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(54) **BI-ILLUMINANT DICHROMATIC REFLECTION MODEL FOR IMAGE MANIPULATION**

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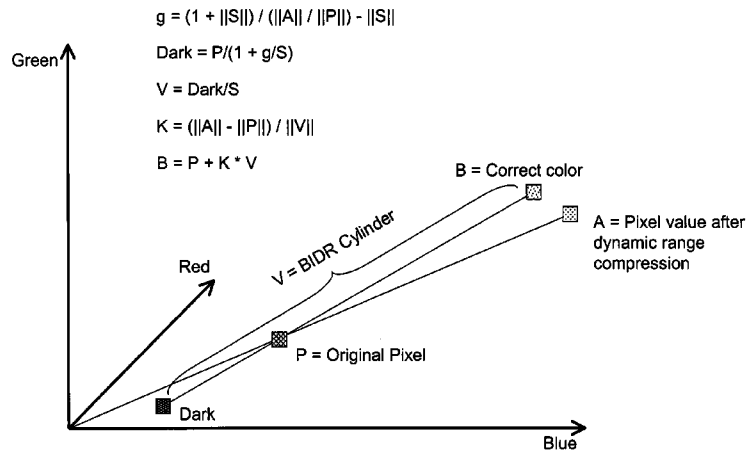
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(57)   **ABSTRACT**

In a first exemplary embodiment of the present invention, an automated, computerized method for manipulating an image comprises the steps of deriving a bi-illuminant dichromatic reflection model representation of the image, and utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image.

13 Claims, 12 Drawing Sheets

$$g = (1 + \|S\|) / (\|A\| / \|P\|) - \|S\|$$
$$\text{Dark} = P/(1 + g/S)$$
$$V = \text{Dark}/S$$
$$K = (\|A\| - \|P\|) / \|V\|$$
$$B = P + K * V$$

B = Correct color
A = Pixel value after dynamic range compression
V = BIDR Cylinder
P = Original Pixel
Dark
Green
Red
Blue

Method of estimating percent of direct illumination (g) from a dynamic range compressed image.

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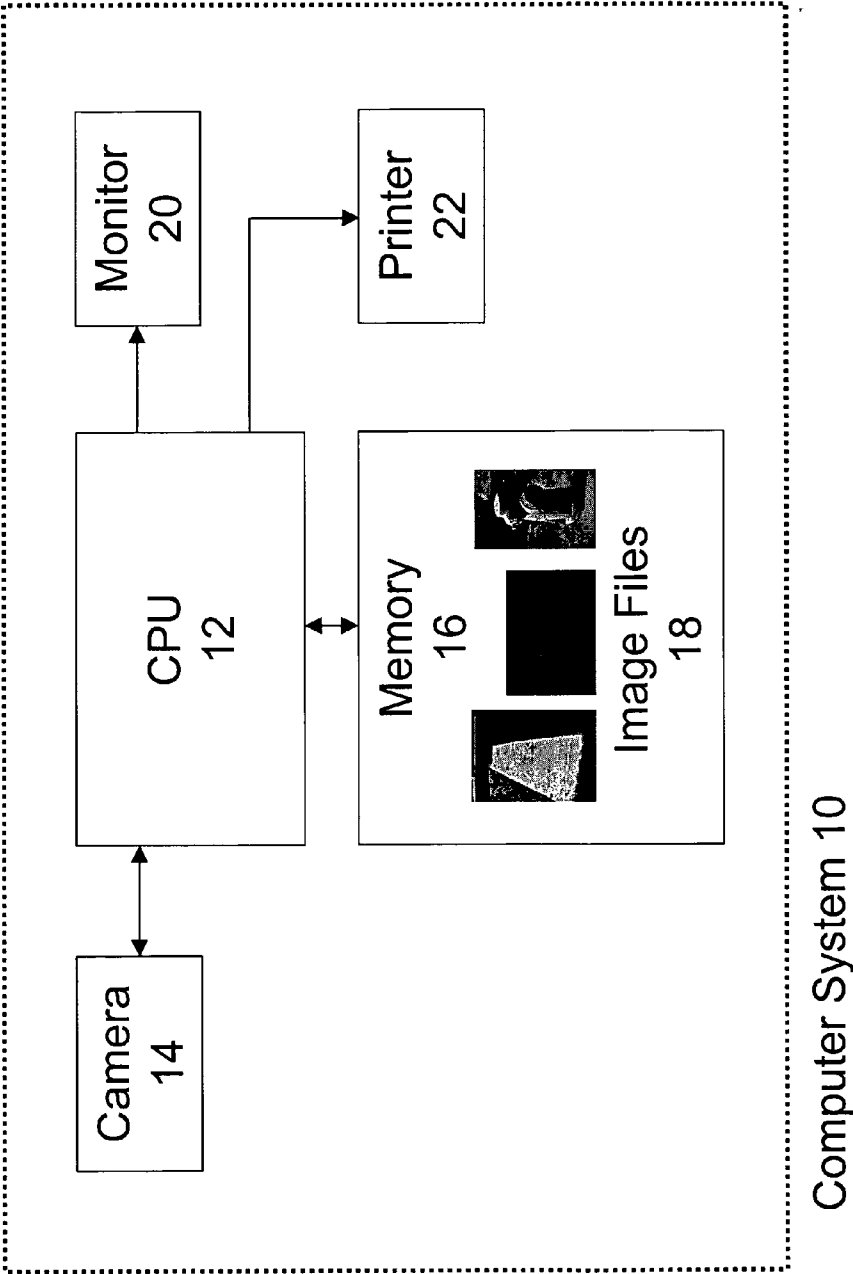
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Computer System 10
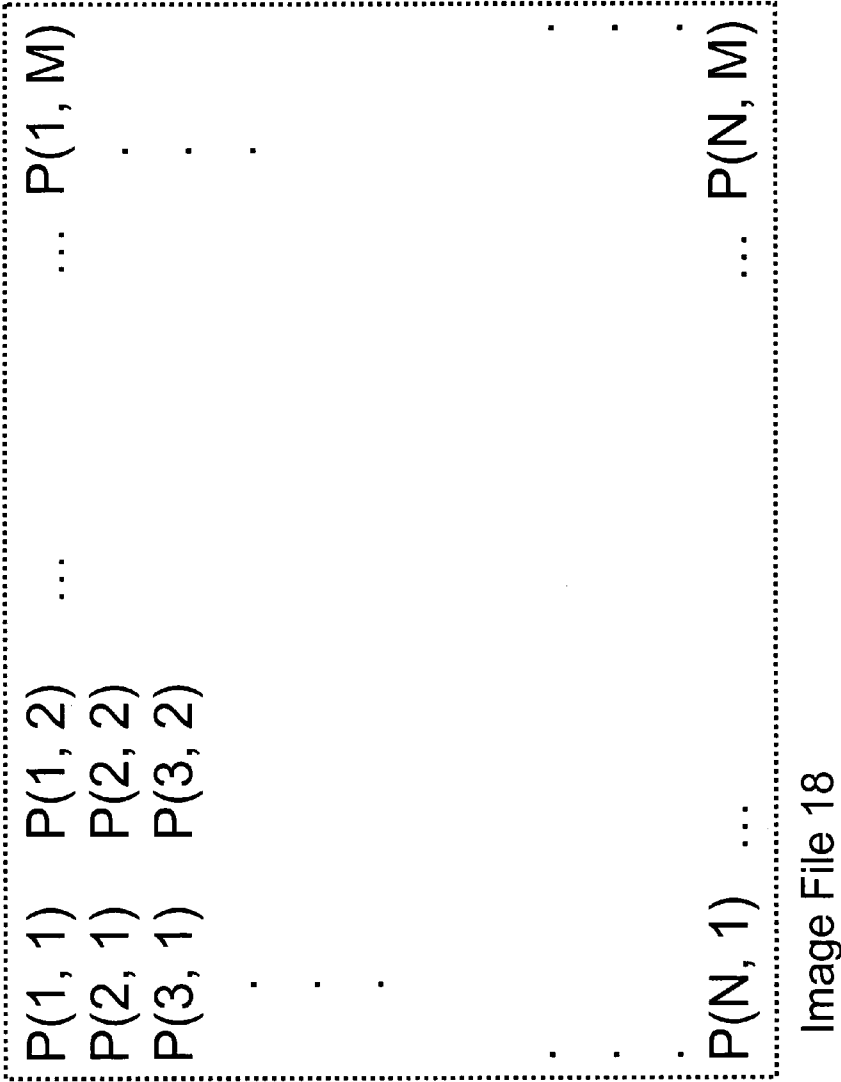
Figure 1: Computer System Configured to Operate on Images

P(1, 1)　P(1, 2)　　⋮　　P(1, M)
P(2, 1)　P(2, 2)
P(3, 1)　P(3, 2)

P(N, 1)　…　　　　　　　P(N, M)

Image File 18

Figure 2: Pixel Array for Storing Image Data

User selects a point or region on a fully lit material in an image

100

User selects a point or region on a fully shadowed part of the same material in the same image

102

Calculate Spectral Ratio
S = Dark / (Bright - Dark)

