

CREATING SYNTHETIC DATA FOR COMPOSITE INSPECTION

BACKGROUND INFORMATION

1. Field:

[0001] The present disclosure relates generally to inspection and more specifically to data training sets for inconsistency identification.

2. Background:

[0002] To identify inconsistencies in manufacturing, data sets are built to train classification models. The quality of a classification model is dependent on the quantity of inconsistency data. Therefore, it would be desirable to have a method and apparatus that takes into account at least some of the issue discussed above, as well as other possible issues.

SUMMARY

[0003] An embodiment of the present disclosure provides a method of generating synthetic data for composite manufacturing inspection. A three-dimensional model of a composite layup is created. An inconsistency is generated in the three-dimensional model of the composite layup. A camera position and a camera orientation is set in the three-dimensional model space. A captured image of the three-dimensional model and the inconsistency is generated from the camera position and the camera orientation. A secondary image is created from the captured image, the secondary image having colorations of a preselected inspection type.

[0004] Another embodiment of the present disclosure provides a method of training a composite inspection system. A captured image of a three-dimensional model of a composite layup with an inconsistency is generated at a predetermined camera position and at a predetermined camera orientation within the three-dimensional model space. The captured image is modified to form a secondary image having coloration of a preselected inspection type. The inconsistency identifier program is trained using the secondary image.

[0005] Yet another embodiment of the present disclosure provides a method of using synthetically generated training data. An inconsistency is generated in a three-dimensional model comprising a plurality of layers of a composite layup. A captured image of the inconsistency and the three-dimensional model is generated at a predetermined camera position and at a predetermined camera orientation based on a head orientation of an inspection system connected to a composite laying head. A secondary image is generated

from the captured image, the secondary image having a coloration of an inspection type of the inspection system. The secondary image is provided as training data for an inconsistency identifier program.

[0006] The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

[0008] **Figure 1** is an illustration of an aircraft in accordance with an illustrative embodiment;

[0009] **Figure 2** is an illustration of a block diagram of a data flow in accordance with an illustrative embodiment;

[0010] **Figure 3** is an illustration of a block diagram of a manufacturing environment in accordance with an illustrative embodiment;

[0011] **Figure 4** is an illustration of a side view of laying down and inspecting composite material in accordance with an illustrative embodiment;

[0012] **Figure 5** is an illustration of a representation of a three-dimensional model in accordance with an illustrative embodiment;

[0013] **Figures 6A and 6B** are flowcharts of a method of generating synthetic data for composite manufacturing inspection in accordance with an illustrative embodiment;

[0014] **Figure 7** is a flowchart of a method of training a composite inspection system in accordance with an illustrative embodiment;

[0015] **Figure 8** is a flowchart of a method of using synthetically generated training data in accordance with an illustrative embodiment;

[0016] **Figure 9** is an illustration of an aircraft manufacturing and service method in a form of a block diagram in accordance with an illustrative embodiment; and

[0017] **Figure 10** is an illustration of an aircraft in a form of a block diagram in which an illustrative embodiment may be implemented.

DETAILED DESCRIPTION

[0018] Turning now to **Figure 1**, an illustration of an aircraft is depicted in accordance with an illustrative embodiment. Aircraft **100** has wing **102** and wing **104** attached to body **106**. Aircraft **100** includes engine **108** attached to wing **102** and engine **110** attached to wing **104**.

[0019] Body **106** has tail section **112**. Horizontal stabilizer **114**, horizontal stabilizer **116**, and vertical stabilizer **118** are attached to tail section **112** of body **106**.

[0020] Aircraft **100** is an example of an aircraft that can have composite inspection models trained by the illustrative examples. Aircraft **100** is an example of an aircraft with composite parts that can be inspected using an inspection system trained on synthetic data.

[0021] Turning now to **Figure 2**, an illustration of a block diagram of a data flow is depicted in accordance with an illustrative embodiment. Three-dimensional model **200** is a model of at least a portion of a part. Three-dimensional model **200** can be a model of at least a portion of at least one of wing **102**, wing **104**, or body **106** of aircraft **100**. Three-dimensional model **200** has any desirable quantity of layers. Three-dimensional model **200** is generated based on a design for a part to be manufactured. In some illustrative examples, three-dimensional model **200** has a same design as a layup for the part. In some illustrative examples, by being based on the layup of the part, the curvature of three-dimensional model **200** is the same as the part to be manufactured.

[0022] Three-dimensional model **200** is used to generate synthetic data **202**. Synthetic data **202** has sufficient resolution to be used for training inconsistency

identifier program **204**. By training inconsistency identifier program **204** using synthetic data **202** instead of or in addition to using inspection data **206**, a greater quantity of training data can be provided to inconsistency identifier program **204**. By training inconsistency identifier program **204** using synthetic data **202** instead of or in addition to using inspection data **206**, fewer resources can be used. In some illustrative examples, training inconsistency identifier program **204** using synthetic data **202** reduces time. In some illustrative examples, training inconsistency identifier program **204** using synthetic data **202** reduces manufacturing trial and error, thereby reducing manufacturing time. In some illustrative examples, training inconsistency identifier program **204** using synthetic data **202** reduces manufacturing trial and error, thereby reducing material waste.

