US 20090052762A1

(19) United States
(12) Patent Application Publication (10) Pub. No.: US 2009/0052762 A1
Dugan et al. (43) Pub. Date: Feb. 26, 2009

(54) MULTI-ENERGY RADIOGRAPHIC SYSTEM FOR ESTIMATING EFFECTIVE ATOMIC NUMBER USING MULTIPLE RATIOS

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(21) Appl. No.: 12/129,371

(22) Filed: May 29, 2008

Related U.S. Application Data

(60) Provisional application No. 60/940,632, filed on May 29, 2007.

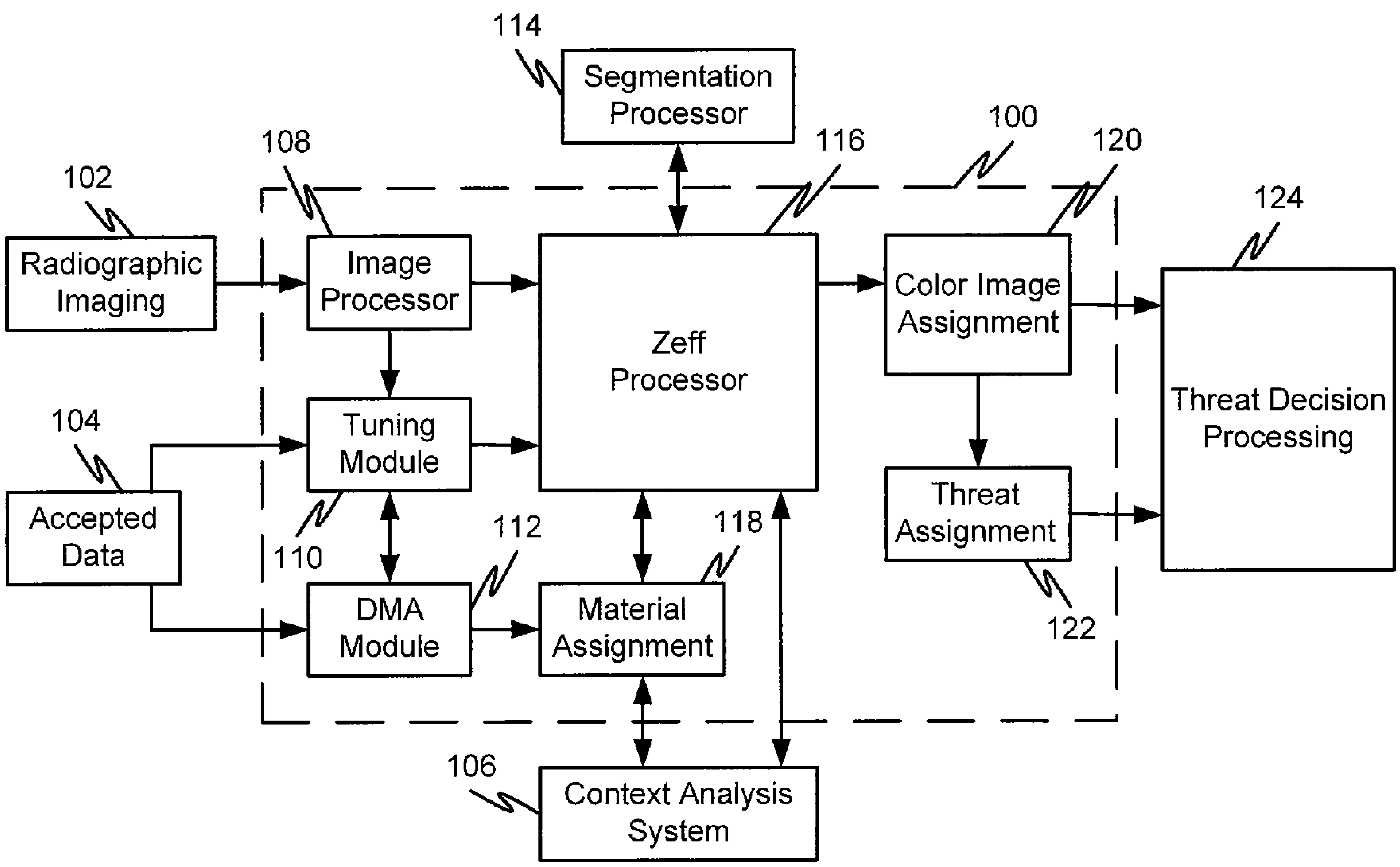
Publication Classification

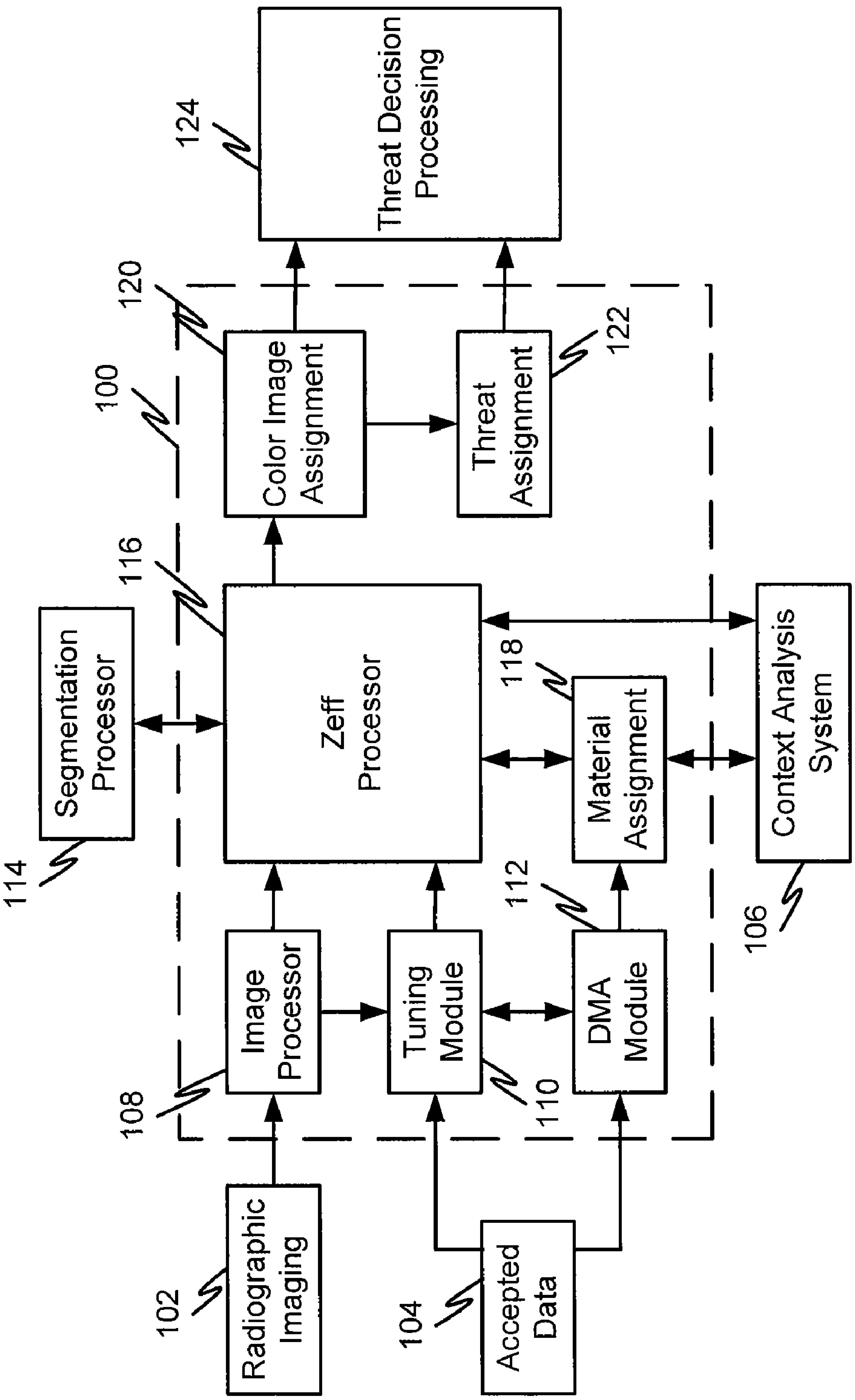
(51) Int. Cl.
G06K 9/00 (2006.01)

