

[005] What is needed is a system and method for efficiently detecting features from surface-image data through computer image processing with sufficient resolution and accuracy. More specifically, an image processing and monitoring system which isolates features and can be used to quantify material deformation of structures from image data collected using optical inspection devices.

[006] It is with respect to these and other considerations that the disclosure made herein is presented.

SUMMARY OF THE INVENTION

[007] The present invention is directed to a computer implemented method for detecting deformation of a structure from multi-dimensional image data of a surface of the structure captured with an optical inspection device.

[008] In one aspect, a computer implemented method for detecting deformation of a structure from multi-dimensional image data of the structure captured using an optical inspection device is provided. In particular, the method includes the step of providing the multi-dimensional image data of the surface of the structure at a processor, wherein the image data comprises a plurality of data-points that are measured using the optical inspection device. More specifically, each data-point includes: 1) location data identifying a respective location on the surface that a respective data-point was captured in at least two dimensions; and 2) feature value data including at least a respective z value for the respective data-point measured using the inspection device. The method also includes the step of applying, with the processor, a surface dividing model to the image data. More specifically, applying the surface dividing model includes the step of dividing the surface represented by the image data into multiple parallelogram-shaped planes, and subdividing each of the parallelogram-shaped planes into two triangle planes, respectively. The method also includes the step of calculating, with the processor, an approximate feature value Z for each of the triangle planes. More specifically, the feature value for a respective triangle plane is calculated based on a measured feature value z of one or more of the data-points within the respective triangle plane. The method also includes the step of calculating, with the processor based on the approximate feature value Z, an adjusted feature value V for each of the plurality of data-points. More specifically, the adjusted feature value V for a respective data-point is calculated based on the measured feature value z for the respective data-point and the calculated approximate feature value Z for a triangle plane that the respective data-point is within. The method also includes

the step of generating a processed multi-dimensional image of the surface in which the data set for the processed multi-dimensional image differs from the data set in the provided image data. More specifically, the multi-dimensional image of the surface is generated with the processor based on the adjusted feature value V of each data-point. The method also includes the step of outputting by the processor on a display, the processed multi-dimensional image of the surface wherein the processed multi-dimensional image depicts in a graphical representation the detected deformation of the surface within a particular triangular plane of the surface dividing model of the image data.

[0009] According to another aspect, a system for detecting deformation a structure from multi-dimensional image data of a surface captured with an optical inspection device is provided. The system comprises a computer readable storage medium, a communication interface and a display. The system also comprises one or more processors configured to access the storage medium and that are in operative communication with the communication interface and the display. In addition, the system includes software modules that are stored on the storage medium and executable by the processor.

[0010] The software modules include a communication module that, when executed by the processor, configures the processor to receive the multi-dimensional image data including a plurality of data-points that were measured using the optical inspection device. In particular, the data-points comprise: location data identifying, in at least two dimensions, a respective location on the surface that a respective data-point was captured, and feature value data that includes at least a respective feature value z for the respective data-point measured using the inspection device.

[0011] The software modules also include a surface dividing module that, when executed by the processor, configures the processor to divide the surface represented by the image data into multiple parallelogram-shaped planes according to a surface dividing model and also subdivide each of the parallelogram-shaped planes into two triangle planes, respectively.

[0012] The software modules also include a feature detection module that, when executed by the processor, configures the processor to calculate a respective approximate feature value Z for each of the triangle planes. In particular, the approximate feature value Z for a respective triangle plane is calculated based on a measured feature value v of one or more of the data-points within the respective triangle plane. In addition, wherein the feature detection module further configures the processor to calculate an adjusted feature value V for each of the

plurality of data-points. In particular, the adjusted feature value V for a respective data-point is calculated based on the measured feature value z for the respective data-point and the calculated approximate feature value Z for a triangle plane that the respective data-point is within.

[0013] The software modules also include an image generation module that, when executed by the processor, configures the processor to generate, based on the adjusted feature value V of each data-point, a processed multi-dimensional image of the surface in which the data set for the processed multi-dimensional image differs from the data set in the provided image data. The image generation module also configures the processor to output the processed multi-dimensional image of the surface using the display. More specifically, the processed multi-dimensional image depicts in a graphical representation the detected deformation of the surface within a particular triangular plane of the surface dividing model of the image data.

[0014] These and other aspects, features, and advantages can be appreciated from the accompanying description of certain embodiments of the invention and the accompanying drawing figures and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a schematic view of an inspection apparatus for capturing multi-dimensional image data of a structure according to an embodiment of the present invention;

[0016] FIG. 2 is a schematic block diagram of components of a computing device for analyzing multi-dimensional image data according to an embodiment of the present invention;

[0017] FIG. 3 is a systematic flowchart illustrating a routine for analyzing multi-dimensional image data according to an embodiment of the present invention;

[0018] FIG. 4A is a conceptual diagram illustrating an data structure of image data according to an embodiment of the present invention;

[0019] FIG. 4B is a graphical representation of surface-image data at various stages of processing according to an embodiment of the present invention;

[0020] FIG. 4C is a graphical representation of a triangle-plane network of surface-image data according to an embodiment of the present invention;

$$\text{Equation 9: } Z(x_i, y_i) = \frac{D - Ax_i + Bx_i}{c}$$

[0061] As noted, in the exemplary practical NDT application, the approximate Z value can represent hue. Effectively, calculating the approximate Z value for each plane serves to generate an approximate representation of hue value for points within each plane. Furthermore, the contiguous network of so approximated triangle planes serves to generate an approximate representation of the entire set of surface-image data.

