that the damage is within the range bounded by those thresholds, a determination is made that a repair should be performed. If the UAV that performed the NDE is not adequately equipped to perform the repair, a UAV equipped with the appropriate repair tools is dispatched to the repair site. While the UAV is stationary, a repair tool is activated to perform a repair operation on the structure. Once the repair has been completed, a UAV equipped with a camera or an NDE sensor unit may be used to assess the state of the repaired structure. Depending on the result of the assessment, a determination is made whether to place the structure back in service or not.

The overall process described in the preceding three paragraphs seeks to minimize the number of steps used (saving time and effort), with the number of steps depending upon the result of the visual and NDE data sets. This process may have manifold benefits. The complete structural assessment process using UAVs proposed herein enables significant cost, time and labor savings as well improving safety. The process enables very rapid and potentially complete disposition of potential damage on large composite structures. The process further allows rapid return of vehicles or structures to service, thereby avoiding extended downtime. The process further allows users such as wind turbine owners to do damage detection, NDE and repair of their structures without any direct access to the damage locations. All data collected can be used for assessments, tracking and trending.

Although various embodiments of methods for inspecting and repairing a damaged portion of a large structure or object using one or more UAVs are described in some detail later herein, one or more of those embodiments may be characterized by one or more of the following aspects.

One aspect of the subject matter disclosed in detail below is a method for inspecting and repairing a structure using one or more unmanned aerial vehicles, comprising the following steps: (a) flying an unmanned aerial vehicle equipped with a camera to a position in a vicinity of an area on a surface of a structure; (b) acquiring image data representing one or more images of the structure in the area using the camera; determining that the image data acquired in step (b) indicates damage in the area above a first “use as is” threshold before proceeding to step (c); (c) flying an unmanned aerial vehicle equipped with a non-destructive evaluation (NDE) sensor unit until the NDE sensor unit is within measurement range of the structure in the area; (d) acquiring sensor data representing structural characteristics of the structure in the area using the NDE

sensor unit while the NDE sensor unit is within measurement range of the structure in the area; (e) moving an unmanned aerial vehicle equipped with a repair tool to a location that places the repair tool in contact with the surface in the area; and (f) repairing the structure in the area using the repair tool while the unmanned aerial vehicle equipped with the repair tool is at the location. In accordance with some embodiments, the method further comprises: determining that the sensor data acquired in step (d) indicates damage in the area above a second “use as is” threshold before proceeding to step (f); and determining that the sensor data acquired in step (d) indicates damage in the area below a “remote repair” threshold before proceeding to step (f).

In one proposed implementation of the method described in the immediately preceding paragraph, the structure is an aircraft and the method further comprises: (g) receiving a report at an aircraft maintenance operations center that an object has impacted the aircraft; and (h) determining the current position on the ground of the aircraft, wherein steps (g) and (h) are performed prior to step (a).

Another aspect of the subject matter disclosed in detail below is a method for inspecting and repairing a structure using an unmanned aerial vehicle equipped with a camera, an NDE sensor unit and a repair tool. The method comprises the following steps: (a) flying the unmanned aerial vehicle to a location in a vicinity of an area on a surface of a structure; (b) acquiring image data representing one or more images of the surface in the area using the camera while the unmanned aerial vehicle hovers at the location; (c) flying the unmanned aerial vehicle until the NDE sensor unit is within measurement range of the structure in the area; (d) acquiring sensor data representing structural characteristics of the structure in the area using the NDE sensor unit while the NDE sensor unit is within measurement range of the structure in the area; (e) moving the unmanned aerial vehicle until the repair tool is in contact with the surface in the area; and (f) repairing the structure in the area using the repair tool.

A further aspect of the subject matter disclosed in detail below is an unmanned aerial vehicle comprising: a frame; a plurality of rotor motors mounted to the frame; a plurality of rotors operatively coupled to respective rotor motors of

the plurality of rotor motors; a camera supported by and rotatable relative to the frame; anon-destructive evaluation (NDE) sensor unit supported by the frame; a repair tool supported by the frame; and a computer system configured to execute the following operations: determine whether image data acquired by the camera has a value greater than a first “use as is” threshold or not; activate the NDE sensor unit in response to a determination that the image data has a value greater that the first “use as is” threshold; determine whether NDE sensor data acquired by the NDE sensor has a value greater than a second “use as is” threshold and less than a “remote repair threshold or not; and activate the repair tool in response to a determination that the NDE sensor data has a value greater than the second “use as is” threshold and less than the “remote repair threshold”. -

In one proposed implementation, the unmanned aerial vehicle described in the immediately preceding paragraph further comprises: a camera turret motor mounted to the frame; and a camera turret rotatably coupled to the frame, operatively coupled to the camera turret motor and supporting the camera. The camera turret is rotatable between a first angular position and a second angular position. The NDE sensor unit is in a field-of-view of the camera when the camera turret is in the first angular position and is not in the field-of-view of the camera when the camera turret is in the second angular position. The repair tool is in the field-of-view of the camera when the camera turret is in the second angular position and is not in the field-of-view of the camera when the camera turret is in the first angular position. In the illustrated embodiments, one or more UAVs (20, 20a, 20b, 20c) may be utilized to perform the inspections and repairs described herein. For example, a first UAV 20 may be equipped with a camera, a second UAV may be equipped with an NDE sensor unit, and a third UAV may be equipped with a repair tool. Optionally, a single UAV 20 may be include the camera, the NDE sensor unit and/or the repair tool. Thus, one or more UAVs may be equipped to perform one or more aspect of the inspection and repair methods described herein.