(52) U.S. Cl. 382/132

(57) ABSTRACT

A method of determining an effective atomic number, Z_{eff}, of an object may include obtaining a plurality of radiographic images of the object. Each radiographic image can be obtained using a different independent X-ray energy level. An intensity value for each pixel in a region of interest in each radiographic image can be determined. A plurality of measured ratios, R, can be formed using attenuation coefficients from a pair of different radiographic images. At least one adjusted measured ratio, R_m, can be calculated based on the plurality of measured ratios, R, and at least one corresponding estimation coefficient, α. Z_{eff} values can be assigned based on a comparison of the at least one adjusted measured ratio, R_m to a material attenuation database.





Radiographic Imaging
102
Accepted Data
104
Image Processor
108
Tuning Module
110
DMA Module
112
Segmentation Processor
114
Zeff Processor
116
Material Assignment
118
Context Analysis System
106
Color Image Assignment
120
Threat Assignment
122
Threat Decision Processing
124
100

FIG. 1

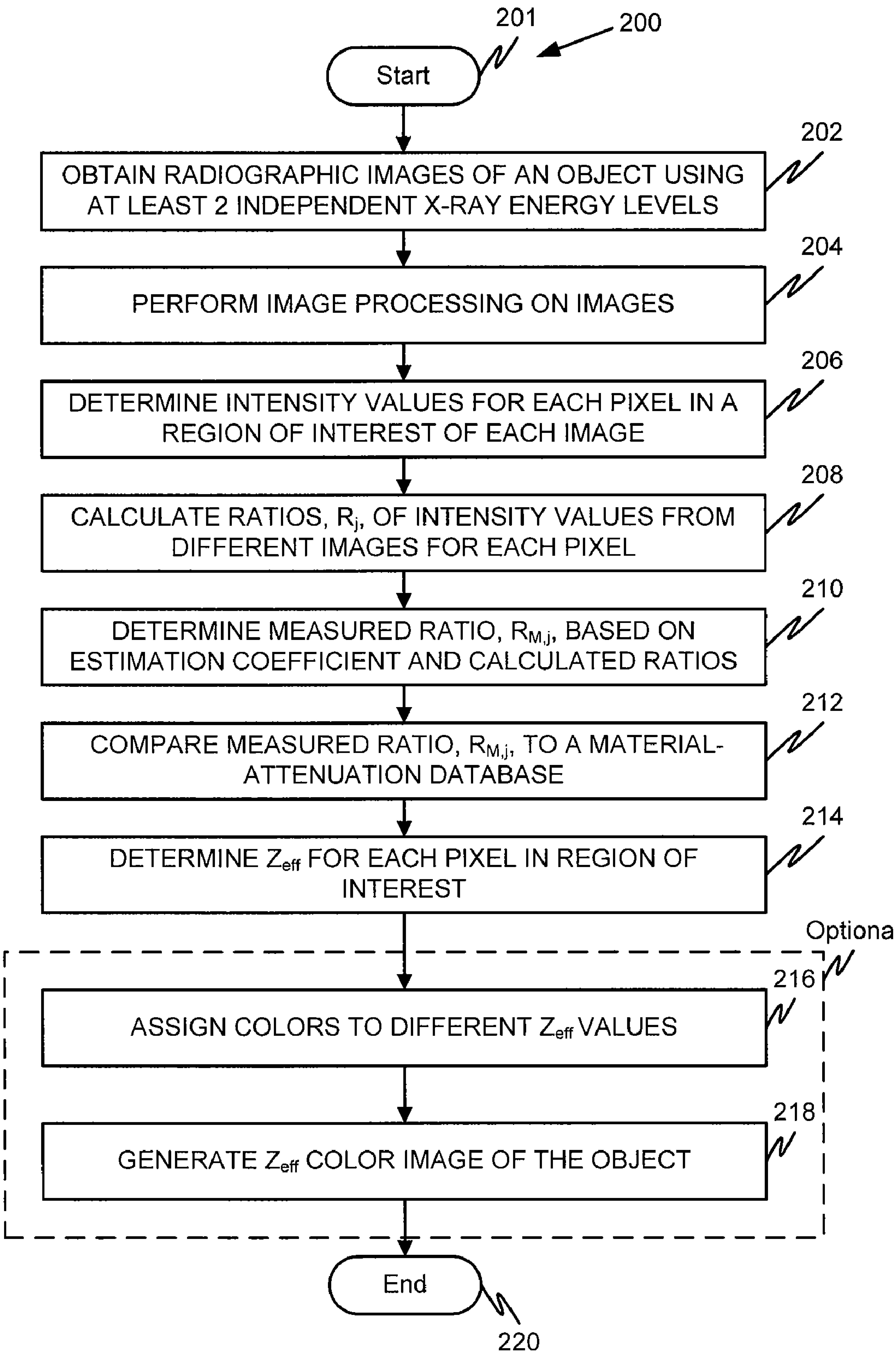

201
200
Start
OBTAIN RADIOGRAPHIC IMAGES OF AN OBJECT USING AT LEAST 2 INDEPENDENT X-RAY ENERGY LEVELS
202
PERFORM IMAGE PROCESSING ON IMAGES
204
DETERMINE INTENSITY VALUES FOR EACH PIXEL IN A REGION OF INTEREST OF EACH IMAGE
206
CALCULATE RATIOS, R_j, OF INTENSITY VALUES FROM DIFFERENT IMAGES FOR EACH PIXEL
208
DETERMINE MEASURED RATIO, $R_{M,j}$, BASED ON ESTIMATION COEFFICIENT AND CALCULATED RATIOS
210
COMPARE MEASURED RATIO, $R_{M,j}$, TO A MATERIAL-ATTENUATION DATABASE
212
DETERMINE Z_{eff} FOR EACH PIXEL IN REGION OF INTEREST
214
Optional
ASSIGN COLORS TO DIFFERENT Z_{eff} VALUES
216
GENERATE Z_{eff} COLOR IMAGE OF THE OBJECT
218
End
220

