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(54) ENHANCING THE TONAL AND COLOR CHARACTERISTICS OF DIGITAL IMAGES USING EXPANSIVE AND COMPRESSIVE TONE SCALE FUNCTIONS

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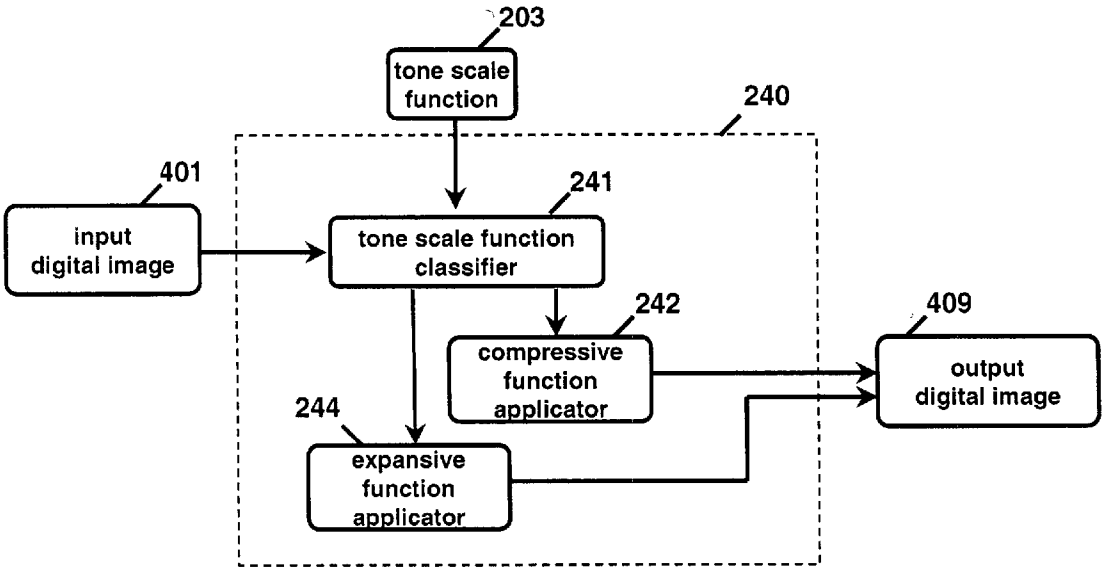
(57) **ABSTRACT**

A method of enhancing the tonal and chrominance characteristics of a digital image, includes receiving a source digital image including wherein the source digital image is in a luminance-chrominance representation having a luminance digital image channel and at least two chrominance digital image channels; producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image; classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive; using the tone scale function and the luminance digital image channel to produce an enhanced luminance digital image channel; and amplifying the chrominance digital image channels to produce modified chrominance digital channels when the tone scale function has been classified as expansive.



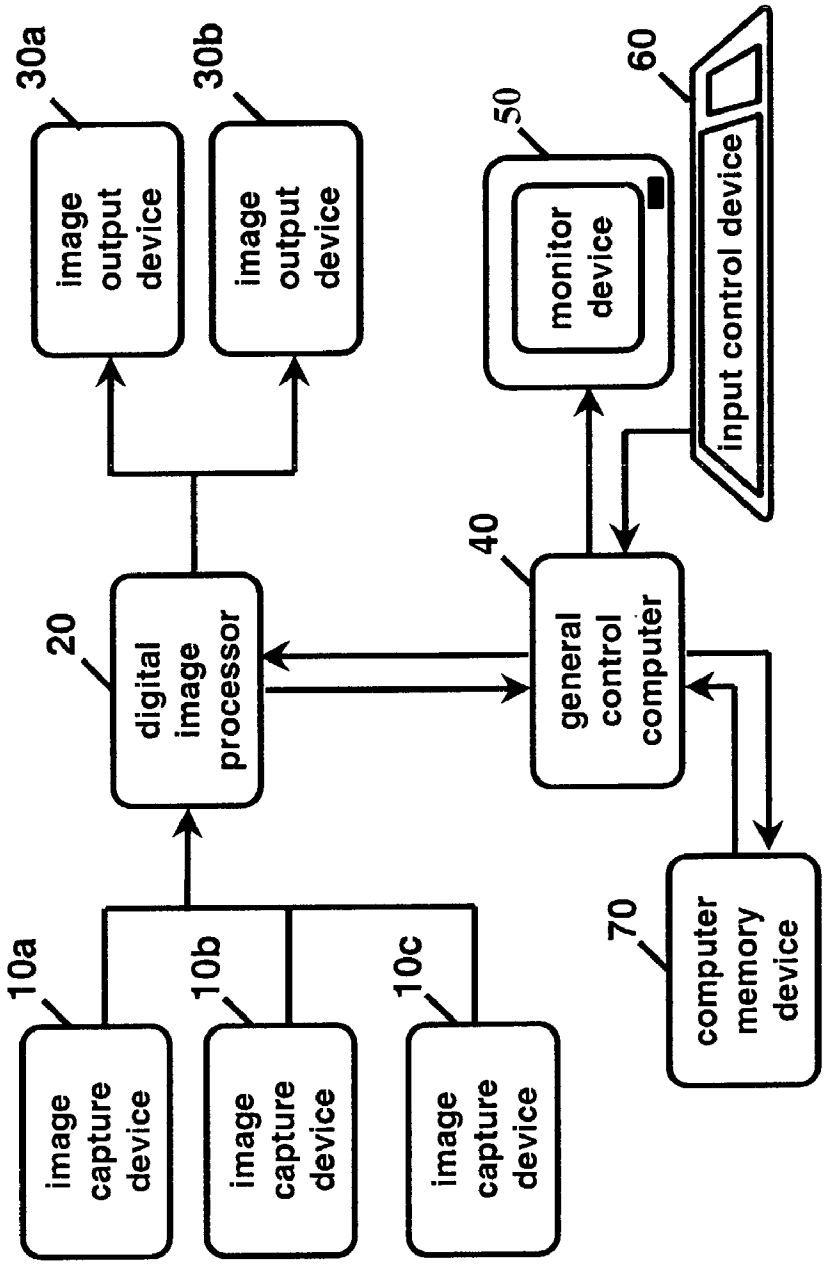

10a
image capture device
10b
image capture device
10c
image capture device
20
digital image processor
30a
image output device
30b
image output device
40
general control computer
50
monitor device
60
input control device
70
computer memory device

Fig. 1

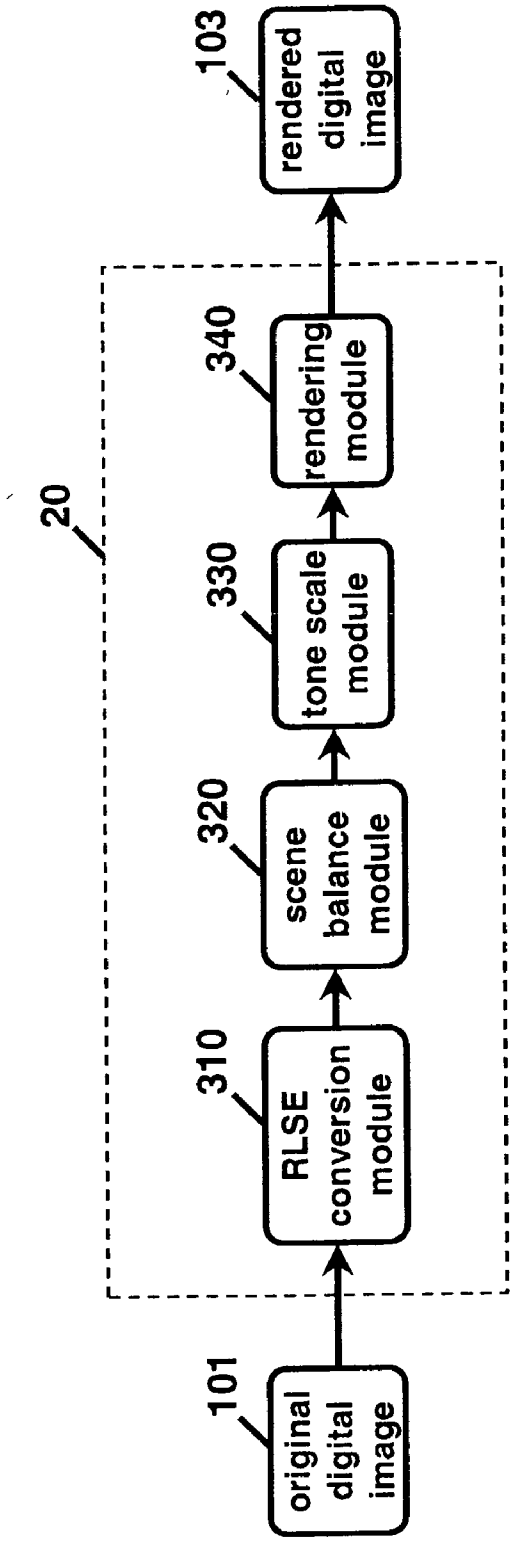

20
101
original digital image
310
RLSE conversion module
320
scene balance module
330
tone scale module
340
rendering module
103
rendered digital image

Fig. 2

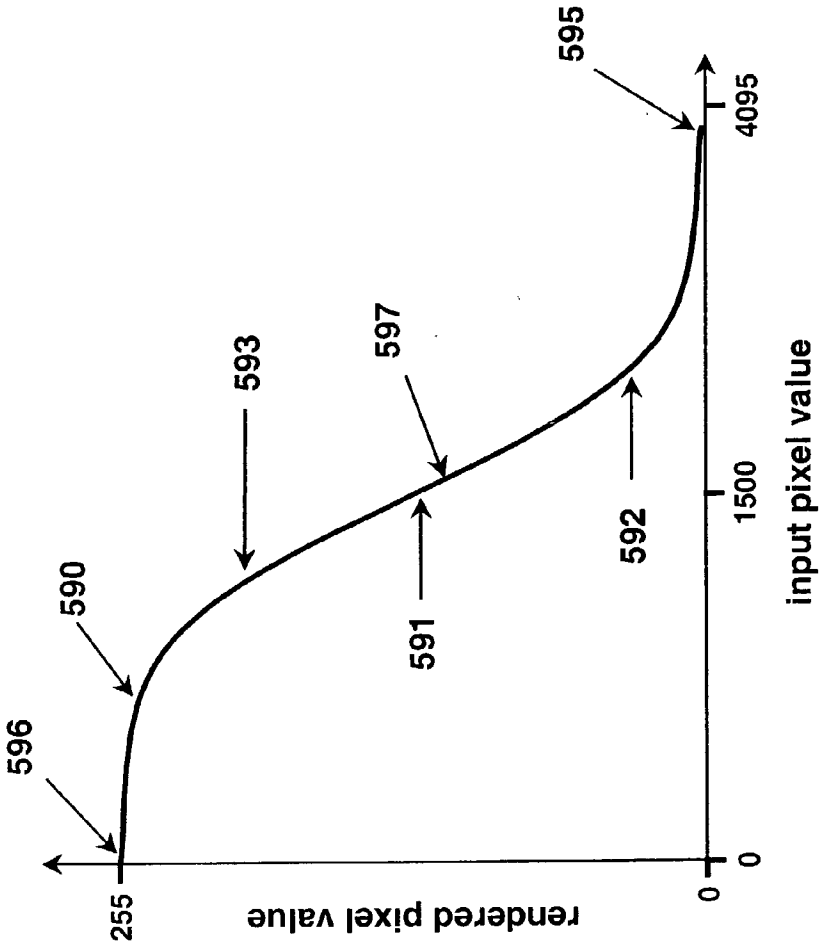

596
590
593
597
591
592
595
255
rendered pixel value
0
0
1500
4095
input pixel value

Fig. 3a

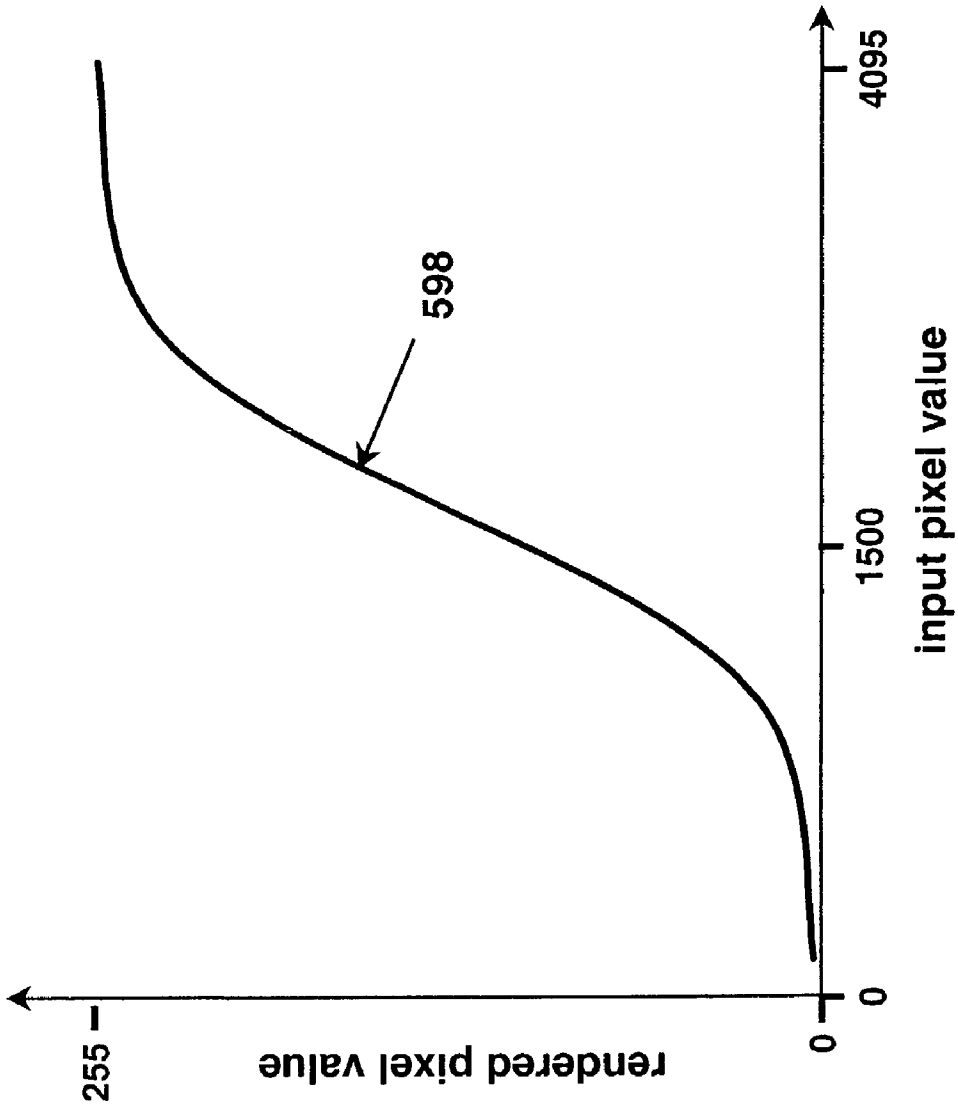


Fig. 3b

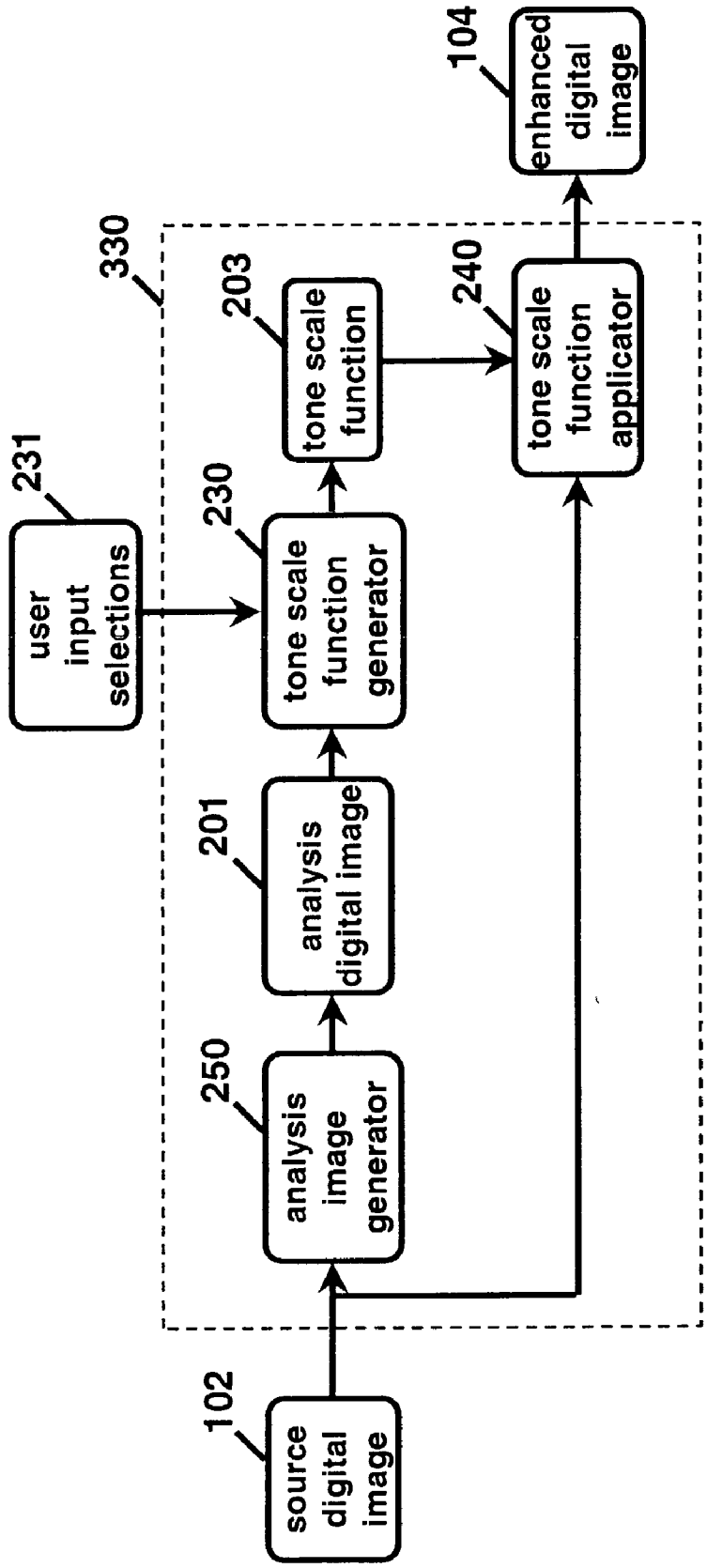

102
source digital image
250
analysis image generator
201
analysis digital image
231
user input selections
230
tone scale function generator
203
tone scale function
330
240
tone scale function applicator
104
enhanced digital image

Fig. 4

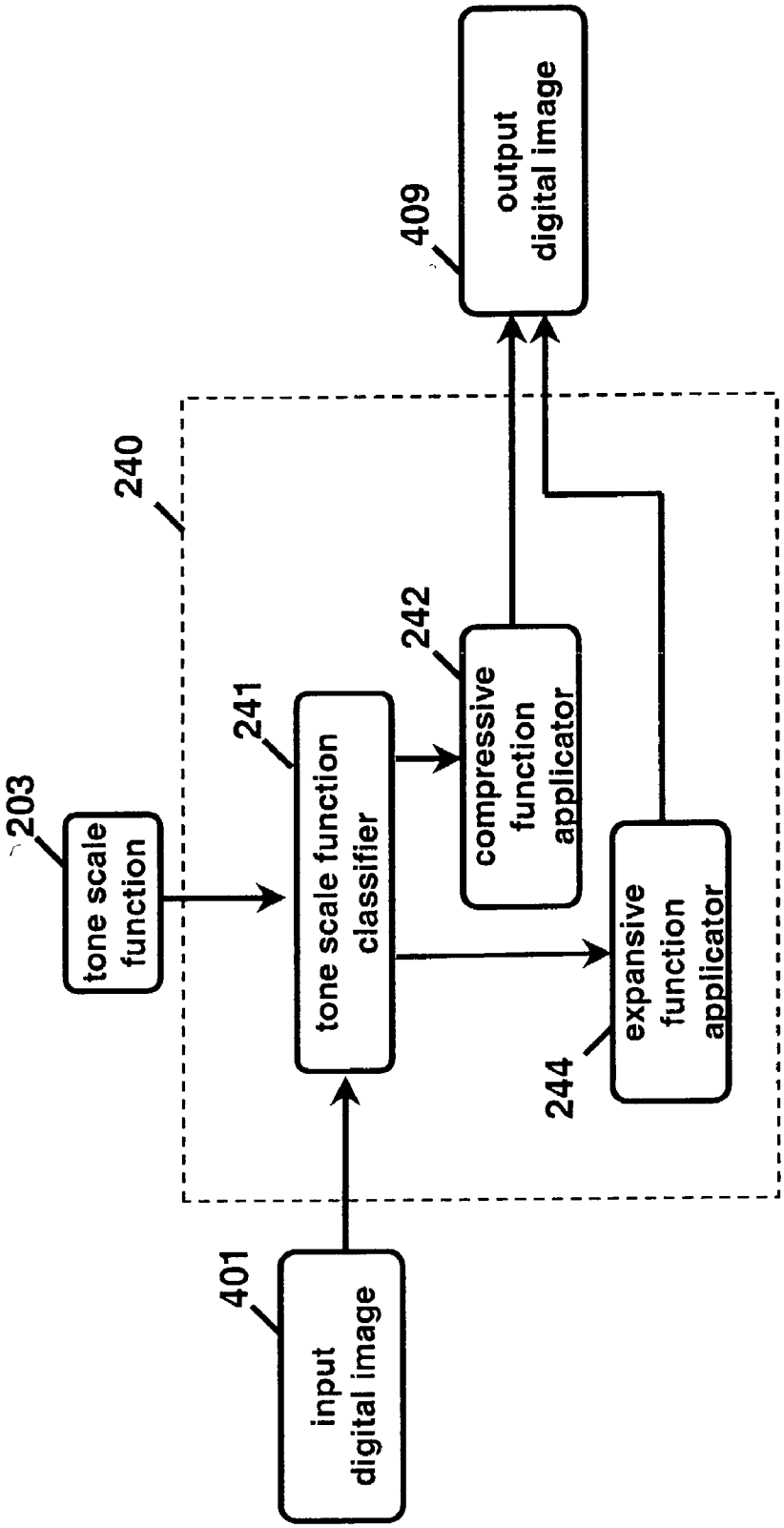

203
tone scale function
240
241
tone scale function classifier
242
compressive function applicator
244
expansive function applicator
401
input digital image
409
output digital image