104

User provides region to be corrected and the degree of adjustment

106

Use spectral ratio to adjust the intensity and color of the selected region

108

Smoothing, feathering, or other processing of region boundaries
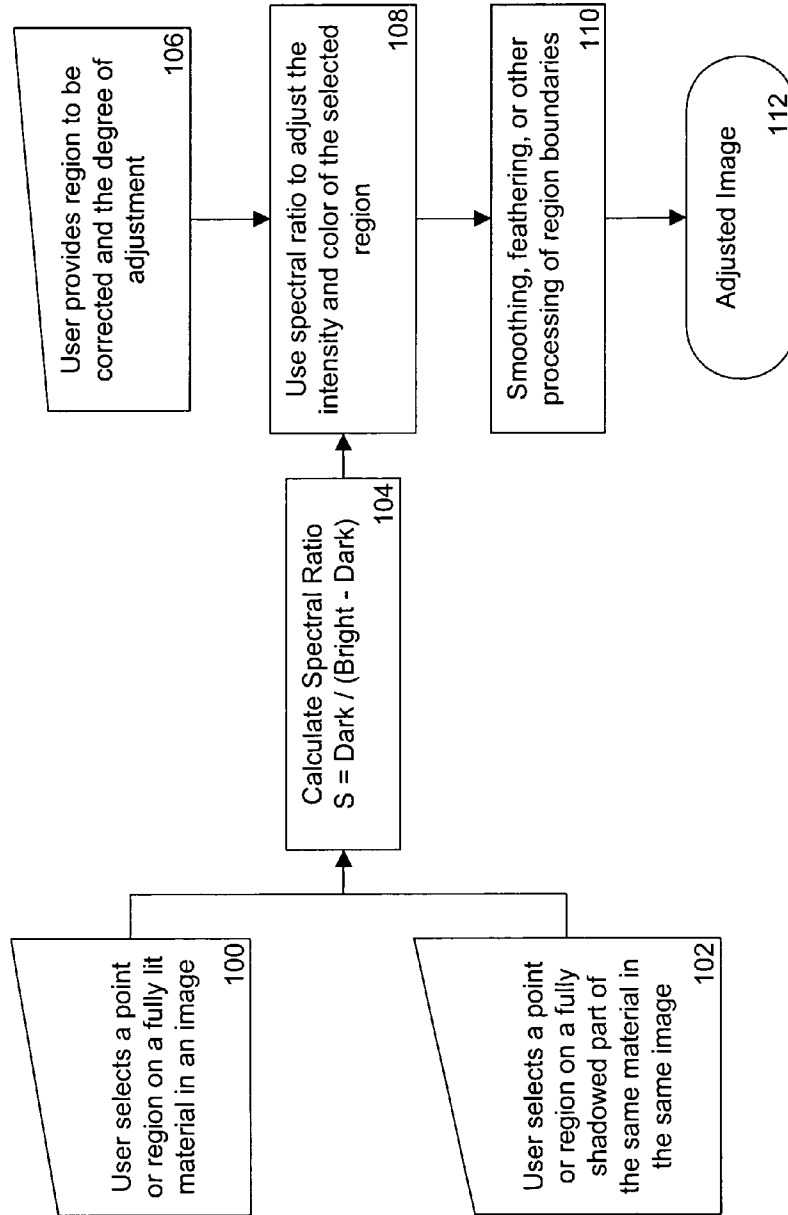
110

Adjusted Image
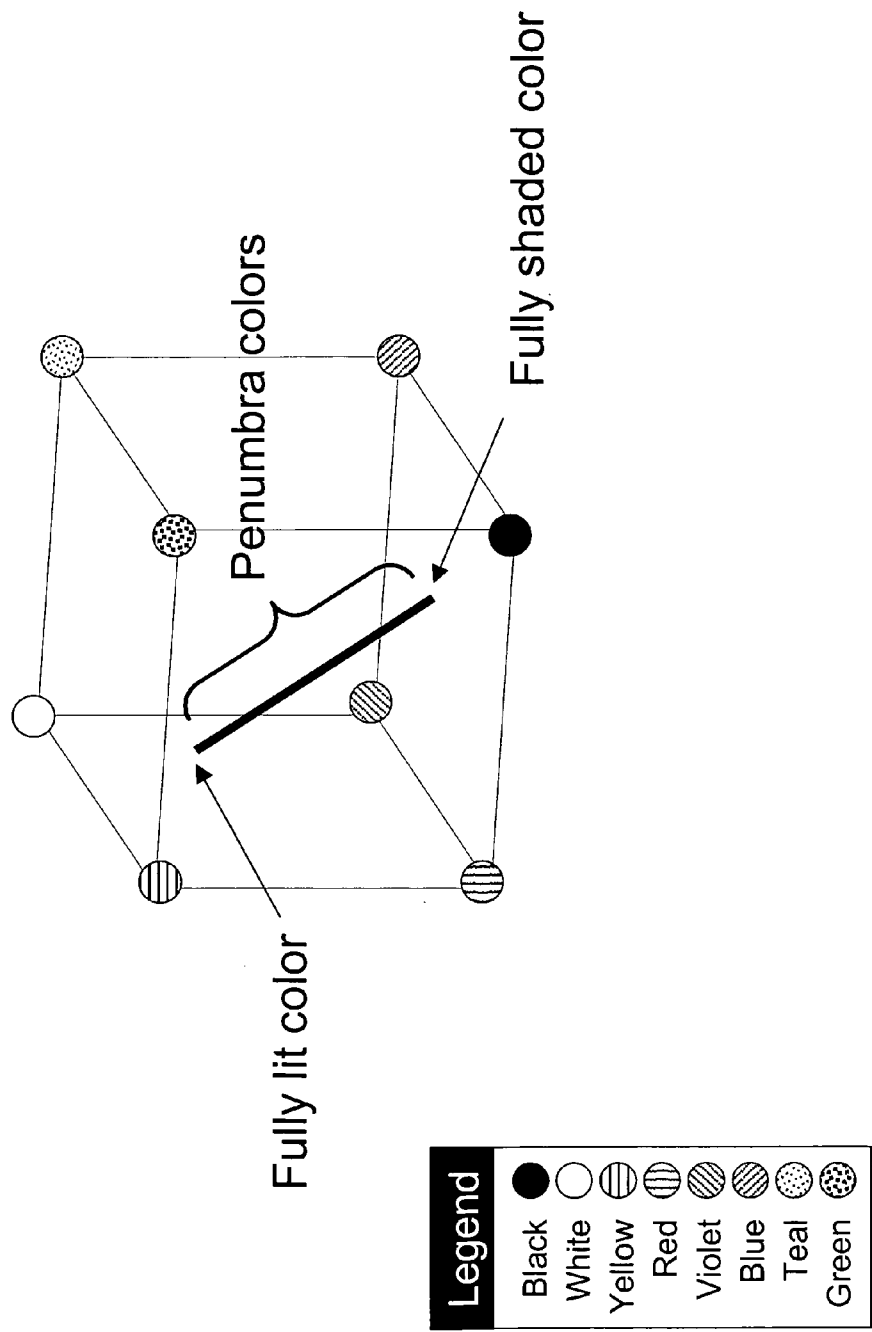
112

Figure 3: Modifying a Shadow with Manual Input

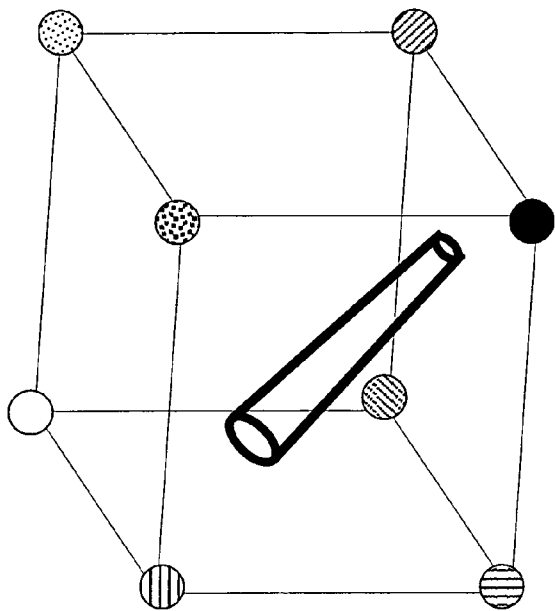Figure 4: Representation of Body Reflection in RGB Space

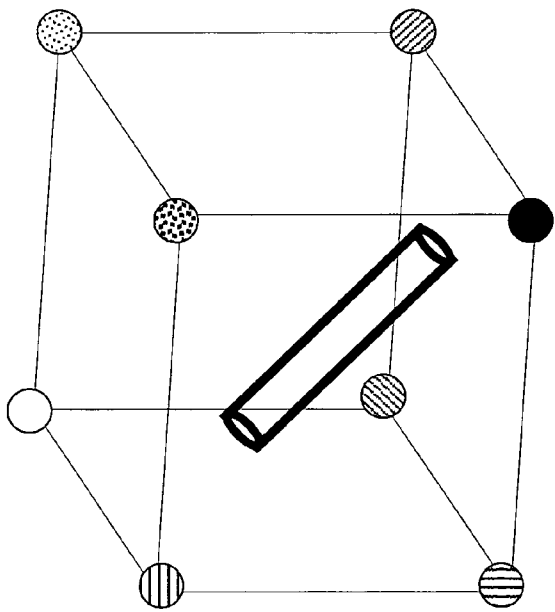Figure 5B: Body reflection with non-uniform error bounds that are tighter at the dark end.