FIG. 2

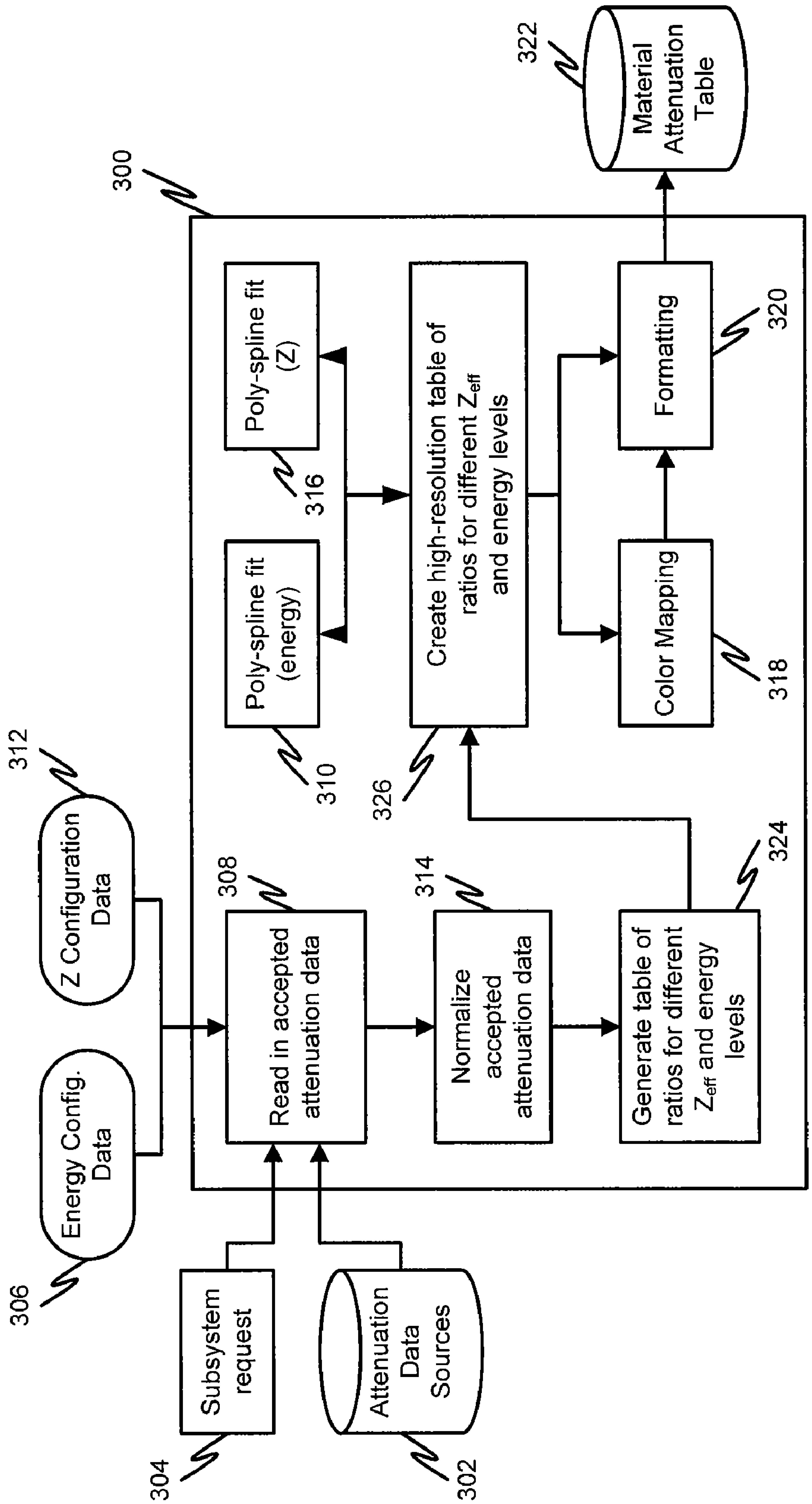
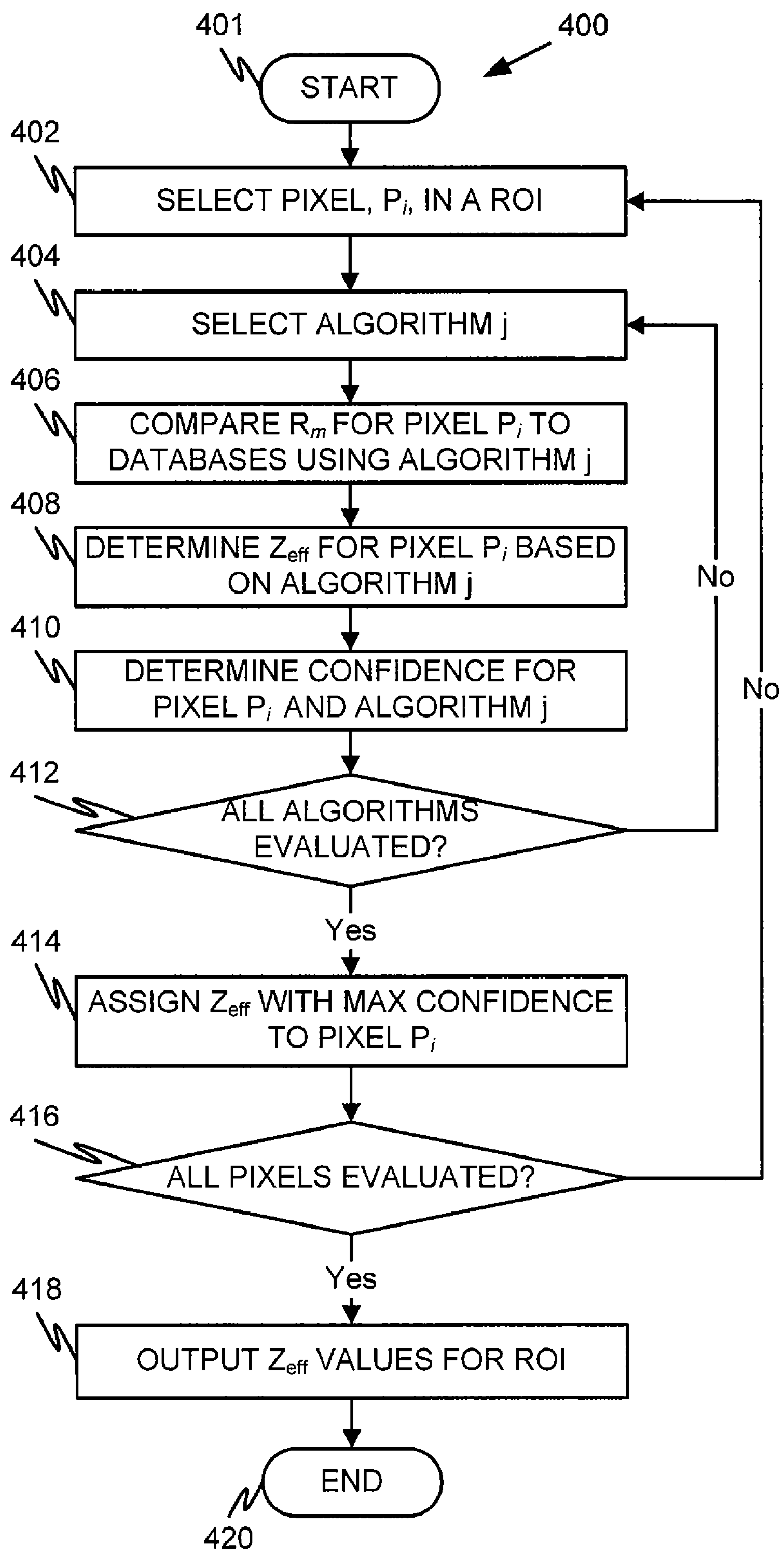

300
302
Attenuation Data Sources
304
Subsystem request
306
Energy Config. Data
312
Z Configuration Data
308
Read in accepted attenuation data
314
Normalize accepted attenuation data
324
Generate table of ratios for different Z_{eff} and energy levels
310
Poly-spline fit (energy)
316
Poly-spline fit (Z)
326
Create high-resolution table of ratios for different Z_{eff} and energy levels
318
Color Mapping
320
Formatting
322
Material Attenuation Table

FIG. 3



400
401
START
402
SELECT PIXEL, P_i, IN A ROI
404
SELECT ALGORITHM j
406
COMPARE R_m FOR PIXEL P_i TO DATABASES USING ALGORITHM j
408
DETERMINE Z_{eff} FOR PIXEL P_i BASED ON ALGORITHM j
410
DETERMINE CONFIDENCE FOR PIXEL P_i AND ALGORITHM j
412
ALL ALGORITHMS EVALUATED?
No
Yes
414
ASSIGN Z_{eff} WITH MAX CONFIDENCE TO PIXEL P_i
416
ALL PIXELS EVALUATED?
No
Yes
418
OUTPUT Z_{eff} VALUES FOR ROI
END
420

FIG. 4

MULTI-ENERGY RADIOGRAPHIC SYSTEM FOR ESTIMATING EFFECTIVE ATOMIC NUMBER USING MULTIPLE RATIOS

[0001] The present application claims the benefit of U.S. Provisional Patent Application No. 60/940,632, entitled "Threat Detection System", filed May 29, 2007, which is hereby incorporated by reference in its entirety.