[0023] By training inconsistency identifier program **204** using synthetic data **202** instead of or in addition to using inspection data **206**, less waste is generated. For example, if physical inconsistencies were to be intentionally generated for training, this would generate physical waste. As another example, by utilizing synthetic data **202**, fewer reworks will be performed, generating less waste. By training inconsistency identifier program **204** using synthetic data **202** instead of or in addition to using inspection data **206**, inconsistency identifier program **204** can be trained prior to manufacturing the part. By training inconsistency identifier program **204** using synthetic data **202** instead of or in addition to using inspection data **206**, training time can be reduced.

[0024] Synthetic data **202** comprises captured images **208** and secondary images **210**. Captured images **208** are

images taken of three-dimensional model **200** in a computer simulation. Captured images **208** can have any desirable view within three-dimensional model **200**.

[0025] Captured images **208** generated from three-dimensional model **200** can be used for any desirable inspection type. For example, captured images **208** can be generated for optical inspection, infrared (IR) inspection, laser inspection, or any other desirable type of inspection. To create captured images **208** for a predetermined inspection type, at least one of a camera orientation, a camera position, a field of view, material properties of three-dimensional model **200**, colors of three-dimensional model **200**, or other aspects of three-dimensional model **200** can be modified based on the predetermined inspection type. In some illustrative examples, at least one of a camera orientation, a camera position, or a field of view can be modified based on a respective inspection system. In some illustrative examples, captured images **208** include a variety of camera orientations, camera positions, and fields of view to cover different inspection system positioning options for a single type of predetermined inspection type.

[0026] Secondary images **210** are images generated from captured images **208**. In some illustrative examples, captured images **208** are modified to form secondary images **210**. In some illustrative examples, filters are applied to captured images **208** to generate secondary images **210**. Secondary images **210** can be provided as training data to inconsistency identifier program **204**. In some illustrative examples, resolution of captured images **208** is modified to create secondary images **210**. In some illustrative examples, coloration of captured images **208** is modified to create secondary images **210**. In some illustrative examples, intensity of captured images **208**

is modified to create secondary images **210**. In some illustrative examples, only selected areas within captured images **208** are modified. In some illustrative examples, portions of captured images **208** are sampled to determine whether modifications are to be performed. This sampling can compare pixel values in captured images **208** to pixel values in inspection images captured during manufacturing. In some illustrative examples, inspection images captured during manufacturing with an inspection system of a desired inspection type are used to define a pixel value profile that is applied to captured images **208** to create secondary images **210**. For example, pixel value normalization and min/max rescaling can be performed on captured images **208** to match inspection images gathered during manufacturing. In some illustrative examples, a portion of inspection images **212** can be used to define a pixel value profile.

[0027] In some illustrative examples, three-dimensional model **200** is created such that captured images **208** have desired pixel values and desired coloration without additional modifications. In some illustrative examples, material characteristics within three-dimensional model **200** are set to have coloration of a predetermined inspection type. In these illustrative examples, secondary images **210** are optional. In these illustrative examples, captured images **208** can be sent to inconsistency identifier program **204** as training data.

[0028] After sufficient synthetic data **202** is generated to train inconsistency identifier program **204**, inconsistency identifier program **204** can be used to evaluate inspection images **212**. Inspection images **212** are inspection data **206** generated during manufacturing of the part. During inspection, inspection images **212** are evaluated by inconsistency identifier program **204**.

Inconsistency identifier program **204** locates inconsistencies within inspection images **212**. Inconsistency identifier program **204** identifies types of inconsistencies within inspection images **212**.

[0029] Turning now to **Figure 3**, an illustration of a block diagram of a manufacturing environment is depicted in accordance with an illustrative embodiment.

Manufacturing environment **300** is an environment in which portions of aircraft **100** can be manufactured. Three-dimensional model **336** is an example of three-dimensional model **200** of **Figure 2**.

[0030] Composite laying head **302** lays composite tows **304** to form portion **306** of part **308**. Part **308** is a component of platform **310**. Platform **310** can take any desirable form, such as a vehicle, building, or vessel. Platform **310** can take the form of a car, a boat, a spaceship, a train, a bus, or any other desirable type of vehicle. In some illustrative examples, platform **310** takes the form of aircraft **312**.

[0031] Inspection system **314** is mounted to composite laying head **302**. Inspection system **314** has inspection type **316** and head orientation **318**. Inspection type **316** comprises the technology utilized for inspection system **314**. Inspection type **316** can include IR inspection, laser inspection, optical inspection, or any other desirable type of inspection. Inspection type **316** has coloration **320**. Coloration **320** includes saturation, intensity, and other values of pixels in inspection type **316**.

[0032] Inspection system **314** generates inspection images **322** as composite laying head **302** lays composite tows **304**. For quality control of platform **310**, inspection images **322** are evaluated for the presence of inconsistencies. It is desirable for a machine vision

system to identify and classify inconsistencies within inspection images **322**. In these illustrative examples, inconsistency identifier program **324** reviews inspection images **322** for inconsistencies **326**.

[0033] Inconsistency identifier program **324** is an example of a machine vision/machine learning algorithm. Machine vision/machine learning algorithms require a large amount of training images in order to build models. With automated fiber placement (AFP) applications, it is challenging to 'force' situations that would provide the quantity and types of data for training inconsistency identifier program **324** from real world data. Synthetic data **332** is generated to support quality model training.