[0062] It should be understood that, addition to modulating the size of the individual planes to adjust the resolution of the image and selectively highlight different types of features, the particular mathematical algorithm for approximating the individual planes can also be adjusted according to the particular application of the technology.

[0063] Then at step 325, adjusted feature values from the original surface data are generated. Step 325 effectively highlights and isolates salient features of the surface-image at respective locations on the surface. In particular, in an exemplary implementation, the processor 240, which is configured by executing one or more of the software modules, including, preferably, the feature detection module 292, can calculate the adjusted feature value V for respective data-points in the surface-image by baseline/base-plane subtraction. More specifically, the configured processor can subtract the approximated Z value of a respective plane from the observed z value of each point of the surface-image data set having the corresponding x and y coordinates, and such difference is defined as the adjusted feature value V .

[0064] The exemplary mathematic relationship for calculating the adjusted feature value V for an individual data-points is shown as in equation 10:

$$\text{Equation 10: } V = z(x_i, y_i) - Z(x_i, y_i)$$

[0065] It should be appreciated that, in some implementations, the measured feature values z represented by the original surface-image data set can be absolute values (e.g., a measured magnitude) and, as a result of baseline subtraction, the adjusted feature value V is relative to the approximated feature value Z of the corresponding triangle plane. It should also be understood that additional processing can be performed to further refine the adjusted feature value V for the data-points. For instance, the adjusted feature value of hue can be converted based on known mathematical relationships into a measure of displacement. In addition or alternatively, a “tare” operation can be performed in which with an expected value (e.g., the expected feature value or displacement corresponding to an un-deformed structure) can be

exemplary implementations, a feature value change crosses multiple triangular planes and remains as a sharp feature in the processed image after baseline subtraction. The peak 555 on the right of FIG. 5C is an example of a sharp feature value that crosses multiple triangular planes. As noted, a sharp change in feature value that crosses multiple triangular planes has
 5 been, to some degree, smoothed out (e.g., decreased in magnitude) through baseline subtraction, while the sharp value within a single triangle remains relatively unaffected.

[0072] In step 330, a processed multi-dimensional image of the surface can be generated. More specifically, the processor 240, which is configured by executing one or more of the software modules, including, preferably, the image generation module 294, can generate a graphical
 10 representation (e.g., an image) depicting the surface based on the adjusted feature value V of each data-point. As can be appreciated, through generating the processed multi-dimensional image of the surface based on the adjusted feature values V of each data-point, the data set defining the processed multi-dimensional image of the surface differs from the data set in the provided image data. FIG. 5D is an exemplary graphical illustration of a processed multi-
 15 dimensional image 530 showing the adjusted feature values V .

[0073] By way of further example, FIG. 5E is a three-dimensional graphical representation of processed surface-image data overlaid on a triangulated graphical representation of surface-image data. In particular, FIG. 5E illustrates an alternative example in which adjusted feature values representing sharp feature value changes persist in the data set after baseline subtraction
 20 and wherein both instances of sharp feature value changes do not cross a triangle plane boundary (e.g., remain within or on the boundary of one triangular plane, respectively). FIG. 5F graphically illustrates the processed multi-dimensional image 530 showing the adjusted feature values V without being overlaid on the triangulated map of surface image data.

[0074] In some implementations, the processed multi-dimensional image generated by the
 25 processor can contain several layers of information generated at various steps of the exemplary routine 300. For instance, as shown in FIG. 5G, the layers of information can include a location data layer 575, a triangular network layer 570 illustrating the subdivisions of the surface image, an original measured feature value layer 580 (e.g., the original surface image illustrating measured value of hue for respective locations), and a final surface-image layer 585 generated
 30 based on the adjusted feature value. The configured processor output the final processed image and layers together or separately. In addition, the image that is generated can be formatted as vector data or raster data, as would be understood in the art.

[0075] In step 335, one or more image layers including, preferably, the processed multi-dimensional image of the surface can be output by the processor 240 using the display 270 of computing device 200. More specifically, the processor 240 using the display 270 can graphically output the final processed image to an operator and thereby graphically present features from the original surface-image that correspond to material deformation, as detected and isolated according to steps 305-330 of the routine 300. For instance, the graphical output can include

[0076] Whereas the existing technologies primarily concentrate on averaging, smoothing and isolating features based on frequency and can be further limited in that they require monitoring and mathematically adjusting for changing environmental and inspection conditions, the foregoing disclosed embodiments apply a particular set of rules according to a specific approach that is unconventional in the art and achieves practical benefits in terms of accuracy and processing efficiency, among other things. More specifically, according to a salient aspect, the processed multi-dimensional image generated based on the calculated adjusted feature values V depicts, in a graphical representation, changes in measured feature values z occurring within a given triangle plane with greater emphasis relative to changes in measured feature values z occurring over an area comprising multiple triangle planes. Moreover, benefits achieved by the disclosed systems and methods in the NDT implementation include the ability to identify deformations irrespective of changes in inspection condition variables, i.e., lighting, relative orientation of the inspection device and the material, distance of the inspection device and the material, etc. As a further result, the deformation analysis is simplified and more efficient, not only from a computational point of view, but also from an operational point of view, as the inspection device does not necessarily require sensors for monitoring inspection conditions (e.g., using a proximity sensor, angle sensor and even specific light sources).

[0077] Illustrative embodiments and arrangements of the present systems and methods provide a system and a computer implemented method, computer system, and computer program product for analyzing multi-dimensional surface image data to, *inter alia*, detect deformation of the imaged structure. The flowchart and block diagrams in the figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments and arrangements. In this regard, each block in the flowchart or block diagrams can represent a module, segment, or portion of code, which comprises one or more executable instructions