J_z[x,y]_{out}, a_z[x, y]_{out}, b_z[x,y]_{out}\})$. In some implementations, the system **700** may be one example of the adaptive detail processor **330** of FIG. **3**. With reference for example to FIG. **3**, the local display data $\{J_z[x,y]_{LM}, a_z[x, y]_{LM}, b_z[x,y]_{LM}\}$ may beone example of the local color values **306** and the output display data $\{J_z[x, y]_{out}, a_z[x,y]_{out}, b_z[x,y]_{out}\}$ may be one example of the display data **308**.

[0075] The system **700** includes a tone variance estimation component **710**, a detail extraction component **720**, a tone blending component **730**, and a saturation correction component **740**. The tone variance estimation component **710** is configured to determine a difference $(\Delta J_z[x,y])$ between the J_z channel of the local display data $J_z[x,y]_{LM}$ and the J_z channel of the original image data $(J_z[x,y]_{in})$ from which the local display data is derived (where $\Delta J_z[x,y]=|J_z[x,y]_{LM}-J_z[x,y]_{in}|$). For example, the original image data may be one example of the image data $\{J_z[x,y]_{in}, a_z[x,y]_{in}, b_z[x,y]_{in}\}$ of FIG. **4** or the image data **302** of FIG. **3**.

[0076] The detail extraction component **720** is configured to detect edges or textures in the image based on the values of $\Delta J_z[x,y]$. In some aspects, the detail extraction component **720** may produce a control signal **702** based, at least in part, on the detected edges or textures. More specifically, the control signal **702** may indicate whether each pixel value is associated with a flat region or a textured region of the image. In some implementations, where a pixel value is associated with a textured region of the image, the control signal **702** may further indicate an amount of contrast associated with the textured region.

[0077] The tone blending component **730** is configured to produce the J_z channel of the output display data $J_z[x,y]_{out}$ based on the J_z channel of the image data $J_z[x,y]_{in}$, the J_z channel of the local display data $J_z[x,y]_{LM}$, and the control signal **702**. More specifically, each value of $J_z[x,y]_{out}$ may be a blend of a respective value of $J_z[x,y]_{in}$ and a respective value of $J_z[x,y]_{LM}$. In some implementations, the tone blending component **730** may control or adjust the amount of blending based on the control signal **702** to preserve high-frequency details in low-contrast regions of the image.

[0078] For example, the tone blending component **730** may refrain from blending the value of $J_z[x,y]_{LM}$ with a respective value of $J_z[x,y]_{in}$ if the control signal **702** indicates that the pixel value is associated with a flat region of the image. As a result, the value of $J_z[x,y]_{out}$ may be equal to the value of $J_z[x,y]_{LM}$ for pixel values associated with flat regions of the image $(J_z[x,y]_{out}=J_z [x,y]_{LM})$. By contrast, the tone blending component **730** may blend the value of $J_z[x,y]_{LM}$ with a respective value of $J_z[x,y]_{in}$ if the control signal **702** indicates that the pixel value is associated with a textured region of the image. As a result, the value of $J_z[x,y]_{out}$ may be a combination of the values of $J_z[x,y]_{LM}$ and $J_z[x,y]_{in}$ for pixel values associated with texture regions of the image $(J_z[x,y]_{out}=\alpha J_z[x,y]_{LM}+\beta J_z[x,y]_{in}$, where α and β depend on the amount of contrast in the region).

[0079] The saturation correction component **740** is configured to map the a_z and b_z channels of the local display data $a_z[x,y]_{LM}$ and $b_z[x,y]_{LM}$ to the a_z and b_z channels of the output display data $a_z[x,y]$out and $b_z[x,y]_{out}$ based on the Jchannel of the output display data $J_z[x,y]_{out}$. As described with reference to FIG. **5**, the brightness of an image may affect the perception of colors in the image. Thus, in some implementations, the local saturation mapping component **520** may adjust the hue h_z and chroma C_z of a given pixel (using Equations 5 and 6) to compensate for any changes made to the brightness of the pixel (such as by the tone blending component **730**).

[0080] FIG. **8** shows another block diagram of an example image processing system **800**, according to some implementations. The image processing system **800** is configured to convert image data captured by a source device (such as an image capture device) to display data for display by a target device (such as a display device). In some implementations, the image processing system **800** may be one example of the image processor **120** of FIG. **1** or the image processing system **200** of FIG. **2**.

[0081] The image processing system **800** includes a device interface **810**, a processing system **820**, and a memory **830**. The device interface **810** is configured to communicate with the source device and the target device. In some implementations, the device interface **810** may include an image source interface (I/F) **812** and an image target interface **814**. The image source interface **812** is configured to receive the image data from the source device. In some implementations, the image source interface **812** may receive first image data representing an image produced by an image capture device based on an opto-electric transfer function (OETF). The image target interface **814** is configured to provide the display data to the target device.