[0034] The illustrative examples recognize and take into account that the training data can be very configuration specific. The illustrative examples recognize and take into account that changes made to the layup **339** of portion **306** of part **308** or layout of part **308** can result in generating a whole new data set.

[0035] If training data is only collected from a single orientation, from a single speed, or when the background temperature is a specific value this leaves gaps in the training data that make it difficult to apply the same code in inconsistency identifier program **324** across multiple machines and use cases. Synthetic data **332** can be used to fill those data gaps. In some illustrative examples, synthetic data **332** can be used to train inconsistency identifier program **324** without real world data. In some illustrative examples, synthetic data **332** can be used to train inconsistency identifier program **324** in coordination with real world data images.

[0036] Inconsistency identifier program **324** is a classification model trained using training data **328**. Training data **328** comprises at least one of captured

images **358** or secondary images **330**. Captured images **358** and secondary images **330** are synthetic data **332** generated from three-dimensional model space **334**.

[0037] Three-dimensional model space **334** can be used to create three-dimensional models for generating synthetic data **332**. Three-dimensional model space **334** can be any desirable type of three-dimensional modeling software.

[0038] Three-dimensional model **336** comprises composite layup **338**. Three-dimensional model **336** is a representation of portion **306** of part **308**. Composite layup **338** is based on layup **339** of portion **306** of part **308**. In some illustrative examples, three-dimensional model **336** of composite layup **338** is generated using layup **339** of portion **306** of part **308**. In some illustrative examples, plurality of layers **340** are representative of each of plurality of layers **341** of portion **306** of part **308**. In some illustrative examples, layup **339** comprises plurality of layers **341** of composite material **303** and three-dimensional model **336** comprises plurality of layers **340** arranged the same as plurality of layers **341** of composite material **303**.

[0039] In some illustrative examples, plurality of layers **340** form curvature **343** of surface **342** of composite layup **338**. In some illustrative examples, plurality of layers **340** are designed such that curvature **343** is the same as a curvature of portion **306** of part **308**. In some illustrative examples, plurality of layers **340** has fewer layers than plurality of layers **341** of portion **306** of part **308**.

[0040] Three-dimensional model **336** can be modified when a design for part **308** is changed. By modifying three-dimensional model **336**, training data **328** can be

generated for inconsistency identifier program **324** to take into account changes to the design of part **308**.

[0041] To form synthetic data **332**, inconsistency **344** is generated in three-dimensional model **336** of composite layup **338**. Inconsistency **344** takes any desirable form. In some illustrative examples, inconsistency **344** is one of overlapping tows **346**, foreign object debris **348**, or gaps **350**. In some illustrative examples, inconsistency **344** is one of fuzzballs, resin balls, foreign object debris **348**, edge folds/twists, heat damage, untacked tows, or missing tows.

[0042] Inconsistency **344** can be generated in three-dimensional model **336** dependent on a type of inconsistency **344**. For example, when inconsistency **344** is a fuzzball, inconsistency **344** can be constructed in three-dimensional model **336** as a plurality of randomly oriented lines of varying lengths passing through a reference center point.

[0043] When inconsistency **344** is an edge fold, inconsistency **344** can be constructed in three-dimensional model **336** by identifying a distance along an outer tow edge and solving the optimization problem:

$$\min \|\Delta x\|^2, \sum \|x_i - x_{i+1}\| = d$$

where x is a list of points that form a curve along the outer tow edge, d is the required arc-length for the edge and Δ is the umbrella Laplacian for the points which averages neighbors of points of x .

[0044] When inconsistency **344** is a twist, inconsistency **344** can be constructed in three-dimensional model **336** by removing a portion of a tow over some distance and building new geometry by connecting the lower tow boundary to the upper tow boundary and visa-versa. When inconsistency **344** is an untacked tow,

inconsistency **344** can be constructed in three-dimensional model **336** by identifying a distance along a tow at the tow start or end and lifting the tow off the three-dimensional part surface along a quadratic curve while maintaining tow length.

[0045] When inconsistency **344** is one of overlapping tows **346** or gaps **350**, inconsistency **344** can be constructed in three-dimensional model **336** by identifying a portion of a tow over some distance and shifting the tow centerline up or down by some amount. When inconsistency **344** is a missing tow, inconsistency **344** can be constructed in three-dimensional model **336** by identifying a tow in the three-dimensional model **336** and removing it from the simulated geometry.

[0046] Virtual camera **352** is a representation of a field of view within three-dimensional model space **334**. Virtual camera **352** has camera position **354** and camera orientation **356** in three-dimensional model space **334**. Camera position **354** can be modified based on at least one of inspection type **316** or a mounting position of inspection system **314** to composite laying head **302**. Camera position **354** can be modified to change an amount of three-dimensional model **336** visible in captured images **358**. Camera position **354** can be modified to change a section of three-dimensional model **336** visible in captured images **358**.

[0047] In some illustrative examples, head orientation **318** of inspection system **314** attached to composite laying head **302** in manufacturing environment **300** is determined and camera position **354** and camera orientation **356** are set in three-dimensional model space **334** by setting camera orientation **356** based on head orientation **318**.

