US012390934B2

(12) **United States Patent**
Marvi et al.

(10) **Patent No.: US 12,390,934 B2**
(45) **Date of Patent: Aug. 19, 2025**

(54) **SYSTEMS AND METHODS FOR ROBOTIC SENSING, REPAIR AND INSPECTION**

(71) Applicants: **Hamidreza Marvi**, Tempe, AZ (US); **Ehsan Dehghan-Niri**, Las Cruces, NM (US); **Mahdi Ilami**, Tempe, AZ (US)

(72) Inventors: **Hamidreza Marvi**, Tempe, AZ (US); **Ehsan Dehghan-Niri**, Las Cruces, NM (US); **Mahdi Ilami**, Tempe, AZ (US)

(73) Assignee: **Arizona Board of Regents on Behalf of Arizona State University**, Tempe, AZ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 248 days.

(21) Appl. No.: **18/055,712**

(22) Filed: **Nov. 15, 2022**

(65) **Prior Publication Data**

US 2023/0182310 A1 Jun. 15, 2023

Related U.S. Application Data

(63) Continuation of application No. 16/844,519, filed on Apr. 9, 2020, now Pat. No. 11,504,854.

(60) Provisional application No. 62/831,268, filed on Apr. 9, 2019.

(51) **Int. Cl.**
B25J 9/16 (2006.01)

(52) **U.S. Cl.**
CPC ***B25J 9/1694*** (2013.01); ***B25J 9/1664*** (2013.01)

(58) **Field of Classification Search**
CPC B25J 9/1694; B25J 9/1664; B25J 9/065; B25J 15/0009; B25J 15/0038; B25J 15/0213; B25J 19/026; B25J 9/162; B25J 9/1625; B25J 9/1669; B25J 15/0033; G01N 2291/0234; G01N 2291/0258; G01N 2291/0427; G01N 2291/2634; G01N 29/069; G01N 29/225; G01N 29/228; G01N 29/2412; G01N 29/06; G01N 29/36; G01N 29/44; G01N 2203/0658; G01N 29/262; G01N 29/265; G01N 29/0654; G01N 29/041; G01N 29/043; G01N 29/04; G01N 29/048; B62D 57/024; B06B 3/00; B06B 3/04; G01H 1/04; G01H 1/06; G01H 1/14; G01H 9/00; G01H 9/002; G01H 17/00

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,193,402 B2 * 11/2015 Chin B08B 1/165
9,879,981 B1 1/2018 Dehghan Niri et al.

(Continued)

FOREIGN PATENT DOCUMENTS

WO 2020191399 A1 9/2020
WO 2021041471 A1 3/2021

OTHER PUBLICATIONS

Salamone et al, "A multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures", 2015 (Year: 2015).*

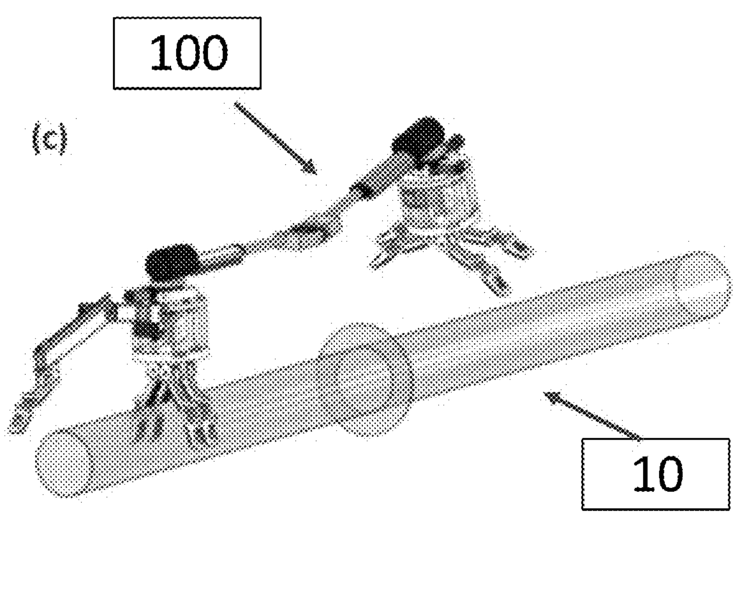
(Continued)

Primary Examiner — Abby Y Lin
Assistant Examiner — Esvinder Singh
(74) *Attorney, Agent, or Firm* — Polsinelli PC

(57) **ABSTRACT**

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

5 Claims, 9 Drawing Sheets
(9 of 9 Drawing Sheet(s) Filed in Color)



(56) **References Cited**

U.S. PATENT DOCUMENTS

2010/0283482	A1*	11/2010	Valcore	G01N 29/075 324/620
2016/0025684	A1	1/2016	Deneuville	
2016/0170013	A1*	6/2016	Laster	G01S 7/003 367/87
2017/0168024	A1	6/2017	Dehghan Niri et al.	
2017/0176397	A1	6/2017	Oono et al.	
2017/0191966	A1	7/2017	Niri et al.	
2017/0199160	A1	7/2017	Dehghan Niri et al.	
2017/0370857	A1	12/2017	Dehghan Niri et al.	
2018/0038779	A1	2/2018	Dehghan Niri et al.	
2019/0054637	A1	2/2019	Adada et al.	
2019/0077472	A1	3/2019	Harris et al.	
2019/0168384	A1*	6/2019	Ur	B25J 9/1697
2020/0108501	A1	4/2020	Hong et al.	
2020/0262261	A1	8/2020	Loosararian et al.	
2020/0286657	A1	9/2020	Marvi et al.	
2020/0355575	A1*	11/2020	Chapuis	G01N 29/0654
2021/0071801	A1*	3/2021	Lisnyak	G01N 21/952
2021/0310991	A1	10/2021	Kassis et al.	

OTHER PUBLICATIONS

Jayne, et al., Effects of incline on speed, acceleration, body posture and hindlimb kinematics in two species of lizard *Callisaurus draconoides* and *Uma scoparia*, J. Exp. Biol. 201 (1998) 273-287.

Kamperman, et al., Functional adhesive surfaces with gecko effect: The concept of contact splitting, Adv. Eng. Mater. 12 (2010) 335-348.

Lee H, Yang J and Sohn H. Baseline-free pipeline monitoring using optical fiber-guided laser ultrasonics. Struct Health Monit 2012; 11: 684-695.

Leonard, et al., Guided wave helical ultrasonic tomography of pipes. J Acoust Soc Am 2003; 114: 767-774.

Leonard, et al., Lamb wave tomography of pipe-like structures. Ultrasonics 2005; 43: 574-583.

Leonard, et al., Multi-mode Lamb wave tomography with arrival time sorting. J Acoust Soc Am 2005; 117: 2028-2038.

Leonard, et al., Ultrasonic Lamb wave tomography, Inverse Probl. 18 (2002) 1795-1808. doi:10.1088/0266-5611/18/6/322.

Li, et al., A novel mobile robot for finned tubes inspection, Robotica 21.6 (2003): 691-695.

Li, et al., Excitation and propagation of non-axisymmetric guided waves in a hollow cylinder. J Acoust Soc Am 2001; 109: 457-464.