[0082] The memory **830** includes an image data buffer **831** configured to store the received image data and any intermediate data resulting from the image processing operation. The memory **830** also includes a non-transitory computer-readable medium (including one or more nonvolatile memory elements, such as EPROM, EEPROM, Flash memory, or a hard drive, among other examples) that may store at least the following software (SW) modules:

- **[0083]** an inverse opto-electric transfer function (IOETF) SW module **832** to transform the first image data into second image data based on an inverse of the OETF associated with the image capture device, where the second image data includes red (R), green (G), and blue (B) channels associated with an RGB color space;
- **[0084]** a uniform color space (UCS) conversion SW module **833** to convert the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space;
- **[0085]** a color volume mapping (CVM) SW module **834** to map the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display device; and
- **[0086]** a target render SW module **835** to process the first display data for display by the display device.

Each software module includes instructions that, when executed by the processing system **820**, causes the image processing system **800** to perform the corresponding functions.

[0087] The processing system **820** may include any suitable one or more processors capable of executing scripts or instructions of one or more software programs stored in the image processing system **800** (such as in the memory **830**). For example, the processing system **820** may execute the IOETF SW module **832** to transform the first image data into second image data based on an inverse of the OETF associated with the image capture device, where the second image data includes R, G, and B channels associated with an RGB color space. The processing system **820** also may execute the UCS conversion SW module **833** to convert the second image data to third image data having J_z, a_z, and b_z channels associated with a $J_za_zb_z$ color space. The processing system **820** may further execute the CVM SW module **834** to map the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display device. Still further, the processing system **820** may execute the target render SW module **835** to process the first display data for display by the display device.

[0088] FIG. **9** shows an illustrative flowchart depicting an example operation **900** for image processing, according to some implementations. In some implementations, the example operation **900** may be performed by an image processing system (such as the image processor **120** of FIG. **1** or any of the image processing systems **200** or **800** of FIGS. **2** and **8**, respectively).

[0089] The image processing system receives first image data representing an image produced by an image capture device based on an OETF (**910**). The image processing system transforms the first image data into second image data based on an inverse of the OETF, where the second image data includes red (R), green (G), and blue (B) channels associated with an RGB color space (**920**). The image processing system further converts the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space (**930**). The image processing system maps the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display device (**940**). The image processing system processes the first display data for display by the display device (**950**).

[0090] In some implementations, the converting of the second image data to the third image data may include converting the second image data to fourth image data having long (L), medium (M), and short(S) channels associated with an LMS color space; transforming the fourth image data into fifth image data based on a perceptual quantizer (PQ) transfer function; and converting the fifth image data to the third image data in a PQ domain associated with the PQ transfer function.

[0091] In some aspects, the image processing system may further receive metadata associated with the first image data, where the metadata indicates a dynamic range or color gamut associated with a mastering display. In some implementations, the metadata may include color calibration data associated with the mastering display, a maximum frame average light level, a maximum content light level, RGB primaries, white point, or display maximum and minimum light levels.

[0092] In some implementations, the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z, a_z, and b_z channels of the first display data may include generating a plurality of lookup tables (LUTs) based at least in part on the received metadata and the dynamic range or color gamut associated with the display device; mapping the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data based at least in part on one or more first LUTs of the plurality of LUTs; and mapping the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data based at least in part on one or more second LUTs of the plurality of LUTs.

[0093] In some implementations, the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data may include mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs; classifying one or more features in the image based on a neural network model; and remapping the global saturation values to the a_z and b_z channels of the first display data based at least in part on the classifications of the one or more features.

[0094] In some implementations, the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data may include mapping the J_z, a_z, and b_z channels of the third image data to global tone values within a spectrum of values based on the one or more first LUTs, where the spectrum is partitioned into a plurality of bands; and remapping the global tone values in each band of the plurality of bands to respective equalized tone values within the band based on histogram equalization of the global tone values.

[0095] In some implementations, the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data may further include extracting details in the image based on differences between the equalized tone values and the J_z channel of the third image data; and adjusting the equalized tone values based on the extracted details.

[0096] In some implementations, the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data may include mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs; and dynamically adjusting the global saturation values based at least in part on the equalized tone values.

[0097] In some implementations, the processing of the first display data may include converting the first display data to second display data having R, G, and B channels associated with the RGB color space; and transforming the second display data into third display data based on an inverse of an EOTF associated with the display device.

[0098] Those of skill in the art will appreciate that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0099] Further, those of skill in the art will appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the aspects disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the disclosure.

[0100] The methods, sequences or algorithms described in connection with the aspects disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor.

[0101] In the foregoing specification, embodiments have been described with reference to specific examples thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader scope of the disclosure as set forth in the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative sense rather than a restrictive sense.

What is claimed is:

1. A method of image processing, comprising:

receiving first image data representing an image produced by an image capture device based on an opto-electrical transfer function (OETF);

transforming the first image data into second image data based on an inverse of the OETF, the second image data having red (R), green (G), and blue (B) channels associated with an RGB color space;

converting the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space;

mapping the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display device; and

processing the first display data for display by the display device.

2. The method of claim **1**, wherein the converting of the second image data to the third image data comprises:

converting the second image data to fourth image data having long (L), medium (M), and short(S) channels associated with an LMS color space;

transforming the fourth image data into fifth image data based on a perceptual quantizer (PQ) transfer function; and

converting the fifth image data to the third image data in a PQ domain associated with the PQ transfer function.