Fig. 5

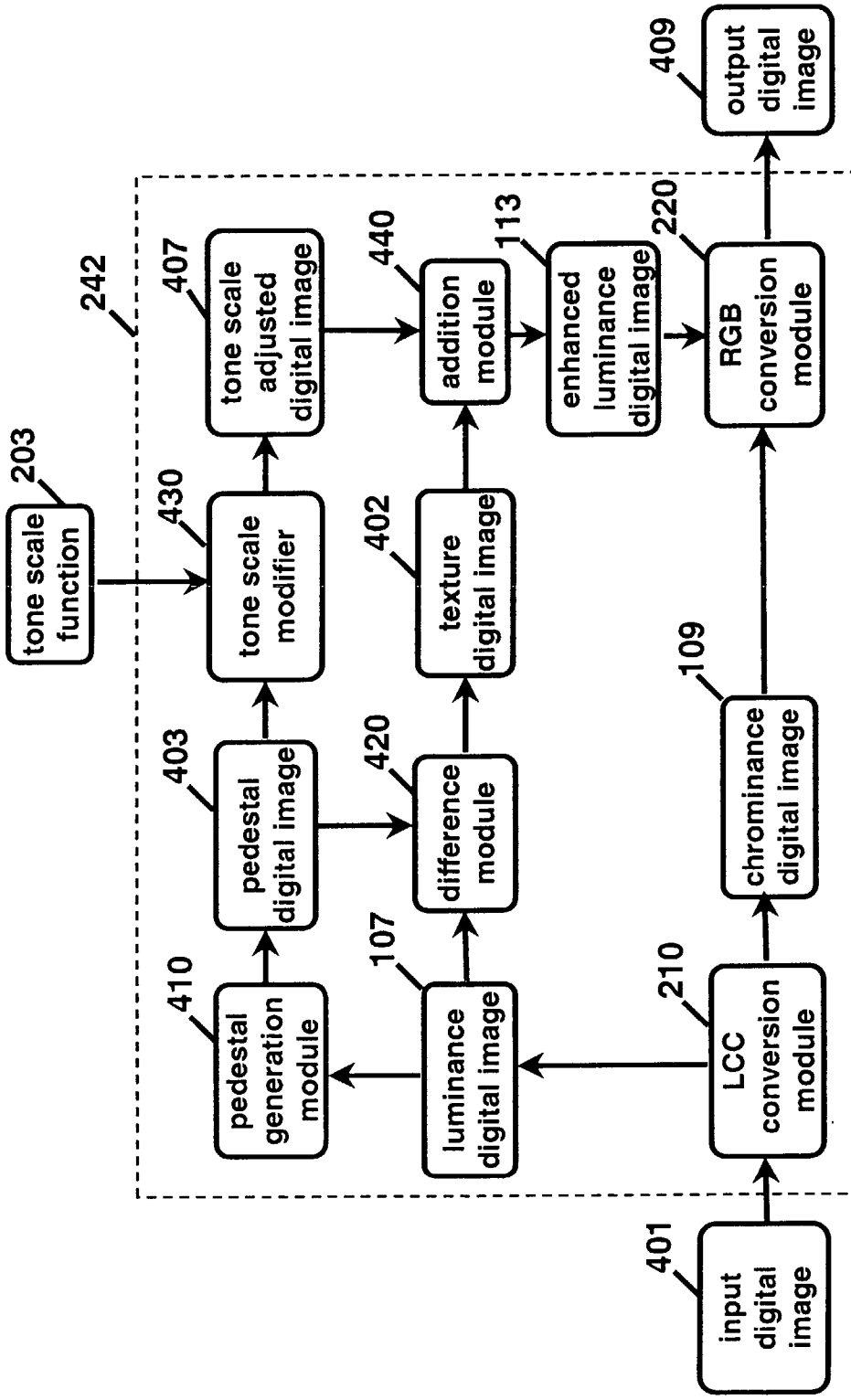

tone scale function
203
242
tone scale modifier
430
tone scale adjusted digital image
407
pedestal digital image
403
pedestal generation module
410
luminance digital image
107
difference module
420
texture digital image
402
addition module
440
enhanced luminance digital image
113
LCC conversion module
210
chrominance digital image
109
RGB conversion module
220
output digital image
409
input digital image
401

Fig. 6a

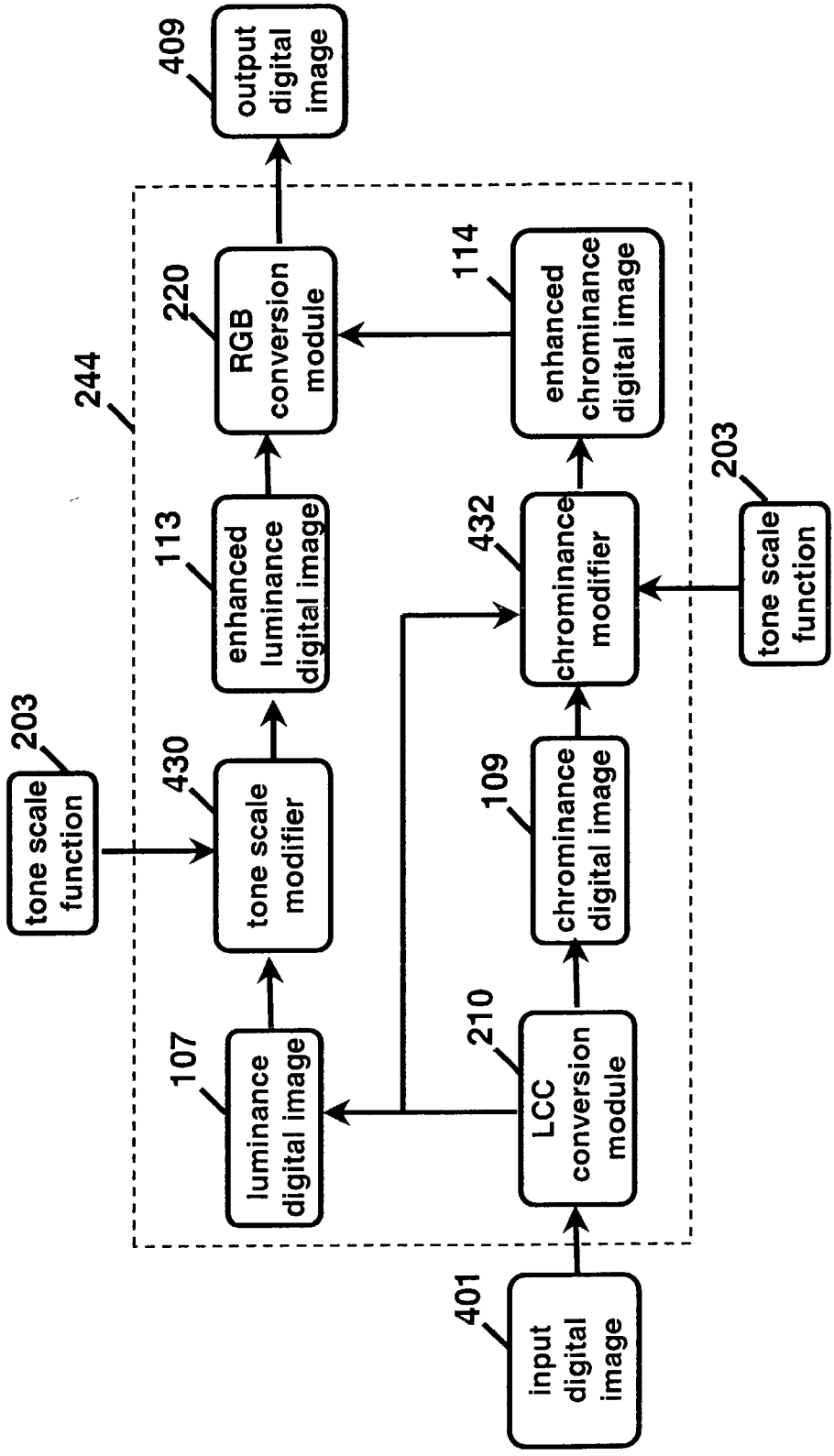

409
output digital image
244
220
RGB conversion module
114
enhanced chrominance digital image
113
enhanced luminance digital image
432
chrominance modifier
203
tone scale function
203
tone scale function
430
tone scale modifier
109
chrominance digital image
107
luminance digital image
210
LCC conversion module
401
input digital image

Fig. 6b

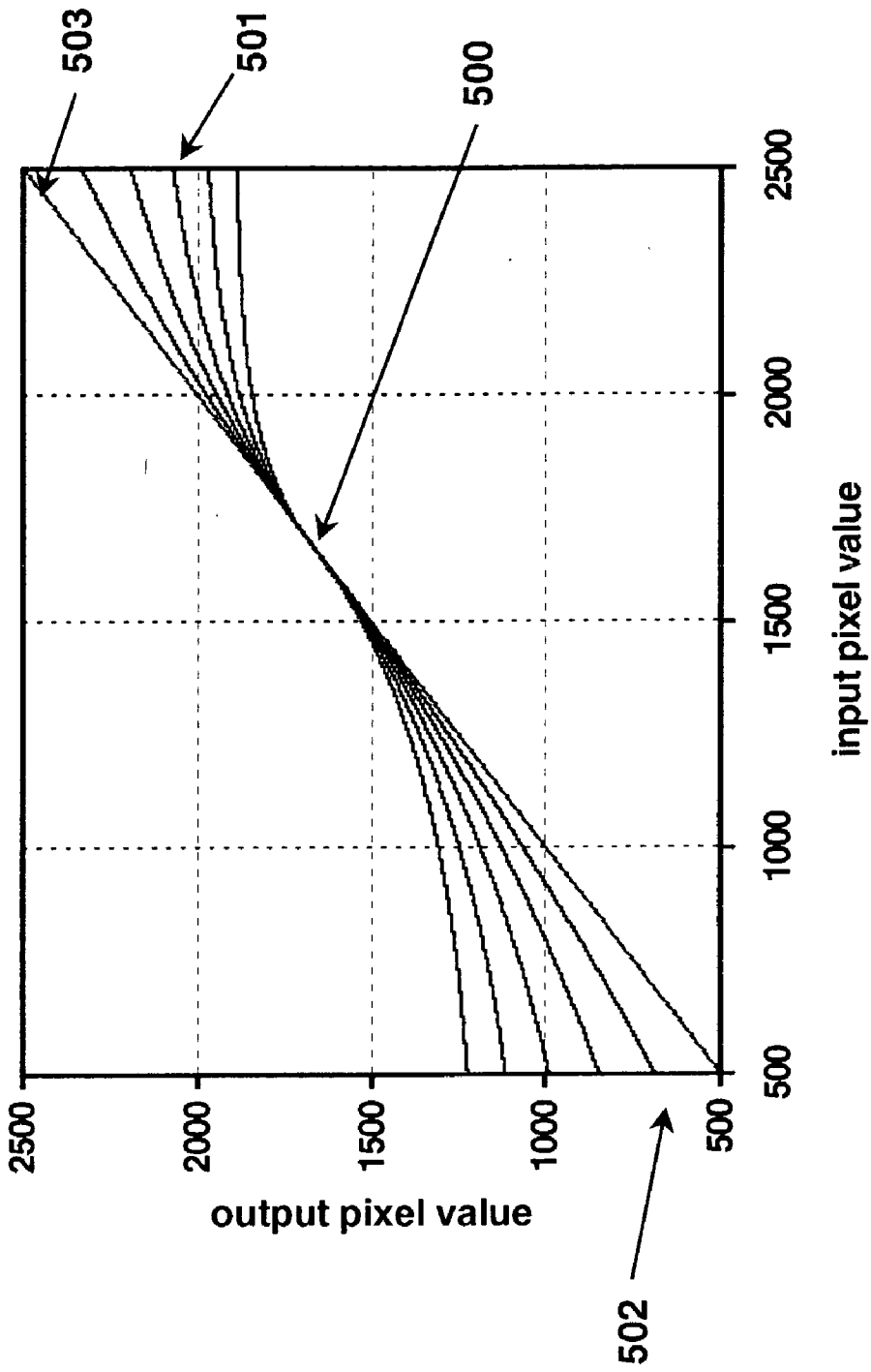

503
501
500
2500
2000
1500
1000
500
output pixel value
500
1000
1500
2000
2500
input pixel value
502

Fig. 7

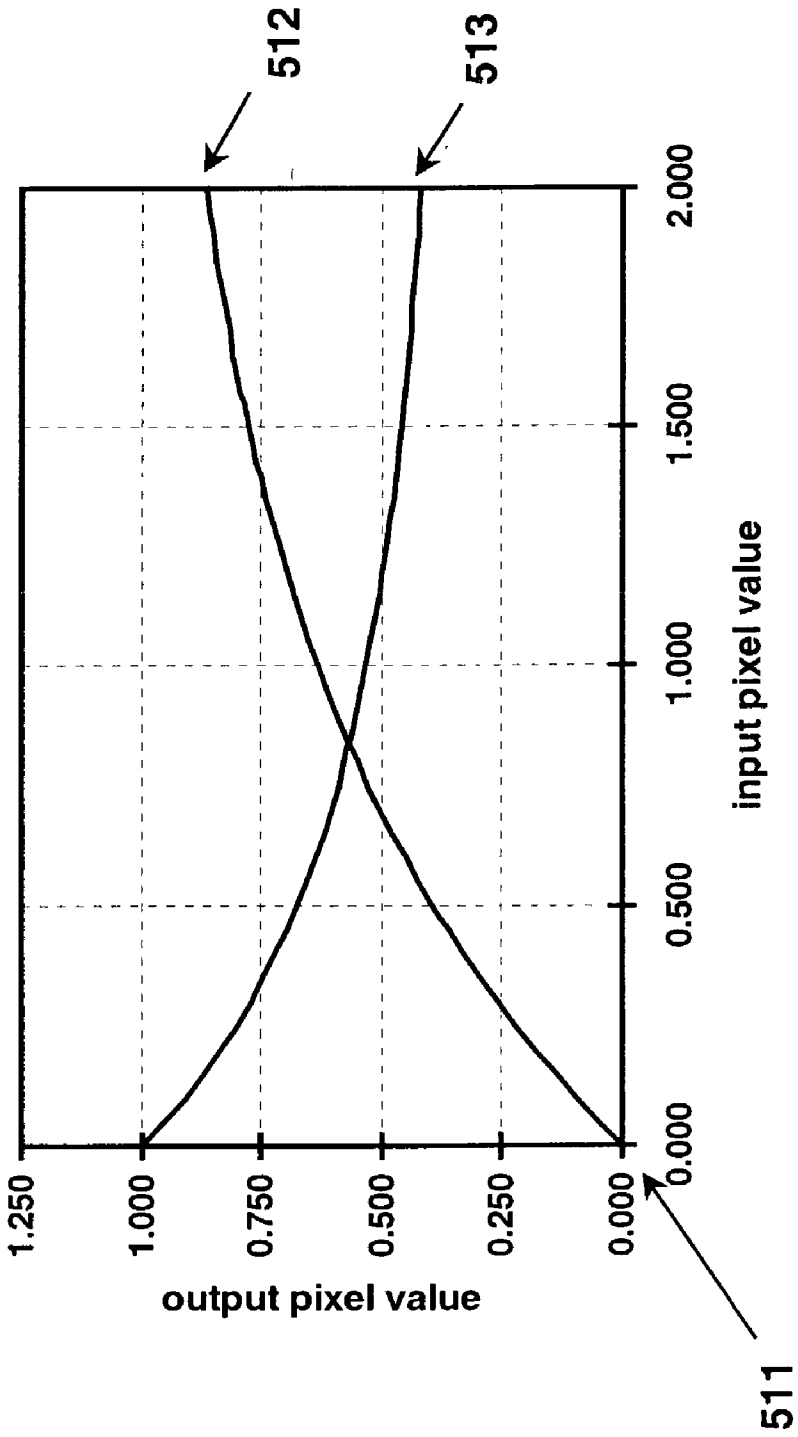

512
513
1.250
1.000
0.750
0.500
0.250
0.000
output pixel value
0.000
0.500
1.000
1.500
2.000
input pixel value
511

Fig. 8a

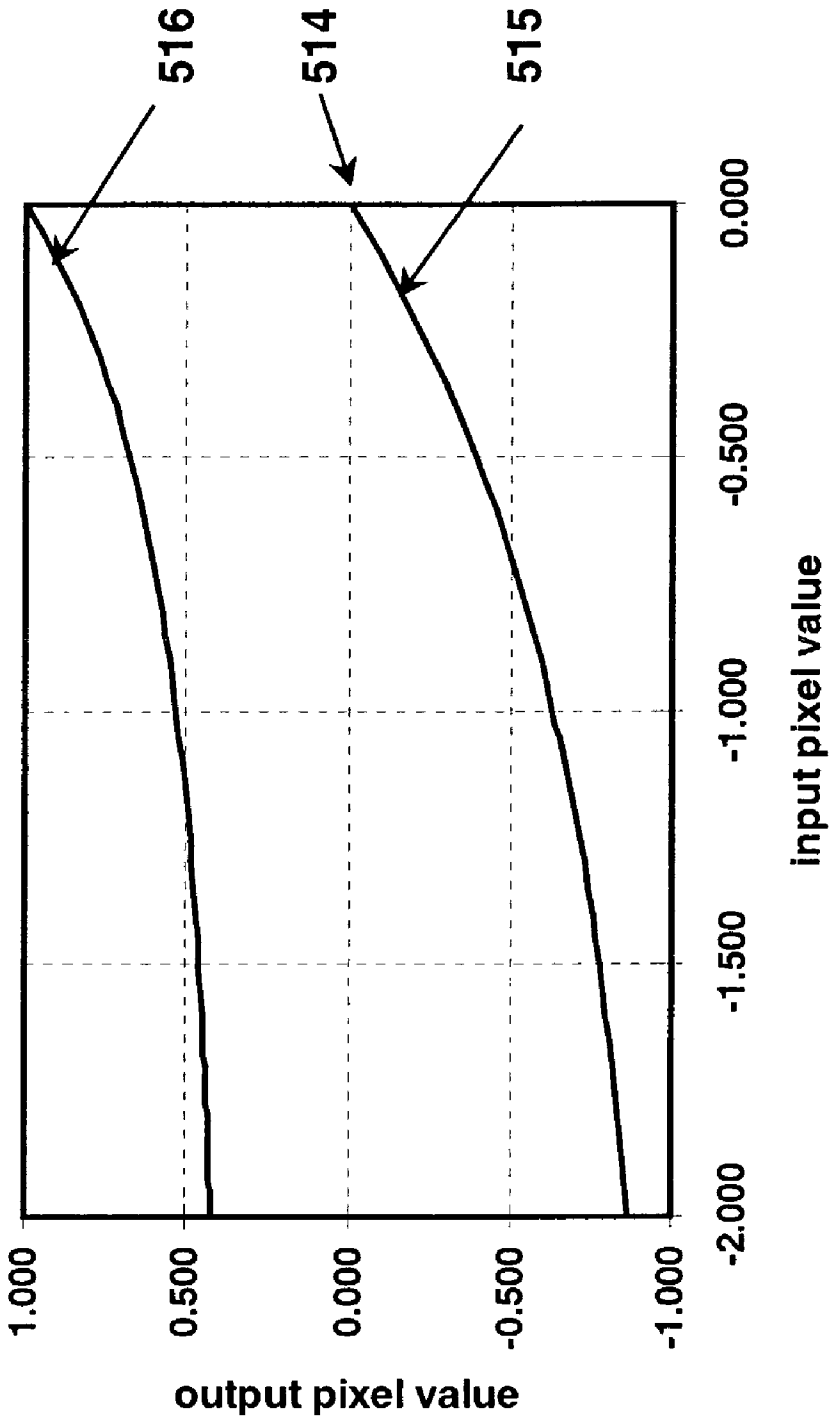

516
514
515
1.000
0.500
0.000
-0.500
-1.000
output pixel value
-2.000
-1.500
-1.000
-0.500
0.000
input pixel value

