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Systems and methods for robotic sensing, repair and inspection

Abstract

Various embodiments of a bio-inspired robot operable for detecting crack and corrosion defects in tubular structures are disclosed herein.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS (1) This is a continuation patent application of U.S. Non-Provisional application Ser. No. 16/844,519 filed on 9 Apr. 2020, now U.S. Pat. No. 11,504,854, that claims benefit to U.S. Provisional Patent Application Ser. No. 62/831,268 filed 4 Apr. 2019, which is herein incorporated by reference in its entirety.

FIELD
(1) The present disclosure generally relates to non-destructive testing (NDT); and in particular, to a bio-inspired robot for non-destructive testing and inspection of tubular structures using multi-

transducer imaging.

BACKGROUND

(2) Tubular structures are commonly used in boilers and heat exchangers. Working under extreme conditions such as high temperatures, large stress loads, hot and high-velocity steam and pressure leads to corrosion, cracks, and stress-corrosion cracks in either the body or welded connections of these components. Regular inspection of these components is vital to avoid tube leakages. This task can be challenging, time-consuming and in many cases, impossible. Using robots for inspection is a promising solution to these challenges. Typical robotic systems show limitation in interacting with complex environments, however, bio-inspired robotics systems have proven helpful in overcoming these limitations. Tokay geckos, for instance, have one of the most effective and versatile attachment systems which enable them to attach quickly and reversibly to surfaces of varying chemistry and topography.

(3) Detecting and characterizing corrosion and crack type defects on tubular structures is one of the major problems faced by the power generation industry. One approach for the measurement of remaining wall thickness and crack detection is to use ultrasound. Contact ultrasound testing (UT) based on bulk waves is time-consuming and requires prepared surfaces of adequate couplant for point-by-point scanning. Recent developments in couplant-free UT may remove a need for couplant in ultrasound technologies, and the development of advanced Lamb wave-based imaging may eliminate the need for point-by-point inspection of the cross-section of a tubular structure.

(4) It is with these observations in mind, among others, that various aspects of the present disclosure were conceived and developed.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) The present patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

(2) FIG. **1** is a perspective view of one embodiment of a bio-inspired robot (e.g. lizard-inspired tube inspector (LTI) robot).

(3) FIGS. **2**A, **2**B, and **2**C are illustrations showing three different tube configuration scenarios that the lizard-inspired tube inspector (LTI) robot may be operable to handle: a 180 degree elbow, a 90 degree elbow, and a flange, respectively.

(4) FIG. **3**A is an illustration showing a first embodiment of the gripper assembly of the lizard-inspired tube inspector (LTI) robot of FIG. **1**;

(5) FIG. **3**B is an illustration showing a second embodiment of the gripper assembly of the lizard-inspired tube inspector (LTI) robot of FIG. **1**;

(6) FIG. **4** is an illustration showing one embodiment of the tail assembly of the lizard-inspired tube inspector (LTI) robot of FIG. **1**.

(7) FIG. **5** illustrates helical paths between a pair of transducers/sensors on a tubular surface.

(8) FIGS. **6**A and **6**B are graphical representations of multi helical ultrasound imaging (MHUI) for corrosion detection and evaluation on a tubular surface using six omnidirectional Lamb wave transducers/sensors; FIG. **6**A depicts helical paths between the six transducers and FIG. **6**B is the resulting MHUI image showing corrosion on the tubular surface.

(9) FIGS. **7**A and **7**B are illustrative of Lamb wave-based total focusing method (TFM) for crack detection and evaluation; FIG. **7**A is a photograph of two clusters of transducers on an aluminum plate during experimental testing and FIG. **7**B is the resulting Lamb wave-based TFM image depicting a crack in the aluminum plate.

(10) FIG. **8** is an illustration showing data collection for MHUI and Lamb-wave TFM data as well

as coverage area through one cycle of movement of the lizard-inspired tube inspector robot of FIG. **1**.
(11) Corresponding reference characters indicate corresponding elements among the view of the drawings. The headings used in the figures do not limit the scope of the claims.

DETAILED DESCRIPTION

(12) A bio-inspired robotic device for detection and evaluation of crack and corrosion defects in tubes is disclosed herein. In one embodiment, the robotic device includes a pair of gripper blocks, each gripper block including a motor and a plurality of toes. Each of the plurality of toes includes a network of couplant-free ultrasound transducers for non-destructive testing of surfaces. In addition, each toe includes frictional pads that can be used for effective climbing of tubes or other surfaces. In some embodiments, the pair of gripper blocks are linked by a bendable “backbone” which is capable of elongation to allow the robot to maneuver along pipes and surfaces. In some embodiments, the robotic device further includes a tail equipped with various transducers for further examination of tube surfaces. Referring to the drawings, embodiments of the tube-inspector robotic device, herein referred to as “the robot”, are illustrated and generally indicated as **100** in FIGS. **1-8**.