[0002] The present invention relates generally to radiographic imaging, and, more particularly, to determination of the effective atomic number, Z_{eff}, of a material using multi-energy radiographic imaging.

[0003] Standard techniques using high-energy radiographic systems exist to determine or estimate atomic composition of a material. For example, two X-ray energy levels may be used to image an object of interest. The gray level intensity values measured for each of the two energy levels are used to compute a corresponding ratio. The ratio of the intensity values for an unknown material is compared against known materials. The known material with the closest ratio to that measured is used to estimate the unknown material's effective atomic number (Z_{eff}) of the unknown material. However, these radiographic systems may be prone to noise and other non-linear effects that can cause errors in Z_{eff} determination, especially in high-Z materials. Elements with high-Z include special nuclear materials, such as plutonium and highly enriched uranium, as well as elements that would be extremely effective in shielding special nuclear materials from passive radiation detection techniques.

[0004] Using a radiographic system with only two X-ray energy levels, two common problems can occur. First, insufficient penetration may occur when high-Z or high density materials do not allow enough energy to penetrate through the object of interest to a detector. Second, low-Z or low density materials may induce over-saturation. In the case of over-saturation, little to no attenuation may occur at a particular X-ray energy level. To overcome the problem of over-saturation, lower energies may be used, whereas higher energies may be used in cases of insufficient penetration. Higher energies may solve insufficient penetration issues but exacerbate over-saturation issues and vice versa. Thus, in dual energy systems, the solution for overcoming over-saturation issues may be at odds with the solution for overcoming insufficient penetration. Embodiments of the present invention may address the above-mentioned problems and limitations, among other things.

[0005] An embodiment of the present invention can include a method of determining an effective atomic number, Z_{eff}, of an object including obtaining a plurality of radiographic images of the object. Each radiographic image can be obtained using a different independent X-ray energy level. Each image can also include a plurality of pixels. The images can be registered and normalized. Noise may be removed from the images. An intensity value for each pixel in the region of interest in each radiographic image can be determined. A plurality of measured ratios, R, for each pixel in the region of interest can be formed. Each measured ratio can be formed using intensity values from corresponding pixels in a pair of different radiographic images. The method can include calculating at least one adjusted measured ratio, R_m, for each pixel in the region of interest based on the plurality of measured ratios, R, and at least one corresponding estimation coefficient, α, and comparing the at least one adjusted measured ratio, R_m, for each pixel in the region of interest to a material attenuation database. The method can include assigning a Z_{eff} value to each pixel in the region of interest based on the comparison and outputting the assigned Z_{eff} values.

[0006] Another embodiment may include a computer program product including a computer readable medium encoded with software instructions for causing a computer to perform the steps of receiving more than two radiographic images of an object and determining an intensity value for each pixel in each of the plurality of radiographic images. Each image can be obtained using a different independent X-ray energy level and can have a plurality of pixels. The steps can also include forming a plurality of measured ratios, R. Each measured ratio, R, can be formed using intensity values from corresponding pixels in a pair of different radiographic images. The steps can also include calculating at least one adjusted measured ratio, R_m, based on the plurality of measured ratios, R, and at least one corresponding estimation coefficient, α, and comparing the at least one adjusted measured ratio, R_m, to a material attenuation database. The steps can include assigning a Z_{eff} value based on the comparison and outputting the assigned Z_{eff} value.

[0007] Another embodiment may include a system for determining an effective atomic number, Z_{eff}, of an object. The system may include at least one processor. The at least one processor can form a plurality of measured ratios, R. Each measured ratio may be formed using intensity values taken from a pair of different radiographic images. The at least one processor can calculate at least one adjusted measured ratio, R_m, based on the plurality of measured ratios, R, and at least one corresponding estimation coefficient, α. The at least one processor can output a Z_{eff} value based on a comparison of the at least one adjusted measured ratio, R_m, to a material attenuation database.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1** is a block diagram showing an overview of an embodiment of a system for estimating Z_{eff}.

[0009] FIG. **2** is a flowchart showing a process overview of an embodiment of a process for estimating Z_{eff}.

[0010] FIG. **3** is a block diagram showing an embodiment of a dynamic material attenuation processor for use in estimating Z_{eff}.

[0011] FIG. **4** is a flowchart showing a process overview of an embodiment of Z assignment arbitration for use in estimating Z_{eff}.

DETAILED DESCRIPTION

[0012] The present invention is directed to identifying material compositions by estimating their effective atomic number or Z_{eff} value. The present invention further seeks to overcome the limitations of the above-mentioned ratio method by using a multi-energy approach. Multiple energies are used to determine intensity ratios that are proportional to attenuation coefficient ratios. These intensity ratios can then be used to build a series of measured ratios. These measured ratios can then be used to build a series of adjusted measured ratios for use in a Z_{eff} determination that may be more accurate than conventional methods.

[0013] Imaging of a material relies on the application of Beer's law. Beer's law equation can be stated using an arbitrary energy level k as,

$$I(k)=I_o(k)e^{-\mu_k t}, \quad (1)$$

[0014] where I(k) is the measured intensity of the radiation at energy level k, $I_O(k)$ is the input intensity of the radiation at energy level k, μ_k is the linear attenuation coefficient of the material at energy level k, and t is the energy independent material thickness.

[0015] Experimentally, the linear attenuation coefficient depends on the material cross-section coefficient, σ. Since attenuation is energy dependent, each material has the basic regions of energy scatter, including photoelectric absorption σ_{pe}, coherent scatter σ_{cs}, incoherent scatter σ_{is}, and pair-wise production σ_{pp}. Each material has a material combined cross-sectional coefficient which depends on the sum of the individual cross-sections. For example,

$$\sigma=\sigma_{pe}+\sigma_{cs}+\sigma_{is}+\sigma_{pp}. \quad (2)$$

[0016] The cross-sections and linear attenuation coefficients are related by:

$$\mu=\frac{\sigma N\rho}{A}, \quad (3)$$

[0017] where μ is the material linear attenuation coefficient, σ is the material combined cross-sectional coefficient, N is Avogadro's number, A is atomic weight, and ρ is density.

[0018] Using any two energies, denoted as x and y, the following intensity ratio may apply:

$$R_j=\frac{\ln\left(\frac{I(x)}{I_O(x)}\right)}{\ln\left(\frac{I(y)}{I_O(y)}\right)}=\frac{\mu_x t}{\mu_y t}=\frac{\mu_x}{\mu_y}, \quad (4)$$

[0019] where R_j is the ratio of the logarithm of the respective intensity ratios and x and y represent the upper and lower energy levels. This expression eliminates the dependency on mass thickness. Thus, the R_j value may be compared against attenuation curves at the upper and lower energy levels for various materials to determine the Z_{eff} of an unknown material.

[0020] Intensity values can be determined from measured radiographic images and used in the determination of a plurality of ratios for different pairs of radiographic source energy levels. Any number of energy levels in the X-ray regime may be used. For example, at least two energy levels and corresponding measured ratios can be used. In another example, four different energy levels and corresponding measured ratios can be used.