Figure 5A: Body reflection with uniform error bounds

Legend

Black
White
Yellow
Red
Violet
Blue
Teal
Green

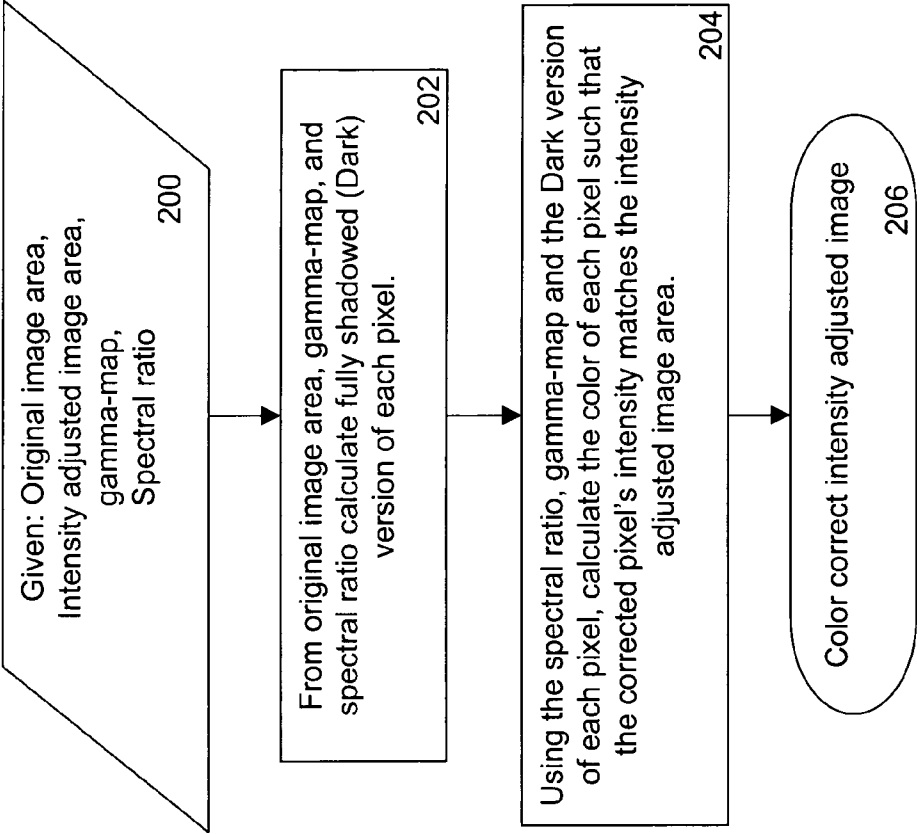Figure 5A, 5B: Representation of Body Reflection with Noise

Given: Original image area,
Intensity adjusted image area,
gamma-map,
Spectral ratio

200

From original image area, gamma-map, and
spectral ratio calculate fully shadowed (Dark)
version of each pixel.

202

Using the spectral ratio, gamma-map and the Dark version
of each pixel, calculate the color of each pixel such that
the corrected pixel's intensity matches the intensity
adjusted image area.

204

Color correct intensity adjusted image

206

Figure 6A: Color Correct Brightness Adjustment

$g = (1 + ||S||) / (||A|| / ||P||) - ||S||$

$Dark = P/(1 + g/S)$

$V = Dark/S$

$K = (||A|| - ||P||) / ||V||$

$B = P + K * V$

A = Pixel value after dynamic range compression

B = Correct color

$V = B|DR$ Cylinder

P = Original Pixel

Dark

Green

Red

Blue
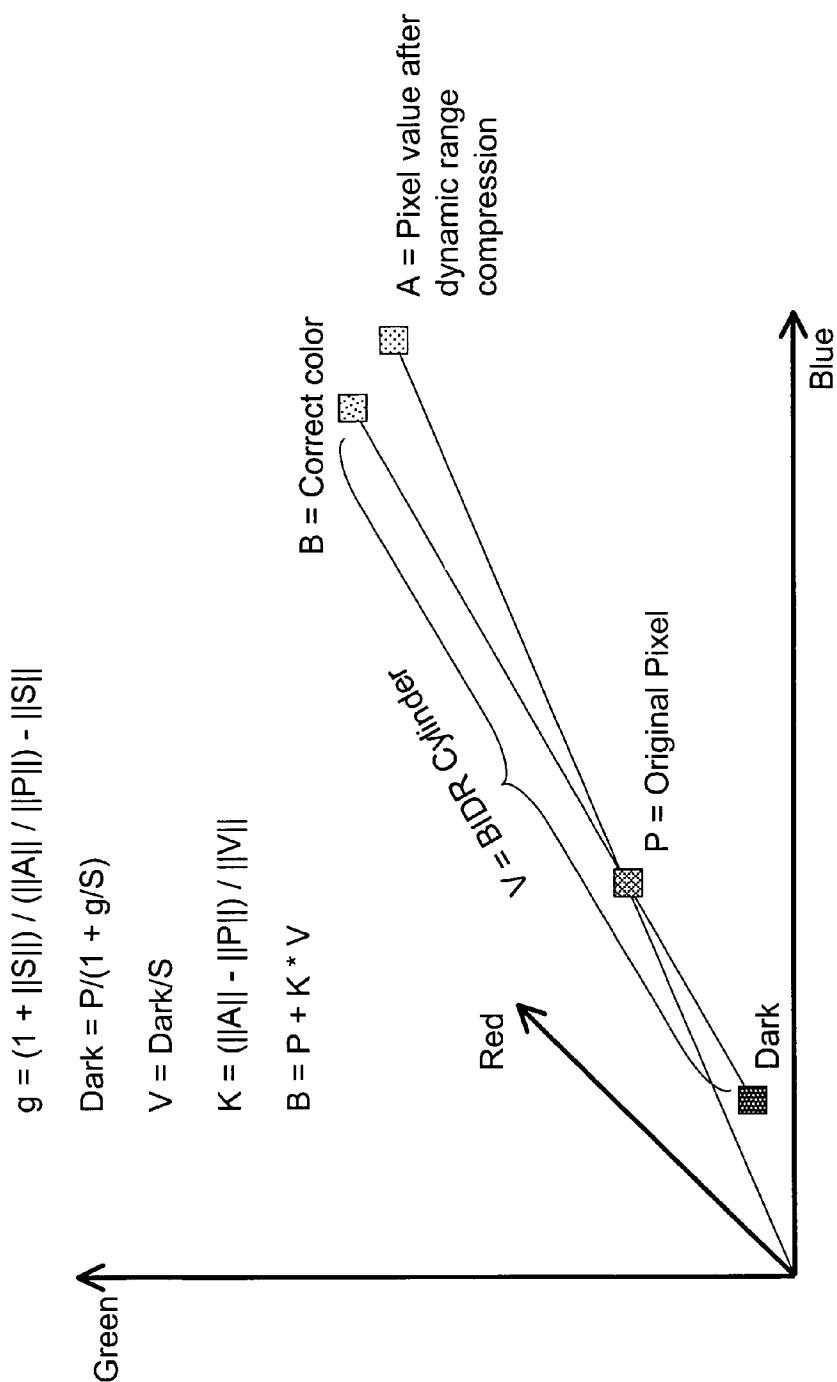
Figure 6B. Method of estimating percent of direct illumination (g) from a dynamic range compressed image.

Given: Original image area,
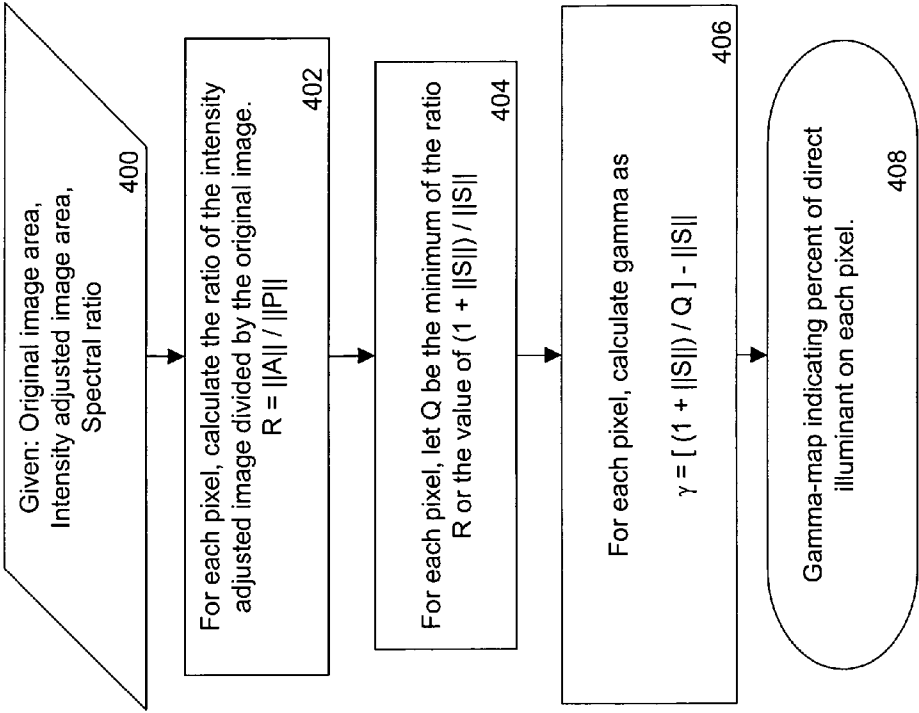Intensity adjusted image area,
Spectral ratio

400

For each pixel, calculate the ratio of the intensity
adjusted image divided by the original image.
R = ||A|| / ||P||

402

For each pixel, let Q be the minimum of the ratio
R or the value of (1 + ||S||) / ||S||

404

For each pixel, calculate gamma as

γ = [(1 + ||S||) / Q] - ||S||

406

Gamma-map indicating percent of direct
illuminant on each pixel.

