



(51) International Patent Classification:

G01M 5/00 (2006.01) A61B 34/00 (2016.01)
G01L 1/14 (2006.01)

(21) International Application Number:

PCT/US2023/015547

(22) International Filing Date:

17 March 2023 (17.03.2023)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

63/387,043 12 December 2022 (12.12.2022) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO,

(54) Title: SYSTEM, METHOD, AND APPARATUS FOR SENSING THE SHAPE OF ELONGATED ELASTIC BODIES USING REFLECTOMETRY

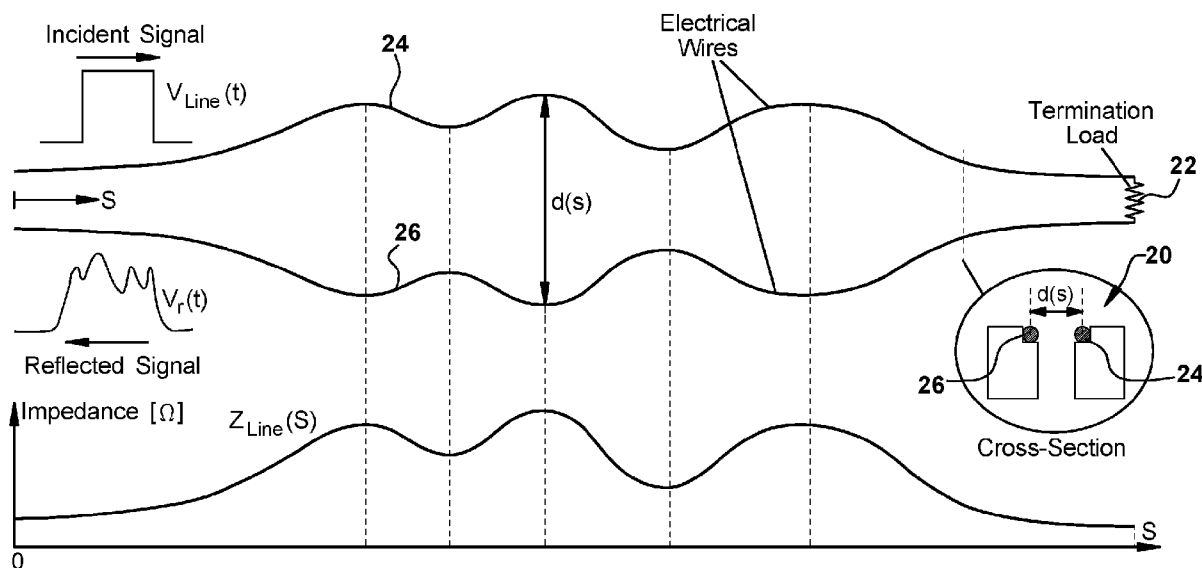


FIG. 2

(57) Abstract: A system for sensing the shape of an elastic body and/or forces acting on an elastic body includes a transmission line configured to be secured to the elastic body along its length. The transmission line includes a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body. The transmission line is configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body. The system also includes sensor electronics operatively connected to the transmission line. The sensor electronics are configured to perform a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line, and combine the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH,
TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS,
ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

SYSTEM, METHOD, AND APPARATUS FOR SENSING THE SHAPE OF ELONGATED ELASTIC BODIES USING REFLECTOMETRY

Related Application Data

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 63/387,043, filed December 12, 2022. The provisional application is hereby incorporated by reference in its entirety for all purposes.

Government Rights

[0002] This invention was made with government support under grant number 2133027 awarded by the National Science Foundation. The government has certain rights in the invention

Technical Field

[0003] This disclosure relates to sensing the shape of elongated elastic bodies using reflectometry. More specifically, in one example implementation, this disclosure relates to sensing the shape of continuum devices.

Background

[0004] In the field of robotics, a continuum device is a type of robot that is characterized by infinite degrees of freedom and number of joints. These characteristics allow continuum robots to adjust and modify their shape at any point along their length, granting them the possibility to work in confined spaces and complex environments where standard rigid-link robots cannot operate, such as those encountered when conducting minimally invasive surgical procedures.

[0005] The main characteristic of the design of continuum devices, sometimes referred to as “continuum manipulators” or “continuum robots,” is the presence of a continuously curving core structure, referred to as a backbone, the shape of which can be actuated and controlled. The backbone must also be compliant, *i.e.*, it must yield smoothly to external loads. One particular type of continuum

device is a concentric-tube device, constructed of concentric tubes that have a pre-curved configuration. Through relative translation and rotation of the tubes, the overall curvature of the device and the position of the device tip can be controlled robotically. Other types of continuum devices include endoscope-like devices that are actuatable (e.g., via pull wires) to bend into different curved configurations. Other examples include robots used in industrial settings that perform a wide variety of tasks, including inspection, part positioning/placement, welding, and spray painting.