TABLE 1

Multi-Energy Attenuation Coefficient and Ratio Table

Source Energy Levels (1 < 2 < 3 < 4)	Corresponding Attenuation Coefficients (μ_x, μ_y)	Energy Regime	$R_j=\frac{\ln\left(\frac{I(x)}{I_o(x)}\right)}{\ln\left(\frac{I(y)}{I_o(y)}\right)}=\frac{\mu_x}{\mu_y}$
E_1, E_2	μ_1, μ_2	Low	R_i
E_1, E_3	μ_1, μ_3	Low-Medium	R_{ii}
E_1, E_4	μ_1, μ_4	Low-High	R_{iii}
E_2, E_3	μ_2, μ_3	Medium	R_{iv}
E_2, E_4	μ_2, μ_4	Medium-High	R_v
E_3, E_4	μ_3, μ_4	High	R_{vi}

[0021] Table 1 shows an example of an application employing four different source energy levels. Four different source energy levels (E_1-E_4) are used to generate four different radiographic images of an object. E_1 corresponds to the lowest X-ray source energy level. For example, E_1 may be 1MeV. E_4 corresponds to the highest X-ray source energy level. For example, E_4 may be 10 MeV. Measured intensity values I(x) for each energy level, x, are extracted from the corresponding radiographic images and used in the determination of each measured ratio, R_j. Source intensity values $I_o(x)$ for each energy level are known from measurement conditions of the radiographic images and are also used in the determination of the measured ratios, R_j. Although only four source energy levels are discussed in detail with respect to Table 1, it is of course contemplated that more than four or less than four energy levels may be employed.

[0022] Ratios exist for various combinations of intensity values based on the different source energy levels. Therefore, it may be feasible that one could select between low, medium, or high energy ratios for estimating the effective atomic number of the material of the object to minimize errors due to saturation, noise, or insufficient penetration.

[0023] A family of attenuation curves for a group of materials with respect to X-ray energy is typically non-linear, with various ranges of polynomial order. Although the attenuation curves themselves are non-linear, the ratios from energy level to energy level can be modeled using linear methods. At least two energy solutions form a linear attenuation fit based on the ratio. Determining the atomic structure of a material can be based on comparing the slopes of the intensity values from radiographic images with those values of known materials residing in a database. The attenuation coefficient is proportional to measured X-ray intensities.

[0024] Radiographic imagers can use measured X-ray intensity to create a corresponding gray level picture, otherwise known as a radiographic image. The conversion from intensity to gray level can be defined by an inverse linear ratio, but the process of imaging various materials poses several non-linear settings. Despite the nonlinearity, ratios between the measured intensity values are approximately the same as ratios between the true material linear attenuation coefficients when adjusted for gray level conversion. In other words, an adjusted ratio of measured intensity values, as defined in equation (4), may be correlated with a similar ratio of known linear attenuation coefficients in determining the Z_{eff} of an unknown material.

[0025] An adjusted measured ratio, $R_{m,j}$, can be determined from the equation:

$$R_{m,j}=\alpha_j R_j$$

[0026] where R_j is the measured ratio of attenuation coefficients at two different source energy levels, α_j is an estimation coefficient corresponding to the particular two energy levels used in determining R_j, and j is a subscript referring to the particular pair of source energy levels. The estimation coefficient, α_j, can be determined from the mapping of the photon intensity values to a gray level value. Separate adjusted measured ratios, R_m, may be determined for each measured ratio, R, used. Alternately, the multiple separate measured ratios may be combined into a single vector. For example, using the set of ratios defined by Table 1, equation (5) would become:

$$R_m=\alpha_i R_{i\hat{i}i}+\alpha_{ii} R_{ii\hat{i}ii}=\alpha_{iii} R_{iii\hat{i}iii}+\alpha_{iv} R_{iv\hat{i}iv}+\alpha_v R_{v\hat{i}v}+\alpha_{iv} R_{iv\hat{i}iv}$$

[0027] wherein $\hat{\imath}_j$ represents a vector in n-space corresponding to attenuation coefficient R_j. The n-space may be a multi-dimensional space based on the number of energy levels employed or the number of measured ratios formed.

[0028] While it is contemplated that all radiographic images corresponding to different energy levels can be used in the determination of the Z_{eff}, it is also possible that only specific measured ratios of intensity values may be selected depending on the conditions associated with a particular energy level. For example, for a given energy level, an intensity value may not be applicable due to an over-saturation or non-penetration condition. Therefore, the measured energy ratios, R, using the intensity values for that particular energy level may be excluded from the calculation of the adjusted measured ratio, $R_{m,j}$. Alternately, the ratio $R_{m,j}$ corresponding to those conditions of over-saturation or non-penetration may be excluded from use in the determination of Z_{eff}.

[0029] Gray level mapping of the estimation coefficient is nonlinear across material and energy levels. To compensate for the nonlinearity, the estimation coefficients, α, may be determined empirically through experimental evaluation of known materials. Alternately, an algorithm can be used for minimum error tuning so as to optimize the estimation coefficients, α. It should be appreciated that other methods may be used to determine the estimation coefficients.

[0030] In view of the foregoing features described above, structures and methodologies in accordance with various aspects of the present invention will be better appreciated with reference to FIGS. **1-5**.

[0031] FIG. **1** is a block diagram showing an overview of an exemplary embodiment of a system for estimating Z_{eff}. A material domain imaging processor **100** may receive multiple radiographic images and other data as input and may output a multi-energy high Z-mapping for identification of threats. An image processor **108** may receive a set of radiographic images of an object of interest from radiographic imaging system **102** or another processor, system, or database. Each of the radiographic images may be taken at a different X-ray energy level. Each image may be processed by the image processor **108** to register the images, normalize the images, and remove any noise in the images.

[0032] The processed images may be sent to the Z_{eff} processor **116**. The Z_{eff} processor **116** may extract corresponding intensity values from each pixel in each image. In an alternate embodiment, the Z_{eff} processor **116** may only determine an intensity value for each pixel in each image that is within a region of interest. For determination of a region of interest, the images may be sent to an external analysis system, such as segmentation processor **114**. Segmentation processor **114** may use, for example, edge boundary detection, texture based detection, or other region processing in order to determine boundaries within the images and to select a common region of interest for evaluation by the material domain imaging processor **100**. The region of interest in each image may then be communicated to the Z_{eff} processor **116** for determination of intensity values. The relevant pixels for subsequent processing may be limited to those pixels within the region of interest instead of the entirety of pixels in each image. Relevant pixels may also be selected based on penetration conditions (e.g., oversaturation, non-penetration). For example, like regions across the various registered images may be compared to determine penetration conditions.

[0033] After determination of the intensity values, the Z_{eff} processor **116** may use the intensities to form a set of measured ratios, R_j, for the relevant pixels. The measured ratios, R_j, may be formed using the relation set forth in equation (4) above. Normalized intensity values from corresponding pixels in a pair of different radiographic images may also be used to form each measured ratio. Corresponding pixels may refer to pixels in different images which correspond to the same point or location on an imaged object. For example, the set of ratios for each pixel may take the form shown in Table 1.

[0034] The Z_{eff} processor **116** may use estimation coefficients, α_j, with the set of measured ratios, R_j, to determine at least one adjusted measured ratio, $R_{m,j}$, for each relevant pixel. Separate adjusted measured ratios, $R_{m,j}$, may be determined for each energy ratio in the set or only for certain energy ratios within the set. Alternately, the multiple energy ratios may also be combined into a single measured ratio vector, R_m. The estimation coefficients may be provided by tuning module **110**.