3. The method of claim **1**, further comprising:

receiving metadata associated with the first image data, the metadata indicating a dynamic range or color gamut associated with a mastering display.

4. The method of claim **3**, wherein the metadata includes color calibration data associated with the mastering display, a maximum frame average light level, a maximum content light level, RGB primaries, white point, or display maximum and minimum light levels.

5. The method of claim **3**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z, a_z, and b_z channels of the first display data comprises:

generating a plurality of lookup tables (LUTs) based at least in part on the received metadata and the dynamic range or color gamut associated with the display device;

mapping the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data based at least in part on one or more first LUTs of the plurality of LUTs; and

mapping the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data based at least in part on one or more second LUTs of the plurality of LUTs.

6. The method of claim **5**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data comprises:

mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs;
classifying one or more features in the image based on a neural network model; and
remapping the global saturation values to the a_z and b_z channels of the first display data based at least in part on the classifications of the one or more features.

7. The method of claim **5**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data comprises:
mapping the J_z, a_z, and b_z channels of the third image data to global tone values within a spectrum of values based on the one or more first LUTs, the spectrum being partitioned into a plurality of bands; and
remapping the global tone values in each band of the plurality of bands to respective equalized tone values within the band based on histogram equalization of the global tone values.

8. The method of claim **7**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data further comprises:
extracting details in the image based on differences between the equalized tone values and the J_z channel of the third image data; and
adjusting the equalized tone values based on the extracted details.

9. The method of claim **8**, wherein the adjusting of the equalized tone values comprises:
selectively blending the equalized tone values with the J_z channel of the third image data.

10. The method of claim **9**, further comprising:
determining whether each pixel of the image is associated with a flat region or a textured region, the selective blending of the equalized tone values being based on whether each pixel of the image is associated with a flat region or a textured region.

11. The method of claim **7**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data comprises:
mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs; and
dynamically adjusting the global saturation values based at least in part on the equalized tone values.

12. The method of claim **1**, wherein the processing of the first display data comprises:
converting the first display data to second display data having R, G, and B channels associated with the RGB color space; and
transforming the second display data into third display data based on an inverse of an electro-optical transfer function (EOTF) associated with the display device.

13. An image processor comprising:
a processing system; and
a memory storing instructions that, when executed by the processing system, causes the image processor to:
receive first image data representing an image produced by an image capture device based on an opto-electrical transfer function (OETF);
transform the first image data into second image data based on an inverse of the OETF, the second image data having red (R), green (G), and blue (B) channels associated with an RGB color space;
convert the second image data to third image data having lightness (J_z), redness-greenness (a_z), and yellowness-blueness (b_z) channels associated with a $J_za_zb_z$ color space;
map the J_z, a_z, and b_z channels of the third image data to J_z, a_z, and b_z channels of first display data based at least in part on a dynamic range or color gamut associated with a display device; and
process the first display data for display by the display device.

14. The image processor of claim **11**, wherein the converting of the second image data to the third image data comprises:
converting the second image data to fourth image data having long (L), medium (M), and short(S) channels associated with an LMS color space;
transforming the fourth image data into fifth image data based on a perceptual quantizer (PQ) transfer function; and
converting the fifth image data to the third image data in a PQ domain associated with the PQ transfer function.

15. The image processor of claim **11**, wherein execution of the instructions further causes the image processor to:
receive metadata associated with the first image data, the metadata indicating a dynamic range or color gamut associated with a mastering display.

16. The image processor of claim **13**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z, a_z, and b_z channels of the first display data comprises:
generating a plurality of lookup tables (LUTs) based at least in part on the received metadata and the dynamic range or color gamut associated with the display device;
mapping the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data based at least in part on one or more first LUTs of the plurality of LUTs; and
mapping the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data based at least in part on one or more second LUTs of the plurality of LUTs.

17. The image processor of claim **15**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data comprises:
mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs;
classifying one or more features in the image based on a neural network model; and
remapping the global saturation values to the a_z and b_z channels of the first display data based at least in part on the classifications.

18. The image processor of claim **15**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data comprises:
mapping the J_z, a_z, and b_z channels of the third image data to global tone values within a spectrum of values based on the one or more first LUTs, the spectrum being partitioned into a plurality of bands; and
remapping the global tone values in each band of the plurality of bands to respective equalized tone values in the band based on histogram equalization of the global tone values.

19. The image processor of claim **17**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the J_z channel of the first display data further comprises:

extracting details in the image based on differences between the equalized tone values and the J_z channel of the third image data; and

adjusting the equalized tone values based on the extracted details.

20. The image processor of claim **17**, wherein the mapping of the J_z, a_z, and b_z channels of the third image data to the a_z and b_z channels of the first display data comprises:

mapping the J_z, a_z, and b_z channels of the third image data to global saturation values based on the one or more second LUTs; and

dynamically adjusting the global saturation values based at least in part on the equalized tone values.

* * * * *