408

Figure 6C: Estimating Gamma Using a Dynamic Range
Compression Algorithm

Given: Original image area,
Gamma-map,
Spectral ratio

208

From original image area, gamma-map, and
spectral ratio calculate fully shadowed (Dark)
version of each pixel P.
Dark = P / (1 + gamma/S)

210

Image of each material lit only by the ambient illumination
Each material will have a unique and constant appearance.

212
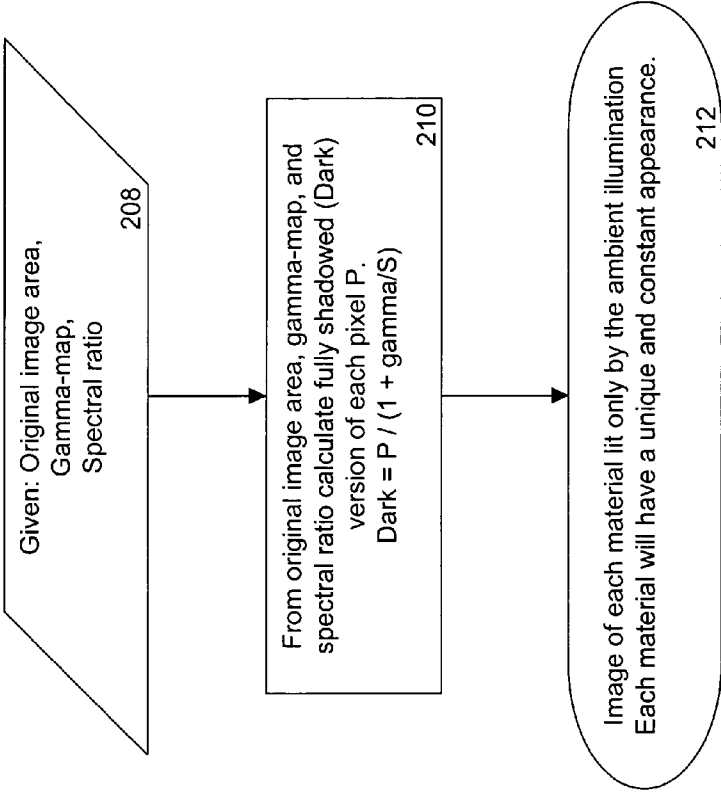
Figure 7: Removing Direct Illumination From an Image Area

Given: Original image area ▪ ,
Gamma-map,
Spectral ratio S,
Ambient illuminant modifier vector V

214

From original image area, gamma-map, and
spectral ratio calculate fully shadowed (Dark)
version of each pixel P.
Dark = P / (1 + gamma/S)

216

Multiply spectral ratio S by V to get S_{new}

220

Multiply Dark by V to get $Dark_{new}$ and adjust
the apparent ambient illuminant

218

Using S_{new} and the gamma-map, calculate the new color for the pixel.l
$P_{new} = Dark_{new} + G(Dark_{new} / S_{new})$

222

Original image area with a modified apparent ambient
illumination

224

Figure 8: Modifying the Apparent Ambient Illumination of an Image Area

Given: Original image area ▪ ,
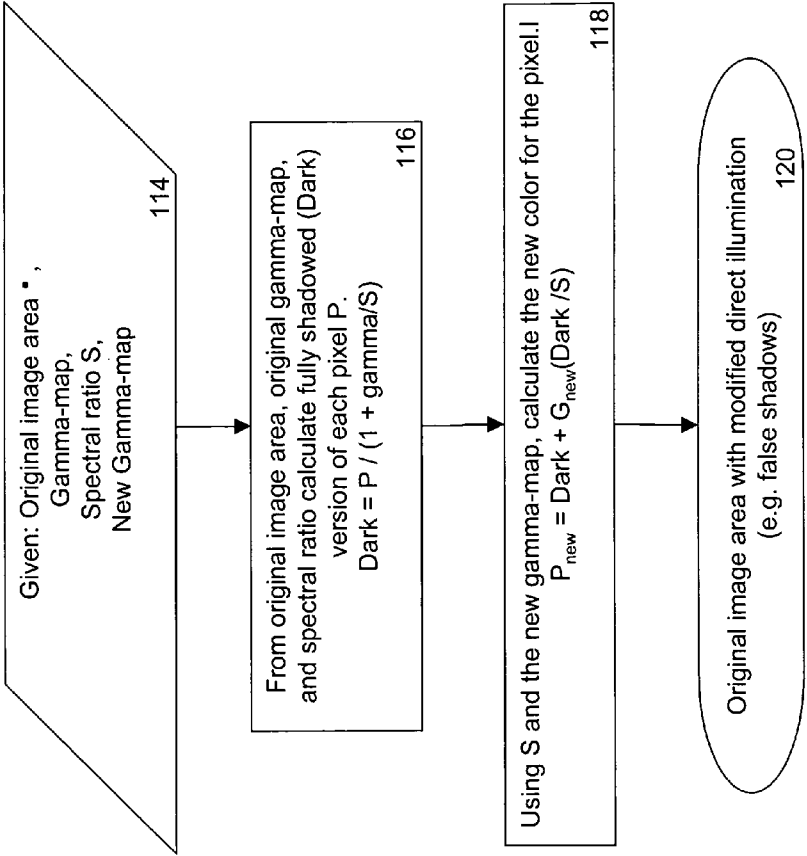Gamma-map,
Spectral ratio S,
Direct illuminant modifier vector V

300

From original image area, gamma-map, and
spectral ratio calculate fully shadowed (Dark)
version of each pixel P.
Dark = P / (1 + gamma/S)

302

Multiply spectral ratio S by 1/V to get S_{new}

304

Using S_{new} and the gamma-map, calculate the new color for the pixel.I
P_{new} = Dark + G(Dark /S_{new})

306

Original image area with a modified apparent direct
illumination

308

Figure 9: Modifying the Apparent Ambient Illumination of an Image Area

Given: Original image area ▪ ,
Gamma-map,
Spectral ratio S,
New Gamma-map

114

From original image area, original gamma-map,
and spectral ratio calculate fully shadowed (Dark)
version of each pixel P.
Dark = P / (1 + gamma/S)

116

Using S and the new gamma-map, calculate the new color for the pixel.I
P_{new} = Dark + G_{new}(Dark /S)

118

Original image area with modified direct illumination
(e.g. false shadows)

120

Figure 10: Modifying the Apparent Level of Direct Illumination of an
Image Area

BI-ILLUMINANT DICHROMATIC REFLECTION MODEL FOR IMAGE MANIPULATION

BACKGROUND OF THE INVENTION

Many significant and commercially important uses of modern computer technology relate to images. These include image processing, image analysis and computer vision applications. A challenge in the utilization of computers to accurately and correctly perform operations relating to images is the development of algorithms that truly reflect and represent physical phenomena occurring in the visual world. For example, the ability of a computer to correctly and accurately distinguish between a shadow and a material object edge within an image has been a persistent challenge to scientists. Edge detection is a fundamental task in image processing because without accurate and correct detection of the edges of physical objects, no other processing of the image is possible. If a cast shadow is indistinguishable from the object casting the shadow, it would not be possible for the computer to recognize the object.

An early and conventional approach to object edge detection involves an analysis of brightness boundaries in an image. In the analysis it is assumed that a boundary caused by a material object will be sharp, while a boundary caused by a shadow will be soft or gradual due to the penumbra effect of shadows. While this approach can be implemented by algorithms that can be accurately executed by a computer, the results will often be incorrect. In the real world there are many instances wherein shadows form sharp boundaries, and conversely, material object edges form soft boundaries. Thus, when utilizing conventional techniques for shadow and edge recognition, there are significant possibilities for false positives and false negatives for shadow recognition. That is, for example, a material edge that imitates a shadow and is thus identified incorrectly by a computer as a shadow or a sharp shadow boundary that is incorrectly interpreted as an object boundary.

Once shadows and object edges are identified, a typical computerized operation is manipulation of the image to, for example, remove shadows from the image. Most scenes depicted in an image have a dominant illuminant, defined as a direct or incident illuminant. The incident illuminant causes shadows. The component of radiance onto a surface in the scene that is not from the incident illuminant, is referred to as an indirect or ambient illuminant. It is the ambient illuminant that is present within a shadow. While much of the energy of the ambient illuminant may come from the incident illuminant, it has generally interacted with the environment.

Typical solutions for manipulating images focus on the incident illuminant. Models have been developed for computerized image pixel manipulation based upon the assumption that the ambient illumination has the same spectral characteristics as the incident illumination or is non-existent. One such known solution is the dichromatic reflection model, which describes the variations in appearance caused by the combination of body and surface reflection on a material. Body reflection is what is normally considered the color of the material. The surface reflection is referred to as a highlight or specularity of the material reflecting the illuminant. The known dichromatic reflection model assumes a single incident illuminant and does not account for a non-zero ambient illuminant. Thus, results of image manipulation based upon the dichromatic reflection model are often not color correct.

Other useful solutions include color spaces such as hue and chromaticity, and other normalized color spaces that attempt to factor out the effect of changing the intensity of the incident illuminant on the intensity of the reflection from a surface. However, these color models have met with limited success in solving practical vision problems. Consequently, there is a growing realization that simple models of illumination do not correctly reflect the visual world, and thus, do not provide color correct manipulations. Recent research has focused upon empirical models of color change over a single material. This approach is not restricted by any prior assumptions about the behavior of illumination color or reflectance.