[0035] The relevant pixels may include, for example, a single pixel, all the pixels in the entire image, or just the pixels within a region of interest. In an alternative embodiment, relevant pixels may be selected based on penetration conditions (e.g., over-saturation, non-penetration, etc.). The material domain imaging processor **100** or a separate system may compare regions across various images to determine penetration conditions. The material domain imaging processor **100** or a separate system (i.e., segmentation processor **114** or context analysis system **106**) may correlate regions with pixel values at a lower extreme of a photon intensity scale as regions of non-penetration, while regions with pixel values at an upper extreme of the photon intensity scale may be correlated as regions of over-saturation. The Z_{eff} processor **116** may be configured to exclude these regions from the list of relevant pixels for further processing.

[0036] In an exemplary embodiment, tuning module **110** can employ an algorithm for minimum error tuning of the estimation coefficients. Accepted attenuation database **104** may be provided to the tuning module **110**. Alternately, accepted attenuation data may be provided by an integrated database, a memory device, or a separate system or processor. The tuning module **110** may use ratios from radiographic images of a known material to optimize the value of the estimation coefficients such that adjusted measured ratios correspond to ratios of accepted attenuation data. The accepted attenuation data may be data from public attenuation sources, such as the NIST public data source. In an alternate embodiment, the tuning module **110** may include a database of previously determined estimation coefficients for use by the Z_{eff} processor **116**. The estimation coefficients may be determined via experimental evaluation or other means.

[0037] The resulting adjusted measured ratios, $R_{m,j}$, can be output from the Z_{eff} processor **116** to the material assignment module **118**. The material assignment module **118** can compare the adjusted measured ratios to a material attenuation database from dynamic material attenuation (DMA) module **112**. Alternately, the Z_{eff} processor **116** may send the measured ratios, R_j, to the material assignment module **118**. In such a scenario, material assignment module **118** would use the estimation coefficients and the measured ratios to form the adjusted measured ratios, $R_{m,j}$, for comparison to the material attenuation database. In either embodiment, the material assignment module **118** may assign a Z_{eff} value to each relevant pixel or to a region of pixels based on the comparison.

[0038] In an exemplary embodiment, the DMA module **112** may be a processor, such as dynamic material attenuation processor **300**, that uses configurable settings to dynamically create a densely populated attenuation ratio lookup table with variable resolution in both the energy scale and the effective atomic number (Z_{eff}) scale. The DMA module **112** can be used for the two or more energies used in the radiographic images for determining Z_{eff} values. Sparse attenuation data from public sources for any material (liquid, solid, gas) can be stored on a disk using a standard format. Alternately, accepted attenuation data (i.e., attenuation coefficients) may be input to the DMA module **112** from accepted attenuation database **104**. Accepted attenuation data may also be provided by an integrated database, a memory device, or a separate system or processor. The accepted attenuation data may be data from public attenuation sources, such as the NIST public data source. The attenuation data can be created using a variety of scattering approaches, such as coherent, incoherent, photoelectric, pairwise production nuclear field, pairwise production electric field, total scatter with coherent, and total scatter without coherent. A user may select the materials used to create the attenuation lookup table, such as water, peroxide, lead, carbon, etc. Using the attenuation data, the attenuation lookup table may be created as a function of the X-ray energy level and the Z_{eff} of the material. Alternately, the DMA module **112** may include a database of previously determined attenuation lookup tables, such as material attenuation table **322** in FIG. **3**, for use by the material assignment module **118**.

[0039] Material assignment module **118** may include a plurality of independent material assignment algorithms. Each material assignment algorithm may employ a different methodology or use different measured ratios for comparison to the same attenuation database to generate a set of candidate Z_{eff} values for each relevant pixel. Each material assignment algorithm can also assign a confidence value to the candidate Z_{eff} values.

[0040] The set of candidate Z_{eff} values may be sent to the Z_{eff} processor **116**. The Z_{eff} processor **116** may compare the confidence values for each Z_{eff} value in the set and may select the Z_{eff} value for each relevant pixel with the highest associated confidence value. The result can be a Z_{eff} image with each pixel having an assigned Z_{eff} value with the highest confidence. In an exemplary embodiment, the Z_{eff} processor **116** may output the result to external analysis system, such as context analysis system **106**, for evaluation of regions of non-penetration or over-saturation for inclusion in the final processor output. For example, context analysis system **106** may use a-priori information, in the way of configuration data, to assist in identifying non-penetrable and false alarm cases.

[0041] The result from the Z_{eff} processor **116** can be sent to a color image assignment module **120**. The color image assignment module **120** can map a color scale to a range of corresponding Z_{eff} values. Thus, each relevant pixel may be assigned a color based on the assigned Z_{eff} value, thereby creating a color image of the object. This color image can be output from the material domain imaging processor **100** to threat decision processor **124**. In addition, the color image and Z_{eff} values may be further processed by a threat assignment module **122**. The Z_{eff} value for each pixel can be compared with a threat threshold by the threat assignment module **122** to determine regions where the threshold is exceeded, i.e., those regions where a threat exists. These regions and associated confidence values may be output from the material domain imaging processor **100** to the threat decision processor **124** for further processing or integrated decision making.

[0042] FIG. **2** shows a process flow **200** of an exemplary embodiment of a method of material domain image processing. The process begins at step **201** and proceeds to step **202**. In step **202**, radiographic images may be obtained of an object. Each radiographic image of an object may be obtained at a different X-ray energy level. For example, at least two independent X-ray energy levels can be used. In another example, four X-ray energy levels can be used to generate four independent radiographic images of an object. In step **204**, the radiographic images may be subject to image processing. The image processing may be any of a number of processing steps known in the art. For example, each radiographic image may be registered with the other radiographic images such that regions of interest in the object are aligned. Further, the radiographic images may be normalized to a gray scale. In addition, noise filtering may be employed to reduce noise artifacts in the image.

[0043] In step **206**, an intensity value may be determined for each relevant pixel in each processed image. The relevant pixels may include a single pixel, pixels within a designated region of interest, or all pixels within each image. At step **208**, the intensity values may be used to create a set of measured ratios, R_j, for each relevant pixel based on the different images, with each image corresponding to a different X-ray energy level. For example, the set of measured ratios, R_j, for each pixel may be formed as shown in Table 1. At step **210**, at least one adjusted measured ratio, $R_{m,j}$, for each relevant pixel can be determined. The measured ratio can be based on the product of at least one estimation coefficient, α_j, and the set of measured ratios, R_j, from step **208**. Separate adjusted measured ratios, $R_{m,j}$, may be determined for each measured ratio, R_j, in the set or only for certain energy ratios within the set.

[0044] The resulting set of adjusted measured ratios, $R_{m,j}$, may be compared to a material attenuation database in step **212** using at least one algorithm. The material attenuation database can be a densely populated attenuation ratio lookup table based on data from public sources of attenuation data. For example, this comparison may be a determination of an error, ϵ, for each measured ratio with respect to the corresponding accepted attenuation ratio, as given by:

$$\epsilon=|R_{m,j}-R_{T,j}|=|(\alpha_j*R_j)-R_{T,j}| \quad (7)$$

[0045] where α_j is the estimation coefficient corresponding to the measured ratio, R_j, and $R_{T,j}$ is an accepted attenuation ratio derived from the densely populated attenuation ratio lookup table.

[0046] Results of the comparison in step **212** can be used in step **214** to determine the Z_{eff} for each relevant pixel. In an exemplary embodiment, step **212** can provide a comparison using a set of algorithms. Each algorithm may employ a different methodology, different adjusted measured ratios, and/or different estimation coefficients for comparison to the same database. The results of this comparison may be used to generate a set of candidate Z_{eff} values and associated confidence values for each relevant pixel in step **214**. An arbitration step may be included in step **214** to select the Z_{eff} value that has the highest associated confidence value for the given measurement conditions.