Li, et al., Multi-functional foot use during running in the zebra-tailed lizard (*Callisaurus draconoides*), J. Exp. Biol. 215 (2012) 3293-3308.

Li, et al., Natural beam focusing of non-axisymmetric guided waves in large-diameter pipes., Ultrasonics. 44 (2006) 35-45. doi:10.1016/j.ultras.2005.07.002.

Lum, et al., Shape-programmable magnetic soft matter, in: Proc. Natl. Acad. Sci., 2016: p. 201608193.

Ma, et al., Controlled flight of a biologically inspired, insect-scale robot, Science (80-.). 340 (2013) 603-607.

Malyarenko, et al., Fan beam and double crosshole Lamb wave tomography for mapping flaws in aging aircraft structures. J Acoust Soc Am 2000; 108: 1631-1639.

Malyarenko, et al., Ultrasonic Lamb wave diffraction tomography. Ultrasonics 2001; 39: 269-281.

Marketsandmarkets.com, Global Non-Destructive Testing Market—By Type (Equipment, Service), Technique (Volumetric Examination, Surface Examination, Condition Monitoring, Integrity Examination), Technology, Industry, Geography, Trends, Forecast—(2017-2022), 2017.

Marvi, et al., Actively controlled fibrillar friction surfaces, Appl. Phys. Lett. 106 (2015) 51602.

Marvi, et al., Experimental investigation of optimal adhesion of mushroomlike elastomer microfibrillar adhesives, Langmuir. 31 (2015) 10119-10124.

Marvi, et al., Friction enhancement in concertina locomotion of snakes, J. R. Soc. Interface. 9 (2012) 3067-3080.

Marvi, et al., Scalybot: a snake-inspired robot with active control of friction, in: ASME 2011 Dyn. Syst. Control Conf. Bath/ASME Symp. Fluid Power Motion Control, merican Society of Mechanical Engineers, 2011: pp. 443-450.

Marvi, et al., Sidewinding with minimal slip: Snake and robot ascent of sandy slopes, Science (80-.). 346 (2014) 224-229.

Marvi, et al., Snakes mimic earthworms: propulsion using rectilinear travelling waves, J. R. Soc. Interface. 10 (2013) 20130188.

Marvi, et al., Snakes move their scales to increase friction, Biotribology. (2015).

Mckeon, et al., Parallel projection and crosshole Lamb wave contact scanning tomography. J Acoust Soc Am 1999; 106: 2568-2577.

Menon, et al., Gecko inspired surface climbing robots, 2004 IEEE International Conference on Robotics and Biomimetics. IEEE, 2004.

Moustafa, et al., Corrosion monitoring of post-tensioned concrete structures using fractal analysis of guided ultrasonic waves, Struct. Control Heal. Monit. 21 (2014). doi:10.1002/stc.1586.

Moustafa, et al., Fractal dimension-based Lamb wave tomography algorithm for damage detection in plate-like structures. J Intel Mat Syst Str 2012; 23: 1269-1276.

Murphy, et al., Disaster robotics, in Springer Handb. Robot., Springer, 2016: pp. 1577-1604.

Nagy, et al., Corrosion and erosion monitoring in plates and pipes using constant group velocity Lamb wave inspection. Ultrasonics 2014; 54: 1832-1841.

Park, et al., Development of mobile robot systems for automatic diagnosis of boiler tubes in fossil power plants and large size pipelines. IEEE/RSJ International Conference on Intelligent Robots and Systems. vol. 2. IEEE, 2002.

Pattantyus-Abraham, et al., Recent advances in nanostructured biomimetic dry adhesives, Front. Bioeng. Biotechnol. 1 (2013).

Pei, et al., Lamb wave tomography and its application in pipe erosion/corrosion monitoring. In: Proceedings of the IEEE ultrasonics symposium 1995, Seattle, WA, Nov. 7-10, 1995, vol. 1, pp. 795-798. New York: IEEE.

Pierce, et al., Elastic wave propagation from point excitations on thin-walled cylindrical shells. J Vib Acoust 1990; 112: 399-406.

Qing, et al., Development of a real-time active pipeline integrity detection system. Smart Mater Struct 2009; 18: 115010.

Raibert, et al., The rough-terrain quadruped robot, in: 17th World Congr., 2008: pp. 10822-10825.

Roman, Robotic applications in PSE&G's nuclear and fossil power plants, IEEE transactions on energy conversion 8.3 (1993): 584-592.

Rose, A baseline and vision of ultrasonic guided wave inspection potential. J Press Vess: T ASME 2002; 124: 273-282.

Rose, et al., Ultrasonic guided wave NDE for piping. Mater Eval 1996; 54: 1310-1313.

Sadek, NDE technologies for the examination of heat exchangers and boiler tubes—Principles, advantages and limitations, Insight Non-Destructive Test. Cond. Monit. 48 (2006) 181-183. doi:10.1784/insi.2006.48.3.181.

Sameoto, et al., Recent advances in the fabrication and adhesion testing of biomimetic dry adhesives, Smart Mater. Struct. 19 (2010) 103001.

Schmitz, et al., Experiences with synthetic aperture focusing technique in the field, Ultrasonics. 38 (2000) 731-738.

Seher, et al., Model-Based Design of Low Frequency Lamb Wave EMATs for Mode Selectivity, J. Nondestruct. Eval. 34 (2015). doi:10.1007/s10921-015-0296-6.

Spies, et al., Aperture focusing for defect reconstruction in anisotropic media, Ultrasonics. 41 (2003) 125-131.

Stefanini, et al., A novel autonomous, bioinspired swimming robot developed by neuroscientists and bioengineers, Bioinspir. Biomim. 7 (2012) 25001.

Stepinski, et al., Beamforming of Lamb waves using 2D arrays: A comparative study, in: Fu-Kuo Chang (Ed.), 9th Int. Work. SHM, 2013: pp. 2210-2217.

Tesch, et al., Parameterized and scripted gaits for modular snake robots, Adv. Robot. 23 (2009) 1131-1158.