There is also significant amount of research attempting to determine the complete illumination environment. These methods are based upon multiple images of the same scene and/or knowledge of the scene geometry. In one research project, the existence and importance of complex indirect illumination is acknowledged. However, the method requires both a known geometry of a scene and two images. While these research efforts approach a solution that can extract and represent illumination environments of significant complexity, they cannot be used in environments such as, for example, consumer photography, or with existing photos or in any situation where either taking multiple images of a scene from different points of view or inserting objects into a scene are not readily possible or are unreasonable.

SUMMARY OF THE INVENTION

The present invention provides a bi-illuminant dichromatic reflection model (BIDR model) as a representation of an image to facilitate color correct image manipulation.

In a first exemplary embodiment of the present invention, an automated, computerized method for manipulating an image comprises the steps of deriving a bi-illuminant dichromatic reflection model representation of the image, and utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image.

In a second exemplary embodiment of the present invention, an automated, computerized method for manipulating an image comprises the steps of deriving a material and illumination representation of the image, and utilizing the material and illumination representation to manipulate the image.

In a third exemplary embodiment of the present invention, a computer system comprises a CPU and a memory storing an image file. Pursuant to a feature of the present invention, the computer system is arranged and configured to execute a routine to derive a material and illumination representation of the image and to utilize the material and illumination representation to manipulate the image.

In a fourth exemplary embodiment of the present invention, an automated, computerized method for representing a pixel of an image comprises the steps of deriving a BIDR cylinder/γ/spectral ratio representation of the pixel, and utilizing the BIDR cylinder/γ/spectral ratio representation of the pixel to manipulate the pixel.

In accordance with yet further embodiments of the present invention, computer systems are provided, which include one or more computers configured (e.g., programmed) to perform the methods described above. In accordance with other embodiments of the present invention, computer readable media are provided which have stored thereon computer executable process steps operable to control a computer(s) to implement the embodiments described above. The automated, computerized methods can be performed by a digital computer, analog computer, optical sensor, state machine,

sequencer or any device or apparatus that can be designed or programed to carry out the steps of the methods of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a computer system arranged and configured to perform operations related to images.

FIG. **2** shows an n×m pixel array image file for an image stored in the computer system of FIG. **1**.

FIG. **3** is a flow chart for modifying a shadow in an image with a manual input, according to a feature of the present invention.

FIG. **4** is a graph in RGB color space showing colors for a material, from a fully shaded color value to a fully lit color value, as determined by execution of a simplified bi-illuminant dichromatic reflection model according to a feature of the present invention.

FIGS. **5**a & b are graphs in RGB color space showing colors for a material, from a fully shaded color value to a fully lit color value, with error bounds forming a cylinder, as determined by execution of the bi-illuminant dichromatic reflection model according to a feature of the present invention.

FIG. **6**a is a flow chart for a color correct brightness adjustment to an intensity adjusted image, according to a feature of the present invention.

FIG. **6**b is a graph in RGB space showing an intensity adjusted pixel value for the intensity adjusted image of FIG. **6**a.

FIG. **6**c is a flow chart for estimating a gamma (γ) value for the pixel of FIG. **6**b using a dynamic range compression algorithm.

FIG. **7** is a flow chart for removing direct or incident illumination from an image area, according to a feature of the present invention.

FIG. **8** is a flow chart for modifying apparent ambient illumination of an image area, according to a feature of the present invention.

FIG. **9** is a flow chart for modifying apparent direct or incident illumination of an image area, according to a feature of the present invention.

FIG. **10** is a flow chart for modifying apparent level of direct or incident illumination of an image area, according to a feature of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, and initially to FIG. **1**, there is shown a block diagram of a computer system **10** arranged and configured to perform operations related to images. A CPU **12** is coupled to a device such as, for example, a digital camera **14** via, for example, a USB port. The digital camera **14** operates to download images stored locally on the camera **14**, to the CPU **12**. The CPU **12** stores the downloaded images in a memory **16** as image files **18**. The image files **18** can be accessed by the CPU **12** for display on a monitor **20**, or for print out on a printer **22**.

Alternatively, the CPU can be implemented as a microprocessor embedded in a device such as, for example, the digital camera **14** or a robot. The CPU can also be equipped with a real time operating system for real time operations relating to images, for example, in connection with a robotic operation or an interactive operation with a user.

As shown in FIG. **2**, each image file **18** comprises an n×m pixel array. Each pixel, p, is a picture element corresponding to a discrete portion of the overall image. All of the pixels

together define the image represented by the image file **18**. Each pixel comprises a digital value corresponding to a set of color bands, for example, red, green and blue color components (RGB) of the picture element. The present invention is applicable to any multi-band image, where each band corresponds to a piece of the electromagnetic spectrum. The present invention can also be utilized in connection with a grayscale image (a single band). The pixel array includes m columns of n rows each, starting with the pixel p (1,1) and ending with the pixel p(n, m). When displaying or printing an image, the CPU **12** retrieves the corresponding image file **18** from the memory **16**, and operates the monitor **20** or printer **22**, as the case may be, as a function of the digital values of the pixels in the image file **18**, as is generally known.

In an image operation, the CPU **12** operates to analyze the RGB values of the pixels of a stored image file **18** to achieve various objectives, such as, for example, manipulation of the image to modify a shadow or to make a color correct brightness adjustment. A fundamental observation underlying a basic discovery of the present invention, is that an image comprises two components, material and illumination. All changes in an image are caused by one or the other of these components.

In a first exemplary embodiment of the present invention, shadowed and fully lit regions of an image are manually selected by a user. What is visible to the human eye upon display on the monitor **20** of a stored image file **18** by the CPU **12**, is the pixel color values caused by the interaction between specular and body reflection properties of material objects in, for example, a scene photographed by the digital camera **14** and illumination flux present at the time the photograph was taken. As noted above, the illumination flux comprises an ambient illuminant and an incident illuminant. The incident illuminant is light that causes a shadow and is found outside a shadow perimeter. The ambient illuminant is light present on both the bright and dark sides of a shadow, but is more perceptible within the dark region.

FIG. **3** is a flow chart for modifying a shadow in an image with a manual input, according to a feature of the present invention. In two input steps the user selects a point or region on a fully lit (Bright) material of an image **18** selected by the user (step **100**) and a point or region on a fully shadowed (Dark) part of the same material in the same image **18** (step **102**). These steps **100**, **102** can be implemented by an interactive clicking by the user on the monitor **20** operating to display the subject image file **18**. A user can select such regions because human eye physiology is capable of distinguishing between shadows and actual physical objects.

In step **104**, the CPU **12** operates on the user input selections to calculate a spectral ratio, S=Dark/(Bright−Dark), where Dark, for example, is a pixel in the fully shadowed material of the region selected by the user, and Bright is a pixel in the fully lit portion of that material selected by the user. A normalized version of the spectral ratio can be used in the methods according to the present invention. According to a feature of the present invention, the spectral ratio is used to manipulate pixel values for a color correct adjustment. Based upon the fundamental observation of the present invention that an image comprises two components, material and illumination, the computer system **10** can be operated to differentiate between material aspects and illumination flux through recognition of a spectral shift caused by the interplay between the incident or direct illuminant and the ambient illuminant. When one of material and illumination is known in an image, the other can be readily deduced. The spectra for the incident illuminant and the ambient illuminant can be different from one another. A spectral shift caused by a

shadow, i.e., a decrease of the intensity of the incident illuminant, will be substantially invariant over different materials present in a scene depicted in an image.

Pursuant to a feature of the present invention, this spectral shift information is detected by determination of an illuminant ratio, or a characteristic spectral ratio formed by the interplay of the incident illuminant and the ambient illuminant. A spectral ratio is a ratio based upon a difference in color or intensities between two areas of a scene depicted in an image, which may be caused by different materials, an illumination change or both.

An automated, computerized method for determining a characteristic spectral or illuminant ratio due to illumination flux, for an image, is disclosed in co-pending application Ser. No. 11/341,742, filed on even date herewith, entitled: "Method and System For Identifying Illumination Flux In An Image," published as US 2006/0177149 on Aug. 10, 2006, which is hereby incorporated by reference. As disclosed in the co-pending application Ser. No. 11/341,742, to improve the accuracy and correctness of the characteristic ratio for an image, the spectral ratio information for illumination boundaries is determined on a local level, that is, an illuminant ratio is determined for each of several preselected local areas of a scene depicted in an image. An analysis of a boundary is then executed utilizing the spectral ratio for the specific location of the boundary within the image. The determination of locally relevant spectral ratios accommodates complexities that may be encountered in a real world image, for example, the interplay of several different sources of light in a room, interreflections, and so on.