Fig. 8b

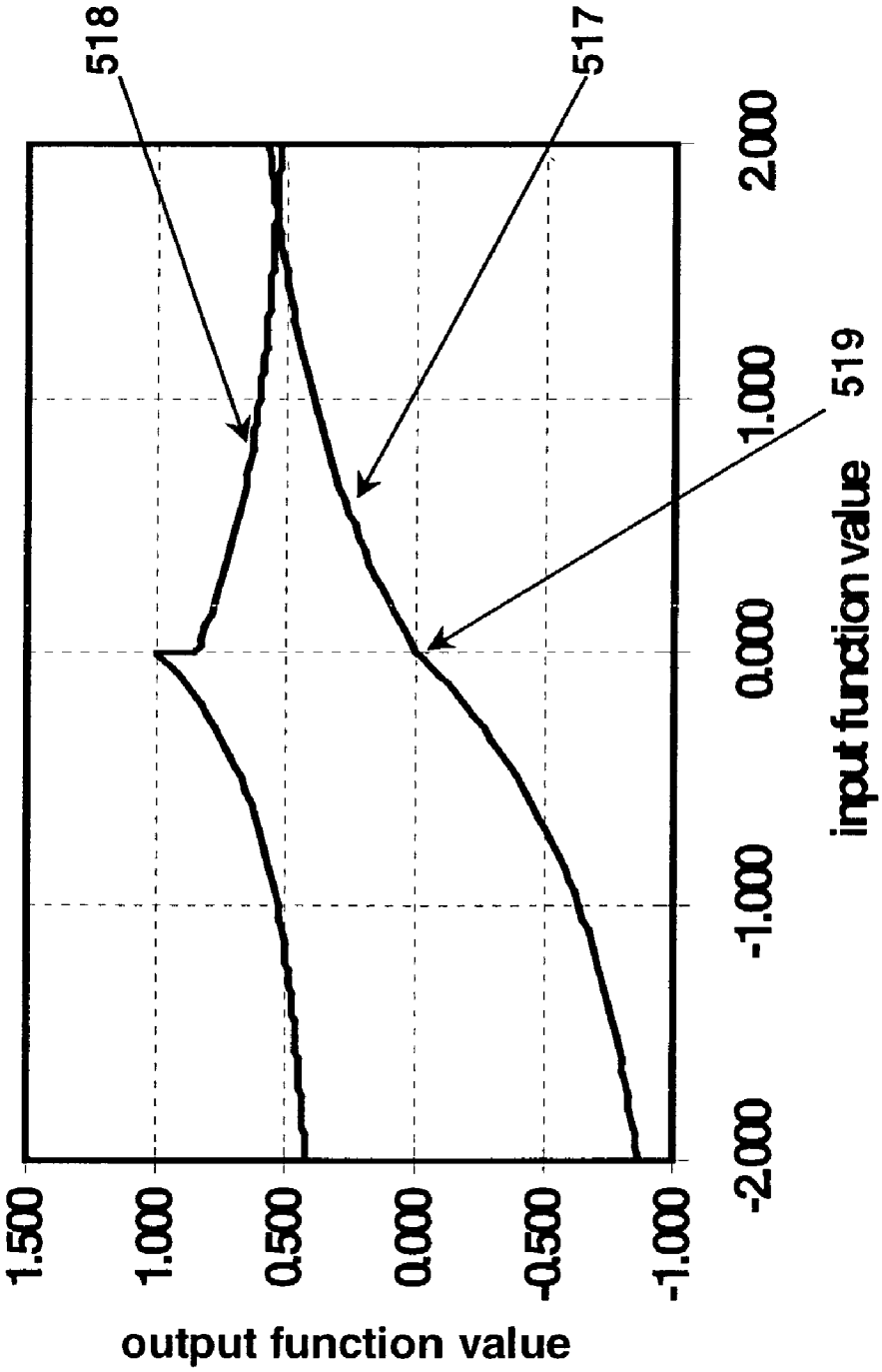

518
517
519
1.500
1.000
0.500
0.000
-0.500
-1.000
output function value
-2.000
-1.000
0.000
1.000
2.000
input function value

Fig. 8c

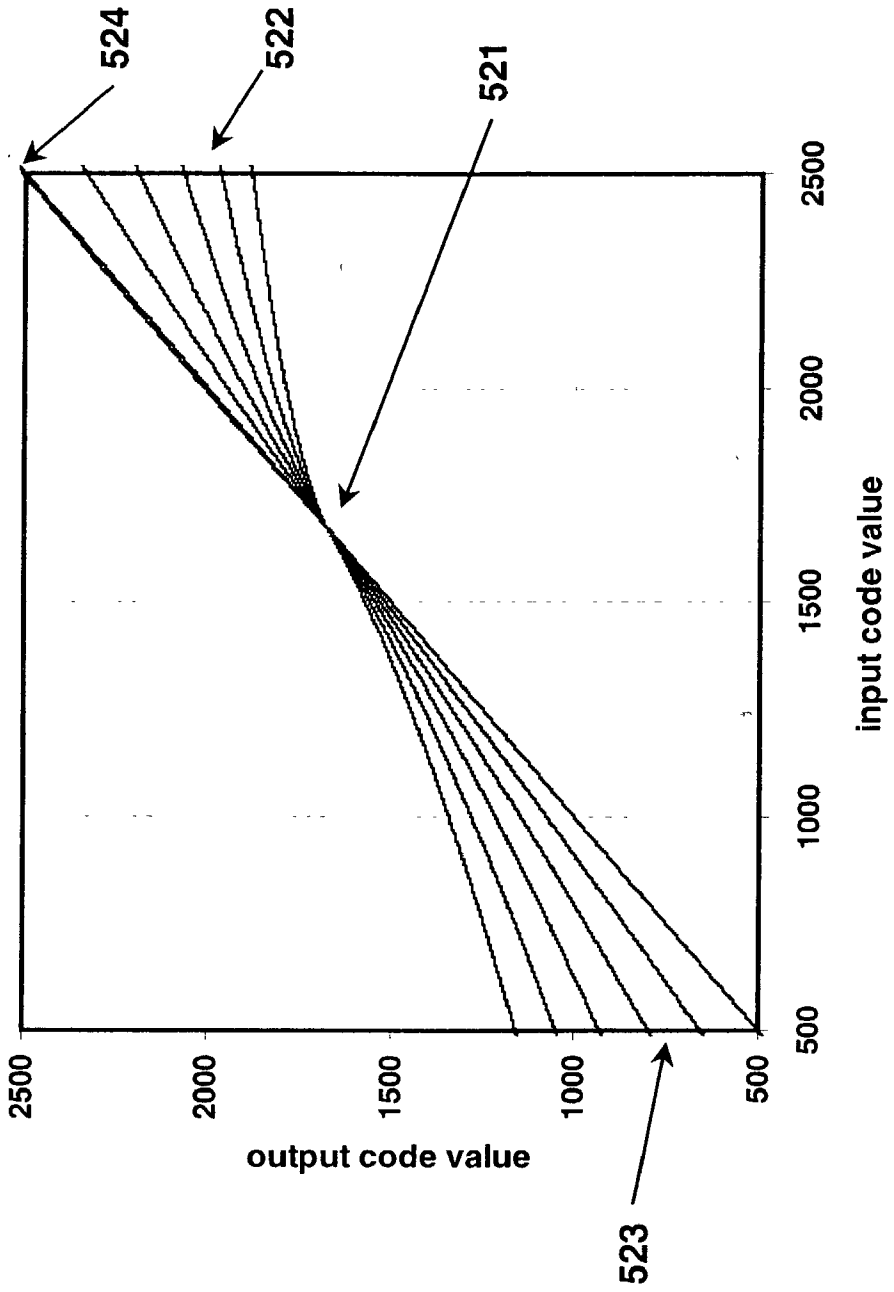

524
522
521
523
2500
2000
1500
1000
500
output code value
500
1000
1500
2000
2500
input code value

Fig. 9

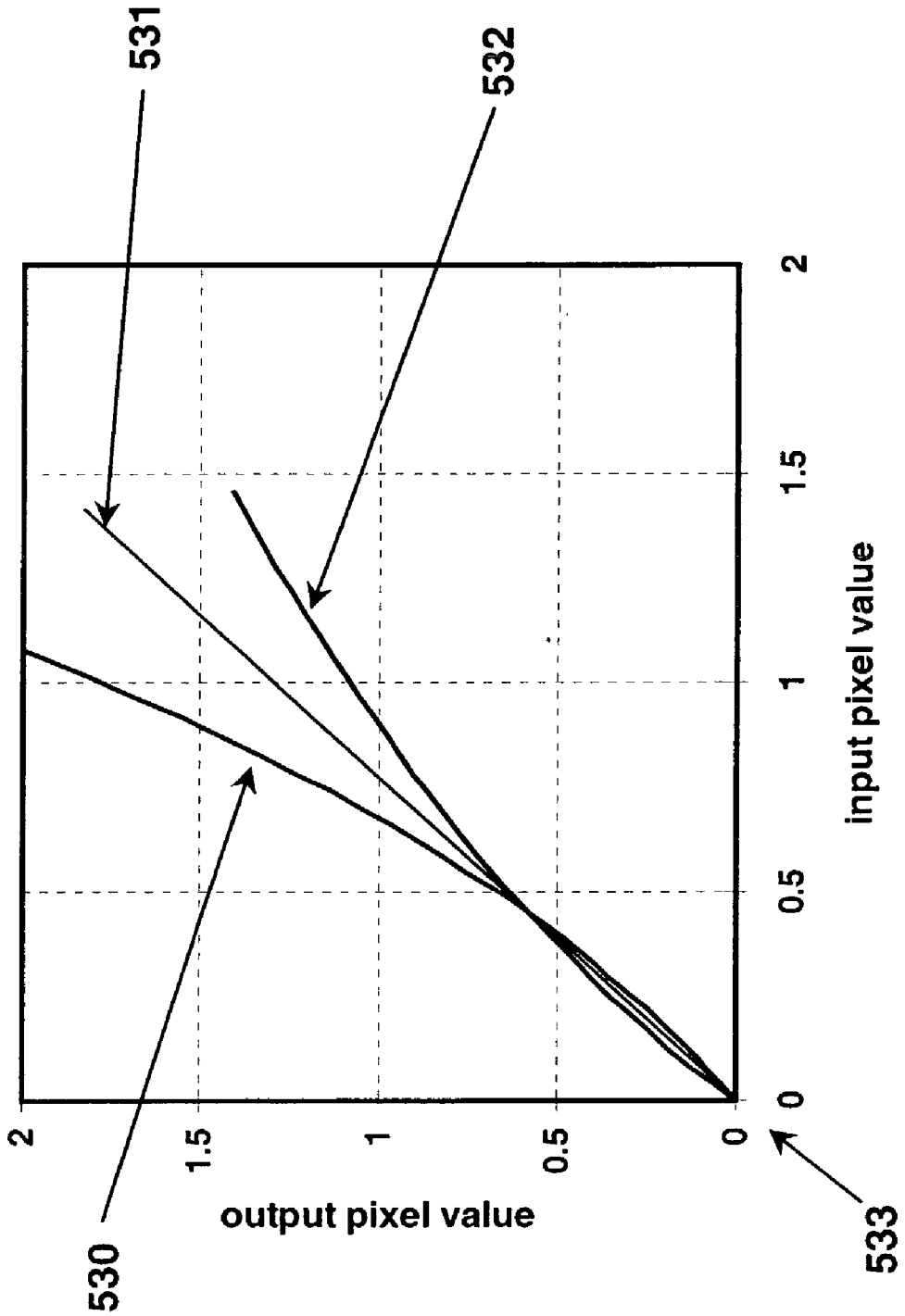

531
532
530
533
output pixel value
input pixel value
2
1.5
1
0.5
0
0
0.5
1
1.5
2

Fig. 10a

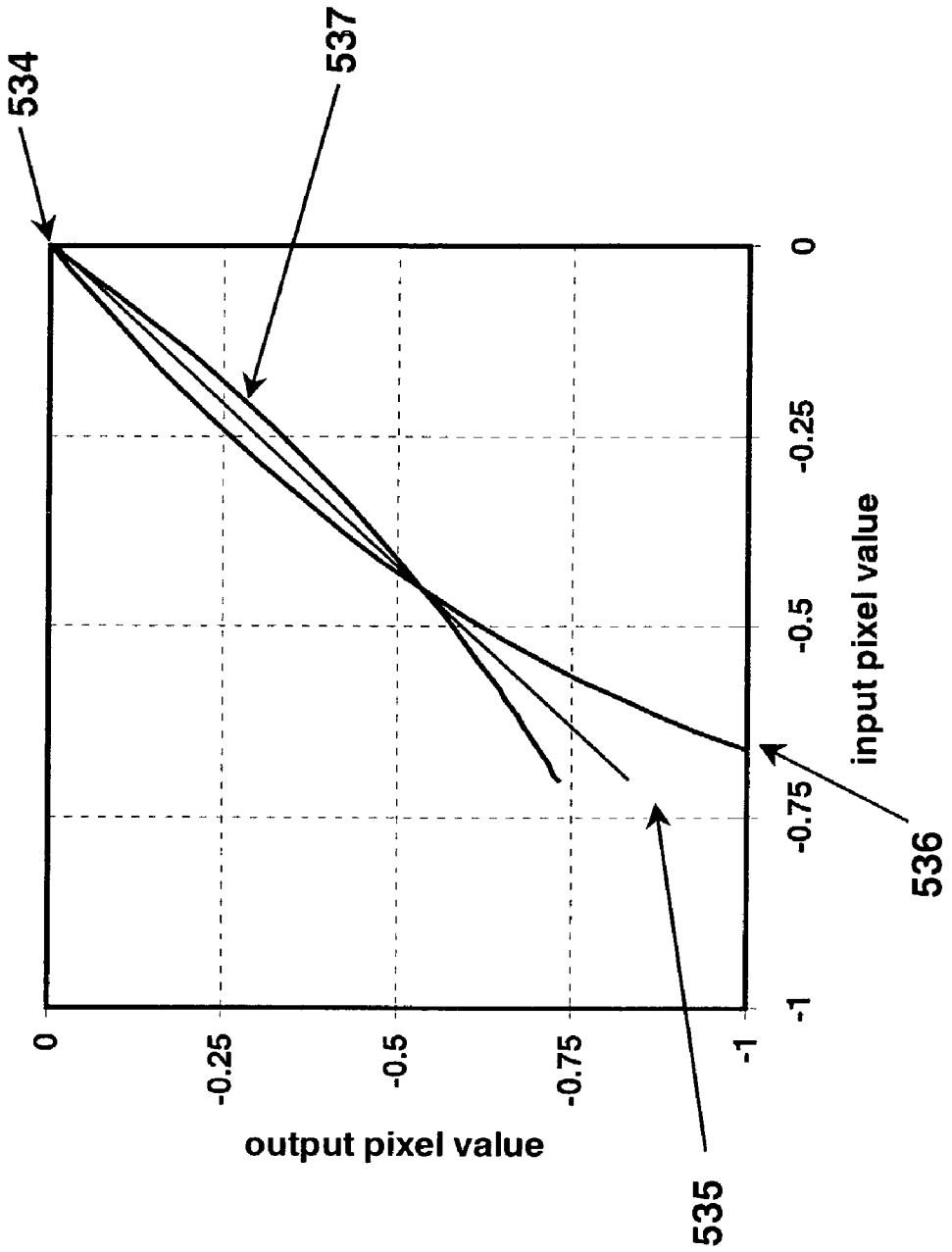

534
537
0
-0.25
-0.5
-0.75
-1
output pixel value
0
-0.25
-0.5
-0.75
-1
input pixel value
535
536