(13) Robot Structure: Bio-Inspired Design

(14) Referring to FIG. **1**, a robot **100** for inspection and repair of tubes is shown including a pair of dexterous gripper blocks **104**, each gripper block **104** having a plurality of toes **126**. In some embodiments, each of the plurality of toes **126** is equipped with a friction pad **127** that can grip tubular surfaces **10** of different sizes having smooth or corroded surfaces. The gripper blocks **104** are connected by a backbone **108** that includes a first linear actuator **142**A and a second linear actuator **142**B linked by a rotational actuator **144**. Referring to FIGS. **2**A, **2**B and **2**C, the actuators **142** and **144** respectively enable forward/backward motion of the robot **100** and maneuvering on flanges, boiler walls, and elbows of 45, 90, and 180-degree angles. In some embodiments, the robot **100** includes a first and second motor **145**A and **145**B respectively engaging each gripper block **104** with the first and second linear actuators **142**A and **142**B. The first and second motor **145**A and **145**B serve to rotate each gripper block **104** relative to the backbone **108**.

(15) Embodiments of the gripper block **104** are shown in FIG. **3**A-**3**B, featuring a motor **124** surrounded by a housing **122**. Each of the plurality of toes **126** extend from an underside **129** of each gripper block **104**. In some embodiments, each of the plurality of toes **126** includes the friction pad **127** and a transducer **128**. FIG. **3**A shows one embodiment having each of the toes **126** including a first and second segment **126**A and **126**B linked by a middle segment **126**C. In an alternate embodiment shown in FIG. **3**B, each of a plurality of toes **226** defines a curved profile. The curved profile includes a concave surface for engagement with a tubular structure **10**. The concave surface further includes the friction pad **227** and the transducer **128**. Referring to FIGS. **1** and **4**, the robot **100** further includes a tail **106**, shown in FIG. **4**, for additional stability and inspection. The tail **106** carries one or more transducers **130** including a borescope **130**A for tube inspection at desired locations that might be hard to access by the robot **100**. In some embodiments, the tail **106** includes one or more tail friction pads **137** for additional support when climbing on tubular structures **10**. The robot **100** includes one or more onboard controllers programmed in C. However, depending on the mission, data and power may be transmitted to/from the robot **100** wirelessly or through a tether. A combination of machining and rapid prototyping techniques (e.g. 3D printing, laser cutting, and hybrid deposition manufacturing) are used for fabrication of the robot **100**. The gripper blocks **104** are fabricated using Hybrid Deposition Manufacturing (HDM) technique. The friction pads **127** are fabricated using soft lithography with micro-scale feature (e.g. fibers) out of Polydimethylsiloxane (PDMS) and Polyurethane. In some embodiments, shown in FIG. **1**, a camera **131** is installed on at least one of the gripper blocks **104** for visual inspection.

(16) Couplant-Free Ultrasound Generation

(17) Couplant-free ultrasound transducers **128** are placed on the toes **126** of the gripper blocks **104**.

Recent developments in couplant-free ultrasound techniques in addition to development of advanced Lamb wave-based imaging remove the need for couplant and would also allow for inspection of a line between two transducers instead of point-by-point inspecting the cross section of a tube **10**. To be able to use the toes **126** of the gripper blocks **104** as transducers, ultrasound waves need to transmit through the surfaces of the toes **126** with the friction pads **127**.

(18) Two separate sensing methods may be utilized for generating and receiving Lamb waves: high-voltage ultrasound generation with pressurized contacted interfaces (achieved through the use of a piezoelectric transducer, which converts analog pressure into electrical signals), and an Electro Magnetic Acoustic Transducer (EMAT). A material and geometry of the friction pads **127** are optimized to maximize energy transmission. Ultrasound imaging based on guided ultrasound waves provides a unique solution to inspect a line between two transducers **128** instead of point by point inspection of material. This capability can be exploited in the case of cylindrical structures (i.e. tubular structures **10**) since theoretically there are infinite helical paths (lines to be inspected) between the two transducers **128**, as illustrated in FIG. **5**.