[0048] Captured image **360** of three-dimensional model **336** and inconsistency **344** is generated from camera

position **354** and camera orientation **356**. Captured image **360** is one of captured images **358**. In some illustrative examples, captured images **358** are taken from more than one camera position **354**. In some illustrative examples, captured images **358** are taken from more than one camera orientation **356**. Captured images **358** have sufficient resolution to be used as training data **328** for inconsistency identifier program **324**.

[0049] In some illustrative examples, composite layup **338** is formed with material properties **345** such that captured images **358** can be used as training data **328**. In these illustrative examples, material properties **345** cause captured images **358** to have desired coloration, intensity, and other properties for preselected inspection type **366**, such as inspection type **316**.

[0050] In other illustrative examples, processing is performed on captured images **358** to form secondary images **330**. In these illustrative examples, secondary images **330** are used as training data **328**. In some illustrative examples, secondary image **362** is created from captured image **360**, secondary image **362** having colorations of preselected inspection type **366**. In some illustrative examples, captured image **360** can be processed to form secondary images **330** for a plurality of different inspection types.

[0051] In some illustrative examples, number of filters **364** is applied to captured image **360** to create secondary image **362**. Applying number of filters **364** to captured image **360** creates secondary image **362** that has characteristics of images of preselected inspection type **366**.

[0052] In some illustrative examples, applying number of filters **364** to captured image **360** creates coloration **368** of preselected inspection type **366** to captured image

360 to create secondary image **362**. In some illustrative examples, applying number of filters **364** to captured image **360** creates coloration **368** of an IR image.

[0053] In some illustrative examples, applying number of filters **364** to captured image **360** creates coloration **368** characteristic of the inconsistency type for preselected inspection type **366** within pixels of secondary image **362** with inconsistency **344**. For example, when inconsistency **344** is foreign object debris **348**, applying number of filters **364** to captured image **360** creates coloration **368** characteristic of foreign object debris **348** for preselected inspection type **366** within pixels of secondary image **362** with inconsistency **344**. As a specific example, when inconsistency **344** is foreign object debris **348** and preselected inspection type **366** is IR inspection **370**, applying number of filters **364** to captured image **360** creates coloration **368** characteristic of foreign object debris **348** for IR inspection **370** within pixels of secondary image **362** with inconsistency **344**.

[0054] In some illustrative examples, creating secondary image **362** comprises sampling colors from pixels of inconsistency **344** in captured image **360** and adjusting color values for the pixels to values within a range for an inconsistency type of inconsistency **344** in stock images of preselected inspection type **366**. After training inconsistency identifier program **324**, inconsistency identifier program **324** can be used to evaluate inspection images **322** of composite tows **304** after composite tows **304** are laid.

[0055] As depicted, computer system **372** includes three-dimensional model space **334** and inconsistency identifier program **324**. In other illustrative examples, three-dimensional model space **334** and inconsistency

identifier program **324** are present on separate computer systems in communication with each other.

[0056] Generating training data **328** from three-dimensional model space **334** reduces at least one of training time, cost, and operator time. Three-dimensional model **336** can be used to generate training data **328** for multiple inspection types. Three-dimensional model **336** can be used to generate training data **328** for multiple travel speeds. Three-dimensional model **336** can be used to generate training data **328** for multiple different camera orientations.

[0057] Synthetic data **332** can also provide thermal information when preselected inspection type **366** is IR inspection **370**. When synthetic data **332** does not include thermal information such as coloration **368**, models, such as inconsistency identifier program **324**, only rely on contrast differences to pick out inconsistencies. When thermal data, such as coloration **368**, is present in synthetic data **332**, shifts in overall temperature or the camera being used in an auto-gain mode can be accommodated.

[0058] The addition of thermal information adds context to synthetic data **332** provided to machine learning algorithms, such as inconsistency identifier program **324**. Including thermal information allows for training of inconsistency identifier program **324** that considers overall environmental temperatures when looking at contrast differences as well as tracking gradual temperature changes that would not be apparent in a simple contrast only image.

[0059] Three-dimensional model space **334** allows for detailed simulated data sets to be generated. In some illustrative examples, the synthetic data can be generated using three-dimensional model space **334** prior

to the first build of a physical component in manufacturing environment **300**. Three-dimensional model space **334** can include the material system, machine configuration, part configuration, layup plan, heater plan, camera information, camera field of view, and other desirable parameters to allow for very detailed simulated data sets.

[0060] The illustration of manufacturing environment **300** in **Figure 3** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be unnecessary. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

[0061] For example, secondary images **330** can be optional. In some illustrative examples, material characteristics of plurality of layers **340** are set such that captured images **358** can be used as training data **328**. In these illustrative examples, filtering or other modifications to produce secondary images **330** is not performed.

[0062] Turning now to **Figure 4**, an illustration of a side view of laying down and inspecting composite material is depicted in accordance with an illustrative embodiment. View **400** is a view of laying down composite material **402** on substrate **404**. In some illustrative examples, composite material **402** takes the form of composite tows. Inspection system **406** is mounted to composite laying head **408**. As composite laying head **408** lays composite material **402**, inspection system **406**

generates inspection images of composite material **402**. Field of view **410** of inspection system **406** is affected by an inspection type of inspection system **406**, a head orientation of inspection system **406**, and a mounting position relative to composite laying head **408**.