(56) **References Cited**

OTHER PUBLICATIONS

Thoesen, et al., Screw-powered propulsion in granular media: An experimental and computational study, in: IEEE Int. Conf. Robot. Autom., 2018.
Wilcox, et al., The excitation anddetection of Lambwaveswith planar coil electromagnetic acoustic transducers, IEEETrans. Ultrason. Ferroelectr. Freq.Control. 52 (2005) 2370-2383.
Willey, et al., Guided wave tomography of pipes with high-order helical modes. NDT&E Int 2014; 65: 8-21.
Wright, et al., Air-coupled Lamb wave tomography. IEEE T Ultrason Ferr 1997; 44: 53-59.
Xueqin, et al., The design of an inspection robot for boiler tubes inspection, 2009 International Conference on Artificial Intelligence and Computational Intelligence. vol. 2. IEEE, 2009.
Yoon, et al., New algorithm for acoustic emission source location in cylindrical structures. J Acoust Emiss 1992; 9: 237-242.
Zhao, et al., Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring, Smart Mater. Struct. 16 (2007) 1208-1217. doi:10.1088/0964-1726/16/4/032.
Zhou, et al., Recent advances in gecko adhesion and friction mechanisms and development of gecko-inspired dry adhesive surfaces, Friction. 1 (2013) 114-129.
Ghyabi et al., Total Focusing Method Development for Lamb Wave Based Structural Health Monitoring, ASNT 26th Annual Research Symposium, Mar. 26-29, 2018, Orlando, FL, 15 pages.
Salamone, A multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures, Jan. 2015, Structural Health Monitoring vol. 14, pp. 73-85 (year: 2015).
U.S. Appl. No. 17/105,011, filed Nov. 25, 2020, Marvi et al.
U.S. Appl. No. 17/201,616, filed Mar. 15, 2021, Marvi et al.
Hirao, et al., EMATs for Science and Industry: Noncontacting Ultrasonic Measurements, KluwerAcademic Publishers, 2003.
Shull, Nondestructive evaluation: theory, techniques, and applications. New York: Marcel Dekker, 2002.
Speight, Coal-Fired Power Generation Handbook, Wiley, 2013.
Zhang, Ultra-Supercritical Coal Power Plants, First, Woodhead Publishing, 2013.
Alleyne, et al., The reflection of guided waves from circumferential notches in pipes. J Appl Mech 1998; 65: 635-641.
Autumn, et al., Adhesive force of a single gecko foot-hair, Nature. 405 (2000) 681-685.
Autumn, et al., Evidence for van der waals adhesion in gecko setae, in: Proc. Natl. Acad. Sci., 2002: pp. 12252-12256.
Badodkar, et al., EMAT integrated with vertical climbing robot for boiler tube inspection, Proceedings of the National Seminar & Exhibition on Non-Destructive Evaluation (NDE 2009), Chennai. 2009.
Bagheri, et al., Animal and robotic locomotion on wet granular media, in: Conf. Biomim. Biohybrid Syst., Springer, 2017: pp. 13-24.
Bagheri, et al., Reference-free damage detection by means of wavelet transform and empirical mode decomposition applied to Lamb waves. J Intel Mat Syst Str 2013; 24: 194-208.
Belanger, et al., Feasibility of low frequency straight-ray guided wave tomography. NDT&E Int 2009; 42: 113-119.
Belanger, et al., Guided wave diffraction tomography within the born approximation., IEEE Trans. Ultrason. Ferroelectr. Freq. Control. 57 (2010) 1405-18. doi:10.1109/TUFFC.2010.1559.
Bhushan, Biomimetics: lessons from nature—an overview, 2009.
Buhl, et al., Humidity influence on the adhesion of biomimetic fibrillar surfaces, Int. J. Mater. Res. 100 (2009) 1119-1126.
Caprari, et al., Highly compact robots for inspection of power plants, Journal of Field Robotics 29.1 (2012): 47-68.
Carandente, et al., The influence of sharp edges in corrosion profiles on the reflection of guided waves. NDT&E Int 2012; 52: 57-68.
Cawley, et al., Corrosion monitoring strategies—choice between area and point measurements. J Nondestruct Eval 2013; 32: 156-163.
Curet, et al., Mechanical properties of a bio-inspired robotic knifefish with an undulatory propulsor, Bioinspir. Biomim. 6 (2011) 26004.
Cutkosky, et al., Design and fabrication of multi-material structures for bioinspired robots, Philos. Trans. R. Soc. London A Math. Phys. Eng. Sci. 367 (2009) 1799-1813.
Dehghan Niri, et al., A Probabilistic Framework for Acoustic Emission (AE) Source Localization in Plate-Like Structures, Smart Mater. Struct. (2012).
Dehghan Niri, et al., Adaptive multisensor data fusion for acoustic emission source localization in noisy environment, Struct. Heal. Monit. 2012; 12:59-77 (2013). doi:10.1177/1475921712462937.
Dehghan Niri, et al., Nonlinear Kalman Filtering for acoustic emission source localization in anisotropic panels., Ultrasonics. 54 (2013) 486-501. doi:10.1016/j.ultras.2013.07.016.
Dehghan-Niri, et al., A multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures, Struct. Heal. Monit. (2014). doi:10.1177/1475921714548937.
Dehghan-Niri, et al., Phase-space topography characterization of nonlinear ultrasound waveforms, Ultrasonics. 84 (2018). doi:10.1016/j.ultras.2017.12.007.
Dehghan-Niri, Quantitative corrosion imaging of pipelines using multi helical guided ultrasonic waves, Struct. Monit. Maint. 3 (2016). doi:10.12989/smm.2016.3.3.215.
Del Campo, et al., Contact shape controls adhesion of bioinspired fibrillar surfaces, Langmuir. 23 (2007) 10235-10243.
Ditri, Utilization of guided elastic waves for the characterization of circumferential cracks in hollow cylinders. J Acoust Soc Am 1994; 96: 3769-3775.
Fan, et al., A comparison between ultrasonic array beamforming and super resolution imaging algorithms for non-destructive evaluation., Ultrasonics. 54 (2014) 1842-1850.
Farhidzadeh, et al., Post-earthquake evaluation of pipelines rehabilitated with cured in place lining technology using acoustic emission, Constr. Build. Mater. 54 (2014). doi:10.1016/j.conbuildmat.2013.12.048.
Fessler, Pipeline corrosion. Report, US Department of Transportation Pipeline and Hazardous Materials Safety Administration, Baker, Evanston, IL, Nov. 2008.
Fischer, et al., Foldable magnetic wheeled climbing robot for the inspection of gas turbines and similar environments with very narrow access holes, Industrial Robot: An International Journal 37.3 (2010): 244-249.
Gao, et al., Boiler maintenance robot with multi-operational schema, 2008 IEEE International Conference on Mechatronics and Automation. IEEE, 2008.
Gao, et al., Multifunctional robot to maintain boiler water-cooling tubes, Robotica 27.6 (2009): 941-948.
Glasheen, et al., Size-dependence of water-running ability in basilisk lizards (*Basiliscus basiliscus*), Exp. Biol. 199 (1996) 2611-2618.
Gorb, Biological attachment devices: exploring nature's diversity for biomimetics, Philos. Trans. R. Soc. London A Math. Phys. Eng. Sci. 366 (2008) 1557-1574.
Guo, et al., A new transducer holder mechanism for pipe inspection. J Acoust Soc Am 2001; 110: 303-309.
Hall, et al., Minimum variance ultrasonic imaging applied to an in situ sparse guided wave array. IEEE T Ultrason Ferr 2010; 57: 2311-2323.
Han, et al.,m Fiberbot: A miniature crawling robot using a directional fibrillar pad, in: Robot. Autom. (ICRA), 2015 IEEE Int. Conf., 2015: pp. 3122-3127.
Hay, et al., A comparison of embedded sensor Lamb wave ultrasonic tomography approaches for material loss detection, Smart Mater. Struct. 15 (2006) 946-951. doi:10.1088/0964-1726/15/4/007.
Heepe, et al., Biologically inspired mushroom-shaped adhesive microstructures, Annu. Rev. Mater. Res. 44 (2014) 173-203.
Hinders, et al., Contact scanning Lamb wave tomography. J Acoust Soc Am 1998; 104: 1790-1791.
Holmes, et al., The dynamics of legged locomotion: Models, analyses, and challenges, Siam Rev. 48 (2006) 207-304.
Huber, et al., Influence of surface roughness on gecko adhesion, Acta Biomater. 3 (2007) 607-610.