[0006] To properly and safely use continuum robots, it is important to have an accurate force and shape sensing system. Traditionally, this is done using cameras, which are not suitable for some of the applications. The cameras allow the continuum device to be visualized so that its shape/position can be viewed. In doing so, the forces being exerted by the device, and the resulting reaction of the device itself, can also be viewed. For example, a camera view of the continuum robot might not be available for minimally invasive surgical procedures. In this instance, medical imaging systems are used to view the robot. Other applications where a view of the robot might not be possible include, for example, inspections in confined spaces and shipwreck exploration.

[0007] Model-based control schemes can be used to control the operation of the continuum robots. This control method relies on a kinematic model of the continuum robot. Essentially, once the model is defined, the kinematics are inverted to define actuator operation that will produce the desired robotic motion. While these and other control schemes and methods can result in the ability to control the motion of the continuum robot with accuracy and precision in open space, they cannot account for external forces, such as those associated with engaging tissue in a minimally invasive surgical setting, acting on and distorting the shape of the robot during use.

[0008] Accordingly, it would be advantageous if the actual shape of the continuum robot could be measured accurately without the need for using cameras or other imaging/vision systems.

Summary

[0009] A system, method, and apparatus senses the shape of an elongated elastic body using a shape sensing technique based on electrical impedance using time domain reflectometry (TDR). The TDR method senses the deformed shape of the elastic body based on the impedance between two conductive elements, embedded in or adhered to the elastic body, which extend side-by-side along its length. The method uses standard copper wires and sensor electronics, such as a vector network analyzer (VNA), which is an electronic instrument that is widely known and used for applications such as electronics testing.

[0010] The shape change detection is based on the change in capacitance and inductance of an electrical transmission line as it undergoes mechanical deformation. These changes are used to measure the shape of an elongated elastic body, in this case a continuum device, in a continuous manner using TDR. The TDR method involves sending an electrical pulse from a source over a conductor pair in the form of a ground and a signal wire, which together form a transmission line. When the pulse encounters a change in impedance, a portion of the pulse is reflected back to the source. The reflected waves are measured at the source and used to interpret the condition of the transmission line along its length, which is used to determine the shape of the elastic member.

[0011] A transmission line can be described by its impedance, $Z(s)$, along its length, s . When the impedance changes at a point along the length of the transmission line, some portion of the signal will reflect backwards, and some portion will be transmitted forward; the ratio of transmission and reflection is a direct function of the change in the impedance. The shape of the conductors, spacing between them, and dielectric properties of the materials in the cross-section of the transmission line affect the impedance $Z(s)$. The TDR methodology disclosed herein takes advantage of the relation between the spacing of the conductors and impedance.

[0012] According to the disclosed TDR methodology, transmission line conductors are mechanically attached on an elongated elastic body in parallel

with a nominal spacing between the wires. As the elastic body is deformed at specific point along the arclength, the spacing between the conductors change which, due to capacitive and inductive properties, cause a change in impedance in the transmission line. As a result, portions of electrical pulses are reflected at the location of changed impedance back to the source. These reflections can be sensed, measured, and used with timing measurements to determine the location along the length of the transmission line where the impedance change occurred. Modeling can be used to associate the detected change in impedance at the location with a corresponding change in shape of the elastic body.

[0013] To measure the shape of a cylindrical elastic body, such as a continuum device, the parallel conductors making up the transmission line are wrapped helically around the length of the device. In this manner, the wire spacing is directly related to the bending and elongation of the continuum device. Areas of compression in the continuum device resulting from bending moves the wires closer together. Areas of tension in the continuum device resulting from bending moves the wires apart. These local strains can then be used to sense the shape of the continuum device using the model-based technique.

[0014] Because the force and moment action on a continuum device and deflection of the continuum device are coupled problems, the system, method, and apparatus disclosed herein can also be used as a distributed load sensor. The apparatus includes a mechanically flexible sensor body for attachment to the continuum device. The system can implement calibrated stiffness values for the continuum device and sensor material. Deflection measured *via* the TDR shape sensing methodology can therefore be used to determine the external loads on the continuum device in a localized manner.

[0015] In an example implementation, the conductor for the transmission line is formed with circular cross-section wires. Alternative conductors, such as rectangular cross-section wires or thin strip, *e.g.*, printed circuit conductors, can also be implemented. Liquid conductors are also contemplated, as they are

“flexible” in all directions and would advantageously permit shape sensing in all directions, including the conductor axis direction.

[0016] Additionally, the methodology is not limited to measuring TDR *via* a vector network analyzer. For example, a dedicated time domain reflectometer or even a simple pulse generator combined with oscilloscope can be used. Once the reflected signal is obtained, regardless of the equipment/sensor electronics used to do the measuring, the method can be used to sense the shape. It is for this reason that an application specific controller can be developed, for example, for implementation in a controller or actuator for a continuum robot system.