In order to facilitate an accurate and correct manipulation of pixel values, to modify, for example, the pixel from a shaded color (Dark) to a correct fully lit color (Bright), the present invention recognizes the characteristic spectral ratio (illuminant ratio) as an analytical representation of image properties and characteristics pursuant to a bi-illuminant dichromatic reflection model. The bi-illuminant dichromatic reflection model (BIDR) combines terms relevant to the ambient illuminant with the dichromatic reflection model described above. The two illuminants of the BIDR model correspond to the incident illuminant and the ambient illuminant. The BIDR model can be stated as follow:

$$I_{(x,y,z,\theta,\phi,\lambda)}=[m_b(\theta_i)c_b(\lambda)+m_s(\theta_i,\phi_i,\theta_e,\phi_e)c_s(\lambda)]l_d(\lambda)+M_a(\lambda)c_b(\lambda)+M_{as}(\theta_e,\phi_e,\lambda)c_s(\lambda),$$

where:

$I_{(x,y,z,\theta,\phi,\lambda)}$ is the radiance of a surface point at (x, y, z) in the direction θ, φ, for the wavelength λ,

$m_b(\theta_i)$ is the spectrum independent body reflectance based on geometric factors,

$c_b(\lambda)$ is the geometry independent body reflectance of a surface for the wavelength λ,

$m_s(\theta_i, \phi_i, \theta_e, \phi_e)$ is the spectrum independent surface reflectance based on geometric factors,

$c_s(\lambda)$ is the geometry independent surface reflectance of a surface for the wavelength λ,

$l_d(\lambda)$ is the incident illuminant for the wavelength λ.

θ_i is the incident tilt angle of the illuminant onto a surface relative to the surface normal.

ϕ_i is the incident pan angle: the angle between the incident illuminant and a fixed axis on the tangent plane of a surface.

θ_e is the exitent tilt angle: the angle of an outgoing ray relative to the surface normal.

ϕ_e is the exitent pan angle: the angle between an outgoing ray and a fixed axis on the tangent plane of a surface.

All of the above terms comprise the dichromatic reflection model. The remaining terms of the BIDR model relate to the ambient illuminant, where:

$M_a(\lambda)$ is the integral of the ambient illuminant and geometric body reflectance over a hemisphere, excluding the incident illuminant, and

$M_{as}(\theta_e, \phi_e, \lambda)$ is the integral of the ambient illuminant and geometric surface reflectance over the hemisphere, excluding the incident illuminant.

In the dichromatic reflection model, the radiance, $I_{(x, y, z, \theta, \phi, \lambda)}$, for a surface at a point viewed from the orientation by θ, φ is expressed as the sum of two bipartite terms multiplied by the illumination intensity and color $l_d(\lambda)$ to reflect the effect of the incident illuminant. The first reflectance term explains body reflection. $m_b(\theta_i)$ is the amount of incident illuminant energy reflected by the body reflection, referred to as diffuse reflection, as a function of the geometric relationship of the light source and the surface, expressed by the incident angle θ_i. $c_b(\lambda)$ is the fraction of the incident illuminant energy reflected by the body reflection for each wavelength λ and describes what is considered the body color. The second reflection term explains surface reflection. $m_s(\theta_i, \phi_i, \theta_e, \phi_e)$ is the amount of the incident energy reflected by the surface reflection as a function of the geometry as expressed by the incident angles θ_i, ϕ_i and exit angles θ_e, ϕ_e. $c_s(\lambda)$ is the fraction of the incident energy reflected by the surface reflection for each wavelength λ. The power of the dichromatic reflection model is that the model predicts that the appearance, or color, of a uniform color dielectric surface under a single incident illuminant falls within a plane defined by the two color vectors c_b and c_s in RGB space, even with variation in the amount of incident illuminant and specularities on the surface.

According to a feature of the present invention, the BIDR model adds body and surface reflection terms for the ambient illuminant, which, as noted above may have a significantly different spectrum from the incident illuminant. Unlike the incident illuminant, the ambient illuminant is radiated from the whole hemisphere visible from the surface point.

Thus, $M_a(\lambda)$ is the integral of the ambient body reflection:

$$\int m_b(\theta_i)l_a(\theta_i,\phi_i,\lambda)d\theta_i\,d\phi_i.$$

$M_{as}(\theta_e, \phi_e, \lambda){:}\int m_s(\theta_i, \phi_i, \theta_e, \phi_e)l_a(\theta_a(\theta_i, \phi_i, \lambda)d\theta_i\,d\phi_i$. This function represents the integral of the ambient illuminant and geometric surface reflectance over the hemisphere, excluding the incident illuminant.

The above functions are an integration of all incoming illumination other than incident illuminant, as integrated over θ_i, $\phi_i \ne \theta_L$, ϕ_L (incident illuminant). The BIDR model according to the present invention can accurately and correctly accommodate and predict tremendous complexity in the appearance of a surface, even a surface of uniform material. If, for example, the ambient environment is both bright and changes quickly across a surface, the ambient illuminant terms can cause deviations from the plane predicted by the dichromatic reflection model. Indeed, unlike the dichromatic reflection model, the BIDR model according to the present invention predicts a plane in the RGB space that does not necessarily pass through the zero point of the space, but in fact most often exhibits an offset from the zero point that comprises the color of the ambient illumination multiplied by the object color. The offset results in color correct changes when a pixel value is manipulated using the BIDR model of the present invention.

Given that the ambient illuminant is often an order of magnitude or more than the incident illuminant, the ambient specularity or body surface reflectance $M_{as}(\theta_e, \phi_e, \lambda)$ term has a minimal effect on the appearance of a surface and can be

discarded without significantly affecting the quality of the model. The BIDR model then reduces to three terms:

$$I_{(x,y,z,\theta,\phi,\lambda)}=[m_b(\theta_i)c_b(\lambda)+m_s(\theta_i,\phi_i,\theta_e,\phi_e)c_s(\lambda)]l_d(\lambda)+$$
$$M_a(\lambda)c_b(\lambda).$$

Inasmuch as the appearance of cast shadows on a surface is also relevant to the uses of the BIDR model, a shadow term or factor $s_{x,\,y,\,z} \in [0,1]$ can be added to multiply the incident illuminant term:

$$I_{(x,y,z,\theta,\phi,\lambda)}=[m_b(\theta_i)c_b(\lambda)+m_s(\theta_i,\phi_i,\theta_e,\phi_e)c_s(\lambda)]l_d(\lambda)s_{x,y,}$$
$$z+M_a(\lambda)c_b(\lambda).$$

A fully lit pixel will have a shadow factor, s=1, and a fully shadowed pixel will have an s=0, with the only remaining term in the model at s=0 being the ambient body reflection. The model can be restated by substituting γ_b, the product of the shadow factor $s_{x,\,y,\,z}$ and the geometric factor $m_b(\theta_i)$, for those non-spectral factors in the body reflection, and γ_s, the product of the shadow factor $s_{x,\,y,\,z}$ and the geometric factor $m_s(\theta_i, \phi_i, \theta_e, \phi_e)$, for those non-spectral factors in the surface reflection. The BIDR model is thus restated as: $I_{(x,\,y,\,z,\,\theta,\,\phi,\,\lambda)}=c_b(\lambda)l_d(\lambda)\gamma_b+c_s(\lambda)l_d(\lambda)\gamma_s+M_a(\lambda)c_b(\lambda)$.

In the absence of specularities in a material, the second term of the BIDR model, $c_s(\lambda)$ la (λ) γ_s, is zero, and the measured values of a surface will exist on a single theoretical line in, for example, RGB space. With no specularity term, the BIDR model is given by: $I_{(x,\,y,\,z,\,\theta,\,\phi,\,\lambda)}=c_b (\lambda) I_d (\lambda) \gamma_b+M_a (\lambda) c_b (\lambda)$. FIG. 4 shows a graph in RGB color space for colors for a material, from a fully shaded color value to a fully lit color value, as determined by execution of a simplified bi-illuminant dichromatic reflection model from γ_b=0 to γ_b=1, according to a feature of the present invention. As shown in FIG. 4, the model predicts that all of the measured colors of a particular material in shadow, light and penumbra extend along a line in RGB space (the cube shown in FIG. 4). An adjustment to a pixel value along a line predicted according to the BIDR model yields a color correct result. For a further discussion regarding the generation of BIDR cylinder representations of an image, reference should be made to co-pending application Ser. No. 11/341,753, filed on even date herewith, entitled "Method And System For Identifying Illumination Fields In an Image," published as US 2007/0177797 on Aug. 2, 2007, which is hereby incorporated by reference.

In practice, a camera or other sensor used to record an image typically has noise, and no material in an image is of a completely uniform color. Accordingly, the appearance values of the surface fall within a cylinder having a width determined by variation in material and imaging sensor noise characteristics. The cylinder representing body reflection, according to the incident and ambient illuminants considered in the BIDR model of the present invention, has a unique starting place for every intrinsic color in the scene. The starting point is determined by the product of the ambient illumination and the body color, and the slope of the cylinder in RGB space is determined by the product of the incident illumination and the body color.

FIGS. 5a & b are graphs in RGB color space showing colors for a material, from a fully shaded color value to a fully lit color value, with error bounds forming a cylinder. In FIG. 5a, a cylinder is shown around the RGB line predicted by the BIDR model (a BIDR cylinder), with the dimensions of the cylinder diameter being a function of the noise of the recording device used to record the image, and variations.

FIG. 5b, illustrates a cone shaped BIDR cylinder in recognition that the same absolute distance at the fully shadowed end represents a greater actual color difference than the same absolute distance from the line at the fully lit end of the line.

This is due to the fact that the magnitude of the color band intensities at the shadow end are a greater percentage of the actual distance from the line in the shadow end than at the lit end. For example, consider a color at the shadow end of the cylinder of (RGB)=(5, 6, 8) and a color at the lit end of (100, 120, 160). If the CPU 12 modifies the color value for each 10 units toward the color red from both color values, the result is a shadow color value of (15, 6, 8) and a lit color of (110, 120, 160). At the dark end, the color shifted from a distinctly blue color to a distinctly red color, while at the lit end the color remains blue. In order to compensate for the difference, an adjustment is made to the cylinder to be narrower at the shadow end and wider at the lit end such that a same magnitude of color change will have a correspondingly accurate absolute distance from the line.