[0063] Inspection images generated by inspection system **406** are examples of images that can be inspected by inconsistency identifier program **324** of **Figure 3**. Inspection system **406** is an example of a physical implementation of inspection system **314** of **Figure 3**.

[0064] Turning now to **Figure 5**, an illustration of a representation of a three-dimensional model is depicted in accordance with an illustrative embodiment. Three-dimensional model space **500** is a representation of three-dimensional model space **334** of **Figure 3**. Three-dimensional model **502** of composite layup **504** is present in three-dimensional model space **500**. Inconsistency **506** is present on surface **507** of three-dimensional model **502**.

[0065] Camera **508** is representation of a viewpoint within three-dimensional model space **500**. Field of view **510** of camera **508** is depicted. Camera **508** has camera position **512** and camera orientation **514** within three-dimensional model space **500**. As depicted, there are 6 dimensions for camera position and orientation. There are 3 dimensions for camera position **512**: x, y, and z coordinates. There are 3 dimensions for camera orientation **514** (pitch, roll, yaw).

[0066] Synthetic data for different parts can be created by modifying three-dimensional model **502** or create a different three-dimensional model. Synthetic data for different types of inconsistencies can be created by modifying inconsistency **506**. Synthetic data for different types of inspection systems can be created by modifying at least one of camera position **512**, camera

orientation **514**, and material properties of three-dimensional model **502**. Thus, three-dimensional model space **500** can be used to generate synthetic data for any part, any desirable type of inspection system, and any desirable position of the inspection system.

[0067] Turning now to **Figures 6A** and **6B**, a flowchart of a method of generating synthetic data for composite manufacturing inspection is depicted in accordance with an illustrative embodiment. Method **600** can be used to generate synthetic data **202** to train inconsistency identifier program **204** of **Figure 2**. Method **600** can be used to generate synthetic data to train inconsistency identifier program **324** of **Figure 3**. Method **600** can be used to generate synthetic data that can be used to train an inconsistency identifier program for analyzing inspection data from inspection system **406** of **Figure 4**. Method **600** can be implemented in three-dimensional model space **500**.

[0068] Method **600** creates a three-dimensional model of a composite layup in a three-dimensional model space (operation **602**). The three-dimensional model has material characteristics that can be modified as desired.

[0069] Method **600** generates an inconsistency in the three-dimensional model of the composite layup (operation **604**). The inconsistency can have any desirable form. In some illustrative examples, the inconsistency is on the surface of the three-dimensional model. In some illustrative examples, the inconsistency is below the surface and within the layers of the three-dimensional model.

[0070] Method **600** sets a camera position and a camera orientation in the three-dimensional model space (operation **606**). Method **600** generates a captured image of the three-dimensional model and the inconsistency from

the camera position and the camera orientation (operation **608**). Method **600** creates a secondary image from the captured image, the secondary image having colorations of a preselected inspection type (operation **610**). The preselected inspection type is an inspection type for which the secondary image will be used to train an inconsistency identifier program. In some illustrative examples, the preselected inspection type can be one of IR inspection, laser inspection, optical inspection, or another desirable form of inspection. Afterwards, method **600** terminates.

[0071] In some illustrative examples, method **600** determines a layup of a portion of a part (operation **612**). The portion of the part can be any desirable section of the part. The part can be any desirable component. Layup information includes an order of composite layers, type of composite material, width of composite material, shape of each layer of composite, and other variables for laying down the composite material to form the portion of the part. In some illustrative examples, method **600** generates the three-dimensional model of the composite layup using the layup of the portion of the part (operation **614**). In these illustrative examples, the three-dimensional model will resemble the portion of the part. In some illustrative examples, the layup comprises a plurality of layers of composite material and the three-dimensional model comprises a plurality of layers arranged the same as the plurality of layers of composite material (operation **616**).

[0072] In some illustrative examples, the inconsistency is one of overlapping tows, gaps between tows, or foreign object debris (operation **618**). In some illustrative examples, the inconsistency is one of

fuzzballs, resin balls, foreign object debris, edge folds/twists, heat damage, untacked tows, or missing tows.

[0073] In some illustrative examples, method **600** determines a head orientation of an inspection system attached to a composite laying head in a manufacturing environment, wherein setting the camera position and the camera orientation in the three-dimensional model space comprises setting the camera orientation based on the head orientation (operation **620**). In these illustrative examples, the captured image has a field of view substantially similar to the field of view of images captured by the inspection system attached to the composite laying head.

[0074] In some illustrative examples, creating the secondary image comprises applying a number of filters to the captured image to create the secondary image (operation **622**). In some illustrative examples, applying the number of filters to the captured image creates colorations of an IR image (operation **624**).

[0075] In some illustrative examples, the inconsistency has an inconsistency type, and wherein applying the number of filters to the captured image creates colorations characteristic of the inconsistency type for the preselected inspection type within pixels of the secondary image with the inconsistency (operation **626**). In some illustrative examples, for a preselected inspection type, each inconsistency type can have associated colors identified from previous real world collected data. For example, fuzzballs in an IR image may have associated colors for pixels within the inconsistencies. As another example, missing tows in an IR image may have their own respective associated colors for pixels within the inconsistencies.