Fig. 10b

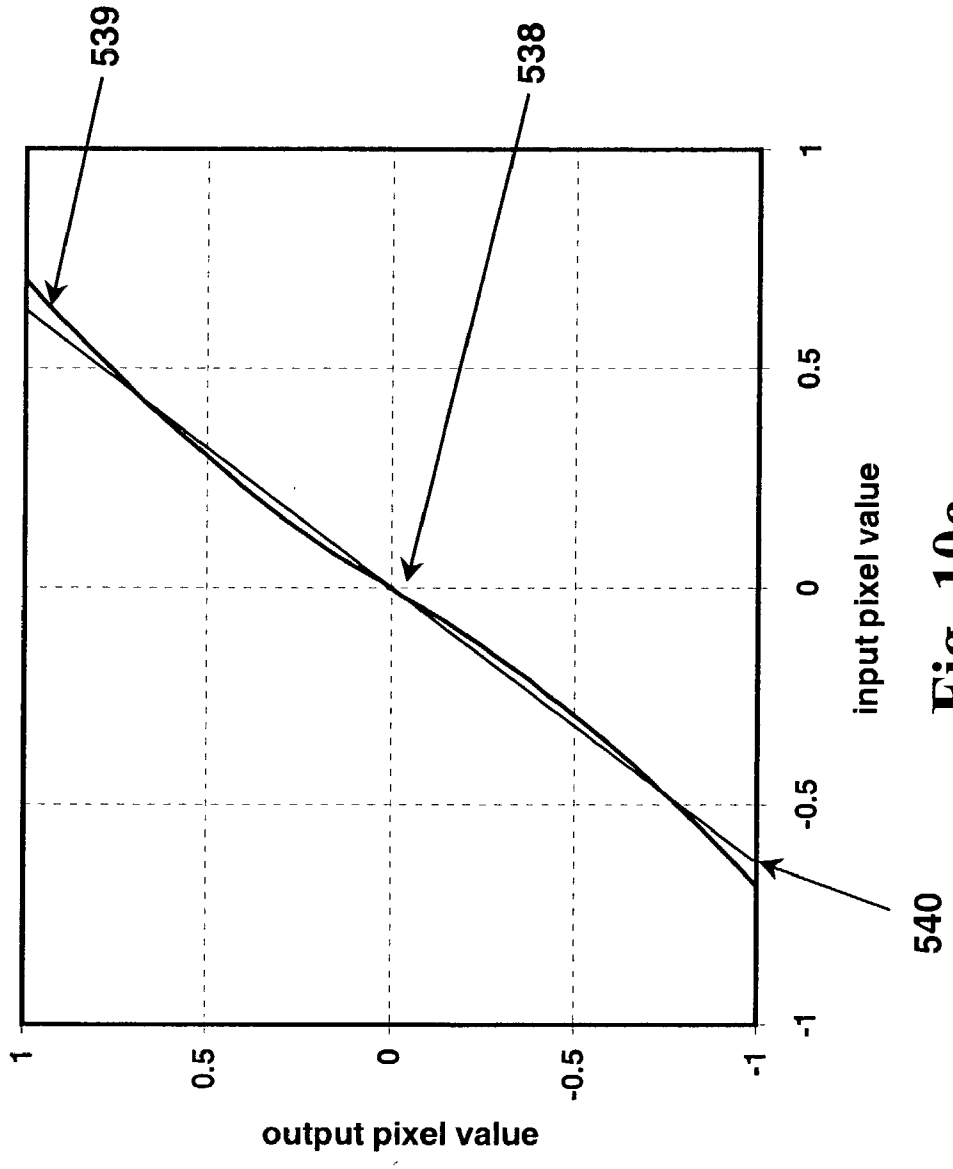

539
538
1
0.5
0
-0.5
-1
output pixel value
-1
-0.5
0
0.5
1
input pixel value
540

Fig. 10c

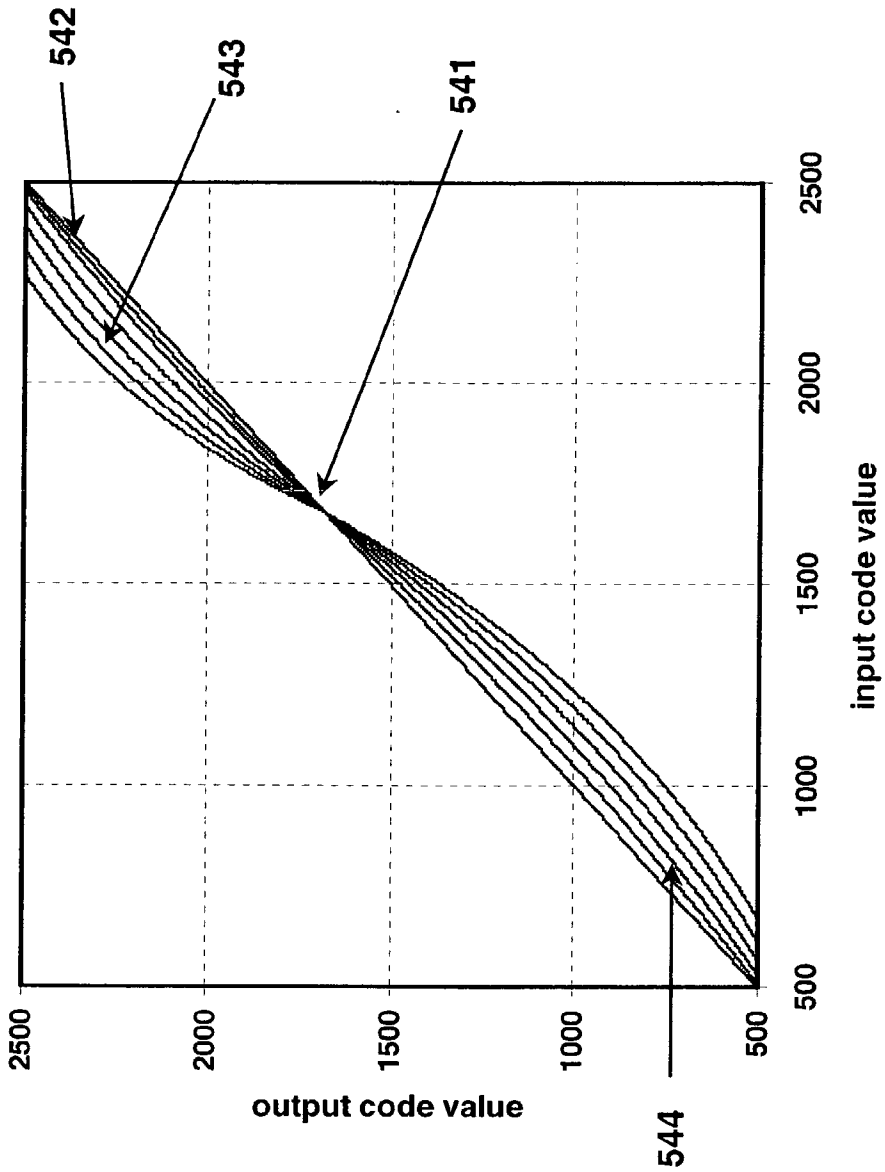

542
543
541
2500
2000
1500
1000
500
output code value
500
1000
1500
2000
2500
input code value
544

Fig. 11

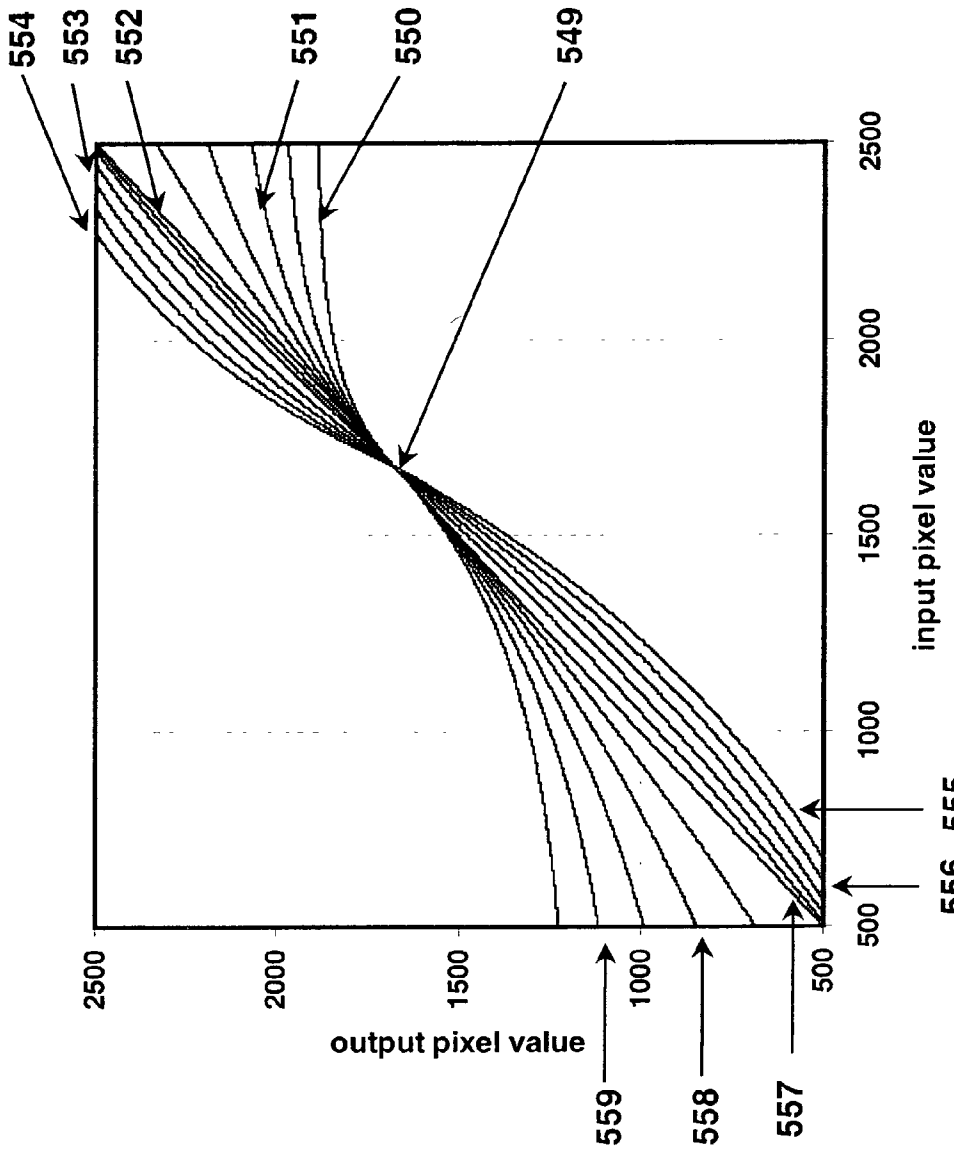

554
553
552
551
550
549
2500
2000
1500
1000
500
output pixel value
559
558
557
500
1000
1500
2000
2500
input pixel value
556
555

Fig. 12a

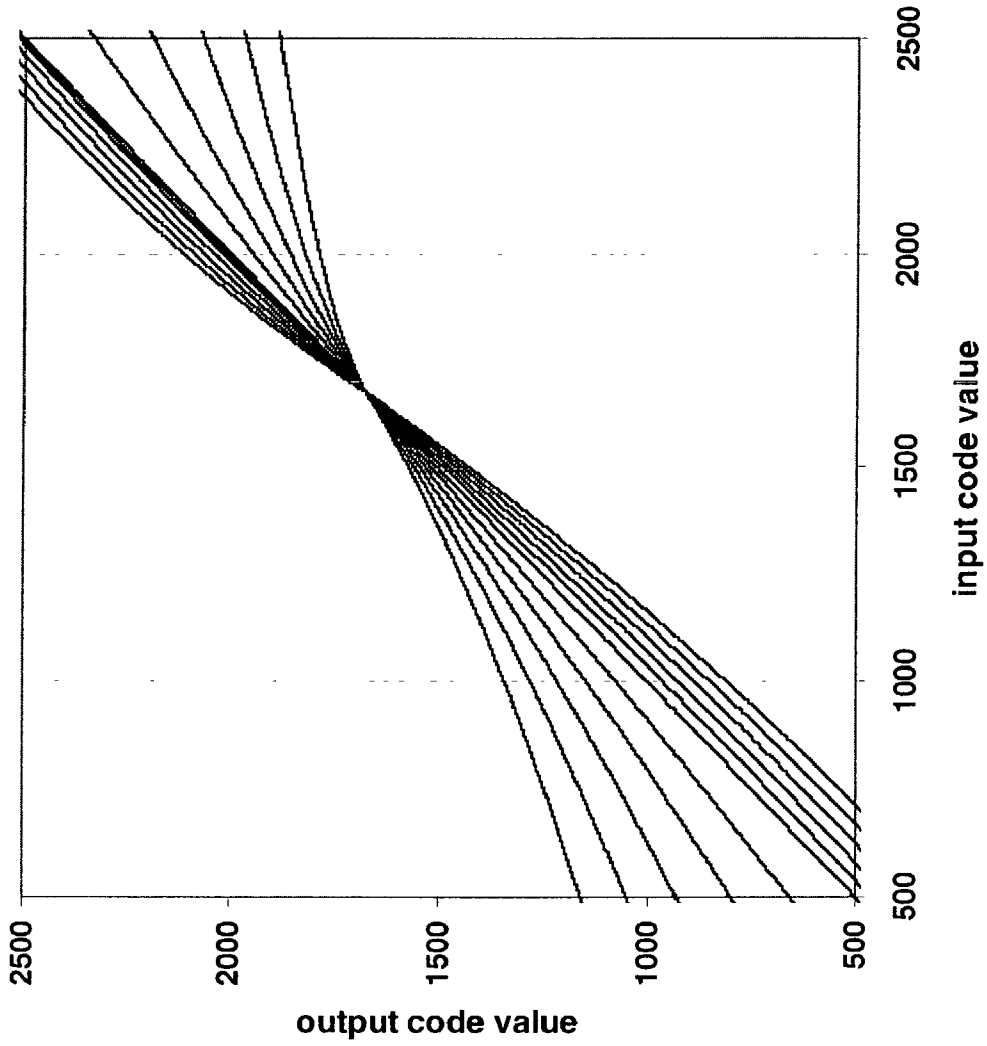

2500
2000
1500
1000
500
output code value
500
1000
1500
2000
2500
input code value

Fig. 12b

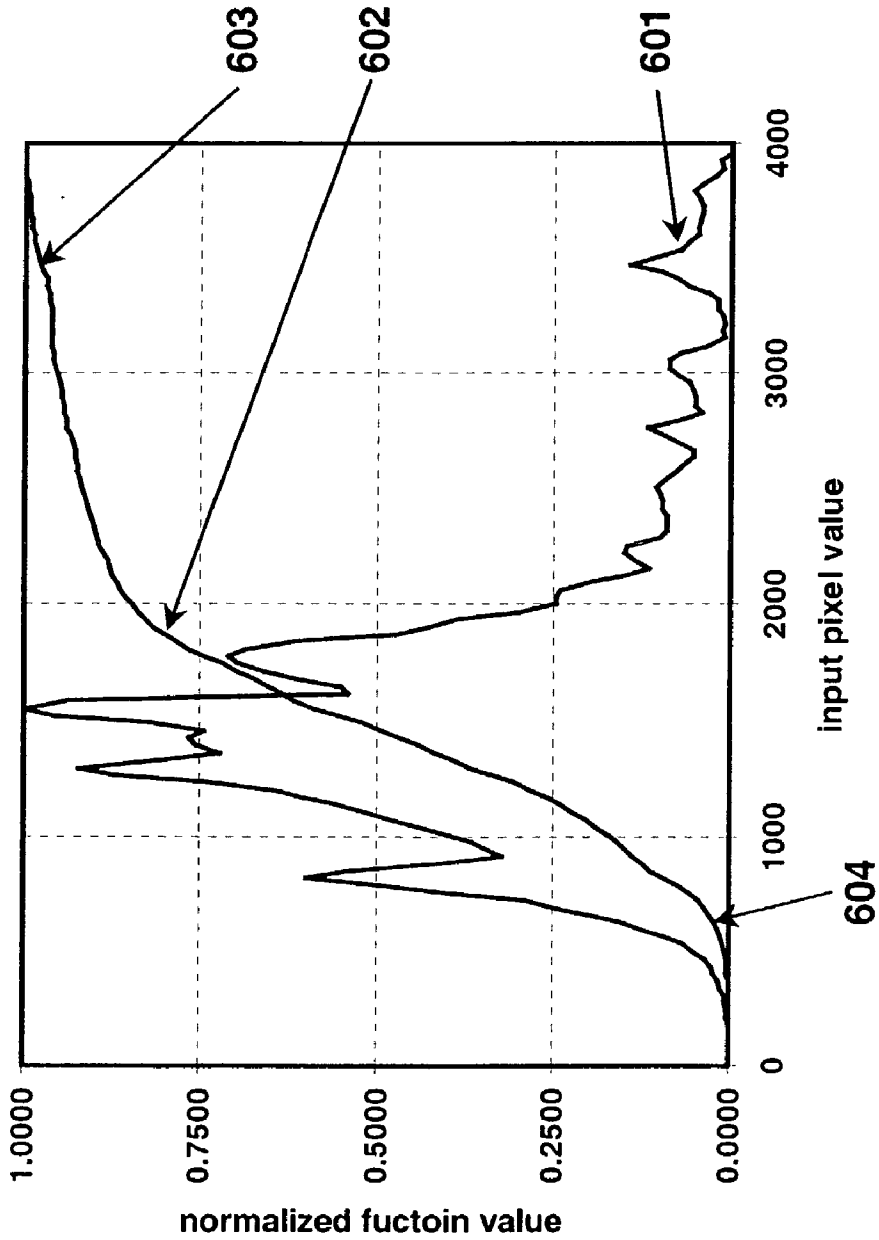

603
602
601
604
1.0000
0.7500
0.5000
0.2500
0.0000
normalized fuctoin value
0
1000
2000
3000
4000
input pixel value

Fig. 13

ENHANCING THE TONAL AND COLOR CHARACTERISTICS OF DIGITAL IMAGES USING EXPANSIVE AND COMPRESSIVE TONE SCALE FUNCTIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] Reference is made to commonly-assigned U.S. patent application Ser. No. 10/178,260, filed Jun. 24, 2002, entitled "Enhancing the Tonal Characteristics of Digital Images" by Edward B. Gindele, U.S. patent application Ser. No. _____ filed Sep. 19, 2002, entitled "Enhancing the Tonal Characteristics of Digital Images Using Inflection Points in a Tone Scale Function" by Edward B. Gindele, and U.S. patent application Ser. No. _____ filed concurrently herewith, entitled "Enhancing the Tonal Characteristics of Digital Images Using Expansive and Compressive Tone Scale Functions" by Edward B. Gindele et al, the disclosures of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This invention relates to digital image processing and in particular to processing a digital image to enhance its color, brightness, and tone scale characteristics.

BACKGROUND OF THE INVENTION

[0003] Many digital imaging systems enhance the contrast and lightness characteristics of digital images through the application of a tone scale curve. For a generalized tone scale curve $f(\ )$, the input pixel value x is transformed to an output pixel value $f(x)$. The shape of the tone scale curve determines the visual effect imparted to the processed digital image. Some tone scale curves applied to digital image are independent of the pixel values in the digital image to be processed. Such image independent tone scale curves are useful for establishing a photographic look to the processed digital images. While image independent tone scale curves can be used to enhance many digital images, digital images that are either too high or low in contrast can benefit from the application of a tone scale curve that is responsive to the distribution of pixel values in the digital image to be processed. For image dependent tone scale curves, the mathematical formula used to generate the function $f(x)$ determines the degree and nature of the image enhancement.

[0004] When a compressive tone scale function, i.e. the tone scale function designed to reduce the numerical range of pixel values, is applied directly to image pixel data, the spatial detail in the image can be diminished. In addition, if the compressive tone scale function is applied directly to a color digital image that is in a red-green-blue representation, the tone scale function can reduce the colorfulness (saturation) characteristics of the processed digital image. In general, better results can be achieved if the compressive tone scale function is applied directly to the luminance signal of a luminance-chrominance image representation. This procedure leaves the chrominance signals unchanged but can lead to processed images that have diminished spatial detail.

[0005] In the method disclosed by commonly-assigned Gallagher and Gindele in U.S. Pat. No. 6,167,165, the spatial detail of the processed image can be mostly restored. In this method, a tone scale function is applied directly to the luminance signal and the spatial frequency detail of the tone scale modified luminance signal is adjusted inversely proportional to the slope of the applied tone scale function. The resultant processed digital images have more spatial detail and appear more natural.

[0006] A spatial filter can be used to apply a tone scale function to a digital image in such a manner that the image spatial detail will be relatively unaffected. This is particularly useful for compressive tone scale functions designed to reduce the image dynamic range. Such spatial filtering methods have been disclosed in commonly-assigned U.S. Pat. Nos. 6,317,521 and 6,285,798. When applying compressive tone scale functions to the luminance signal with a spatial filter, the color characteristics of the processed digital images look more natural even though the chrominance signals are not modified.

[0007] Some of the color problems incurred with the application of tone scale functions to luminance-chrominance representation digital images can be solved using the method disclosed by Gallagher and Gindele in commonly-assigned U.S. Pat. No. 6,408,103. In this method the chrominance signals are modified as a function of the slope of the applied tone scale function. Modifying the chrominance signals in this manner tends to alleviate the unnatural color effects that would otherwise result.

[0008] Some images naturally have a low numerical range to the pixel values and can be enhanced by applying an expansive tone scale function designed to increase the numerical range of pixel values. Simple histogram stretching methods are well known in the art. Typically a histogram is calculated from the image pixel values and the minimum and maximum pixel values are obtained. A tone scale function is constructed using a linear transform equation that expands the pixel values to achieve a predetermined goal. For example the minimum pixel value is mapped to a lower pixel value while the maximum pixel value is mapped to a higher pixel value. Applying an expansive tone scale function to image pixel data when in a red-green-blue representation has the effect of increasing image contrast, spatial detail, and color saturation. In general, the increase in contrast and spatial detail is viewed as an improvement in image quality. However, the increase in color saturation can lead to super-saturated color that can appear unnaturally colorful. Applying an expansive tone scale function to the luminance signal of a luminance-chrominance representation has the effect of increasing image contrast and spatial detail, but decreasing the apparent color saturation even though the chrominance signals are mathematically unaltered.

[0009] The above mentioned methods are individually designed to either avoid or remedy specific problems with image spatial detail and color characteristics when for applying tone scale functions to digital images. However, these methods have been designed to work primarily for compressive tone scale functions.

SUMMARY OF THE INVENTION

[0010] It is an object of the present invention to provide an improved way for applying a tone scale function to a digital image to enhance the tonal and color characteristics of the processed digital image.

[0011] This object is achieved in a method of enhancing the tonal and chrominance characteristics of a digital image, comprising the steps of:

[0012] a) receiving a source digital image including a plurality of pixels wherein the source digital image is in a luminance-chrominance representation having a luminance digital image channel and at least two chrominance digital image channels;

[0013] b) producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image;

[0014] c) classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

[0015] d) using the tone scale function and the luminance digital image channel to produce an enhanced luminance digital image channel; and

[0016] e) amplifying the chrominance digital image channels to produce modified chrominance digital channels when the tone scale function has been classified as expansive.

[0017] By practicing the present invention, the color characteristics of the digital image are significantly enhanced when also applying a tone scale function.

[0018] The present invention facilitates using functions that are either compressive or expansive to improve image luminance and color contrast wherein the color contrast characteristics are amplified when the applied tone scale function has been classified as expansive and are not amplified when the applied tone scale function has been classified as compressive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] **FIG. 1** is a functional block diagram showing the component parts of a system implementation of the present invention;

[0020] **FIG. 2** is a functional block diagram of the digital image processor;

[0021] **FIG. 3***a* is a graph of an example of a rendering function;

[0022] **FIG. 3***b* is a graph of another example of a rendering function;

[0023] **FIG. 4** is a functional block diagram of the tone scale module;

[0024] **FIG. 5** is a functional block diagram of the tone scale function applicator;

[0025] **FIG. 6***a* is a functional block diagram of the compressive function applicator;

[0026] **FIG. 6***b* is a functional block diagram of the expansive function applicator;

[0027] **FIG. 7**. is a graph illustrating a family of highlight tone scale segments and a family of shadow tone scale segments;

[0028] **FIG. 8***a* is a graph of an example of a compressive highlight component function and its corresponding slope function;

[0029] **FIG. 8***b* is a graph of an example of a compressive shadow component function and its corresponding slope function;

[0030] **FIG. 8***c* is a graph of an example of a tone scale function constructed from a compressive highlight and shadow tone scale segment and its corresponding slope function;

[0031] **FIG. 9** is a graph illustrating a family of highlight tone scale segments and a family of shadow tone scale segments constructed;

[0032] **FIG. 10***a* is a graph illustrating the construction details of an expansive highlight component function;

[0033] **FIG. 10***b* is a graph illustrating the construction details of an expansive shadow component function;

[0034] **FIG. 10***c* is a graph of an example of a tone scale function constructed from an expansive highlight and shadow tone scale segment and its corresponding slope function;

[0035] **FIG. 11** is a graph illustrating a family of highlight tone scale segments and a family of shadow tone scale segments;

[0036] **FIG. 12***a* is a graph illustrating a family of highlight tone scale segments and a family of shadow tone scale segments for both compressive and expansive type functions;

[0037] **FIG. 12***b* is another graph illustrating a family of highlight tone scale segments and a family of shadow tone scale segments for both compressive and expansive type functions; and

[0038] **FIG. 13** is a graph illustrating an example image histogram function and its corresponding cumulative histogram function.