When stating the spectral ratio, S=Dark/(Bright−Dark), in terms of the BIDR model, $S=M_a(\lambda)c_b(\lambda)/([c_b(\lambda)l_d(\lambda)\gamma_b+M_a(\lambda)c_b(\lambda)]-M_a(\lambda)c_b(\lambda))$. This equation reduces to $S=M_a(\lambda)/l_d(\lambda)\gamma_b$. Inasmuch as γ_b is scalar, the relative proportions of different color bands in the spectral ratio, for example, RGB values, are constant. Thus, for a given pair of direct and ambient illuminants in an image, the normalized spectral ratio is constant for all Bright and Dark pairs that correspond to the same material when Dark is assumed to have a γ_b=0, and the Bright is receiving some incident illuminant. The spectral ratio is therefore a representation of image properties and characteristics that, according to the BIDR model, can be utilized as a basis for manipulation of pixel values for a color correct adjustment, for example, as a prediction of color adjustments that fall within a color correct cylinder in RGB space, as illustrated in FIG. 5b.

In addition, the BIDR model can be used as a basis for representing pixel values. Rather than an RGB value, each pixel is represented by a BIDR cylinder in RGB space and a γ value, to indicate where in a specific BIDR cylinder, for example, the cylinder of FIG. 5b, the color of a specific pixel is located. Moreover, a spectral ratio based upon the Dark and Bright pixels of a specific BIDR cylinder can be calculated as a local characteristic or illuminant ratio for the image, as discussed above. The BIDR cylinder/γ/spectral ratio representation for a pixel provides a comprehensive and unique form of pixel representation that permits color correct manipulations of the pixel.

In step 106, the user selects an area from within the regions provided by the user in steps 100, 102, to be manipulated or corrected, and the degree of adjustment. The degree of adjustment is reflected in the value of γ_b, with, for example, γ_b=0.5 being selected if the user desired a half-shadow. In step 108, the CPU 12 uses the spectral ratio calculated in step 104 to adjust the intensity and color of the selected region to achieve the degree of adjustment selected by the user.

FIG. 10 is a flow chart for modifying apparent level of direct or incident illumination of an image area, according to a feature of the present invention. The flow chart of FIG. 10 can be utilized to carry out step 108 of FIG. 3. In the routine of FIG. 10, the CPU 12 is given, in addition to the spectral ratio calculated by the CPU 12 from Dark, for example, a pixel in the fully shadowed material of the region selected by the user, and Bright, a pixel in the fully lit portion of that material selected by the user (step 104), the set of pixels comprising the area selected by the user (step 106), a gamma (γ) map for the set of pixels, and a new gamma map set at a level corresponding to the degree of adjustment selected by the user, for example, a γ_b=0.5 if the user desired a half-shadow (step 114).

A method for generating an approximate gamma map for the pixels of the image can comprise a dynamic range com-

pression algorithm as an input. Examples of such algorithms include a Retinex based algorithm, marketed by Hewlett-Packard or a gamma correction algorithm, an industry standard image compression algorithm. Note that a gamma correction process is distinct from a gamma map that indicates a gamma (γ corresponding to $γ_b$ of the BIDR model representation). For a further discussion of gamma map generation, see the description of FIGS. **6***b* and **6***c*, below.

In step **116**, the CPU **12** operates to calculate a fully shadowed (Dark) version of each pixel in the selected area, Dark=P/(1+γ/S), where P is the color vector in RGB space of a pixel in the selected area of the subject image **18**, gamma (γ) is the value of gamma for that pixel from the gamma map, and S is the spectral ratio calculated by the CPU **12** in step **104** of FIG. **3**. The use of the spectral ratio as a representation of the BIDR model for the subject image **18** results in a color correct Dark determination corresponding to the end point of the cylinder predicted by the BIDR model for the pixel, as depicted in FIG. **5***b*. Thus, the Dark value correctly corresponds to the $M_a(λ)c_b(λ)$ term for that pixel in the selected area of the subject image **18**.

In step **118**, the CPU **12** calculates a color adjusted new value for each pixel in the selected area as a function of the new gamma map designated by the user: P_{new}=Dark+$γ_{new}$ (Dark/S), where $γ_{new}$ is the new value for the pixel from the new gamma map designated by the user. In step **120**, the CPU **12** outputs the image area with the modified incident illuminant (step **108** of FIG. **3**).

Referring once again to FIG. **3**, the CPU **12** can smooth, feather or implement other known techniques to the modified image (step **110**) and then output the modified image, for example for display on the monitor **20** or print out on the printer **22** (step **112**).

FIG. **6***a* shows a flow chart for a color correct brightness adjustment to an intensity adjusted image, according to a feature of the present invention. The CPU **12** is given an original image area, an intensity adjusted image area, a gamma map and a spectral ratio S for the original image area (step **200**). The intensity adjusted image area can be the output of a known dynamic range compression algorithm, such as, for example, the Retinex-based dynamic range compression algorithm marketed by Hewlett-Packard or a Foveon statistics-based dynamic range compression algorithm. These algorithms brighten darker areas of an image for a more pleasing appearance, by adjusting the intensity but not the color of pixels: f*(R, G, B)=>(fR, fG, fB). The routine of FIG. **6***a* is meant to shift the colors as well as the intensity for each pixel for a color correct image adjustment. The gamma (γ) map can be estimated by ascertaining a difference between the intensity adjusted image and the original image.

To that end, reference is made to FIGS. **6***b* and **6***c*. FIG. **6***b* is a graph in RGB space showing an intensity adjusted pixel value for the intensity adjusted image input to the CPU **12** in the routine of FIG. **6***a*. The graph shows the RGB value of the original pixel P and the intensity adjusted value for the pixel A. The graph also shows the position of a fully shadowed version of the pixel Dark, and a color correct fully lit version B, as predicted by the BIDR model according to a feature of the present invention. As can be clearly seen in the graph of FIG. **6***b*, the color of A is displaced in RGB space from the color correct value for the intensity adjusted pixel, B. The result of execution of the routine of FIG. **6***a* by the CPU **12** is an adjustment of A to the value of B, for a color correct depiction of the scene in the image.

FIG. **6***c* is a flow chart for estimating a gamma (γ) value for the pixel of FIG. **6***b* using a dynamic range compression algorithm. In step **400**, the CPU **12** is provided with the input

information corresponding to the input to the CPU **12** in step **200** of FIG. **6***a*, absent the gamma value to be determined by the routine of FIG. **6***c*. In step **402**, for each pixel in the image **18**, the CPU **12** calculates a ratio of the scalar value of the intensity adjusted pixel of the image divided by the scalar value of the original pixel value P:R=||A||/||P||.

In step **404**, for each pixel, the CPU **12** determines a Q, as the value of the minimum of R or the value of (1+||S||)/||S||. In step **406**, for each pixel, the CPU **12** calculates a gamma value: γ=[(1+||S||)/Q]−||S||. After completing steps **402-406** for each pixel, the CPU outputs a gamma map of the image, with a gamma value for each pixel. The gamma value indicates the percent of incident or direct illuminant on the pixel.

In step **202**, the CPU **12** calculates a fully shadowed version (Dark) for each pixel as performed by the CPU **12** in step **116** of FIG. **10**, utilizing the algorithm Dark=P/(1+γ/S) wherein γ is the estimated value in the map generated from execution of the routine of FIG. **6***c*. In step **204**, the CPU **12** uses the Dark version of each pixel, the spectral ratio and the estimated γ to calculate the color and intensity of each pixel such that the corrected pixel has an intensity that matches the intensity adjusted image with a correct color. Initially the CPU **12** calculates a bright version of each pixel: P_{bright}=$P_{original}$*(1+S)/(γ+S). P_{bright} is the color correct version of $P_{original}$. Next, the CPU **12** determines an RGB vector relative to intensity change for each pixel: V=P_{bright}−Dark.

Thereafter, the CPU **12** calculates a fraction representing the difference between the goal intensity, that is, the intensity of the intensity adjusted image, and the intensity of the P_{bright}: fraction=($P_{goal\ intensity}$−$P_{bright\ intensity}$)/$V_{intensity}$. The adjustment required to the intensity of P_{bright} to reach the intensity of the intensity adjusted image is Adjustment=fraction*V. The final pixel value is then: P_{final}=P_{bright}+Adjustment.

After the CPU **12** completes step **204** for each pixel in the image area, the CPU **12** outputs a color correct intensity adjusted image (step **206**).

FIG. **7** is a flow chart for removing direct or incident illumination from an image area, according to a feature of the present invention. In step **208**, the CPU **12** is given an original image area, which can be, for example, an area of an image file **18** selected by a user, a gamma map for the image area, and a characteristic spectral ratio S for the image area.

In step **210**, the CPU calculates a shadowed version (Dark) of each pixel in the image area, again as performed by the CPU **12** in step **116** of FIG. **10**, utilizing the algorithm Dark=P/(1+γ/S). Upon completion of step **210** for all pixels, the CPU **12** outputs an image with all materials lit only by the ambient illuminant (step **212**).

FIG. **8** shows a flow chart for modifying apparent ambient illumination of an image area, according to a feature of the present invention. In step **214**, the CPU **12** is given an original image area, a gamma map, a characteristic spectral ratio S for the image area, and an ambient illuminant modifier vector V. The ambient illuminant modifier vector is a vector in, for example, RGB space that, when multiplied by the actual vector of a fully shadowed pixel in the image (Dark), provides a modified version of the pixel with a new apparent ambient illumination.