[0076] In some illustrative examples, applying the filters to the captured image will change the pixels in the inconsistency in the captured image such that the pixels have colors associated with the inconsistency type. In some illustrative examples, applying the filters to the captured image generate a secondary image with an inconsistency having colors associated with the inconsistency type for the preselected inspection type.

[0077] In some illustrative examples, creating the secondary image comprises sampling colors from pixels of the inconsistency in the captured image and adjusting color values for the pixels to values within a range for an inconsistency type of the inconsistency in stock images of the preselected inspection type (operation **628**). In some illustrative examples, for a preselected inspection type, each inconsistency type can have a range of pixel values identified from previous real world collected data. For example, fuzzballs in an IR image may have a range of values for pixels within the inconsistencies. As another example, missing tows may have a range of values for pixels within the inconsistencies. In some illustrative examples, creating the secondary image comprises adjusting the values of the pixels in a missing tow in the captured image to have values within the range of values for pixels sampled in the real world collected data.

[0078] In some illustrative examples, method **600** supplies the secondary image as training data to an inconsistency identifier program (operation **630**). In some illustrative examples, method **600** generates inspection images of composite tows after the composite tows are laid (operation **632**). In some illustrative examples, method **600** evaluates the inspection images

using the inconsistency identifier program trained using the secondary images (operation **634**).

[0079] Turning now to **Figure 7**, a flowchart of a method of training a composite inspection system is depicted in accordance with an illustrative embodiment. Method **700** can be used to generate synthetic data **202** to train inconsistency identifier program **204** of **Figure 2**. Method **700** can be used to generate synthetic data to train inconsistency identifier program **324** of **Figure 3**. Method **700** can be used to generate synthetic data that can be used to train an inconsistency identifier program for analyzing inspection data from inspection system **406** of **Figure 4**. Method **700** can be implemented in three-dimensional model space **500** of **Figure 5**.

[0080] Method **700** generates a captured image of a three-dimensional model of a composite layup with an inconsistency at a predetermined camera position and at a predetermined camera orientation within the three-dimensional model space containing the three-dimensional model (operation **702**). Method **700** modifies the captured image to form a secondary image having coloration of a preselected inspection type (operation **704**). Method **700** trains an inconsistency identifier program using the secondary image (operation **706**). Afterwards, method **700** terminates.

[0081] Although operations **702** through **706** discuss a single captured image and secondary image, in some illustrative examples, a plurality of synthetic images can be used to train the inconsistency identifier program. In some illustrative examples, operations **702** through **706** are performed iteratively prior to using the inconsistency identifier program to evaluate inspection images from manufacturing.

[0082] In some illustrative examples, modifying the captured image comprises applying a number of filters to the captured image to create the secondary image (operation **712**). In some of these illustrative examples, the number of filters are applied to provide characteristics of the inspection type to the secondary image.

[0083] In some illustrative examples, modifying the captured image comprises sampling colors from pixels of the inconsistency in the captured image and adjusting color values for the pixels to values within a range for an inconsistency type of the inconsistency in stock images of the preselected inspection type (operation **714**). In these illustrative examples, real world data in the form of stock images provides information for modifying the captured synthetic images.

[0084] In some illustrative examples, method **700** inspects composite tows as the composite tows are laid down to form inspection images (operation **716**). In some illustrative examples, method **700** evaluates the inspection images using the inconsistency identifier program trained using the secondary images (operation **718**).

[0085] In some illustrative examples, the composite tows are inspected using an inspection system, and wherein the predetermined camera orientation within the three-dimensional model space is based on a head orientation of the inspection system (operation **720**). The three-dimensional model can be imaged from a plurality of different predetermined camera orientations for inspection systems at different head orientations and/or different inspection types.

[0086] In some illustrative examples, inspecting the composite tows comprises generating IR images of the

composite tows after deposition (operation **722**). Applying the composite tows comprises heating the composite tows prior to laying the composite tows on a substrate. The IR images provide information regarding heat distribution in the composite tows after being laid on the substrate. The substrate can take the form of prior layers of composite tows.

[0087] In some illustrative examples, method **700** determines a head orientation of an inspection system attached to a composite laying head in a manufacturing environment (operation **708**). In some illustrative examples, method **700** sets the predetermined camera position and the predetermined camera orientation in the three-dimensional model space based on the head orientation (operation **710**).

[0088] Turning now to **Figure 8**, a flowchart of a method of using synthetically generated training data is depicted in accordance with an illustrative embodiment. Method **800** can be used to generate synthetic data **202** to train inconsistency identifier program **204** of **Figure 2**. Method **800** can be used to generate synthetic data to train inconsistency identifier program **324** of **Figure 3**. Method **800** can be used to generate synthetic data that can be used to train an inconsistency identifier program for analyzing inspection data from inspection system **406** of **Figure 4**. Method **800** can be implemented in three-dimensional model space **500** of **Figure 5**.

[0089] Method **800** generates an inconsistency in a three-dimensional model comprising a plurality of layers of a composite layup (operation **802**). The inconsistency can have any desirable form. In some illustrative examples, the inconsistency is on the surface of the three-dimensional model. In some illustrative examples,

the inconsistency is below the surface and within the layers of the three-dimensional model.