[0047] In steps **216** and **218**, which are optional, the Z_{eff} value for each relevant pixel may be used in the construction of a color image. In step **216**, colors may be assigned to correspond with different Z_{eff} values. For example, the assignment of colors may be predetermined or set dynamically to correspond with the range of measured Z_{eff} values. In step **218**, colors may be assigned to each pixel according to the Z_{eff} value of the pixel so as to generate a Z_{eff} color image of the object. The method can end at step **220**.

[0048] FIG. **3** illustrates a dynamic material attenuation processor **300**, which may be used as DMA module **112** in the embodiment of FIG. **1**. The dynamic material attenuation processor **300** may be used to dynamically create a densely populated attenuation ratio lookup table for use by the material assignment module **118** in the determination of Z_{eff} values. The processor **300** can use configurable settings to create, for example, a table of accepted attenuation coefficient ratios, $R_{T,j}$, with variable resolution in both the energy scale and Z_{eff}. Similar to equation (4) above, the accepted attenuation coefficient ratio, $R_{T,j}$, can be expressed as:

$$R_{T,j} = \frac{\mu_x}{\mu_y}. \tag{8}$$

[0049] Inputs into the dynamic material attenuation processor **300** may be derived from public attenuation data source **302**, such as periodic attenuations, liquid attenuations, or other forms available through the NIST public data source, for example. The public attenuation data source **302** may include a sparsely populated database. The data from the public attenuation data source **302** may provide attenuation data of various material compositions at different radiographic energy levels under a variety of scattering conditions, including, but not limited to, coherent, incoherent, photoelectric, pair-wise production nuclear field, pair-wise production electric field, total coherent, and total non-coherent. Using this data, the processor **300** may build a fully connected table of Z_{eff} values versus ratio of accepted attenuation coefficients at different energy levels. For example, the table may have rows with different Z_{eff} values. Each column in the table may have an accepted attenuation coefficient ratio, $R_{T,j}$, that corresponds with a different pair of source energy levels used in the radiographic images by Z_{eff} processor **116**.

[0050] The densely populated attenuation ratio lookup table may be dynamically configurable based on user inputs or configuration data. For example, the dynamic material attenuation processor **300** may receive a subsystem request **304**. This request **304** may include, for example, a particular source energy range and a particular Z_{eff} range. This information may also be provided by configuration data. Configuration data can control the energy density needed for the resultant attenuation data table as well as the Z_{eff} density needed. At **306**, the requested energy values and energy resolution may be obtained from the configuration data. At **312**, the requested Z_{eff} values and Z_{eff} resolution may be obtained from the configuration data. Although shown in FIG. **3** as being external to processor **300**, the configuration data may be integrated and stored with the processor **300**. The configuration data may be predetermined based on the radiographic system or object under test. Alternately, the configuration data may be input by a user.

[0051] At **308**, the dynamic material attenuation processor **300** can receive the request **304**, the energy configuration data **306**, and/or the Z_{eff} configuration data **312** and may obtain the necessary attenuation data from public attenuation data source **302**. At **314**, the attenuation data may be normalized for both energy and Z_{eff} values. The resultant attenuation data may then be formed into accepted attenuation coefficient ratios, $R_{T,j}$, and organized into tabular form at **324**. Publicly available attenuation data source **302** may lack some of the Z_{eff} values or the source energy values requested in subsystem request **304**. Accordingly, the dynamic material attenuation processor **300** may create a high-resolution table so as to account for this missing information. At **326**, the tabular form of accepted attenuation coefficient ratios, $R_{T,j}$, from **324** may be expanded based on the subsystem request **304**, the energy configuration data **306**, and/or the Z_{eff} configuration data **312**. Any data missing in the table generated by **326** may be interpolated using a polynomial spline fit. Poly-spline fit **310** may interface with the high-resolution table created in **326** to interpolate missing information with respect to source energy values. Poly-spline fit **316** may interface with the high-resolution table created in **326** to interpolated missing information with respect to Z_{eff} values (i.e., material composition). The result can be an attenuation ratio lookup table based on source energy values and Z_{eff} values. Thus, sparse input data and configuration information can be used to create a densely populated configurable attenuation ratio lookup table.

[0052] A color map to the Z_{eff} values may also be created to coincide with the Z_{eff} value settings. The attenuation ratio lookup table may be output to **318** for assigning colors to the various Z_{eff} values. The resultant attenuation ratio lookup table and the assigned colors may then be output to **320** for formatting to a given data standard. Alternately, the attenuation ratio lookup table may be sent directly from **326** to **320** for formatting to the standard. The format may be any available data standard. For example, the standard can be an N42 standard, such as ANSI N42.42. After formatting, the attenuation ratio table may be output as a material attenuation ratio table **322** for use by material assignment module **118**.

[0053] FIG. **4** illustrates a Z algorithm arbitration process **400** for use in estimating Z_{eff}. The process starts at step **401** and continues to step **402**. In step **402**, a pixel may be selected in a region of interest for which at least one adjusted measured ratio, R_m, has been determined. At step **404**, an algorithm may be selected from a set of algorithms. Using the selected algorithm, the at least one adjusted measured ratio, R_m, may be compared to a densely-populated attenuation lookup table in step **406**. Based on the comparison, the selected algorithm can determine a Z_{eff} value for the relevant pixel at step **408**. At step **410**, the selected algorithm may also determine a confidence value for the Z_{eff} value. This confidence value may be based on measurement conditions. Alternately, the confidence value may be based on a particular set of estimation coefficients employed and the resulting range of Z_{eff} determined. At step **412**, the arbitration process can check to see if all algorithms within the set have been evaluated. The process can repeat steps **404-410** until all algorithms have been evaluated. Once all algorithms have been evaluated, thereby generating a set of candidate Z_{eff} values with associated confidence values, the process may proceed to step **414**. At step **414**, the Z_{eff} value with the highest confidence value can be selected and assigned to the relevant pixel. At step **416**, the arbitration process can check to see if all relevant pixels have been evaluated. The process can repeat steps **402-414** until all relevant pixels have been evaluated. If all pixels have been evaluated, the process may proceed to step **418**, wherein the Z_{eff} values and associated confidence values for each relevant pixel may be output for further processing. For example, the Z_{eff} values may be output to color image assignment module **120** for subsequent color imaging of the Z_{eff} values. The process may continue to step **420** where the process may end.

[0054] It should be appreciated that the steps of the present invention may be repeated in whole or in part in order to perform the contemplated Z_{eff} estimation. Further, it should be appreciated that the steps mentioned above may be performed on a single or distributed processor. Also, the processes, modules, and units described in the various figures of the embodiments above may be distributed across multiple computers or systems or may be co-located in a single processor or system.

[0055] Embodiments of the method, system, and computer program product for determining an effective atomic number, Z_{eff}, of an object, may be implemented on a general-purpose computer, a special-purpose computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element, an ASIC or other integrated circuit, a digital signal processor, a hardwired electronic or logic circuit such as a discrete element circuit, a programmed logic circuit such as a PLD, PLA, FPGA, PAL, or the like. In general, any process capable of implementing the functions or steps described herein can be used to implement embodiments of the method, system, or computer program product for determining an effective atomic number, Z_{eff}, of an object.

[0056] Furthermore, embodiments of the disclosed method, system, and computer program product for determining an effective atomic number, Z_{eff}, of an object may be readily implemented, fully or partially, in software using, for example, object or object-oriented software development environments that provide portable source code that can be used on a variety of computer platforms. Alternatively, embodiments of the disclosed method, system, and computer program product for determining an effective atomic number, Z_{eff}, of an object can be implemented partially or fully in hardware using, for example, standard logic circuits or a VLSI design. Other hardware or software can be used to implement embodiments depending on the speed and/or efficiency requirements of the systems, the particular function, and/or particular software or hardware system, microprocessor, or microcomputer being utilized. Embodiments of the method, system, and computer program product for determining an effective atomic number, Z_{eff}, of an object can be implemented in hardware and/or software using any known or later developed systems or structures, devices and/or software by those of ordinary skill in the applicable art from the function description provided herein and with a general basic knowledge of the computer, radiographic, and image processing arts.