Other aspects of methods for inspecting and repairing a damaged portion of a large structure or object using one or more UAVs are disclosed below.

CLAIMS

1. A method for inspecting and repairing a structure using unmanned aerial vehicles, comprising:

(a) flying one or more unmanned aerial vehicles equipped with a camera to a position in a vicinity of an area on a surface of a structure;

(b) acquiring image data representing one or more images of the structure using the camera;

determining that the image data acquired in step (b) indicates damage in the area above a first “use as is” threshold before proceeding to step (c);

(c) flying the one or more unmanned aerial vehicles equipped with a non-destructive evaluation (NDE) sensor unit until the NDE sensor unit is within measurement range of the structure;

(d) acquiring sensor data representing structural characteristics of the structure using the NDE sensor unit while the NDE sensor unit is within measurement range of the structure;

(e) moving the one or more unmanned aerial vehicles equipped with a repair tool to a location that places the repair tool in contact with the surface of the structure; and

(f) repairing the structure using the repair tool while the one or more unmanned aerial vehicles is at the location.

2. The method as recited in claim 1, further comprising determining that the sensor data acquired in step (d) indicates damage in the area above a second “use as is” threshold before proceeding to step (f).

3. The method as recited in claim 1 or 2, further comprising determining that the sensor data acquired in step (d) indicates damage in the area below a “remote repair” threshold before proceeding to step (f).

4. The method as recited in any of claims 1 to 3, further comprising

flying the one or more unmanned aerial vehicles until the NDE sensor unit is within measurement range of the repaired structure; and

acquiring sensor data representing structural characteristics of the repaired structure using the NDE sensor unit while the NDE sensor unit is within measurement range of the repaired structure.

5. The method as recited in any of claims 1 to 4, wherein the structure is an aircraft, the method further comprising:

(g) receiving a report at an aircraft maintenance operations center that an object has impacted the aircraft; and

(h) determining the current position on the ground of the aircraft,

wherein steps (g) and (h) are performed prior to step (a).

6. The method as recited in any of claims 1 to 5, wherein repairing comprises remotely controlling operation of a motorized repair tool that is configured to either remove material from or add material to the structure in the area.

7. An unmanned aerial vehicle comprising:

a frame;

a plurality of rotor motors mounted to the frame;

a plurality of rotors operatively coupled to respective rotor motors of the plurality of rotor motors;

a camera supported by and rotatable relative to the frame;

a non-destructive evaluation (NDE) sensor unit supported by the frame;

a repair tool supported by the frame; and

a computer system configured to:

determine whether image data acquired by the camera has a value greater than a first “use as is” threshold or not;

activate the NDE sensor unit in response to a determination that the image data has a value greater than the first “use as is” threshold;

determine whether NDE sensor data acquired by the NDE sensor unit has a value greater than a second “use as is” threshold and less than a “remote repair threshold” or not; and

activate the repair tool in response to a determination that the NDE

sensor data has a value greater than the second “use as is” threshold and less than the “remote repair threshold”.

8. The unmanned aerial vehicle as recited in claim 7, further comprising:

a camera turret motor mounted to the frame; and

a camera turret rotatably coupled to the frame, operatively coupled to the camera turret motor and supporting the camera, wherein:

the camera turret is rotatable between a first angular position and a second angular position;

the NDE sensor unit is in a field-of-view of the camera when the camera turret is in the first angular position and is not in the field-of-view of the camera when the camera turret is in the second angular position; and

the repair tool is in the field-of-view of the camera when the camera turret is in the second angular position and is not in the field-of-view of the camera when the camera turret is in the first angular position.

9. The unmanned aerial vehicle as recited in claim 7 or 8, wherein the repair tool comprises a subtractive repair tool or an additive repair tool.

10. The unmanned aerial vehicle as recited in any of claims 7 to 9, further comprising a base, wherein the rotors are supported by and rotatable relative to the base, and the camera is rotatable about an axis perpendicular to the plane of base.

11. The unmanned aerial vehicle as recited in any of claims 7 to 10, further comprising a beam having the NDE sensor unit attached to a first end of the beam and a counterweight attached to a second end of the beam.

12. The unmanned aerial vehicle as recited in any of claims 7 to 10, further comprising a beam having the NDE sensor unit attached to a first end of the beam and the repair tool attached to a second end of the beam.

13. The unmanned aerial vehicle as recited in any of claims 7 to 10,

wherein the NDE sensor unit is attached to the end of a manipulator arm, wherein the manipulator arm comprises a gripper, wherein the gripper is operable to manipulate the NDE sensor unit.

14. The unmanned aerial vehicle as recited in any of claims 7 to 13, wherein the NDE sensor unit is selected from the group consisting of: eddy current sensors, ultrasonic sensors, acoustic sensors, mechanical impedance sensors, optical sensors, X-ray backscatter sensors, computed tomography sensors, surface roughness sensors, infrared (IR) thermography devices, microwave sensors, and terahertz sensors.