[0090] Method **800** generates a captured image of the inconsistency and the three-dimensional model at a predetermined camera position and at a predetermined camera orientation based on a head orientation of an inspection system connected to a composite laying head (operation **804**). By generating the captured image at the predetermined camera position and at a predetermined camera orientation, the captured image resembles the field of view of an inspection system in a manufacturing environment.

[0091] Method **800** generates a secondary image from the captured image, the secondary image having a coloration of an inspection type of the inspection system (operation **806**). The secondary image is generated by modifying the captured image in any desirable fashion. Method **800** provides the secondary image as training data for an inconsistency identifier program (operation **808**). Afterwards, method **800** terminates.

[0092] In some illustrative examples, method **800** creates the three-dimensional model based on a layup of a portion of a part to be manufactured (operation **810**). In some illustrative examples, plurality of layers in the three-dimensional model represent each of a plurality of layers of the layup of the portion of the part. In these illustrative examples, the three-dimensional model can be a representation of all composite tows in portion **306** of part **308** of **Figure 3**. In some illustrative examples, a plurality of layers in the three-dimensional model represent a fraction of the plurality of layers of the layup of the portion of the part. In some illustrative examples, the plurality of layers in the three-dimensional model are selected to create a same curvature

as the portion of the part. In some illustrative examples, the plurality of layers in the three-dimensional model are selected such that a surface of the composite layup of the three-dimensional model represents the surface of the portion of the part.

[0093] In some illustrative examples, generating the inconsistency comprises moving at least one tow representation in the three-dimensional model (operation **812**). In some illustrative examples, moving at least one tow representation in the three-dimensional model generates at least one of overlapping tows, gaps, a missing tow, or other tow position inconsistency.

[0094] In some illustrative examples, generating the secondary image comprises applying a number of filters to the captured image to create colorations of an IR image (operation **814**). By colorations of the IR image being present, thermal information is present in the secondary image. The addition of thermal information adds context to the images provided to machine learning algorithms. The addition of thermal information using coloration allows for additional inconsistencies to be identified. The addition of thermal information using coloration allows for temperature changes to be identified.

[0095] As used herein, the phrase "at least one of," when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, "at least one of item A, item B, or item C" may include, without limitation, item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. Of course, any combinations of these items may be present. In other examples, "at least one of" may be, for example, without limitation, two of item A; one of item B; and ten

of item C; four of item B and seven of item C; or other suitable combinations. The item may be a particular object, thing, or a category. In other words, at least one of means any combination items and number of items may be used from the list but not all of the items in the list are required.

[0096] As used herein, "a number of," when used with reference to items means one or more items.

[0097] The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams may represent at least one of a module, a segment, a function, or a portion of an operation or step.

[0098] In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram. Some blocks may be optional. For example, operation **612** through operation **634** may be optional. As another example, operation **708** through operation **722** may be optional. As yet another example, operation **810** through operation **814** may be optional.

[0099] Illustrative embodiments of the present disclosure may be described in the context of aircraft manufacturing and service method **900** as shown in **Figure 9** and aircraft **1000** as shown in **Figure 10**. Turning first

to **Figure 9**, an illustration of an aircraft manufacturing and service method in a form of a block diagram is depicted in accordance with an illustrative embodiment. During pre-production, aircraft manufacturing and service method **900** may include specification and design **902** of aircraft **1000** in **Figure 10** and material procurement **904**.

[00100] During production, component and subassembly manufacturing **906** and system integration **908** of aircraft **1000** takes place. Thereafter, aircraft **1000** may go through certification and delivery **910** in order to be placed in service **912**. While in service **912** by a customer, aircraft **1000** is scheduled for routine maintenance and service **914**, which may include modification, reconfiguration, refurbishment, or other maintenance and service.

[00101] Each of the processes of aircraft manufacturing and service method **900** may be performed or carried out by a system integrator, a third party, and/or an operator. In these examples, the operator may be a customer. For the purposes of this description, a system integrator may include, without limitation, any number of aircraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may be an airline, a leasing company, a military entity, a service organization, and so on.

[00102] With reference now to **Figure 10**, an illustration of an aircraft in a form of a block diagram is depicted in which an illustrative embodiment may be implemented. In this example, aircraft **1000** is produced by aircraft manufacturing and service method **900** of **Figure 9** and may include airframe **1002** with plurality of systems **1004** and interior **1006**. Examples of systems **1004** include one or more of propulsion system **1008**, electrical

system **1010**, hydraulic system **1012**, and environmental system **1014**. Any number of other systems may be included.

[00103] Apparatuses and methods embodied herein may be employed during at least one of the stages of aircraft manufacturing and service method **900**. One or more illustrative embodiments may be manufactured or used during at least one of component and subassembly manufacturing **906**, system integration **908**, in service **912**, or maintenance and service **914** of **Figure 9**.

[00104] The illustrative examples provide methods for generating synthetic data for training inconsistency identifiers. In the illustrative examples, synthetic data is generated using views of a three-dimensional model. Synthetic data for a plurality of different inspection types can be generated from the same three-dimensional model. The three-dimensional model can be modified based on design changes to the part.

[00105] In some illustrative examples, the synthetic data can be synthetic infrared data. Synthetic infrared data can improve and increase the viability of implementation of IR inspection for AFP monitoring as well as general infrared evaluations.