In step **216**, the CPU **12** uses the spectral ratio and gamma map to calculate a fully shadowed (Dark) version of each pixel in the image area, again using the algorithm: Dark=P/(1+γ/S). In steps **218**, **220**, the CPU **12** multiplies each Dark pixel by V to yield $Dark_{new}$ and thereby obtain a new apparent ambient illuminant (step **218**), and also multiply S by V to obtain S_{new} (step **220**).

In step **222**, The CPU **12**, using S_{new} and the gamma map, calculates a new color for each pixel: P_{new}=$Dark_{new}$+γ(Dark-

$_{new}/S_{new}$). Upon completion of step **222** for all pixels, the CPU **12** outputs an image area with a modified apparent ambient illuminant (step **224**).

FIG. **9** is a flow chart for modifying apparent direct or incident illumination of an image area, according to a feature of the present invention. In step **300**, the CPU is given an original image area, a gamma map and spectral ratio for the image area and an incident or direct illuminant modifier vector V. The direct illuminant modifier vector is a vector in, for example, RGB space that can be used to modify the spectral ratio for use in modifying the apparent direct illumination in the image area.

In step **302**, the CPU **12** calculates a Dark version of each pixel, as completed in the routines of the previous figures. In step **304**, a new spectral ratio is determined by the CPU **12** using the vector V, $S_{new}=S*1/V$. The new spectral ratio permits a manipulation of pixel values to in effect, modify the apparent incident illumination. In step **306**, the CPU **12** uses S_{new} and the gamma map to calculate a new color for each pixel: $P_{new}=Dark+\gamma(Dark/S_{new})$. Upon completion of step **306** for all pixels, the CPU **12** outputs an image area with a modified apparent direct or incident illuminant.

In the preceding specification, the invention has been described with reference to specific exemplary embodiments and examples thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention as set forth in the claims that follow. The specification and drawings are accordingly to be regarded in an illustrative manner rather than a restrictive sense.

What is claimed is:

1. An automated, computerized method for manipulating an image, comprising the steps of:

a computer executing the following steps:

providing an image file depicting an image;

deriving a bi-illuminant dichromatic reflection model representation of correct color of material depicted in the image, to represent correct color values for the image, across multiple materials of the image, within a range extending from fully shaded color value to fully lit color value, the bi-illuminant dichromatic reflection model representation of correct color being expressed by a characteristic spectral ratio consistent across multiple materials of the image wherein the characteristic spectral ratio is calculated as a ratio between a bright color and a dark color, each of the bright color and the dark color being a multi-band representation of a single material in the image, to provide an indication of correct color change, from fully shaded color value to fully lit color value, across multiple materials of the image; and

utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image of the image file to generate a manipulated image having correct color of material depicted in the image, the correct color being set at any selected degree of adjustment within the range extending from fully shaded color value to fully lit color value and determined as a function of the correct color values represented by the characteristic spectral ratio expression of the bi-illuminant dichromatic reflection model.

2. The method of claim **1** wherein the characteristic spectral ratio equals Dark/(Bright−Dark) wherein Dark corresponds to the dark color and Bright corresponds to the bright color.

3. The method of claim **2** comprising the further step of normalizing the spectral ratio.

4. The method of claim **1** wherein the step of utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image comprises the steps of:

providing a gamma map and a new gamma map for the image;

calculating a Dark version of each pixel of the image as a function of the spectral ratio and the gamma map; and

calculating a new pixel value for each pixel as a function of the Dark version, the spectral ratio and the new gamma map to modify an apparent level of incident illuminant in the image.

5. The method of claim **1** wherein the step of utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image comprises the steps of:

providing a gamma map and an intensity adjusted image;

calculating a Dark version of each pixel of the image as a function of the spectral ratio and the gamma map; and

calculating a new pixel value for each pixel as a function of the Dark version, the spectral ratio, the gamma map and the intensity adjusted image to provide a color correct brightness adjustment to the image.

6. The method of claim **1** wherein the step of utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image comprises the steps of:

providing a gamma map; and

calculating a Dark version of each pixel of the image as a function of the spectral ratio and the gamma map to remove an incident illuminant from the image and provide an image lit solely by an ambient illuminant.

7. The method of claim **1** wherein the step of utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image comprises the steps of:

providing a gamma map and an ambient illuminant modifier vector;

calculating a Dark version of each pixel of the image as a function of the spectral ratio and the gamma map;

calculating a new Dark version of each pixel as a function of the Dark version and the ambient illuminant modifier vector;

calculating a new spectral ratio as a function of the spectral ratio and the ambient illuminant modifier vector; and

calculating a new pixel value for each pixel of the image as a function of the new Dark version and the new spectral ratio to provide a modified apparent ambient illuminant for the image.

8. The method of claim **1** wherein the step of utilizing the bi-illuminant dichromatic reflection model representation to manipulate the image comprises the steps of:

providing a gamma map and an incident illuminant modifier vector;

calculating a Dark version of each pixel of the image as a function of the spectral ratio and the gamma map;

calculate a new spectral ratio as a function of the spectral ratio and the incident illuminant modifier vector; and

calculating a new pixel value for each pixel of the image as a function of the new spectral ratio to provide a modified apparent incident illuminant for the image.

9. A computer system which comprises:

a CPU; and

a memory storing an image file depicting an image;

the CPU arranged and configured to execute a routine to derive a material and illumination representation of the image to depict correct color of material in the image, across multiple materials of the image, to represent correct color values for the image within a range extending from fully shaded color value to fully lit color value for multiple materials of the image, the material and illumi-

nation representation of the image comprises a bi-illuminant dichromatic reflection model of the image to represent correct color values for the image, across multiple materials of the image, within a range extending from fully shaded color value to fully lit color value, the bi-illuminant dichromatic reflection model being expressed by a characteristic spectral ratio consistent across multiple materials of the image, wherein the characteristic spectral ratio is calculated as a ratio between a bright color and a dark color, each of the bright color and the dark color being a multi-band representation of a single material in the image, to provide an indication of correct color change, from fully shaded color value to fully lit color value, across multiple materials of the image and to utilize the material and illumination model representation to manipulate the image to generate a manipulated image having correct color of material depicted in the image, the correct color being set at any selected degree of adjustment within the range extending from fully shaded color value to fully lit color value and determined as a function of the correct color values represented by the material and illumination representation for multiple materials of the image.

10. An automated, computerized method for representing a pixel of an image, comprising the steps of:

a computer executing the following steps:

providing an image file having a set of pixels depicting an image;

deriving a BIDR cylinder/γ/spectral ratio representation for at least one pixel of the set of pixels by calculating a characteristic spectral ratio consistent across multiple materials of the image, for an area of the image corresponding to the BIDR cylinder and containing the pixel, wherein the characteristic spectral ratio is calculated as a ratio between a bright color and a dark color, each of the bright color and the dark color being a multi-band representation of a single material in the image, to provide an indication of correct color change, from fully shaded color value to fully lit color value, across multiple materials of the image, and determining a γ value for the pixel; and

utilizing the BIDR cylinder/γ/spectral ratio representation of the pixel to manipulate the pixel for correct color of material depicted by the pixel, for any selected value of γ, within a range extending from fully shaded color value to fully lit color value.

11. The method of claim 10 wherein the step of utilizing the BIDR cylinder/γ/spectral ratio representation of the pixel to manipulate the pixel is carried out by calculating a new color value for the pixel as a function of the spectral ratio and the γ value.

12. A non-transitory computer readable media, the computer readable media including computer executable process steps operable to control a computer to:

provide an image file depicting an image, in a computer memory;

derive a bi-illuminant dichromatic reflection model representation of correct color of material depicted in the image file, to represent correct color values for the image file, across multiple materials of the image, within a range extending from fully shaded color value to fully lit color value, the bi-illuminant dichromatic reflection model representation of correct color being expressed by a characteristic spectral ratio consistent across multiple materials of the image wherein the characteristic spectral ratio is calculated as a ratio between a bright color and a dark color, each of the bright color and the dark color being a multi-band representation of a single material in the image, to provide an indication of correct color change, from fully shaded color value to fully lit color value, across multiple materials of the image; and

utilize the bi-illuminant dichromatic reflection model representation to manipulate the image file in the computer memory to generate a manipulated image file in the computer memory having correct color of material depicted in the image file in the computer memory, the correct color being set at any selected degree of adjustment within the range extending from fully shaded color value to fully lit color value and determined as a function of the correct color values represented by the characteristic spectral ratio expression of the bi-illuminant dichromatic reflection model.

13. A non-transitory computer readable media, the computer readable media including computer executable process steps operable to control a computer to:

provide an image file having a set of pixels depicting an image, in a computer memory;

derive a BIDR cylinder/γ/spectral ratio representation for at least one pixel of the set of pixels by calculating a characteristic spectral ratio consistent across multiple materials of the image, for an area of the image corresponding to the BIDR cylinder and containing the pixel, wherein the characteristic spectral ratio is calculated as a ratio between a bright color and a dark color, each of the bright color and the dark color being a multi-band representation of a single material in the image, to provide an indication of correct color change, from fully shaded color value to fully lit color value, across multiple materials of the image, and determining a γ value for the pixel; and

utilize the BIDR cylinder/γ/spectral ratio representation of the pixel to manipulate the pixel in the computer memory for correct color of material depicted by the pixel in the computer memory, for any selected value of γ, within a range extending from fully shaded color value to fully lit color value.

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