[0057] Moreover, embodiments of the disclosed method, system, and computer program product for determining an effective atomic number, Z_{eff}, of an object can be implemented in software executed on a programmed general purpose computer, a special purpose computer, a microprocessor, or the like. Also, the Z_{eff} determination method of this invention can be implemented as a program embedded on a personal computer such as a JAVA® or CGI script, as a resource residing on a server or image processing workstation, as a routine embedded in a dedicated processing system, or the like. The method and system can also be implemented by physically incorporating the method for determining Z_{eff} of an object into a software and/or hardware system, such as the hardware and software systems of multi-energy X-ray inspection systems.

[0058] It is, therefore, apparent that there is provided, in accordance with the present invention, a method, system, and computer program product for determining Z_{eff} of an object. While this invention has been described in conjunction with a number of embodiments, it is evident that many alternatives, modifications and variations would be or are apparent to those of ordinary skill in the applicable arts. Accordingly, Applicants intend to embrace all such alternatives, modifications, equivalents and variations that are within the spirit and scope of this invention.

What is claimed is:

1. A method of determining an effective atomic number, Z_{eff}, of an object, the method comprising the steps of:
- obtaining a plurality of radiographic images of the object, each radiographic image obtained using a different independent X-ray energy level and each image including a plurality of pixels;
- registering the plurality of radiographic images with each other;
- normalizing the plurality of radiographic images;
- removing noise from the plurality of radiographic images;
- determining an intensity value for each pixel in a region of interest in each radiographic image;
- forming a plurality of measured ratios for each pixel in the region of interest, each ratio formed using intensity values from corresponding pixels in a pair of different radiographic images;
- calculating at least one adjusted measured ratio for each pixel in the region of interest based on the plurality of measured ratios and at least one corresponding estimation coefficient;
- comparing the at least one adjusted measured ratio for each pixel in the region of interest to a material attenuation database;
- assigning a Z_{eff} value to each pixel in the region of interest based on the comparing; and
- outputting the assigned Z_{eff} values.

2. The method of claim **1**, wherein the step of obtaining a plurality of radiographic images of the object comprises obtaining more than two radiographic images of the object.

3. The method of claim **1**, wherein said at least one adjusted measured ratio includes a set of adjusted measured ratios and each adjusted measured ratio of the set is based on a corresponding one of the plurality of measured ratios and a corresponding one of a plurality of estimation coefficients.

4. The method of claim **3**, wherein comparing the at least one adjusted measured ratio to a database includes:
- providing a plurality of independent material assignment systems, each material assignment system configured to determine a Z_{eff} value based on at least one different adjusted measured ratio from the set of adjusted measured ratios and the material attenuation database;
- generating a plurality of candidate Z_{eff} values and associated confidence values using the plurality of material assignment systems; and
- selecting the Z_{eff} value from the plurality of candidate Z_{eff} values with the highest associated confidence value.

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

mapping a color scale to a range of Z_{eff} values; and

generating a color image of the object using the color mapping and the assigned Z_{eff} values.

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

comparing the Z_{eff} values to a threat threshold; and

generating an output of a threat region of interest and a confidence value for the threat region of interest based on the comparison of the Z_{eff} values to the threat threshold.

7. The method of claim **1**, wherein the material assignment database comprises a densely populated attenuation ratio lookup table.

8. The method of claim **7**, further comprising:

receiving accepted attenuation data of various materials, the accepted attenuation data providing information regarding attenuation of X-rays at various energy levels based on the corresponding Z_{eff} values of said materials;

receiving configuration data including energy scale resolution and Z_{eff} resolution for said attenuation lookup table; and

generating said attenuation lookup table based on said accepted attenuation data and said configuration data.

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

determining said region of interest through image processing and analysis of the radiographic images.

10. A computer program product comprising:

a computer readable medium encoded with software instructions that, when executed by a computer, cause the computer to perform the steps of:

receiving more than two radiographic images of an object, each image obtained using a different independent X-ray energy level and each image having a plurality of pixels;

determining a normalized intensity value for each pixel in each of the radiographic images of the object;

forming a plurality of measured ratios, each measured ratio formed using the normalized intensity values from corresponding pixels in a pair of different radiographic images;

calculating at least one adjusted measured ratio based on the plurality of measured ratios and at least one corresponding estimation coefficient;

comparing the at least one adjusted measured ratio to a material attenuation database;

assigning a Z_{eff} value based on the comparing; and

outputting the assigned Z_{eff} value.

11. The computer program product of claim **10**, wherein the determining a normalized intensity value includes:

registering the radiographic images with each other;

normalizing the radiographic images;

processing the radiographic images to remove noise; and

determining a plurality of intensity values, each of the plurality of intensity values being determined for a different pixel of the plurality of pixels in one of registered, normalized, and processed radiographic images.

12. The computer program product of claim **10**, wherein the comparing the at least one adjusted measured ratio, includes:

providing a plurality of independent material assignment algorithms for determining Z_{eff} based on the at least one adjusted measured ratio and the material attenuation database;

generating a plurality of candidate Z_{eff} values and associated confidence values using the plurality of independent material assignment algorithms; and

selecting the Z_{eff} value from the plurality of candidate Z_{eff} values with the highest associated confidence value.

13. The computer program product of claim **10**, further comprising the steps of:

mapping a color scale to a range of Z_{eff} values;

generating a color image of the object using the color mapping and the assigned Z_{eff} values;

comparing the Z_{eff} values to a threat threshold to determine a threat region of interest; and

generating an output of the color image, a threat region of interest, and a confidence value for the threat region of interest based on the comparison of the Z_{eff} values to the threat threshold.

14. The computer program product of claim **10**, wherein the material attenuation database comprises a densely populated attenuation lookup table based on accepted attenuation data, the accepted attenuation data providing information regarding attenuation of X-rays at various energy levels based on Z_{eff} values.

15. A system for determining an effective atomic number, Z_{eff}, of an object, the system comprising:

at least one processor configured to perform the steps of:

forming a plurality of measured ratios, each measured ratio formed using intensity values from a pair of different radiographic images of an object;

calculating at least one adjusted measured ratio based on the plurality of measured ratios and at least one corresponding estimation coefficient; and

outputting a Z_{eff} value based on a comparison of the at least one adjusted measured ratio to a material attenuation database.

16. The system of claim **15**, further comprising:

an image processing module configured to register, normalize, and remove noise from each of the radiographic images.

17. The system of claim **15**, further comprising:

a plurality of independent material assignment algorithms for determining a plurality of Z_{eff} values and corresponding confidence values, each material assignment algorithm configured to compare the at least one adjusted measured ratio to the material attenuation database to determine a Z_{eff} value and an associated confidence value,

wherein the at least one processor is configured to assign a Z_{eff} value from the plurality of determined Z_{eff} values based on the associated confidence value and to generate an output at least based on the assigned Z_{eff} value.

18. The system of claim **15**, further comprising:

a color image assignment module configured to map a color scale to a range of Z_{eff} values and to generate a color image of the object using the color mapping and assigned Z_{eff} values.

19. The system of claim **15**, further comprising:

a threat assignment module configured to compare the Z_{eff} values to a threat threshold and to generate an output of at least one threat region of interest and a corresponding confidence value for each threat region of interest.

20. The system of claim **15**, further comprising:

a material attenuation module configured to dynamically generate a densely populated attenuation ratio lookup table based on accepted attenuation data and configuration data.

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