DETAILED DESCRIPTION OF THE INVENTION

[0039] In the following description, a preferred embodiment of the present invention will be described as a software program. Those skilled in the art will readily recognize that the equivalent of such software may also be constructed in hardware. Because image processing algorithms and systems are well known, the present description will be directed in particular to algorithms and systems forming part of, or cooperating more directly with, the method in accordance with the present invention. Other aspects of such algorithms and systems, and hardware and/or software for producing and otherwise processing the image signals involved therewith, not specifically shown or described herein, may be selected from such systems, algorithms, components and elements thereof known in the art. Given the description as set forth in the following specification, all software implementation thereof as a computer program is conventional and within the ordinary skill in such arts.

[0040] Still further, as used herein, the computer program may be stored in a computer readable storage medium, which may comprise, for example: magnetic storage media such as a magnetic disk (such as a floppy disk) or magnetic tape; optical storage media such as an optical disc, optical tape, or machine readable bar code; solid state electronic storage devices such as random access memory (RAM), or

read only memory (ROM); or any other physical device or medium employed to store a computer program.

[0041] A digital image is comprised of one or more digital image channels. Each digital image channel is comprised of a two-dimensional array of pixels. Each pixel value relates to the amount of light received by the imaging capture device corresponding to the geometrical domain of the pixel. For color imaging applications, a digital image will typically consist of red, green, and blue digital image channels. Other configurations are also practiced, e.g. cyan, magenta, and yellow digital image channels. For monochrome applications, the digital image consists of one digital image channel. Motion imaging applications can be thought of as a time sequence of digital images. Those skilled in the art will recognize that the present invention can be applied to, but is not limited to, a digital image channel for any of the above mentioned applications.

[0042] Although the present invention describes a digital image channel as a two-dimensional array of pixels values arranged by rows and columns, those skilled in the art will recognize that the present invention can be applied to mosaic (non-rectilinear) arrays with equal effect.

[0043] The present invention may be implemented in computer hardware. Referring to **FIG. 1**, the following description relates to a digital imaging system which includes an image capture device **10**, a digital image processor **20**, image output devices **30***a* and **30***b*, and a general control computer **40**. The system may include a monitor device **50** such as a computer console or paper printer. The system may also include an input control device **60** for an operator such as a keyboard and or mouse pointer. Still further, as used herein, the present invention may be implemented as a computer program and may be stored in a computer memory device **70**, i.e. a computer readable storage medium, which may comprise, for example: magnetic storage media such as a magnetic disk (such as a floppy disk) or magnetic tape; optical storage media such as an optical disc, optical tape, or machine readable bar code; solid state electronic storage devices such as random access memory (RAM), or read only memory (ROM); or any other physical device or medium employed to store a computer program. Before describing the present invention, it facilitates understanding to note that the present invention is preferably utilized on any well known computer system, such as a personal computer.

[0044] Multiple image capture devices **10***a*, **10***b*, and **10***c* are shown illustrating that the present invention can be used for digital images derived from a variety of imaging devices. For example, **FIG. 1** can represent a digital photofinishing system where the image capture device **10***a* may be a film scanner device which produces digital images by scanning a conventional photographic image, e.g. color negative film or slide film transparencies. Similarly, image capture device **10***b* could be a digital camera. The digital image processor **20** provides the means for processing the digital images to produce pleasing looking images on an intended output device or media. Multiple image output devices **30***a* and **30***b* are shown illustrating that the present invention may be used in conjunction with a variety of output devices which may include a digital photographic printer and soft copy display. It should also be noted that the present invention can be implemented within the hardware and software of a digital camera such that the digital images produced by the digital camera have been processed with the present invention prior to being exported by the digital camera.

[0045] The digital image processor **20** depicted in **FIG. 1** is illustrated in more detail in **FIG. 2**. The cascaded image processing modules shown in **FIG. 2** represents a digital image processing path. An original digital image **101** is received from one of the image input devices shown in **FIG. 1** and processed to produce a rendered digital image **103** that can be realized on an image output device. A RLSE (relative log scene exposure) conversion module **310** receives the original digital image **101** and generates an RLSE digital image that is prepared for balancing and the application of a tone scale function. A scene balance module **320** receives the RLSE digital image and performs a lightness and color balance adjustment resulting in a source digital image. A tone scale module **330** receives the source digital image, generates a tone scale function from the source digital image and applies the tone scale function to the source digital image resulting in an enhanced digital image. If the RLSE conversion module **310** and the scene balance module **320** are omitted from the image processing path of modules, the tone scale module **330** receives the original digital image **101** directly as the source digital image. A rendering module **340** processes the enhanced digital image such that the pixel values of the generated rendered digital image **103** have been prepared to yield a pleasing result when used in conjunction with an output image device such as a digital printer. As part of the processing performed by the rendering module **340**, a rendering function R(x) is applied to the pixel data of the enhanced digital image to achieve the input to output pixel mapping required of the output image device. The configuration of processing modules shown in **FIG. 2** is used for processing digital images that are either monochrome or color in nature. That is, the original digital image **101** includes one or more digital image channels of pixels wherein each digital image channel relates to a different color or pixels such as, an original digital image **101** that includes red, green, and blue representation or a luminance-chrominance representation.

[0046] The tone scale functions produced are designed to work best with digital images that are in a relative log scene exposure representation (RLSE). That is, the pixels of the original digital image **101** have a logarithmic relationship with respect to the original scene intensities of light from which the original digital image **101** is derived. For example, the image capture device **10***a* shown in **FIG. 1** can represent a photographic film scanner that produces digital images that have a linear or logarithmic relationship with the amount of transmitted light projected through a photographic negative or positive film transparency sample. If the pixels values of the resultant original digital image **101** have a logarithmic relationship with the received light (i.e. the pixels are in a density representation), the original digital image **101** is considered to be in a relative log scene exposure representation. If the pixels of the original digital image **101** have a linear relationship with the received light, the original digital image **101** is considered to be in a linear exposure representation since, to within a reasonable approximation, the amount of light transmitted through the photographic film sample is linearly proportional to the amount of light received from the original photographed scene. A linear exposure representation digital image can be transformed into a relative log scene exposure representation

by a linear-to-logarithmic transform implemented as function or as look-up-table (LUT) with the RLSE module **310** shown in **FIG. 2**.

[**0047**] The most common representation of digital images produced with digital cameras is a rendered representation, i.e. the digital image has been processed such that it will be yield a natural appearing image on an electronic display device. For most digital images produced with digital cameras the intended output image device is a CRT monitor device sometimes referred to as a gamma domain representation. Rendered digital images can also be transformed into a relative log scene exposure representation using a LUT transform. For digital images produced with digital cameras, the transform includes an inverse of the power law function associated with the intended electronic display device followed by an inverse rendering tone scale function related to the rendering tone scale function that the digital camera used to produce the original digital image **101**. Alternatively, the method disclosed by McCarthy et al. in commonly-assigned U.S. Pat. No. 6,282,311 can be used to produce an RLSE representation from a rendered digital image.

[**0048**] While the best results are achieved with digital images that are in a relative log scene exposure representation, the present invention can be used to enhance the appearance of digital images that are in other representations such as linear and gamma domain representations described above. In particular, the present invention can be used to process digital images that are in a visual domain such as CIELAB (one of the color spaces defined by the International Commission on Illumination abbreviated as CIE).

[**0049**] The scene balance module **320** receives the RLSE digital image from the RLSE conversion module **310** and performs a lightness and color balance adjustment. The resulting processed digital image is called the source digital image since it is the input digital image to the tone scale module **330**. The lightness adjustment to the pixel data accounts for exposure variability in the original digital image **101**. The present invention can be used with any algorithm that performs a lightness adjustment, or luminance balance, of the input pixel data. In particular, the lightness balance procedure includes calculating one or more prediction features from the RLSE digital image. These predication features are combined using a linear equation of the prediction features into a single brightness balance value that relates to an estimate of the pixel value corresponding to a theoretical 18% gray scene reflector. While there are many such prediction features that are useful, the present invention uses a spatial activity measure as the most important prediction feature. An RLSE luminance-chrominance digital image is generated from the RLSE digital image. Next, a spatial activity filter is applied to the luminance pixel data of the RLSE luminance-chrominance digital image. The spatial activity filter calculates the minimum difference of adjacent pixel values within a 3 by 3 pixel region and assigns the minimum difference to the pixel. Pixels with minimum difference values that exceed a predetermined threshold are averaged to produce the first prediction feature. The second prediction feature is calculated by dividing the luminance pixels of the RLSE luminance-chrominance digital image into four strips and calculating the average the maximum pixel value from each of the four strips. Other prediction features that have proved to be useful are the average pixel value and the 90% cumulative histogram pixel value.

[**0050**] After the brightness balance value of the RLSE digital image has been calculated, the color cast of the RLSE digital image is calculated that can be used to remove an overall color cast. The principle causes of color casts are variation in the color of the source illumination and secondarily the color fidelity of the image sensor that recorded the original digital image. A color balance position is calculated for the RLSE digital image which represents the chrominance coordinates of a theoretical color-neutral scene reflector. The color balance position is calculated using a two dimensional Gaussian weighting surface applied to the chrominance pixel data of the RLSE luminance-chrominance digital image. Although the chrominance pixel data can be averaged in an unweighted manner, better results have been obtained using the two dimensional Gaussian weighting surface. This is principally due to the de-emphasis of highly colorful scene objects from the calculation. A balance look-up-table is calculated for each color of the RLSE digital image using the calculated color balance position and the brightness balance value. The balance look-up-table is applied to the RLSE digital image to produce the source digital image for the tone scale module **330**. As a result of the application of the balance look-up-table, pixel values in the RLSE digital image that have a value equal to the predicted balance value are transformed to a value equal to a system defined reference gray point. Similarly, pixels with corresponding chrominance values that correspond to the color balance position will be transformed to a color neutral position.

[**0051**] It should be noted that it is also possible to combine the operation of the lightness balance procedure described above with the construction of the tone scale function described in later detail below. The lightness balance operation is equivalent to adjusting the reference gray point used in the construction of the tone scale function. If the lightness balance operation is combined with the construction of the tone scale function, the reference gray point is image dependent since the pixels of the digital image being processed are used to calculate the reference gray point.

[**0052**] The rendering module **340** accepts the enhanced digital image from the tone scale module **330** and prepares the pixel data for display on an output image device. The rendering module **340** performs a color transformation, a tonal rendering transformation, and an output encoding transformation. The pixel data must be transformed such that the pixel data representing different original scene colors are appropriate for the color spectral characteristics associated with the output image device. This can be accomplished in a multiple step procedure. First the RLSE representation pixel data of the enhanced digital image is transformed into a linear representation. Next a color matrix transform is applied to the linear representation pixel data. The color matrix can be a 3 by 3 element matrix wherein the elements of the matrix are determined by analyzing a collection of imaged color patch targets and measuring the resultant color produced with the intended output image device.

[**0053**] The other task includes the transformation of the pixel data from the linear or relative-log-scene -exposure representation to a rendered representation with the appli-

cation of a rendering function R(x). In general, the dynamic range of the enhanced digital image is much larger than can be displayed on typical output image devices such as CRT monitors or photographic paper. Therefore, if the pixel data of the enhanced digital image were received by the output image device directly, much of the pixel data would be clipped in the extreme light and dark parts of the image with a substantial loss of spatial detail. The rendering function performs a graceful roll-off of the pixel data such that the processed pixel data when displayed will result in a gradual loss of spatial detail as pixel values approach the limits of the output image device.

[**0054**] The present invention can be used with many different mathematical forms for the rendering function such as a rendering function produced with the method disclosed in commonly-assigned U.S. Pat. No. 5,300,381 by Buhr et al. In general, optimal results are obtained using rendering functions that have a sigmoid shape, i.e., rendering functions having a zero or near slope for extreme input pixel values and having a maximum magnitude slope that is achieved for mid-tone input values. Some rendering functions can have a relatively high slope for the darkest domain of input pixel values but many rendering functions have a zero or near zero slope characteristic for the lightest domain of pixel values. The rendering function, to an extent, mimics the photo response characteristics of photographic paper used in analog imaging applications.

[**0055**] Although it is possible to use a rendering function that is dependent on the digital image being processed, the preferred embodiment of the present invention uses a sigmoid shaped rendering function that is independent of the digital image. Image dependent modification to the digital image being processed is performed by the tone scale module **330** prior to the application of the rendering function. Thus, the tone scale module **330** is responsible for scene dependent changes to the image content while the rendering module **340** is responsible for preparing the final processed image for an image output device.

[**0056**] **FIG. 3***a* shows a graph of an example rendering function R(x) (indicated by curve **590**) that is suitable for use with the present invention. Point **591** corresponds to an input pixel value equal to the reference gray point. Point **592** indicates the rendering function response for a highlight pixel value corresponding to a light region in the original digital image **101**. Point **593** indicates the rendering function response for a shadow pixel value corresponding to a dark region in the original digital image **101**. Point **595** indicates the rendering function response corresponding to brightest reproduced output value of the output image device. Similarly, point **596** indicates the rendering function response corresponding to darkest reproduced output value of the output image device. Point **597** indicates the point on the rendering function for which the instantaneous slope has a maximum magnitude which does not necessarily coincide with the reference gray point **591**. The point of maximum magnitude slope is also the inflection point of the sigmoid function, i.e. a local maximum or minimum in the corresponding slope function of the rendering function R(x). The example rendering function shown in **FIG. 3***a* is appropriate for a digital imaging system that uses a 12-bit pixel value representation for processing digital images. Many output display devices accept digital images with an 8-bit pixel value representation. The example rendering function shown in **FIG. 3***a* maps 12-bit input pixel values ranging from 0 to 4095 to output rendering pixel values ranging from 255 to 0.

[**0057**] The example rendering function shown in **FIG. 3***a* is typical for use with a digital printer that produces digital photographic prints. The output pixel value scale shown can relate to photographic paper densities, e.g. the digital printer can be calibrated such that each pixel code value is equal to 100 times the optical density that will be produced on the print. However, the present invention can also be used with electronic display devices. A typical rendering function for use with an electronic display device is shown in **FIG. 3***b* as indicated by curve **598**. Note that the rendering function R(x) shown in **FIG. 3***b* produces higher numerical output rendering pixel values for higher numerical input pixel values. For a typical computer monitor device, the output pixel values will range from 0 (representing black) to 255 (representing white). The example rendering function shown in **FIG. 3***b* maps 12-bit input pixel values ranging from 0 to 4095 to output rendering pixel values ranging from 0 to 255.

[**0058**] The last operation performed by the rendering module **340** is the encoding of the output pixel values for use with an output image device. Most output image devices are calibrated to accept pixel data with a known implied relationship. For example, some digital image printers are calibrated to accept visual lightness related pixel data while other devices are calibrated for optical density related pixel data. The encoding operation performs an intensity transformation that prepares the pixel data for the specific device.

[**0059**] The rendering module **340** can also perform the operation of preparing the image pixel data of the enhanced digital image for an unspecified output image device. For example, the pixel data can be transformed into CIE XYZ coordinates such as defined by the International Image Consortium's Profile Connection Space.

[**0060**] Referring to **FIG. 2**, the chain of image processing modules is designed to work well with or without the inclusion of the tone scale module **330**. The scene balance module **320** accommodates exposure and illumination system variability. The rendering module **340** prepares the image data for viewing on an output image device. It will be appreciated by those skilled in the art that the digital image processor **20** as depicted in **FIG. 2** without the use of the tone scale module **330** will yield acceptable photographic results. That is, the contrast, lightness, and color reproduction of the system are set for optimal photographic results for the majority of typical digital images. The inclusion of the tone scale module **330** enhances the appearance of the processed digital images such that digital images that deviate from the norm, in terms of dynamic range, will be tonally enhanced and digital images that are at the norm for the system will be unaltered by the tone scale module **330**. For a typical implementation of the present invention, the dynamic range of the original digital images **101** (ratio of corresponding original scene intensities based on the extremes of the image) is approximately 64 to 1. The enhanced digital images corresponding to processed original digital images **101** that have approximately a 64 to 1 dynamic range will be little affected by the tone scale module **330**. Conversely, the enhanced digital images corresponding to processed original digital images **101** that have a dynamic range greater than 64 to 1 and less than 64 to 1 can be significantly enhanced by the tone scale module

330, i.e. rendered with more detail and more color saturation. In particular, low contrast original digital image will, in general, experience a contrast gain, while high contrast original digital images will, in general, experience a reduction in contrast resulting in more spatial detail and more saturated color.

[**0061**] The tone scale module **330** depicted in **FIG. 2** is illustrated in more detail in **FIG. 4**. A source digital image **102** is received by the analysis image generator **250**, which produces a lower spatial resolution digital image from source digital image **102** called an analysis digital image **201**. The tone scale function generator **230** receives the analysis digital image **201**, analyzes the content of the analysis digital image **201**, and produces the tone scale function **203**. The tone scale function **203** is a single valued function that is defined for the range of pixel values in the source digital image **102**. The tone scale function applicator **240** applies the tone scale function **203** to the source digital image **102** to generate the enhanced digital image **104**. The shape of the tone scale function **203** determines the contrast and lightness changes that will be imparted to an enhanced digital image **104**.

[**0062**] A tone scale function applicator **240** shown in **FIG. 4** is shown in more detail in **FIG. 5**. A tone scale function classifier **241** receives and analyzes the tone scale function **203**. The tone scale function **203** is classified into one of two or more categories based on the effect the tone scale function **203** will have on the numerical range of pixel values of a processed digital image. In a preferred embodiment, the tone scale function **203** is classified as a compressive function or an expansive function. The tone scale function **203** is classified as a compressive function if the range of output numerical pixel values is less than the range of input numerical pixel values. Conversely, the tone scale function **203** is classified as an expansive function if the range of output numerical pixel values is greater than the range of input numerical pixel values. The tone scale function classifier **241** also receives an input digital image **401**. If the tone scale function **203** is classified as a compressive function, the input digital image **401** and the tone scale function **203** are directed to a compressive function applicator **242**. Similarly, if the tone scale function **203** is classified as an expansive function, the input digital image **401** and the tone scale function **203** are directed to the expansive function applicator **242**. Therefore, either the compressive function applicator **242** or a expansive function applicator **244** is used to process the input digital image **401** to produce an output digital image **409** which is the enhanced digital image **104** shown in **FIG. 4**. In particular, the compressive function applicator **242** uses the tone scale function **203**, the input digital image **401**, and a spatial filter to generate an output digital image **409** when the tone scale function has been classified as compressive, and the expansive function applicator **244** uses the tone scale function **203** and the input digital image **401** without a spatial filter to generate the output digital image **409** when the tone scale function **203** has been classified as expansive.

[**0063**] While the present invention can be used with any method of generating a tone scale function, the preferred embodiment uses tone scale functions that are constructed from two tone scale segments. However, regardless of the tone scale function construction method, the tone scale function is classified as either compressive or expansive. The present invention can be used with any tone scale function classification method. For example, the average slope of the tone scale function **203** can be calculated and compared with a pre-determined threshold value. If the average slope is greater than the pre-determined threshold the tone scale function **203** is classified as an expansive function. Otherwise the tone scale function **203** is classified as a compressive function.

[**0064**] The preferred embodiment of the present invention uses a histogram based method for determining the tone scale function classification. The input digital image **401** is analyzed by calculating a histogram function of the luminance pixel information, i.e. a frequency of occurrence function. The cumulative 1.0 and 99.0 fixed percentile luminance pixel values are calculated from the histogram function and denoted by P_1 and P_{99} respectively. The value of the corresponding output pixel values produced with the tone scale function **203** are recorded as T_1 and T_{99} respectively. The tone scale function **203** is classified as a compressive function if the difference between T_{99} and T_1 is less than or equal to the difference between P_{99} and P_1. Otherwise the tone scale function **203** is classified as an expansive function. Other classification rules can also be used to classify the tone scale function **203**. For example, the tone scale function **203** can be classified as expansive only if the ratio of the difference between the T_{99} and T_1 relative to the difference between the difference between P_{99} and P_1 exceeds a predetermined threshold value.