(19) Imaging: Corrosion and Crack Detection and Evaluation

(20) Multi-transducer imaging approaches based on through-transmission and pulse-echo technique are considered to develop an imaging method using the data captured by the robot **100** across multiple positions of the gripper blocks **104**. For example, at one location the gripper blocks **104** may need to move and make different configurations. At each configuration, one transducer **128** of the gripper block **104** will excite guided ultrasound waves and another other transducer **128** will receive the ultrasonic waves. This is repeated between each transducer **128** in order to cover a large area of the tube **10**. The robot **100** may change the gripper **104** configuration to capture new sets of data. An imaging method based on guided wave total focusing method (TFM) and Multi-Helical Ultrasound imaging (MHUI) are used to detect and evaluate crack and corrosion. The imaging methods are used as the robot **100** moves to construct images of the covered area. As shown in FIG. **8**, as the robot **100** progresses along the area, based on the new sets of data at each new location, the images are updated. The transducers **128** do not need to contact every single inch of the surface and can instead take procedural ultrasound images which cover a wider range, thus making the inspection rapid and versatile. An illustration can be seen in FIGS. **6**A and **6**B where corrosion can be spotted using MHUI and 6 omnidirectional Lamb wave transducers. Lamb wave-based TFM (Total Focusing Method) creates an image for detecting cracks by combining the signals obtained from multiple transmitters and receivers. Coverage of different combinations of the transducers was estimated for several crack orientations. Experimental tests were carried out on an aluminum plate instrumented with two clusters of omnidirectional piezoelectric transducers **128**, as shown in FIG. **7**A. Results demonstrate the efficacy of the proposed approach by identifying the simulated damage at the correct locations, as shown in FIG. **7**B, where a crack in the aluminum plate can be identified using the TFM image. In some embodiments, the robot **100** simultaneously utilizes both MHUI and TFM imaging techniques to process the information obtained by the couplant-free ultrasound generators to detect and evaluate corrosion and cracks in tubular structures, as shown in FIG. **8**.

(21) In addition, the motion control of the robot **100** may be influenced by an imaging algorithm in order to produce thorough images of problem areas. This is very important to consider that the location of the gripper blocks **104** can be controlled not only for stability and movement goals but also for inspection purposes.

(22) While the robot **100** utilizes TFM and MHUI to obtain images of a tubular surface, the method of sensing is not limited to Lamb-wave based ultrasound imaging. In some embodiments, the toes **126** of the gripper blocks **104** may be outfitted to use magnetic flux, eddy current or automated visual inspection methods to determine defects in the tubular surface **10**. In the case of eddy current-based inspection, the transducers **128** of the toes **126** of the gripper blocks **104** can be modified or otherwise outfitted to detect eddy currents and variations in eddy currents within the

tubular surface **10**. In other embodiments, the visual inspection can be performed using the borescope **130**A along with the camera **131**. In some embodiments, a magnetic gauss meter can be installed onboard the robot **100** for measuring magnetic field along the tubular surface **10**.

(23) In some embodiments, the robot **100** also includes repair equipment including but not limited to welding or brazing equipment to mend cracks and other types of structural damage in copper or other types of tubing that the tubular surface **10** can comprise. In other embodiments, the robot **100** includes equipment to repair composite structures such as fabric and resin. In some embodiments, each of the gripper blocks **104** can be modified to heat surfaces for re-curing or bending.

(24) It should be understood from the foregoing that, while particular embodiments have been illustrated and described, various modifications can be made thereto without departing from the spirit and scope of the invention as will be apparent to those skilled in the art. Such changes and modifications are within the scope and teachings of this invention as defined in the claims appended hereto.

Claims

1. A method, comprising: positioning a robot having a plurality of transducers along a tubular surface, the plurality of transducers being positioned along a plurality of gripper blocks of the robot, and the plurality of gripper blocks collectively covering a first volumetric region along the tubular surface; receiving a first plurality of feedback signals associated with the first volumetric region from the tubular surface using the plurality of transducers; traversing the tubular surface by: lifting, while grasping the tubular surface by applying a clamping force around the tubular surface using a first gripper block of the plurality of gripper blocks, a second gripper block of the plurality of gripper blocks of the robot away from a first location along the tubular surface; and grasping, by the second gripper block, a second location along the tubular surface to cover a second volumetric region between the first gripper block and the second gripper block along the tubular surface; receiving a second plurality of feedback signals associated with the second volumetric region from the tubular surface using the plurality of transducers of the first gripper block and the second gripper block; and combining the first plurality of feedback signals and the second plurality of feedback signals into an image that encompasses the first volumetric region and the second volumetric region.

2. The method of claim 1, wherein the first plurality of feedback signals associated with the first volumetric region are resultant of application of a first plurality of ultrasonic signals traveling through the tubular surface.

3. The method of claim 1, wherein the method is sequentially repeated by positioning the plurality of gripper blocks of the robot on a plurality of locations on the tubular surface.

4. The method of claim 1, wherein the image is produced from the first plurality of feedback signals and the second plurality of feedback signals using a guided wave total focusing method.

5. The method of claim 1, wherein the image is produced from the first plurality of feedback signals and the second plurality of feedback signals using a multi-helical ultrasound imaging method.