(56) **References Cited**

OTHER PUBLICATIONS

Huerzeler, et al., Applying aerial robotics for inspections of power and petrochemical facilities, 2012 2nd International Conference on Applied Robotics for the Power Industry (CARPI). IEEE, 2012.
Huthwaite, et al., High-resolution guided wave tomography. Wave Motion 2013; 50: 979-993.
Irschick, et al., Comparative three-dimensional kinematics of the hindlimb for high-speed bipedal and quadrupedal locomotion of lizards, J. Exp. Biol. 202 (1999) 1047-1065.
Jagota, et al., Mechanics of adhesion through a fibrillar microstructure, Integr. Comp. Biol. 42 (2002) 1140-1145.
Jansen, et al., Immersion tomography using Rayleigh and Lamb waves. Ultrasonics 1992; 30: 245-254.

* cited by examiner

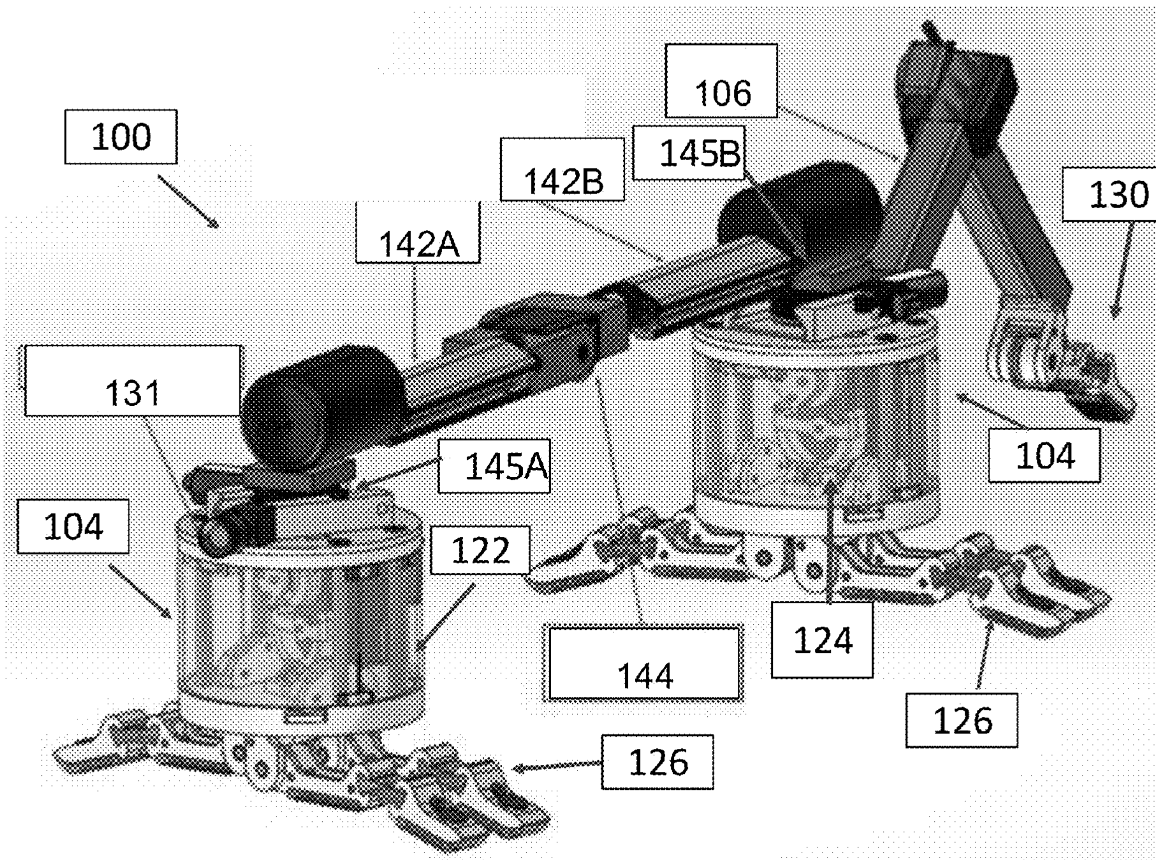


FIG. 1

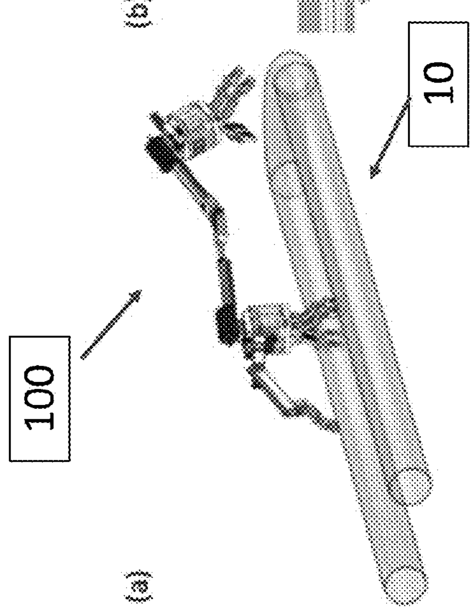


FIG. 2A

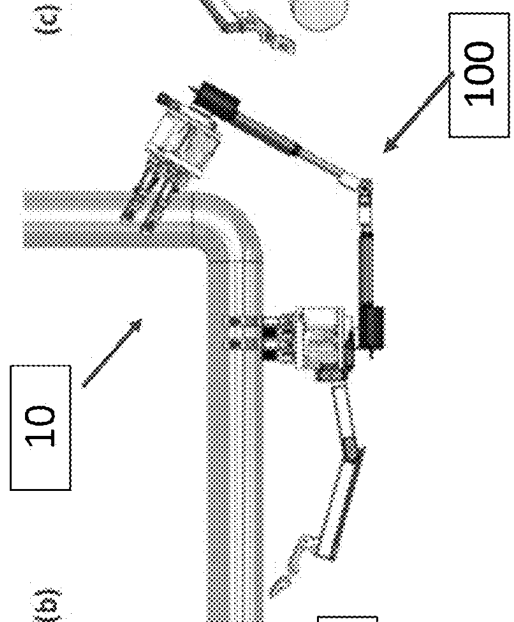


FIG. 2B

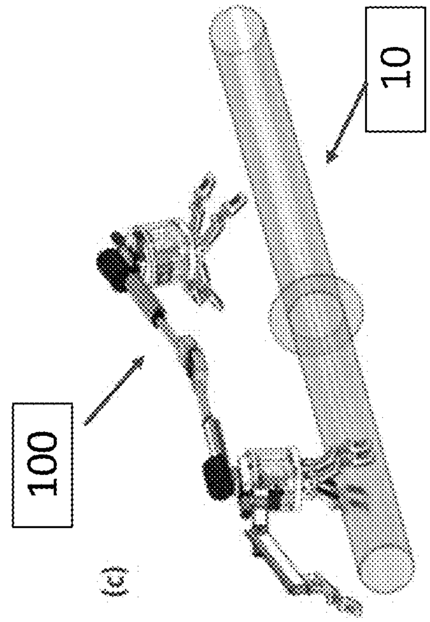