[**0065**] The compressive function applicator **242** shown in **FIG. 5** is shown in more detail in **FIG. 6***a*. A LCC conversion module **210** receives the input digital image **401** in the form of a red-green-blue image representation and generates a luminance digital image **107** and a chrominance digital image **109**. A pedestal generation module **410** receives the luminance digital image **107** and produces A pedestal digital image **403**. The pedestal generation module **410** employs a spatial filter, applied to the luminance digital image **107**, that removes texture from the luminance digital image **107** but leaves edge information. In the context of the present invention, texture refers to image content including fine spatial detail and spatial shading structure. As a natural consequence of the filter, noise is also removed. Thus the pedestal digital image **403** is a highly smoothed version of the luminance digital image **107** with much of the edge content of the luminance digital image **107**. The pedestal digital image **403** is subtracted from the luminance digital image **107** by a difference module **420** resulting in a texture digital image **402**. It will be appreciated that all of the information of the luminance digital image **107** is contained between the pedestal digital image **403** or the texture digital image **402**. A tone scale modifier **430** applies the tone scale function **203** directly to the pixels of the pedestal digital image **403** resulting in a tone adjusted digital image **407**. Therefore, the tonal characteristics of the pedestal digital image **403** are enhanced by the application of the tone scale function **203** without affecting the texture content of the luminance digital image **107**. An addition module **440** combines the tone adjusted digital image **407** with the texture digital image **402** to produce an enhanced luminance digital image **113**. Therefore, the enhanced luminance digital image **113** is a tone scale enhanced version of the luminance digital image **107** that has the texture image structure content of the luminance digital image **107**. An RGB conversion module **220** receives the enhanced luminance digital

image **113** and the chrominance digital image **109** and produces the output digital image **409**.

[**0066**] Applying a tone scale function by using a spatial filter is particularly advantageous when the tone scale function is compressive. When compressive tone scale functions are applied directly to an input digital image, the tonal characteristics will be enhanced but the texture image structure can be diminished in magnitude. Using a spatial filter to apply the tone scale function can achieve the desired tone scale enhancement while maintaining the texture image structure. A variety of spatial filters can be used to achieve an improved result. The present invention uses the spatial filter disclosed in commonly-assigned U.S. Pat. No. 6,317,521 by Gallagher and Gindele which employs the use of a control, or masking, signal to preserve the edges in the pedestal digital image **403**. In this method, the spatial filter produces a first signal containing predominantly low-pass spatial frequency information (the pedestal digital image **403**) and second signal containing predominantly high-pass spatial frequency information (the texture digital image **402**) from the luminance digital image channel such that when the first and second signals are added together the resultant signal would be equal to the luminance digital image channel. This separation of signals is accomplished with a non-linear operation that modifies the spatial filtering based on detecting edges within a low-pass frequency version of the luminance information. The tone scale function **203** is then applied to the first signal to produce a modified first signal. The modified first signal is then combined with the second signal to produce a modified luminance digital image channel.

[**0067**] The present invention can also be used with a similar method disclosed by Lee in commonly-assigned U.S. Pat. No. 6,285,798. Another spatial filter that can be employed is a simple low-pass filter, such as a two dimensional Gaussian filter. However, if a low-pass filter is used, the dimension of the Gaussian standard deviation parameter should be very large, e.g. one quarter of the dimension of the digital image being processed.

[**0068**] It should also be noted that the input digital image **401** input to the compressive function applicator **242** can be processed with the spatial filtering technique directly in a red-green-blue image representation. For this embodiment, the red, green, and blue color digital image channels of the input digital image **401** are spatially filtered individually using the spatial filter described above to produce a first and second signal for each digital image channel. The first and second signal for each digital image channel when added together result in a signal equal to the unfiltered digital image channel. The tone scale function **203** is then applied to the first signal corresponding to each digital image channel to produce a modified first signal. The modified first signal from each digital image channel is then combined with the corresponding second signal to produce a modified digital image channel of each color wherein the modified digital image channels constitute the enhanced digital image **104**.

[**0069**] It is important to note that for tone scale functions classified as compressive functions the chrominance characteristics (the color characteristics apart from the luminance characteristics) of the enhanced digital image **104** are essentially the same as the source digital image **102**. This is true for both the methods of applying the tone scale function **203** to a red-green-blue image representation and applying the tone scale function **203** to a luminance-chrominance image representation. In general, compressive tone scale functions are applied to enhance the luminance characteristics of a digital image. Therefore, the is no need to modify the chrominance characteristics of the processed digital images in a manner related to the nature of the applied compressive tone scale function. This should not be interpreted to imply that no further color enhancement to the enhanced digital image **104** is necessary or advantageous. However, no further processing of the chrominance characteristics are necessary to compensate for the applied compressive tone scale function.

[**0070**] The expansive function applicator **244** shown in **FIG. 5** is shown in more detail in **FIG. 6***b*. The LCC conversion module **210** receives the input digital image **401** in the form of a red-green-blue image representation and generates a luminance digital image **107** containing one digital image channel and a chrominance digital image **109** containing two digital image channels. The tone scale modifier **430** applies the tone scale function **203** directly to the pixels of the luminance digital image **107** resulting in the enhanced luminance digital image **113**. Therefore, the tonal characteristics of the luminance digital image **107** are enhanced by the application of the tone scale function **203** while also amplifying the texture content of the luminance digital image **107**. A chrominance modifier **432** receives the tone scale function **203**, the luminance digital image **107**, and the chrominance digital image **109** and amplifies the chrominance pixel values in accordance with the tone scale function **203**. Specifically, the chrominance modifier **432** first calculates a corresponding slope function s( ) for the received tone scale function **203**. Next a chrominance amplification factor $s(\alpha)$ is calculated for each luminance pixel value (λ) given expression (1)

$$\alpha(\lambda)=\mu(s(\lambda)-1.0)+1.0 \quad (1)$$

[**0071**] where the parameter μ regulates the degree of chrominance amplification. For example, if the parameter μ is set to 1.0, the chrominance pixel values will be amplified by the same degree as the luminance pixel values. That is, the luminance contrast is increased by the same percentage as the color contrast. If the μ parameter is set to zero, the chrominance pixel values will remain the same and there will be no color contrast amplification. Through experimentation, the preferred value for the μ parameter has been determined to be 0.5. By setting the μ parameter to 0.5, low contrast images can be enhanced by an expansive tone scale function without excessively amplifying the color. This is particularly useful for enhancing low contrast images that contain faces.

[**0072**] For digital imaging applications that require or desire a high degree of chrominance amplification (approximately equivalent to using parameter μ=1.0 in Equation (1) above), an alternative embodiment of the expansive function applicator can be used. For this alternative embodiment, the LCC conversion module **210** and the RBG conversion module **220** shown in **FIG. 6***b* can be omitted. The tone scale modifier **430** receives the input digital image **401** directly in a red-green-blue image representation and produces the output digital image **409**. For this alternative embodiment of the expansive function applicator **244**, the corresponding slope function does not need to be calculated.

If the input digital image **401** is received in an LCC representation, the expansive function applicator **244** first converts the input digital image **401** into an RGB representation and then applies the tone scale function **203** directly to each digital image channel of the RGB representation of the input digital image **401**. If the input digital image **401** is received in a red-green-blue representation, the expansive function applicator **244** applies the tone scale function **203** directly to each digital image channel of the input digital image **401** and the compressive function applicator **242** performs the image processing steps as described above.

[**0073**] In a still further alternative embodiment, the input digital image **401** is received in a multi-color image representation, such as a red-green-blue representation, and both the compressive function applicator **242** and the expansive function applicator **244** operate on the red-green-blue image pixel data. In this alternative embodiment, the expansive function applicator **244** applies the tone scale function **203** to the individual digital image channels of the multi-color representation input digital image **401**. However, the compressive function applicator **242** uses the spatial filtering method described above to separate each of the digital image channels into two signals. That is, a first signal that includes mostly low-spatial frequency information and a second signal that includes mostly high-spatial frequency information. The tone scale function **203** is applied to the first signal part derived from each digital image channel to produce a modified first signal. The output digital image **409** is generated by combining the modified first signal with the second signal resulting in a modified multi-color representation digital image. The process of applying the tone scale function **203** to each channel of a multi-color representation digital image with a spatial filter preserves both the color contrast and spatial detail when the applied tone scale function is a compressive function. The process of applying the tone scale function **203** to each channel of a multi-color representation digital image without a spatial filter amplifies both the color contrast and spatial detail when the applied tone scale function is an expansive function.

[**0074**] Thus it will be appreciated that for tone scale functions that have been classified as expansive, the chrominance characteristics (also referred to as the color contrast) of the resultant enhanced digital image **104** are amplified relative to the source digital image **102**. This is true for all the embodiments of the present invention described herein. For example, in the preferred embodiment, the tone scale function **203** is applied to the luminance digital image and the chrominance digital image channels are amplified directly when the tone scale function is classified as an expansive function. In the alternative embodiment, the tone scale function **203** is applied directly to a red-green-blue image representation digital image when the tones scale function is classified as an expansive function. In the latter case, the chrominance characteristics are amplified by virtue of the expansive nature of the tone scale function **203**.

[**0075**] It will also be appreciated that the number of digital image channels of a digital image to be processed can vary based on the classification of the applied tone scale function. For example, when the tone scale function **203** has been classified as a compressive function, the tone scale function can be applied to just a luminance digital image channel. However, when the tone scale function **203** has been classified as an expansive function, the tone scale function **203** can be applied to multiple digital image channels of a multi-color representation digital image. Conversely, as described above, the tone scale function **203** can be applied to multiple digital image channels of a multi-color representation digital image using a spatial filter when the tone scale function **203** has been classified as a compressive function and only the luminance digital image channel tone scale function **203** has been classified as an expansive function.

[**0076**] The LCC module **210** shown in **FIG. 6***a* and **FIG. 6***b* employs a 3 by 3 element matrix transformation to convert the red, green, and blue pixel values of the source digital image **102** into luminance and chrominance pixel values. Let the variables R_{ij}, G_{ij}, and B_{ij} refer to the pixel values corresponding to the red, green, and blue digital image channels located at the ith row and j^{th} column. Let the variables L_{ij}, GM_{ij}, and ILL_{ij} refer to the transformed luminance, first chrominance, and second chrominance pixel values respectively of an LCC representation digital image. The 3 by 3 elements of the matrix transformation are described by (2).

$$L_{ij}=0.333\,R_{ij}+0.333\,G_{ij}+0.333\,B_{ij} \quad (2)$$
$$GM_{ij}=-0.25\,R_{ij}+0.50\,G_{ij}-0.25\,B_{ij}$$
$$ILL_{ij}=-0.50\,R_{ij}+0.50\,B_{ij}$$

[**0077**] The RGB conversion module **220** shown in **FIG. 6***a* and **FIG. 6***b* employs a 3 by 3 element matrix transformation to convert the luminance and chrominance pixel values into red, green, and blue pixel values by performing the inverse matrix operation to the LCC conversion module **210**. The matrix elements of the RGB conversion module are given by (3) and represents the inverse matrix of the matrix given by (1).

$$R_{ij}=L_{ij}-0.666\,GM_{ij}-ILL_{ij} \quad (3)$$
$$G_{ij}=L_{ij}+1.333\,GM_{ij}$$
$$B_{ij}=L_{ij}-0.666\,GM_{ij}+ILL_{ij}$$

[**0078**] A tone scale function generator **230** shown in **FIG. 4** is described in more detail hereinbelow. The tone scale function generator **230** can be used in either an automatic mode, wherein the tone scale function **203** is calculated using the pixels of the analysis digital image **201**, or in a manual mode, wherein the tone scale function **203** is calculated using user input selections **231** provided via a graphical user interface.

[**0079**] The tone scale function **203**, is a single valued function, i.e. one output pixel value for each input pixel value, defined for the range of pixels values in the source digital image **102**. The shape of the tone scale function **203** is important since the shape determines the effect on the processed digital images. The tone scale function **203** is constructed from two function segments wherein the two function segments share just one input pixel value in common. A reference gray point pixel value corresponding to an 18% scene reflector is defined as the input pixel value in common that divides the function domain into the two tone scale segments. The function segment relating to the brighter image regions, i.e. image regions corresponding to bright regions of the original photographed scene, is called the highlight tone scale segment. The function segment relating to the darker image regions, i.e. image regions corresponding to dim regions of the original photographed scene, is called the shadow tone scale segment. It should be noted that

the tone scale function **203** is a continuous function insofar as the implementation in computer software and/or hardware will allow. It should also be noted that the tone scale function **203** can have a continuous first derivative.

[**0080**] An important aspect of the construction of the tone scale function **203** is the use of a different mathematical function for two different tone scale segments. Using a different mathematical function for each tone scale segment allows the tone scale function **203** to be independently controllable in each of the tone scale segments allowing for a greater degree of customization for the digital image to be processed.

[**0081**] The pixel polarity of a digital image used in a digital imaging system is an arbitrary decision made by the system architect. For example, positive pixel polarity digital images have pixels wherein higher numerical values relate to more light having been received. Conversely, negative pixel polarity digital images have pixels wherein higher numerical values relate to less light having been received. The present invention can be used with digital images of either pixel polarity. However, in the interest of clarity, the following description will assume a positive pixel polarity convention. Those skilled in the art will recognize that references made to the increasing or decreasing function slope values are with respect to positive pixel polarity digital images. The description of function slope characteristics must be reversed for systems using negative pixel polarity digital images. This is an important aspect of interpretation since mathematically an increasing or decreasing function is defined with respect to numerically increasing abscissa values. For example, in the description of the construction of the highlight and shadow component functions given hereinbelow, some shadow component functions are described as having a monotonically increasing slope property while some highlight component functions are described as having a monotonically decreasing slope property. This description is with regard to a positive pixel polarity convention. For a negative pixel polarity convention, the equivalent shadow component functions would be described as having a monotonically decreasing slope property while the equivalent highlight component functions would be described as having a monotonically increasing slope property. Similarly, for a positive pixel polarity convention, the tone scale function has a slope function that is always greater than or equal to zero. Conversely, or a negative pixel polarity convention, the tone scale function can have a slope function that is always less than or equal to zero.

[**0082**] The highlight tone scale segment is constructed from one or more component functions some of which satisfy the following constraints: 1) the component function can have a monotonically decreasing slope function for all input pixel values equal to or greater than the reference gray point, and 2) the component function can have a monotonically increasing function value for all input pixel values equal to or greater than the reference gray point and less than or equal to a maximum input pixel value expressed in the digital image. At the reference gray point, the two tone scale function segments can have the same value. A function is monotonic over a given domain if the function has constant sign (for digital implementations the slope function is taken as a reasonable approximation of the first derivative function). It should also be noted that the function characteristics for input pixel values greater than what is expressed in a particular image is an academic issue since no pixels will be affected. Both of the above mentioned constraints are important and require some explanation.

[**0083**] The highlight tone scale segment relates to the bright pixels, i.e. pixels relating to more light having been received. In general, for high dynamic range digital images the corresponding rendered digital images produced without the present invention have little or no spatial detail in the very brightest image regions. This is a consequence of the overall high system contrast required to pleasingly render digital images of average dynamic range. Therefore, for high dynamic range digital images some of the image content contained in the bright pixels cannot be rendered such that spatial detail modulation is preserved in the rendered digital image **103**. Improved spatial detail modulation can be achieved if the tone scale function **203** maps high input pixel values to lower output pixel values. This results in processed digital images with darker highlight content in the resultant rendered digital image **103**. There are many functions that can perform such an input to output mapping operation. However, monotonically increasing functions have been experimentally determined to be more robust, i.e. produce fewer image artifacts, than functions that are not monotonic.

[**0084**] While many monotonic functions can achieve the operation of mapping high input pixel values to lower output pixel values, all functions impose some form of compromise in contrast with regard to image regions corresponding to different average pixel values. In particular, the instantaneous slope value (first derivative) of the component functions used to construct the highlight tone scale segment can significantly affect the perception of contrast and spatial detail modulation in the resultant rendered digital image **103**. Therefore, the highlight tone scale segment constructed using component functions having a monotonically decreasing instantaneous slope value can improve the rendering of spatial detail modulation for bright image regions by mapping highlight pixels to lower output pixel values. Image regions corresponding to higher instantaneous slope values within the domain of the highlight tone scale segment tend to preserve more image detail modulation. Thus the monotonically decreasing instantaneous slope condition advantages image content corresponding to pixel values that are numerically closer in value to the reference gray point. In general, important image content, such as the main subject region, tends to be numerically closer to the reference gray point while background image content tends to be exhibited more uniformly with regard to pixel values.

[**0085**] Similarly, the shadow tone scale segment is constructed from one or more component functions some of which satisfy the following constraints: 1) the component function can have a monotonically increasing slope function for all input pixel values equal to or less than the reference gray point, and 2) the component function can have a monotonically increasing function value for all input pixel values equal to or less than the reference gray point and greater than or equal to a minimum input pixel value expressed in the digital image. Similarly, the monotonicity property of the component functions used to construct the shadow tone scale segment relates to more robust image quality results. The monotonically increasing slope function property of the component functions used to construct the shadow tone scale segment is similarly important since this condition also advantages image content corresponding to

pixel values that are numerically closer in value to the reference gray point. For high dynamic range images, the monotonically increasing slope function property of the component functions used to construct the shadow tone scale segment achieves a low input pixel value to higher output pixel value mapping operation. This results in processed digital images with lighter shadow content in the resultant rendered digital image **103**.

[**0086**] A natural consequence of the above mentioned slope function constraints produces tone scale functions that have high slope function values at the reference gray point. Therefore the choice of the reference gray point value is important since it determines which regions in images will experience high slope function values. A reference gray point value corresponding to an 18% gray scene reflector is chosen since it represents approximately the midpoint of perceptual lightness. Other choices for the value of the reference gray point can also produce excellent results. Reasonable values for the reference gray point range from a 10% scene reflector value to a 25% scene reflector value.

[**0087**] In a first embodiment of the tone scale function generator **230** shown in **FIG. 4**, either the highlight or the shadow tone scale segment is constructed using a single component function based on exponential functions. The component function used for the highlight tone scale segment is given by the formula (4)

$$f_{h1}(x)=\beta_{h1}(1-e^{-(x-x_\rho)/\alpha_{h1}})+x_\rho \quad (4)$$

[**0088**] where x_{92} represents the reference gray point, and β_{h1} and α_{h1} are numerical constants that determine the shape and slope of the component function $f_{h1}(x)$. The component function used for the shadow tone scale segment is given by the formula (5)

$$f_{s1}(x)=\beta_{s1}(1-e^{-(x-x_\rho)/\alpha_{s1}})+x_\rho \quad (5)$$

[**0089**] where β_{s1} and α_{s1} are numerical constants that similarly determine the shape and slope of the component function $f_{s1}(x)$. If a slope constraint of 1.0 is imposed at the reference gray point, the constants β_{h1} and β_{s1} are equal to α_{h1} and α_{s1} respectively. For this condition, the equations for the functions $f_{h1}(x)$ and $f_{s1}(x)$ are given as (6) and (7)

$$f_{h1}(x)=\alpha_{h1}(1-e^{-(x-x_\rho)/\alpha_{h1}})+x_\rho \quad (6)$$

$$f_{s1}(x)=\alpha_{s1}(1-e^{-(x-x_\rho)/\alpha_{s1}})+x_\rho \quad (7)$$

[**0090**] and the expression for the tone scale function **203** T(x) is given by (8).

$$T(x)=f_{h1}(x) \text{ for } x>=x_{92} \quad (8)$$

$$T(x)=f_{s1}(x) \text{ for } x<x_\rho$$

[**0091**] The highlight component function is constrained to pass through a specified coordinate point defined by an abscissa value x_{ho} that results in an ordinate value x_w as given by (9).

$$x_w=\alpha_{h1}(1-e^{-(x-ho-x_\rho)/\alpha_{h1}})+x_\rho \quad (9)$$

[**0092**] This constraint achieves a highlight white point mapping objective. For the highlight component function, the white point value x_w is predetermined based on the pixel value that is preferably mapped by the rendering function R(x) to correspond to a photographic paper density of approximately 0.2. With the variables x_w and x_ρ defined, the value of the variable α_{h1} can be solved for a given value of x_{ho} using expression (9) by an iterative numerical solution. Similarly, the shadow component function is constrained to pass through a specified coordinate point defined by an abscissa value x_{so} that results in an ordinate value x_b as given by (10).

$$x_b=\alpha_{s1}(1-e^{-x_{so}-x_\rho)/\alpha_{s1}})+x_\rho \quad (10)$$

[**0093**] This constraint achieves a shadow black point mapping objective. For the shadow tone scale function, the black point value x_w is predetermined based on the pixel value that is preferably mapped by the rendering function R(x) to correspond to a photographic black paper density of approximately 2.0. Generally speaking, the aforementioned white point value and dark point value represent first and second predetermined target densities or code values. While these target densities have been described with reference to density measurements of photographic paper, those skilled in the art will recognize that the same approach may be used even if the output device is not photographic paper (a computer monitor, for example.) With the variables x_b and x_ρ defined, the value of the variable α_{s1} can be solved for a given value of x_{so} using expression (10) by the iterative numerical solution. The iterative numerical solution for expressions (9) and (10) includes a process of first estimating an initial value of α_{s1}, calculating each side of the equation, calculating an error term as the difference, inspecting the error, making an adjustment to the estimate of α_{s1}, and iterating the procedure until the error term is of an acceptably low magnitude. The iterative solution results are computed for all possible values of α_{s1}, and stored in a LUT. The same calculations and procedure are used to determine the value of α_{h1}.