[00106] The addition of thermal data to the synthetic 'contrast only' data provides context for an infrared inspection. In some illustrative examples, synthetic images are constructed with simulations of visual light with thermal data added in post-processing. The addition of thermal data to the synthetic data can be as simple as setting a max and min temperature value to bound the color palette and as complex as adding algorithms to account for the natural dissipation of heat as it flows through a material and is lost through convection/conduction. The addition of thermal data can

be accomplished through setting material properties in the three-dimensional model. The addition of thermal data can be accomplished through processing of the captured images to form secondary images.

[00107] The illustrative examples provide a virtual representation of the part that takes into account at least one of the part layup, machine, material, and layup path. Virtual representation of the build environment allows for the simulation of multiple part configurations, camera positions, and layup programs/speeds.

[00108] The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

CLAIMS:

What is claimed is:

1. A method of generating synthetic data for composite manufacturing inspection comprising:

creating a three-dimensional model of a composite layup in a three-dimensional model space;

generating an inconsistency in the three-dimensional model of the composite layup;

setting a camera position and a camera orientation in the three-dimensional model space;

generating a captured image of the three-dimensional model and the inconsistency from the camera position and the camera orientation; and

creating a secondary image from the captured image, the secondary image having colorations of a preselected inspection type.

2. The method of claim 1, wherein the inconsistency is one of overlapping tows, gaps between tows, or foreign object debris.

3. The method of claim 1 or 2 further comprising:

determining a layup of a portion of a part; and

generating the three-dimensional model of the composite layup using the layup of the portion of the part.

4. The method of claim 3, wherein the layup comprises a plurality of layers of composite material and the three-dimensional model comprises a plurality of layers arranged the same as the plurality of layers of composite material.

5. The method of any one of claims 1 to 4, wherein creating the secondary image comprises applying a number of filters to the captured image to create the secondary image.

6. The method of claim 5, wherein applying the number of filters to the captured image creates colorations of an IR image.

7. The method of claim 5 or 6, wherein the inconsistency has an inconsistency type, and wherein applying the number of filters to the captured image creates colorations characteristic of the inconsistency type for the preselected inspection type within pixels of the secondary image with the inconsistency.

8. The method of any of claims 1 to 4, wherein creating the secondary image comprises sampling colors from pixels of the inconsistency in the captured image and adjusting color values for the pixels to values within a range for an inconsistency type of the inconsistency in stock images of the preselected inspection type.

9. The method of any one of claims 1 to 8 further comprising:

determining a head orientation of an inspection system attached to a composite laying head in a manufacturing environment, wherein setting the camera position and the camera orientation in the three-dimensional model space comprises setting the camera orientation based on the head orientation.

10. The method of any one of claims 1 to 9 further comprising:

supplying the secondary image as training data to an inconsistency identifier program.

11. The method of claim 10 further comprising:

generating inspection images of composite tows after the composite tows are laid; and

evaluating the inspection images using the inconsistency identifier program trained using the secondary images.

12. A method of training a composite inspection system comprising:

generating a captured image of a three-dimensional model of a composite layup with an inconsistency at a predetermined camera position and at a predetermined camera orientation within a three-dimensional model space containing the three-dimensional model;

modifying the captured image to form a secondary image having coloration of a preselected inspection type; and

training an inconsistency identifier program using the secondary image.

13. The method of claim 12 further comprising:

inspecting composite tows as the composite tows are laid down to form inspection images; and

evaluating the inspection images using the inconsistency identifier program trained using the secondary images.

14. The method of claim 13, wherein the composite tows are inspected using an inspection system, and wherein the

predetermined camera orientation within the three-dimensional model space is based on a head orientation of the inspection system.

15. The method of claim 13 or 14, wherein inspecting the composite tows comprises generating IR images of the composite tows after deposition.

16. The method of any one of claims 12 to 15, wherein modifying the captured image comprises applying a number of filters to the captured image to create the secondary image.

17. The method of any one of claims 12 to 15, wherein modifying the captured image comprises sampling colors from pixels of the inconsistency in the captured image and adjusting color values for the pixels to values within a range for an inconsistency type of the inconsistency in images of the preselected inspection type.

18. The method of any one of claims 12 to 17 further comprising:

determining a head orientation of an inspection system attached to a composite laying head in a manufacturing environment; and

setting the predetermined camera position and the predetermined camera orientation in the three-dimensional model space based on the head orientation.

19. A method of using synthetically generated training data comprising:

generating an inconsistency in a three-dimensional model comprising a plurality of layers of a composite layup;

generating a captured image of the inconsistency and the three-dimensional model at a predetermined camera position and at a predetermined camera orientation based on a head orientation of an inspection system connected to a composite laying head;

generating a secondary image from the captured image, the secondary image having a coloration of an inspection type of the inspection system; and

providing the secondary image as training data for an inconsistency identifier program.

20. The method of claim 19, wherein generating the secondary image comprises applying a number of filters to the captured image to create colorations of an IR image.

21. The method of claim 19 or 20 further comprising:
creating the three-dimensional model based on a layup of a portion of a part to be manufactured.

22. The method of any one of claims 19 to 21, wherein generating the inconsistency comprises moving at least one tow representation in the three-dimensional model.