FIG. 2C

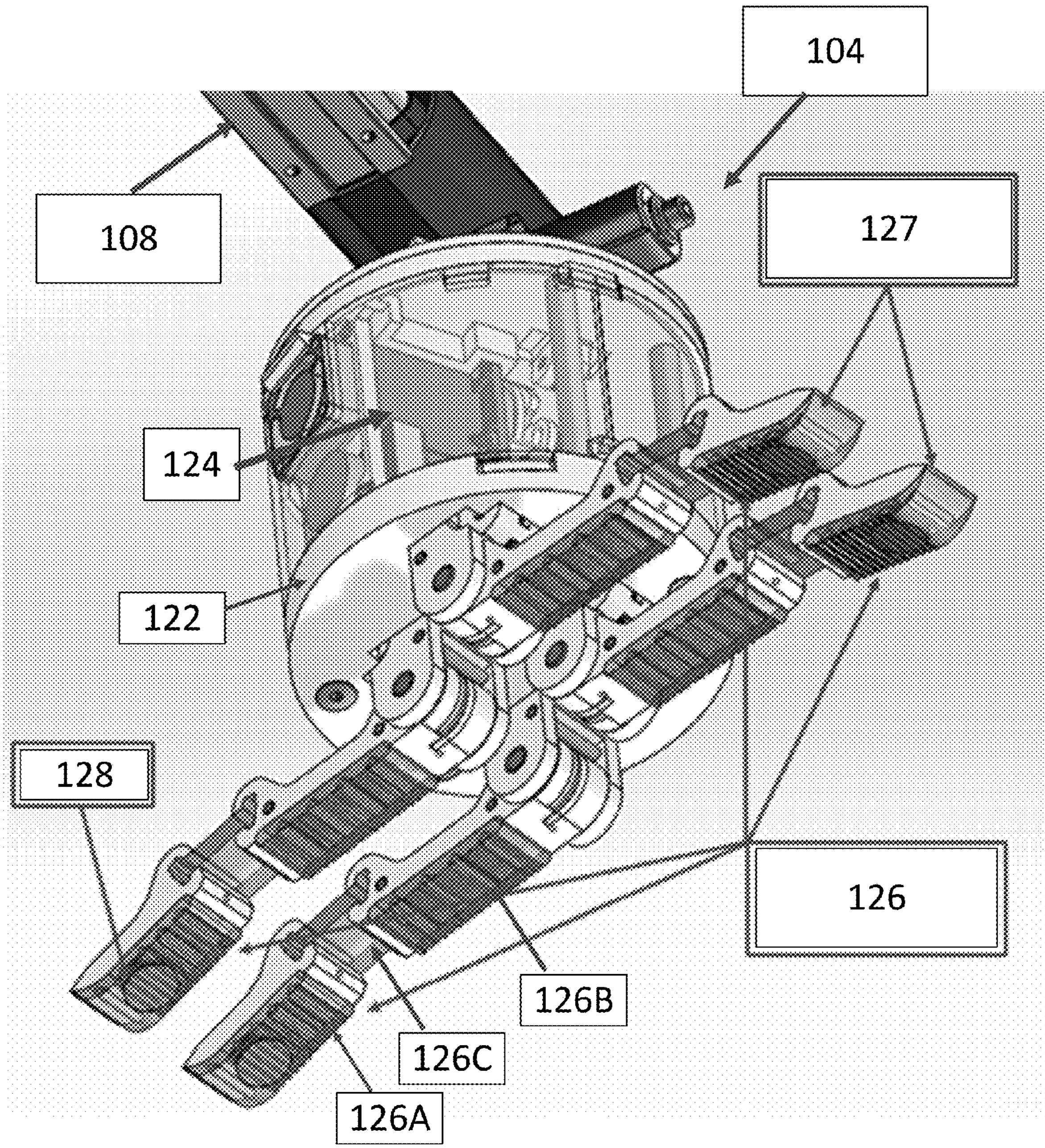


FIG. 3A

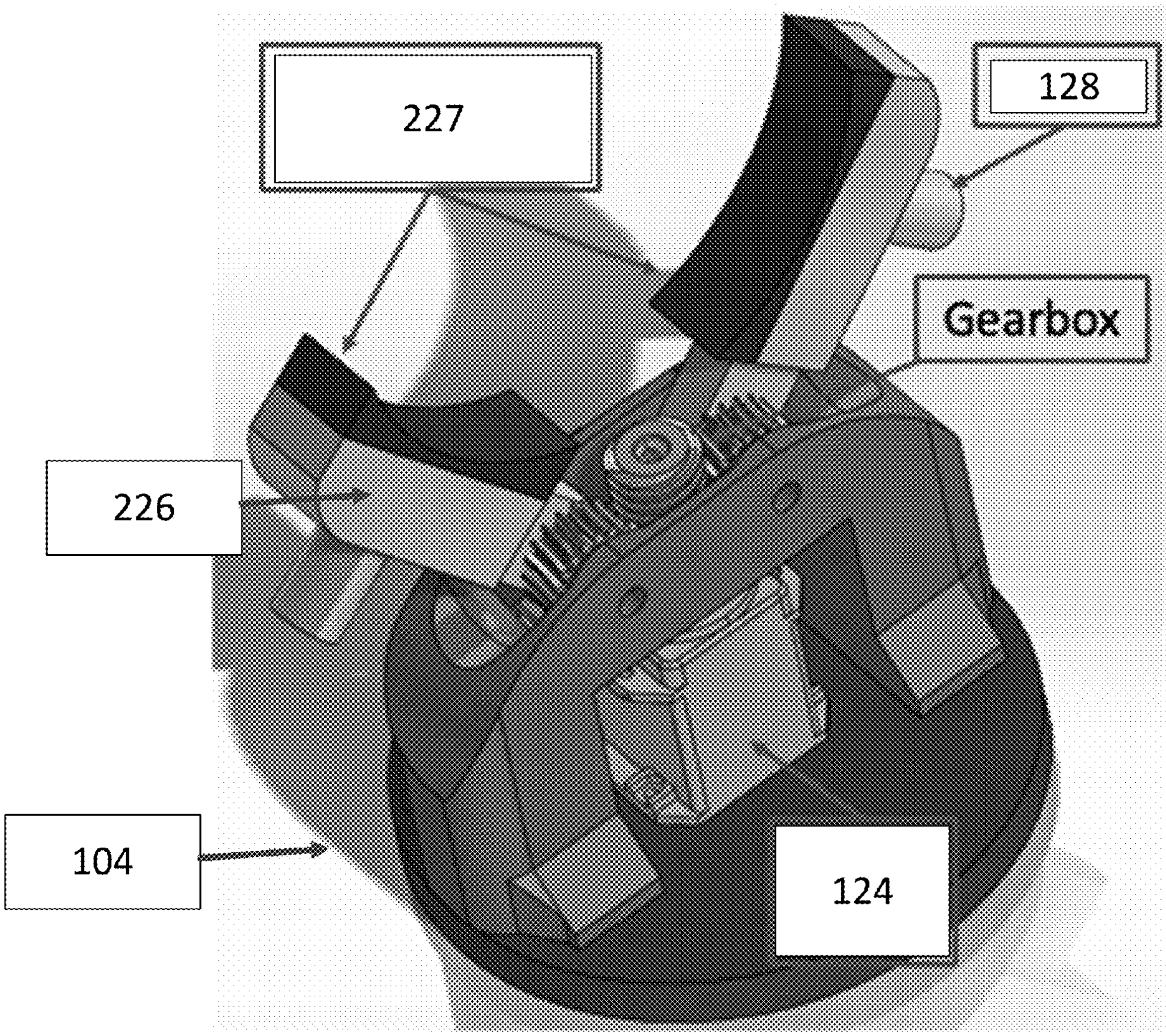


FIG. 3B

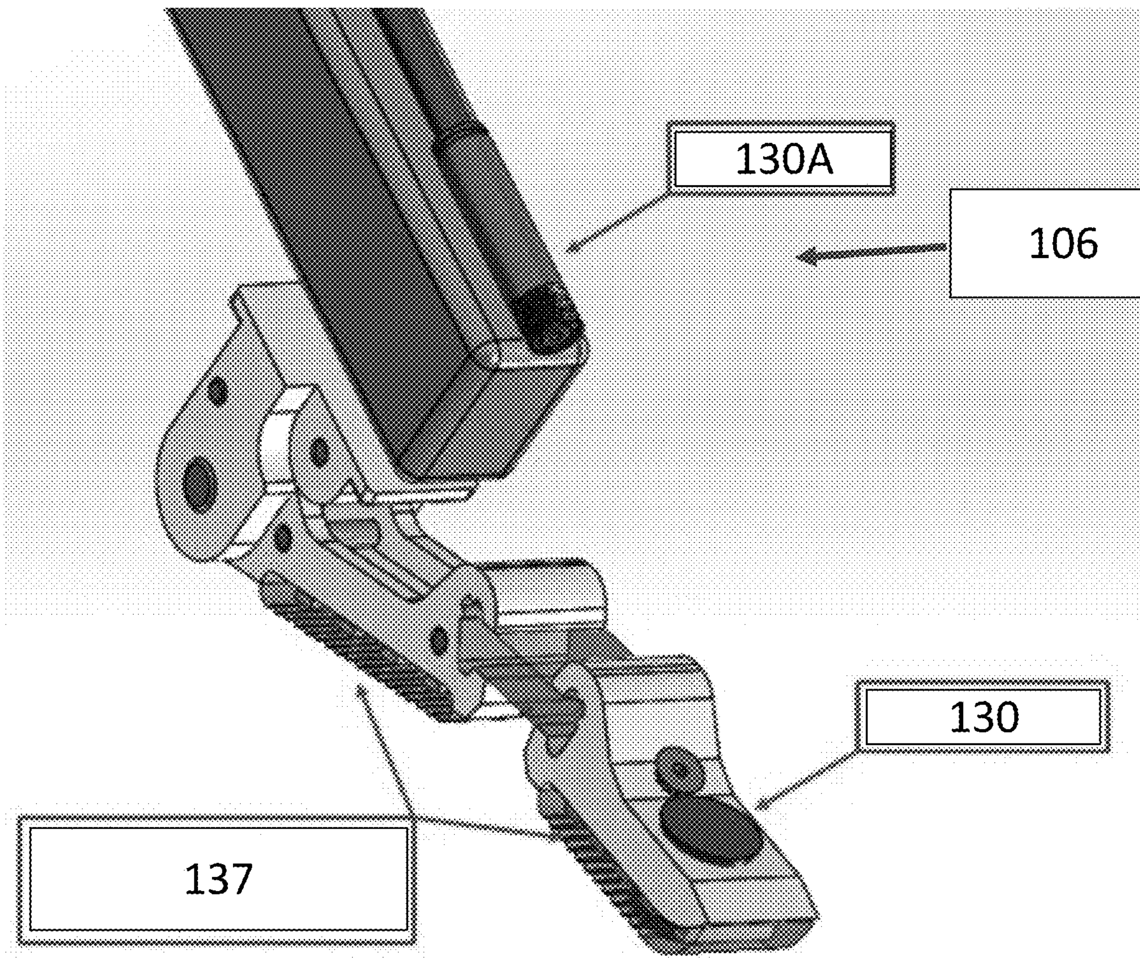


FIG. 4

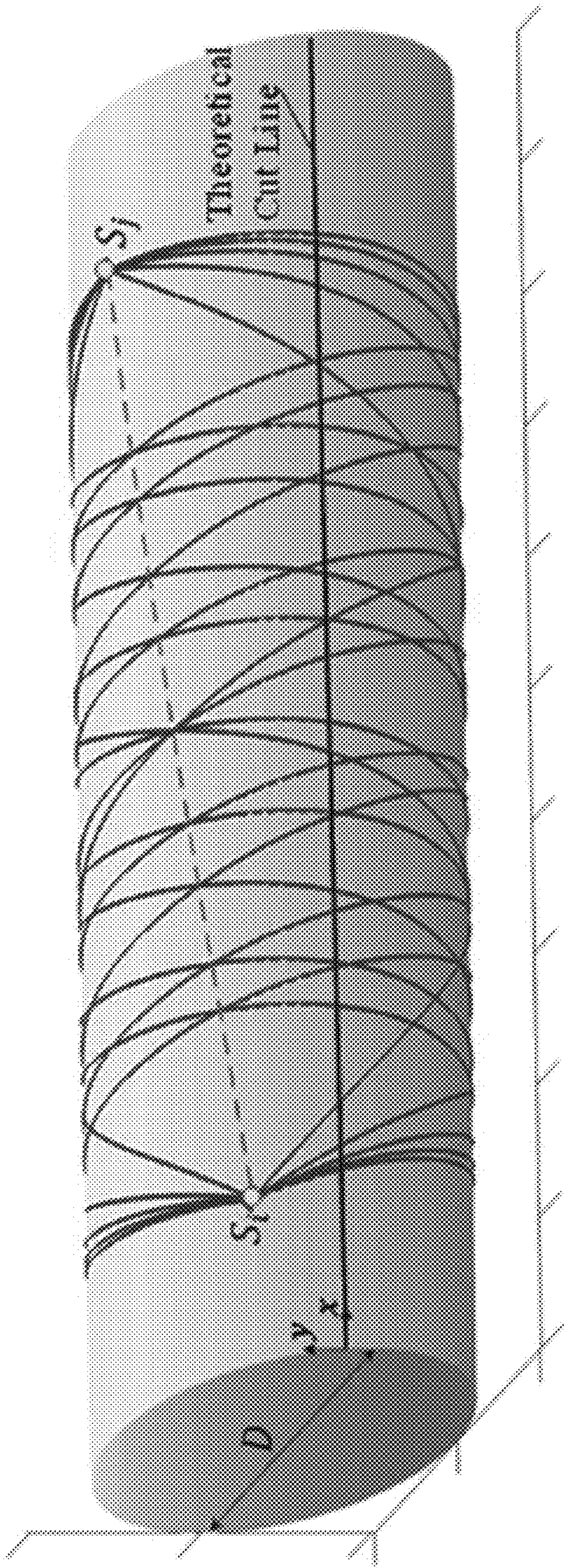
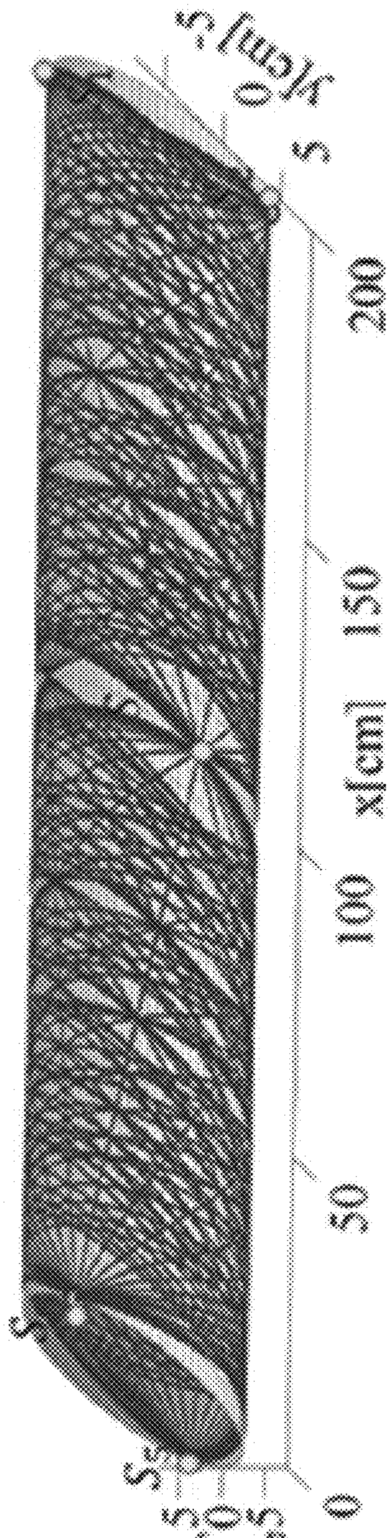
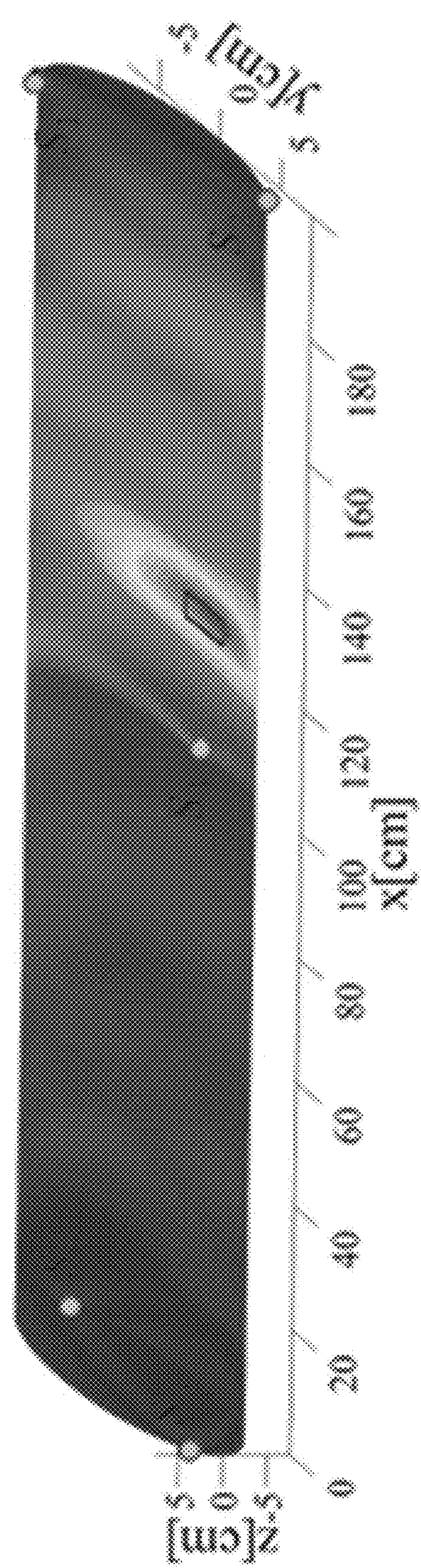