[**0094**] The variables x_{ho} and x_{so} are control variables in the expressions (9) and (10) that, once selected, determine the function shape and slope characteristics for expressions (6) and (7). **FIG. 7** shows a graph depicting a family of curves that represent highlight tone scale segments generated with different values of x_{ho} and a family of curves that represent shadow tone scale segments generated with different values of x_{so}. Point **500** represents the reference gray point x_ρ. Curve **501** represents a highlight tone scale segment constructed from one highlight component function. Curve **502** represents a shadow tone scale segment constructed from one shadow component function. Line **503** represents the one-to-one input-to-output line. For each of the highlight tone scale segments shown in **FIG. 7**, the highlight component function graphed has a monotonically decreasing instantaneous slope value. Similarly, for each of the shadow tone scale segments shown in **FIG. 7**, the component function graphed has a monotonically increasing instantaneous slope value. The variables x_{ho} and x_{so} can be selected independently. Thus the shape of the two tone scale segments can be controlled independent from one another.

[**0095**] The expressions (6) and (7) were derived with the constraint that the slope function (corresponding to the component function), when evaluated at the reference gray point, must be equal to 1.0. In another embodiment, exponential functions are used in similar fashion with a slope constraint imposed. The slope of the highlight component function must be equal to a selected value ϕ_h and the shadow component function must be equal to a selected value ϕ_s. For this embodiment, the imposed slope constraint results in a relationship between the variables β_{h1} and α_{h1} in expression (4) and β_{s1} and α_{s1} in expression (5) given by expressions (11) and (12) respectively.

$$\beta_{h1}=\phi_h\alpha_{h1} \quad (11)$$

$$\beta_{s1}=\phi_s\alpha_{s1} \quad (12)$$

[0096] The expressions for the highlight component function and the shadow component function are given by expressions (13) and (14) respectively.

$$f_{h1}(x)=\phi_h\alpha_{h1}(1-e^{-(x-x_\rho)/\alpha_{h1}})+x_\rho \quad (13)$$

$$f_{s1}(x)=\phi_x\alpha_{s1}(1-e^{-(x-x_\rho)/\alpha_{s1}})+x_\rho \quad (14)$$

[0097] The first derivative functions that represent the slope function of the highlight and shadow component functions are given by expressions (15) and (16) respectively.

$$f_{h1}'(x)=\phi_h e^{-(x-x_\rho)/\alpha_{h1}} \quad (15)$$

$$f_{s1}'(x)=\phi_s e^{-(x-x_\rho)/\alpha_{s1}} \quad (16)$$

[0098] If the value of x_{ho} is greater than the value of x_w, the highlight component function will map a greater range of input pixel values to a lesser range of output pixel values and is therefore considered a compressive function. Conversely, if the value of x_{ho} is less than the value of x_w, the highlight component function will map a lesser range of pixel values to a greater range of pixel values and is therefore considered an expansive function. Similarly, if the value of x_{so} is less than the value of x_b, the shadow component function will map a greater range of input pixel values to a lesser range of output pixels value and is therefore considered a compressive function. Conversely, if the value of x_{so} is greater than the value of x_b, the shadow component function will map a lesser range of pixel values to a greater range of pixel values and is therefore considered an expansive function. Therefore, based on the values of the variables x_{ho} and x_w, the highlight tone scale segment can be classified as compressive, expansive, or neutral. When the value x_{ho} is equal to the value of x_w, the highlight tone scale segment is classified as neutral since for this unique condition the highlight tone scale segment assumes the identity mapping function. Based on the values of the variables x_{so} and x_b, the shadow tone scale segment can be classified as compressive, expansive, or neutral. Similarly, when the value x_{so} is equal to the value of x_b, the shadow tone scale segment is classified as neutral since for this unique condition the shadow tone scale segment assumes the identity mapping function.

[0099] For compressive highlight component functions, the numerical constant α_{h1} is positive. The corresponding slope function of the highlight component function given by expression (15) for positive values of ϕ_h yields positive slope function values for all x values greater than or equal to the reference gray point x_ρ. The expression for the second derivative function, or the slope function of the slope function of the highlight component function is given by expression (17).

$$f_{h1}''(x)=-(\phi_h/\alpha_{h1})e^{-(x-x_\rho)/\alpha_{h1}} \quad (17)$$

[0100] **FIG. 8***a* shows an example graph of a highlight tone scale segment generated with a ϕ_h variable set to 1.0, a reference gray point set to 0.0 and a α_{h1} variable set to 1.0. As can be seen by inspection of the graph shown in **FIG. 8***a* and by expression (17), positive values of α_{h1} and ϕ_h result in a compressive highlight tone scale segment with a monotonically decreasing slope function that assumes values that are greater than or equal to zero. Curve **512** depicts such a highlight component function used to construct a highlight tone scale segment and curve **513** depicts its corresponding slope function. The reference gray point is indicated by point **511**.

[0101] Similarly, for compressive shadow component functions, the numerical constant α_{s1} is negative. The corresponding slope function of the shadow component function given by expression (16) for the positive values of ϕ_s yields positive slope values for all x values less than or equal to the reference gray point x_p. The expression for the second derivative function, or slope function of the slope function of the shadow component function is given by expression (18).

$$f_{s1}''(x)=-(\phi_s/\alpha_{s1})e^{-(x-x_\rho)/\alpha_{s1}} \quad (18)$$

[0102] **FIG. 8***b* shows an example graph of a shadow tone scale segment generated with a ϕ_s variable set to 1.0, a reference gray point set to 0.0 and a α_{s1} variable set to 1.0. As can be seen by inspection of the graph shown in **FIG. 8***b* and by expression (18), positive values of α_{s1} and ϕ_s result in a compressive shadow tone scale segment with a monotonically increasing slope function that assumes values that are greater than or equal to zero. Curve **515** depicts such a shadow component function used to construct a shadow tone scale segment and curve **516** depicts its corresponding slope function. The reference gray point is indicated by point **514**.

[0103] An example tone scale function **203**, shown in **FIG. 8***c*, was constructed from a highlight and shadow tone scale segment, each of which is constructed from a single component function as described above. The equal slope condition, as described above, is not a requirement of the tone scale functions generated by the present invention. In the example tone scale function shown in **FIG. 8***c*, the slopes of the highlight and shadow tone scale segments are not equal when evaluated at the reference gray point. Curve **517** represents the tone scale function **203** and curve **518** its corresponding slope function. The reference gray point is indicated by point **519**. As can be seen in the example graph shown in **FIG. 8***c*, the tone scale function **203** has a discontinuity in the slope function at the reference gray point. Tone scale functions having continuous slope function are, in general, desirable. However, experimentation has shown that the discontinuity in the slope function of a tone scale function when applied to digital images relating to natural photographed scenes is not often a problem. Other methods for generating tone scale functions, such as described in commonly-assigned U.S. Pat. No. 6,285,798 have imposed a continuity of slope constraint on the process of construction. The experimentation performed in support of the present invention has found that the continuity of slope constraint can be unnecessarily restrictive for some digital imaging applications. By not imposing the continuity of slope constraint, a greater diversity of useful tone scale functions can be produced. In particular, tone scale functions that are constructed in a manner responsive to the pixels of the source digital image when applied to the source digital image can achieve a greater level of overall contrast enhancement.

[0104] In another embodiment, the highlight tone scale segment is constructed from a compressive highlight component function. Recall that for compressive highlight component functions x_{ho} is greater than x_w. For this embodiment, the expression given by (6) is combined with a linear function which relaxes the function's slope condition at the

reference gray point. The expression for the highlight component function is given by (19)

$$f_{h1}(x)=(1-\phi_{HC})\alpha_{h1}(1-e^{-(x-x_\rho)/\alpha_{h1}})+\phi_{HC}\gamma_{HC}(x-x_\rho)+x_\rho \quad (19)$$

[0105] where the variable γ_{HC} represents the average slope for the function over the interval from x_ρ to x_{ho} and is given by expression (20).

$$\gamma_{HC}=(x_w-x_\rho)/(x_{ho}-x_\rho) \quad (20)$$

[0106] The variable ϕ_{HC} determines the contribution of the linear function to the highlight component function. The variable ϕ_{HC} can be selected to affect a change in the shape of the highlight tone scale segments that uses expression (19) as a highlight component function. If ϕ_{HC} is set to 0.0, expression (19) reverts to expression (6). If ϕ_{HC} is set to 1.0, the expression (19) assumes a linear function given by expression (21).

$$f_{h1}(x)=\gamma_{HC}(x-x_\rho)+x_\rho \quad (12)$$

[0107] Thus the variable ϕ_{HC} is a control parameter that can be used to select the degree to which the highlight component function behaves as a pure exponential function. Similarly, the expression for the shadow component function is given by (22)

$$f_{s1}(x)=(1-\phi_{SC})\alpha_{s1}(1-e^{-(x-x_\rho)/\alpha_{s1}})+\phi_{SC}\gamma_{SC}(x-x_\rho)+x_\rho \quad (22)$$

[0108] where the variable γ_{SC} represents the average slope for the function over the interval from x_{so} to x_ρ and is given by expression (23).

$$\gamma_{SC}=(x_b-x_\rho)/(x_{so}-x_\rho) \quad (23)$$

[0109] The variable ϕ_{SC} can be selected to change the shape of the shadow tone scale segments that use expression (22) as a shadow component function. If ϕ_{SC} is set to 0.0, expression (22) reverts to expression (7). If ϕ_{SC} is set to 1.0, expression (22) assumes a linear function given by expression (24).

$$f_{s1}(x)=\gamma_{SC}(x-x_\rho)+x_\rho \quad (24)$$

[0110] Thus the variable ϕ_{SC} is a control parameter that can be used to select the degree to which the shadow component function behaves as a pure exponential function.

[0111] Changing the ϕ_{HC} and ϕ_{SC} variables can have a significant impact on the appearance of the processed digital images. Setting the ϕ_{HC} and ϕ_{SC} variables toward 0.0 results in processed digital images that have a more traditional photographic high contrast appearance. Conversely, setting the ϕ_{HC} and ϕ_{SC} variables toward 1.0 results in processed digital images that have a more professional photographic low contrast appearance more appropriate for portraiture. **FIG. 9** shows a graph depicting a family of curves that represent highlight tone scale segments generated with expression (19) using different values of x_{ho} and a family of curves that represent shadow tone scale segments generated with expression (22) using different values of x_{so}. Point **521** represents the reference gray point x_ρ. Curve **522** represents a highlight tone scale segment constructed from one highlight component function. Curve **523** represents a shadow tone scale segment constructed from one shadow component function. Line **524** represents the identity mapping one-to-one input pixel value-to-output pixel value line. The tone scale function **203** can be constructed from any of the highlight tone scale segments depicted in **FIG. 9** or any of the shadow tone scale segments since the variables x_{ho} and x_{so} can be selected independently. It should also be noted that if the variables ϕ_{HC} and ϕ_{SC} are not set to 0.0, the resultant tone scale function will, in general, not have a continuous slope function at the reference gray point.

[0112] A highlight component function constructed with expressions (4), (6), or (13), for the case in which x_{ho} is less than x_w, will result in a function that has a monotonically increasing instantaneous slope. An example of such a function is depicted as curve **530** in **FIG. 10***a*. While the function indicated by curve **530** satisfies the mapping of input pixel value x_{ho} to output pixel value x_w, a tone scale function based on such a function can produce some unnatural looking images. This is mainly due to the fact that the slope of the highlight component function depicted by curve **530** has a slope that is monotonically increasing, not monotonically decreasing, for the input pixel range near the reference gray point. However, a highlight component function can be constructed using the expressions (4), (6), or (13), reflected about the line indicated as line **531** given by (25) for input pixel values greater than or equal to the reference gray point (indicated by point **533**).

$$y(x)=(x_w-x_\rho)/(x_{ho}-x_\rho)(x-x_\rho)+x_\rho \quad (25)$$

[0113] The function produced by the reflection process, as indicated by curve **532** in **FIG. 10***a*, is a monotonically increasing function with a monotonically decreasing instantaneous slope. The functional form of the expansive highlight component function is calculated by the following steps. First the expression (4), (6), or (13) is solved using the constraint $x_{ho}=x_w$ to determine the numerical constant α_{h1}. In the second step, a first rotation transform is applied to a coordinate pair (x,f(x)) resulting in a transformed coordinate pair (u,v) as given by (26)

$$u=x\cos(\theta)+f(x)\sin(\theta) \quad (26)$$
$$v=-x\sin(\theta)-f(x)\cos(\theta)$$

[0114] where the angle θ is given by (27).

$$\theta=\tan^{-1}((x_x-x_\rho)/(x_{ho}-x_\rho)) \quad (27)$$

[0115] The first rotation transform is designed to transform the line described by expression (24) into the x-axis. In the third step the v coordinate is reflected about the new x-axis by taking the negative of the value v coordinate. In the fourth step, a reverse rotation transform is applied to the coordinate pair (u, −v) for the coordinate pair (u',v') as given by (28).

$$u'=u\cos(\theta)+v\sin(\theta) \quad (28)$$
$$v'=x\sin(\theta)-v\cos(\theta)$$

[0116] In the fifth step, the coordinate pair (u',v') defines a highlight component function g(u) and is evaluated for the range of input pixel values.

[0117] Referring to **FIG. 10***b*, an expansive shadow component function can be constructed in similar manner as described above for the case in which $x_{so}>x_b$. The shadow component function can be constructed using the function described by (5), (7), or (14), reflected about the line indicated as line **535** given by (29) for input pixel values less than or equal to the reference gray point (indicated by point **534**) using the constraint $x_{so}=x_b$ to determine the numerical constant α_{s1}.

$$y(x)=x_b-x_\rho)/(x_{so}-x_\rho)(x-x_\rho)+x_\rho \quad (29)$$

[0118] The curve indicated by **536** depicted in **FIG. 10***b* shows a function using (5), (7), or (14) for a positive numerical constant α_{s1}. The corresponding expansive

shadow component function produced via the reflection processing steps is indicated by curve **537**.

[**0119**] An example graph of a tone scale function constructed from an expansive highlight tone scale segment and an expansive shadow tone scale segment constructed with the component functions described above is shown in **FIG. 10***c*. Since both the highlight and shadow tone scale segments are expansive, the tone scale function, indicated by curve **539**, is classified as an expansive function over the range of input pixel values from x_{so} to x_{ho}. The combined linear functions given by expressions (25) and (29) are shown as line **540** with the reference gray point as indicated by point **538**. The tone scale function depicted in **FIG. 8***c* as curve **517** is classified as a compressive function over the range of input pixel values from x_{so} to x_{ho} since both the highlight and shadow tone scale segments used in its construction are compressive component functions. The reference gray point is indicated by point **538**.

[**0120**] It is possible to construct a tone scale function from an expansive shadow component function and a compressive highlight component function or from a compressive shadow component function and an expansive highlight component function since the shape of the two tone scale segments are independently controllable. Such a tone scale function is referred to herein as an eclectic function since the two segments are of different shape classification. While is would be possible to have a tone scale applicator module specific to the eclectic function classification category, the present invention uses the compressive function applicator **242** to apply the tone scale function **203** for eclectic functions. Thus, the eclectic functions are reclassified as compressive functions. For tone scale functions constructed from a highlight and shadow tone scale segment, the present invention classifies the tone scale function **203** as compressive if either tone scale segment individually has been classified as compressive. Otherwise the tone scale function **203** is classified as expansive. It should be noted that other classification rule sets can be used. For example, the eclectic tone scale functions can be classified as expansive tone scale functions.

[**0121**] In a preferred embodiment, the expansive highlight component function $f_{h1}(x)$ is constructed using the expression (4) subject the constraints given by (30) and (31).

$$f_{h1}(x_{ho}')=x_w \tag{30}$$

$$f_{h1}'(x_w)=1.0 \tag{31}$$

[**0122**] where the variable x_{ho}' is given by the expression (32)

$$f_{h1}(x_{ho}')=(1.0-\eta_H)(x_w-x_{ho})+x_{ho} \tag{32}$$

[**0123**] and the variable η_H represents a control parameter that can be used to select the shape of the function. With these two constraints placed on the function $f_{h1}(x)$, the highlight component function achieves the goal of mapping the prescribed input pixel value x_{ho}' to the prescribed output pixel value x_w. The average slope of the function γ_{HE} over the interval from x_ρ to x_{ho}' is given by the expression (33)

$$\gamma_{HE}=(x_w-x_\rho)/(x_{ho}'-x_\rho) \tag{33}$$

[**0124**] which is greater than 1.0 since x_w is greater than x_{ho}'. In a similar manner as described above, the variables α_{h1} and β_{h1} used in the expression (4) are solved by iterative numerical approximation and stored in a LUT for later recall. The variable η_H is preferably set to 0.5. As a further refinement, the highlight component function is combined with a linear function using a control parameter ϕ_{HE}. The final expression for the expansive highlight component function is given by (34).

$$f_{h1}(x)=(1-\phi_{HE})\alpha_{h1}(1-e^{-(x-x_\rho)/\alpha_{h1}})+\phi_{HE}\gamma_{HE}+x_\rho \tag{34}$$

[**0125**] Similarly, the expansive shadow component function $f_{s1}(x)$ is constructed using the expression (5) subject the constraints given by (35) and (36).

$$f_{s1}(x_{so}')=x_b \tag{35}$$

$$f_{s1}'(x_b)=1.0 \tag{36}$$

[**0126**] where the variable x_{so}' is given by the expression (37)

$$f_{s1}(x_{so}')=(1.0-\eta_S)(x_b-x_{so})+x_{so} \tag{37}$$

[**0127**] and the variable η_S represents a control parameter that can be used to select the shape of the function. With these two constraints placed on the functions $f_{s1}(x)$, the shadow component function achieves the goal of mapping the prescribed input pixel value x_{so}' to the prescribed output pixel value x_b. The average slope of the function γ_{SE} over the interval from x_{so}' to x_ρ is given by the expression (38)

$$\gamma_{SE}=(x_\rho-x_b)/(x_\rho-x_{so}') \tag{38}$$

[**0128**] which is greater than 1.0 since x_b is less than x_{so}'. In a similar manner as described above, the variables α_{s1} and β_{s1} used in the expression (5) are solved by iterative numerical approximation and stored in a look-up-table (LUT) for later recall. The variable η_S is preferably set to 0.5. As a further refinement, the shadow component function is combined with a linear function using a control variable ϕ_{SE}. The final expression for the expansive shadow component function is given by (39).

$$f_{s1}(x)=(1-\phi_{SE})\alpha_{s1}(1-e^{-(x-x_\rho)/\alpha_{s1}})+\phi_{SE}\gamma_{SE}+x_\rho \tag{39}$$

[**0129**] **FIG. 11** depicts a family of highlight and shadow tone scale segments each generated from a single expansive component function using expressions (34) and (39) respectively. Point **541** represents the reference gray point x_ρ. Line **542** represents the identity mapping one-to-one input pixel value-to-output pixel value line. Curve **543** represents an example a highlight tone scale segment using expression (34). Curve **544** represents an example shadow tone scale segment using expression (39).