FIG. 5



x[cm]
y[cm]
z[cm]
0
50
100
150
200
5
0
5

FIG. 6A



x[cm]
y[cm]
z[cm]
0
20
40
60
80
100
120
140
160
180
5
0
5

FIG. 6B

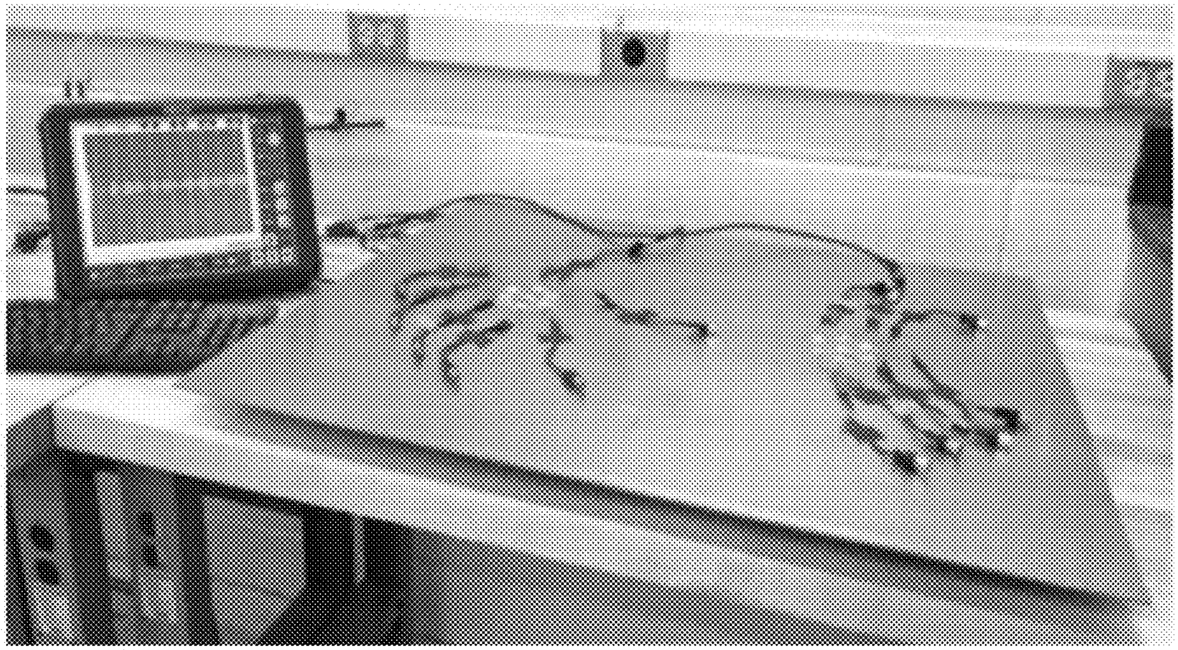


FIG. 7A

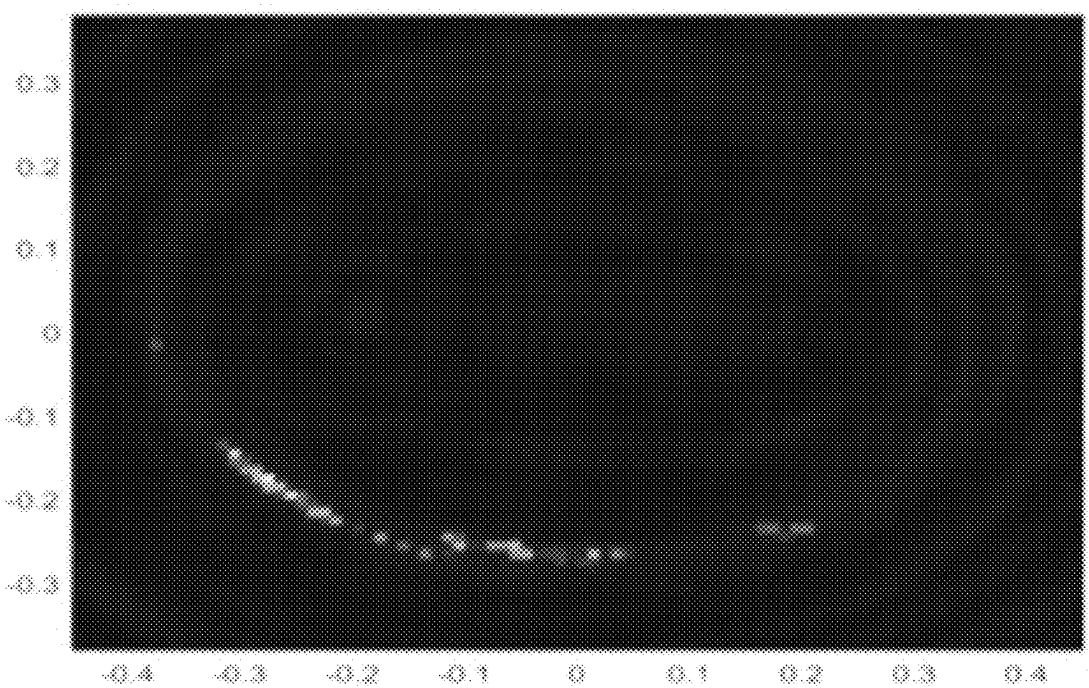


FIG. 7B

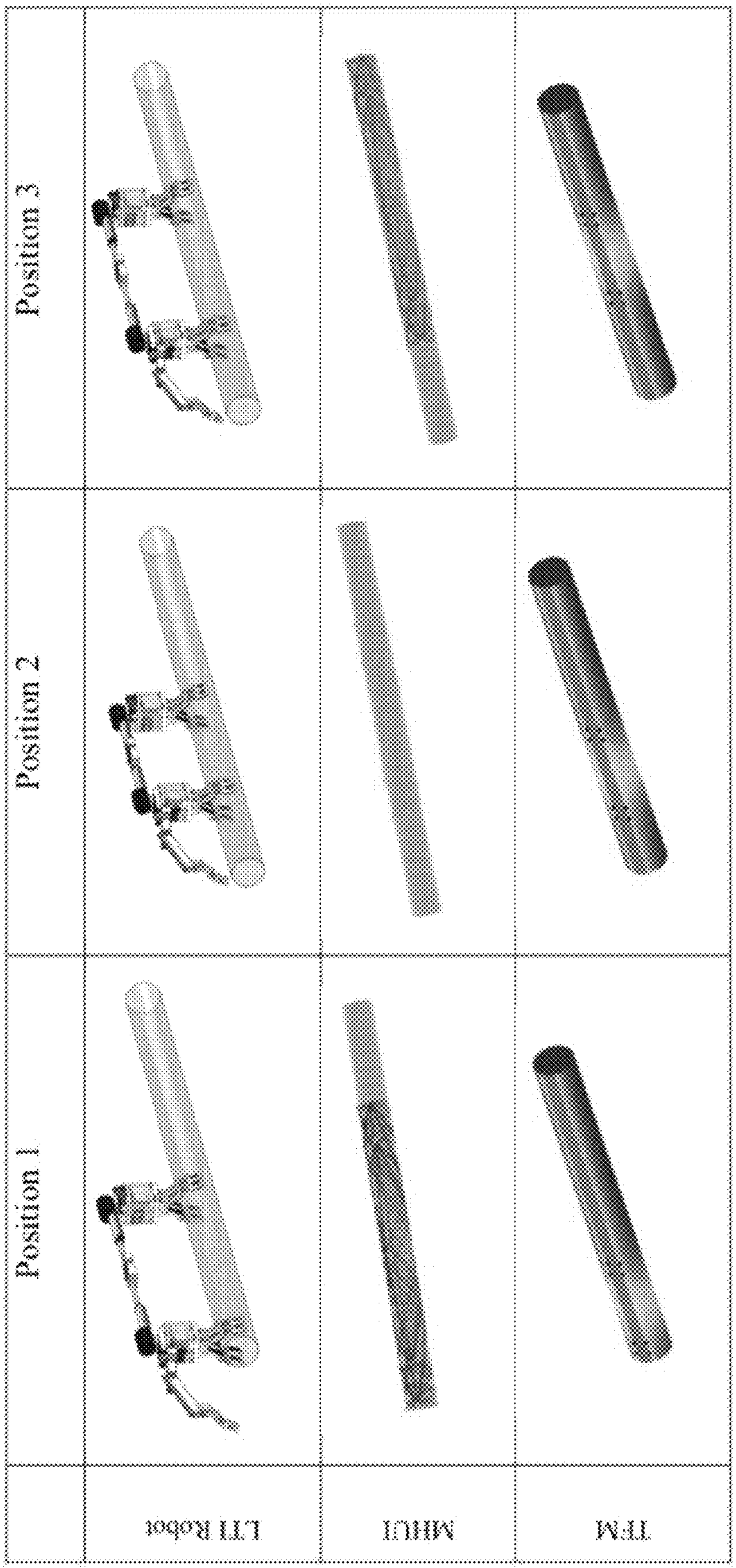


FIG. 8

SYSTEMS AND METHODS FOR ROBOTIC SENSING, REPAIR AND INSPECTION

CROSS REFERENCE TO RELATED APPLICATIONS

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.

GOVERNMENT SUPPORT

The invention was made with government support under DE-FE0031649 awarded by the US Department of Energy. The government has certain rights in the invention.

FIELD

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

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.

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.

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

BRIEF DESCRIPTION OF THE DRAWINGS

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.

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

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.

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**;

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**;

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

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

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.

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.

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**.

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

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**.

Robot Structure: Bio-Inspired Design

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**.

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.

Couplant-Free Ultrasound Generation

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**.

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**.

Imaging: Corrosion and Crack Detection and Evaluation

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**.

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.

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**.

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.

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.

What is claimed is:

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.

* * * * *