[**0130**] An important feature of the tone scale segments constructed with the two-segment method is the gradual transition in function shape corresponding to a transition from compressive to expansive type functions. **FIG. 12***a* depicts a family of highlight tone scale segments constructed from a single highlight component function using expression (19) when the component function is compressive and expression (34) when the component function is expansive. Point **549** indicates the reference gray point. Curve **550** indicates a highly compressive highlight component function while curve **551** indicates a mildly highlight component function. The higher the degree of compression, the greater the curvature of the function. When the highlight component function is neither compressive nor expansive, the function assumes the identity mapping one-to-one input-to-output line indicated by line **552**. Curve **553** indicates a mildly expansive highlight component function. Curve **554** indicates a highly expansive highlight component function. The higher the degree of expansion, the greater the curvature of

the function. Thus for mildly compressive and mildly expansive highlight component functions, the shape of the function is closer to a straight line. For the compressive highlight component functions used to construct the highlight component segments as shown in **FIG. 12***a* a value of 0.0 was used for the variable ϕ_{HC}. For the expansive highlight component functions used to construct the highlight component segments shown in **FIG. 12***a* a value of 0.0 was used for the variable ϕ_{HE}. It should be noted that the value of the ϕ_{HC} variable used in expression (19) can be selected independent of the value of the ϕ_{HE} variable used in expression (34).

[0131] The shape of the shadow tone scale segments also have a graceful transition between compressive and expansive function types. **FIG. 12***a* also depicts a family of shadow tone scale segments constructed from a single shadow component function using expression (22) when the component function is compressive and expression (39) when the component function is expansive. Curve **555** indicates a highly compressive shadow component function while curve **556** indicates a mildly shadow component function. The higher the degree of compression, the greater the curvature of the function. When the shadow component function is neither compressive nor expansive, the function assumes the identity mapping one-to-one input-to-output line indicated by line **557**. Curve **558** indicates a mildly expansive shadow component function. Curve **559** indicates a highly expansive shadow component function. The higher the degree of expansion, the greater the curvature of the function. Thus for mildly compressive and mildly expansive shadow component functions, the shape of the function is closer to a straight line. For the compressive shadow component functions used to construct the shadow component segments as shown in **FIG. 12***a* a value of 0.0 was used for the variable ϕ_{SC}. For the expansive shadow component functions used to construct the shadow component segments shown in **FIG. 12***a* a value of 0.0 was used for the variable ϕ_{SE}. It should be noted that the value of the ϕ_{SC} variable used in expression (22) can be selected independent of the value of the ϕ_{SE} variable used in expression (39).

[0132] **FIG. 12***b* depicts a similar family of highlight and shadow tone scale segments constructed using expressions (19), (34), (22) and (39) with the values of the variables ϕ_{HC}, ϕ_{HE}, ϕ_{SC}, and ϕ_{SE} all set to a value of 0.5. As can be seen from the curves depicted in **FIG. 12***b*, the tone scale segments make a gradual transition in function shape for a corresponding transition from compressive to expansive type functions.

[0133] In another construction method for a compressive highlight component function, the variable ϕ_h is made a function of the degree of compression, i.e. the ratio of (x_w-x_ρ) to $(x_{ho}-x_\rho)$. The expression for the highlight component function $f_{h1}(x)$ is given by (13) where the slope variable ϕ_h in expression (13) is given by (40)

$$\phi_h=1.0-\eta_h(1.0-(x_w/x_{ho})) \quad (40)$$

[0134] and the variable η_h controls the shape of the highlight component function. The variable η_h can be selected. When the variable η_h is set to 1.0, the highlight component function assumes the equation of a line given as expression (21). When the variable η_h is set to 0.0, the highlight component function assumes the equation of the exponential function given as expression (13). Similarly, for a compressive shadow component function, the variable ϕ_s is made a function of the degree of compression, i.e. the ratio of $(x_\rho-x_b)$ to $(x_\rho-x_{so})$. The expression for the shadow component function $f_{s1}(x)$ is given by (14) where the slope variable ϕ_s in expression (14) is given by (41)

$$\phi_s=1.0-\eta_s(1.0-(x_b/x_{so})) \quad (41)$$

[0135] and the variable η_s controls the shape of the shadow component function. When the variable η_s is set to 1.0, the shadow component function assumes the equation of a line given as expression (24). When the variable η_s is set to 0.0, the shadow component function assumes the equation of the exponential function given as expression (14).

[0136] Referring to **FIG. 4**, the pixels of the source digital image, i.e. the input digital image to the tone scale module **330**, can be used to determine the variables x_{ho} and x_{so} and thus determine the shape of the tone scale function. The analysis image generator **250** receives the source digital image and produces an analysis digital image **201** by applying a low-pass spatial filter and performing a sampling operation. The result is a lower spatial resolution version of the source digital image that has fewer pixels representing the same image content. Typical spatial resolutions for the analysis digital image **201** is approximately 64 by 96 pixels. The analysis digital image is also converted to be in a luminance-chrominance representation using expression (2).

[0137] The tone scale function generator **230** calculates the tone scale function **203** by analyzing the pixels of the analysis digital image **201**. A pixel histogram function, i.e. a frequency of occurrence function, is calculated from the pixels of the luminance digital image channel of the analysis digital image **201**. A cumulative histogram function is calculated from the pixel histogram function by integrating the values of the pixel histogram as a function of pixel value. **FIG. 14** shows a graph of an example histogram function indicated by curve **601** and its corresponding cumulative histogram function indicated by curve **602**. The cumulative histogram function is scaled between 0.0 and 1.0 and relates to the percentage area of the digital image with 1.0 corresponding to 100 percent of image area. The ordinate value of the cumulative histogram function relates to a given percentage image area Z. The corresponding abscissa value relates to the pixel value P for which the percentage of pixels in the image that have values less than P is given by Z. The 99.0% cumulative histogram function value is used to determine the value of the highlight point, variable x_{ho}. The 1.0% cumulative histogram function value is used to determine the value of the shadow point, variable x_{so}. The values for the variables x_{ho} and x_{so} are indicated as points **603** and **604** respectively on the graph shown in **FIG. 14**.

[0138] Referring to **FIG. 3** and **FIG. 4**, the tone scale function generator **230** can accept user input selections **231** in the generation of the tone scale function **203**. For example a user of the system shown in **FIG. 1** can view possible selections and/or control parameters on the monitor device **50** and indicate selections using the input control device **60** such as a keyboard or mouse pointing device. When used in this manual user mode, a highlight control parameter and a shadow control parameter are used to change the shape of the component functions that are used to generate the highlight tone scale segment and shadow tone scale segment respectively.

[0139] The present invention is preferably practiced in an image processing system including a source of digital

images, such as a scanner, a computer programmed to process digital images, and an output device such as a thermal or ink-jet printer. The method of the present invention may be sold as a computer program product including a computer readable storage medium bearing computer code for implementing the steps of the invention.

[0140] Computer readable storage medium may include, for example; magnetic storage media such as a magnetic disc (e.g. a floppy disc) or magnetic tape; optical storage media such as optical disc or optical tape; bar code; solid state electronic storage devices such as random access memory (RAM) or read only memory (ROM); or any other physical device or medium employed to store a computer program.

[0141] The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

Parts List

[0142] **10** image capture device
[0143] **10***a* image capture device
[0144] **10***b* image capture device
[0145] **10***c* image capture device
[0146] **20** digital image processor
[0147] **30***a* image output device
[0148] **30***b* image output device
[0149] **40** general control processor
[0150] **50** monitor device
[0151] **60** input control device
[0152] **70** computer memory device
[0153] **101** original digital image
[0154] **102** source digital image
[0155] **103** rendered digital image
[0156] **104** enhanced digital image
[0157] **107** luminance digital image
[0158] **109** chrominance digital image
[0159] **113** enhanced luminance digital image
[0160] **201** analysis digital image
[0161] **203** tone scale function
[0162] **210** LCC conversion module
[0163] **220** RGB conversion module
[0164] **230** tone scale function generator
[0165] **231** user input selections
[0166] **240** tone scale function applicator
[0167] **241** tone scale function classifier
[0168] **242** compressive function applicator
[0169] **244** expansive function applicator
[0170] **250** analysis image generator
[0171] **310** RLSE conversion module
[0172] **320** scene balance module
[0173] **330** tone scale module
[0174] **340** rendering module
[0175] **401** input digital image
[0176] **402** texture digital image
[0177] **403** pedestal digital image
[0178] **407** tone scale adjusted digital image
[0179] **409** output digital image
[0180] **410** pedestal generation module
[0181] **420** difference module
[0182] **430** tone scale modifier
[0183] **432** chrominance modifier
[0184] **440** addition module
[0185] **500** point
[0186] **501** curve
[0187] **502** curve
[0188] **503** line
[0189] **511** point
[0190] **512** curve
[0191] **513** curve
[0192] **514** point
[0193] **515** curve
[0194] **516** curve
[0195] **517** curve
[0196] **518** curve
[0197] **519** point
[0198] **521** point
[0199] **522** curve
[0200] **523** curve
[0201] **524** line
[0202] **530** curve
[0203] **531** line
[0204] **532** curve
[0205] **533** point
[0206] **534** point
[0207] **535** line
[0208] **536** curve
[0209] **537** curve
[0210] **538** point
[0211] **539** curve
[0212] **540** line

[0213] **541** point

[0214] **542** line

[0215] **543** curve

[0216] **544** curve

[0217] **549** point

[0218] **550** curve

[0219] **551** curve

[0220] **552** line

[0221] **553** curve

[0222] **554** curve

[0223] **555** curve

[0224] **556** curve

[0225] **557** line

[0226] **558** curve

[0227] **559** curve

[0228] **590** curve

[0229] **591** point

[0230] **592** point

[0231] **593** point

[0232] **595** point

[0233] **596** point

[0234] **597** point

[0235] **598** curve

[0236] **601** curve

[0237] **602** curve

[0238] **603** point

[0239] **604** point

What is claimed is:

1. A method of enhancing the tonal and chrominance characteristics of a digital image, comprising the steps of:

a) receiving a source digital image including a plurality of pixels wherein the source digital image is in a luminance-chrominance representation having a luminance digital image channel and at least two chrominance digital image channels;

b) producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image;

c) classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

d) using the tone scale function and the luminance digital image channel to produce an enhanced luminance digital image channel; and

e) amplifying the chrominance digital image channels to produce modified chrominance digital channels when the tone scale function has been classified as expansive.

2. The method of claim 1, wherein step e) further includes the steps of:

i) calculating a corresponding slope function for the tone scale function; and

ii) using the corresponding slope function to amplify the pixels values of the chrominance digital image channels.

3. The method of claim 2, wherein step e) further includes the steps of:

calculating a chrominance amplification factor for each pixel of the source digital image by evaluating the corresponding the slope function; and

using the color weighting factors to amplify the pixel values of the chrominance digital image channels.

4. The method of claim 1 further including the step of combining the enhanced luminance digital image channel and the chrominance digital image channels to produce an enhanced digital image when the tone scale function has been classified as compressive and combining the enhanced luminance digital image channel and the modified chrominance digital image channels to produce an enhanced digital image when the tone scale function has been classified as expansive.

5. The method of claim 4 using a sigmoid shaped rendering function independent of the source digital image and the enhanced digital image to produce a rendered digital image.

6. The method of claim 1 further including the step of using the pixels of the source digital image to produce the tone scale function.

7. The method of claim 1 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the tone scale function.

8. The method of claim 7 wherein the tone scale function maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined paper density and a different fixed percentile of the histogram to a predetermined output value relating to a second paper density.

9. The method of claim 1 wherein the pixels of the source digital image have a logarithmic relationship to original scene intensities.

10. The method of claim 1 wherein the tone scale function is manually controlled with at least one control parameter.

11. The method of claim 1 further including the steps of:

producing the tone scale function having a highlight tone scale segment and a shadow tone scale segment defined relative to a reference point on the tone scale function, wherein:

i) the highlight tone scale segment is defined by a different mathematical function than the shadow tone scale segment;

ii) the highlight tone scale segment is defined for points that are equal to or greater than the reference point; and

iii) the shadow tone scale segment is defined for points that are equal to or less than the reference point.

12. The method of claim 11 further including the steps of:

i) classifying the highlight tone scale segment as either expansive or compressive;

ii) classifying the shadow tone scale segment as either expansive or compressive;

iii) classifying the tone scale function as compressive when either the highlight or shadow tone scale segment has been classified as compressive and classifying the tone scale function as expansive when both the highlight and shadow tone scale segment have been classified as expansive.

13. The method of claim 11 wherein the slopes of the highlight and shadow tone scale segments are each equal at the reference point.

14. The method of claim 11 wherein the slopes of the highlight and shadow tone scale segments are unequal at the reference point.

15. The method of claim 11 wherein the tone scale function has an inflection point at the reference point.

16. The method of claim 11 wherein the reference point is calculated using the pixels of the source digital image.

17. The method of claim 11 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the highlight tone scale segment.

18. The method of claim 17 wherein the highlight tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined paper density.

19. The method of claim 17 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the shadow tone scale segment.

20. The method of claim 19 wherein the shadow tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined density.

21. A method of enhancing the tonal and color characteristics of a digital image, comprising the steps of:

a) receiving a source digital image including a plurality of pixels;

b) producing a tone scale function having a highlight tone scale segment and a shadow tone scale segment defined relative to a reference point on the tone scale function, and that is adapted to operate on the source digital image to improve its tonal characteristics, wherein:

i) the highlight tone scale segment is defined by a different mathematical function than the shadow tone scale segment and is defined for points that are equal to or greater than the reference point; and

ii) the shadow tone scale segment is defined for points that are equal to or less than the reference point; and

c) classifying the tone scale function into two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

d) using the tone scale function and the source digital image to produce an enhanced luminance digital image wherein the chrominance characteristics of the enhanced digital image are identical to the source digital image when the tone scale function has been classified as compressive; and using the tone scale function and the source digital image to produce an enhanced luminance digital image wherein the chrominance characteristics of the enhanced digital image are amplified relative to the source digital image when the tone scale function has been classified as expansive.

22. A method of enhancing the tonal characteristics of a digital image, comprising the steps of:

a) receiving a source digital image including a plurality of pixels wherein the source digital image is a color digital image having pixels of at least three colors;

b) producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image;

c) classifying the tone scale function into two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

d) using the tone scale function and the source digital image to produce an enhanced luminance digital image wherein the chrominance characteristics of the enhanced digital image are identical to the source digital image when the tone scale function has been classified as compressive, and using the tone scale function and the source digital image to produce an enhanced luminance digital image wherein the chrominance characteristics of the enhanced digital image are amplified relative to the source digital image when the tone scale function has been classified as expansive.

23. A method of enhancing the tonal and color characteristics of a digital image, comprising the steps of:

a) receiving a source digital image having a plurality of digital image channels corresponding to different colors wherein each digital image channel includes a plurality of pixels;

b) producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image;

c) classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

d) transforming the source digital image into a luminance-chrominance digital image having a luminance digital image channel and two or more chrominance digital image channels, and using the tone scale function and the luminance digital image channel to produce an enhanced luminance digital image channel when the tone scale function has been classified as compressive, and applying the tone scale function directly to the source digital image to produce an enhanced digital image when the tone scale function has been classified as expansive.

24. The method of claim 23 further including the step of combining the enhanced luminance digital image channel

and the chrominance digital image channels to produce an enhanced digital image when the tone scale function has been classified as compressive.

25. The method of claim 24 using a sigmoid shaped rendering function independent of the source digital image and the enhanced digital image to produce a rendered digital image.

26. The method of claim 23 further including the step of using the pixels of the source digital image to produce the tone scale function.

27. The method of claim 23 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the tone scale function.

28. The method of claim 27 wherein the tone scale function maps a first fixed percentile of the histogram to a predetermined output value relating to a predetermined first paper density and a second fixed percentile of the histogram to a predetermined output value relating to a predetermined second paper density.

29. The method of claim 23 wherein the pixels of the source digital image have a logarithmic relationship to original scene intensities.

30. The method of claim 23 wherein the tone scale function is manually controlled with at least one control parameter.

31. The method of claim 23 further including the steps of:

producing the tone scale function having a highlight tone scale segment and a shadow tone scale segment defined relative to a reference point on the tone scale function, wherein:

i) the highlight tone scale segment is defined by a different mathematical function than the shadow tone scale segment;

ii) the highlight tone scale segment is defined for points that are equal to or greater than the reference point; and

iii) the shadow tone scale segment is defined for points that are equal to or less than the reference point.

32. The method of claim 31 further including the steps of:

i) classifying the highlight tone scale segment as either expansive or compressive;

ii) classifying the shadow tone scale segment as either expansive or compressive;

iii) classifying the tone scale function as compressive when either the highlight or shadow tone scale segment has been classified as compressive and classifying the tone scale function as expansive when both the highlight and shadow tone scale segment have been classified as expansive.

33. The method of claim 31 wherein the slopes of the highlight and shadow tone scale segments are each equal at the reference point.

34. The method of claim 31 wherein the slopes of the highlight and shadow tone scale segments are unequal at the reference point.

35. The method of claim 31 wherein the tone scale function has an inflection point at the reference point.

36. The method of claim 31 wherein the reference point is calculated using the pixels of the source digital image.

37. The method of claim 31 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the highlight tone scale segment.

38. The method of claim 37 wherein the highlight tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined density.

39. The method of claim 37 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the shadow tone scale segment.

40. The method of claim 39 wherein the shadow tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined paper density.

41. A method of enhancing the tonal and chrominance characteristics of a digital image, comprising the steps of:

a) receiving a source digital image including a plurality of pixels wherein the source digital image is in a luminance-chrominance representation having a luminance digital image channel and at least two chrominance digital image channels;

b) producing a tone scale function that can be used to enhance the tone characteristics of the source digital image;

c) classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive;

d) using the tone scale function and the luminance digital image channel to produce an enhanced luminance digital image channel when the tone scale function has been classified as compressive, and transforming the source digital image into a multi-color digital image having a plurality of digital image channels each corresponding to a different color and using the tone scale function and the multi-color digital image to produce an enhanced digital image when the tone scale function has been classified as expansive.

42. The method of claim 41 further including the step of combining the enhanced luminance digital image channel and the chrominance digital image channels to produce an enhanced digital image when the tone scale function has been classified as compressive.

43. The method of claim 42 using a sigmoid shaped rendering function independent of the source digital image and the enhanced digital image to produce a rendered digital image.

44. The method of claim 41 further including the step of using the pixels of the source digital image to produce the tone scale function.

45. The method of claim 41 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the tone scale function.

46. The method of claim 45 wherein the tone scale function maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined

paper density and a second fixed percentile of the histogram to a predetermined output value relating to a second paper density.

47. The method of claim 41 wherein the pixels of the source digital image have a logarithmic relationship to original scene intensities.

48. The method of claim 41 wherein the tone scale function is manually controlled with at least one control parameter.

49. The method of claim 41 further including the steps of:

producing the tone scale function having a highlight tone scale segment and a shadow tone scale segment defined relative to a reference point on the tone scale function, wherein:

i) the highlight tone scale segment is defined by a different mathematical function than the shadow tone scale segment;

ii) the highlight tone scale segment is defined for points that are equal to or greater than the reference point; and

iii) the shadow tone scale segment is defined for points that are equal to or less than the reference point.

50. The method of claim 49 further including the steps of:

i) classifying the highlight tone scale segment as either expansive or compressive;

ii) classifying the shadow tone scale segment as either expansive or compressive;

iii) classifying the tone scale function as compressive when either the highlight or shadow tone scale segment has been classified as compressive and classifying the tone scale function as expansive when both the highlight and shadow tone scale segment have been classified as expansive.

51. The method of claim 49 wherein the slopes of the highlight and shadow tone scale segments are each equal at the reference point.

52. The method of claim 49 wherein the slopes of the highlight and shadow tone scale segments are unequal at the reference point.

53. The method of claim 49 wherein the tone scale function has an inflection point at the reference point.

54. The method of claim 49 wherein the reference point is calculated using the pixels of the source digital image.

55. The method of claim 49 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the highlight tone scale segment.

56. The method of claim 55 wherein the highlight tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined paper density.

57. The method of claim 55 further including the step of using the pixels of the source digital image to produce a histogram and using the histogram to produce the shadow tone scale segment.

58. The method of claim 57 wherein the shadow tone scale segment maps a fixed percentile of the histogram to a predetermined output value relating to a predetermined paper density.

59. A method of enhancing the tonal and color characteristics of a digital image, comprising the steps of:

a) receiving a source digital image having a plurality of digital image channels wherein each digital image channel includes a plurality of pixels;

b) producing a tone scale function that can be used to enhance the tonal characteristics of the source digital image;

c) classifying the tone scale function into one of two or more categories based on the effect the tone scale function will have on the numerical range of pixel values of a processed digital image wherein the classification categories include expansive and compressive; and

d) producing an enhanced digital image by applying the tone scale function to exactly one digital image channel derived from the source digital image when the tone scale function has been classified as compressive, and applying the tone scale function to each of a plurality of digital image channels derived from the source digital image when the tone scale function has been classified as expansive.

60. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 1.

61. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 21.

62. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 22.

63. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 23.

64. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 41.

65. A computer storage product having at least one computer storage medium having instructions stored therein causing one or more computers to perform the method of claim 59.

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