[0017] The system, method, and apparatus disclosed herein can be used to measure the effect that external factors have on impedance in the transmission line in a variety of implementations other than continuum robots. For example, in addition to shape-sensing, the system, method, and apparatus can be used to sense other things that affect the local impedance along a transmission line. For example, the proximity of human tissue to the transmission line affects the impedance locally, and can therefore be detected through the disclosed methodology. Because of this, the disclosed methodology can be adapted to other devices, such as touchpads, which can be made more flexible, as the traditional capacitive screens rely on a two-dimensional grid system, whereas the disclosed methodology requires one-dimensional parallel wires forming the transmission line. Generally speaking, anything that effects permittivity (dielectric) and permeability along with the conductor geometry can be sensed and localized with the disclosed system, method, and apparatus.

[0018] As another potential implementation, because the methodology involves sensing the strains and shape while staying flexible, the system, method, and apparatus can be implemented in wearable devices and used to sense the posture of the wearer or other deflection based information. A further implementation, the system, method, and apparatus can be used is to detect continuous moisture/salinity levels along its length. The percentage of moisture or salinity would affect the dielectric properties of surroundings, including the

transmission line, and this can therefore be used to measure these effects continuously along a sensor cable. The implementation of the system, method, and apparatus will become apparent in view of the detailed description provided herein.

[0019] According to one aspect, a system for sensing the shape of an elastic body and/or forces acting on an elastic body includes a transmission line configured to be secured to the elastic body along its length. The transmission line includes a pair of conductive elements that are spaced nominally from each other and extending along the length of the elastic body. The transmission line is configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body. The system also includes sensor electronics operatively connected to the transmission line. The sensor electronics are configured to perform a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line, and combine the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

[0020] According to another aspect, the mechanics model can correlate the shape of the transmission line with the detected displacements. The shape of the elastic body can be determined as corresponding with the shape of the transmission line determined by the mechanics model in response to the detected displacements.

[0021] According to another aspect, the mechanics model can correlate strains on the elastic body and the transmission line as a whole with the detected displacements. The external forces acting on the elastic body and transmission line as a whole can be determined as corresponding with the strains and stiffness model for the elastic body.

[0022] According to another aspect, the displacements of the conductive elements from the nominal spacing can be correlated with strains along the length of the elastic body.

[0023] According to another aspect, the mechanics model can correlate the strains along the length of the elastic body with the shape of the elastic body.

[0024] According to another aspect, the mechanics model can correlate the strains along the length of the elastic body with external forces acting on the elastic body.

[0025] According to another aspect, to perform the TDR function, the sensor electronics can be configured to transmit a pulsed signal in the transmission line, monitor the transmission line for a reflected signal in response to the pulsed signal, detect *via* the reflected signal the displacements of the conductive elements from the nominal spacing, and determine, *via* a signal travel speed function, a location along the length of the transmission line where the change in spacing occurred.

[0026] According to another aspect, detecting a change in the displacements of the conductive elements from the nominal spacing can include detecting a change in impedance of the transmission line.

[0027] According to another aspect, detecting a change in the displacements of the conductive elements from the nominal spacing *via* the reflected signal can include collecting reflection scattering coefficients in the frequency domain and converting the collected scattering coefficients into an equivalent time domain response.

[0028] According to another aspect, determining the location where the change in spacing occurred can include integrating the signal travel speed function.

[0029] According to another aspect, the mechanics model can be a Cosserat rod model configured to combine the detected displacements of the conductive elements from the nominal spacing with a mechanics model for the

predetermined shape of the transmission line to determine the shape of the elastic body.

[0030] According to another aspect, the elastic body can have an elongated cylindrical configuration, and the transmission line can be configured as a helix that extends along the cylindrical elastic body. The mechanics model can be a mechanics model for the transmission line helix. The cylindrical elastic body can be a continuum device.

[0031] According to another aspect, a continuum robot system can include an actuatable continuum device and a robot controller configured to robotically actuate the continuum device. A transmission line can be secured to the continuum device along its length. The transmission line can include a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body. The transmission line can be configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body. The continuum robot system can also include sensor electronics configured to perform time domain reflectometry (TDR) operatively connected to the transmission line. The sensor electronics can be configured to perform a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line. The sensor electronics can also be configured to combine the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

[0032] According to another aspect, a sensor for sensing strain along the length of a flexible elongated element can include a transmission line configured to be secured to the elastic body along its length. The transmission line can include a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body. The transmission line can be configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to

deformation of the elastic body. The sensor can be configured to sense the strain *via* time domain reflectometry, which detects one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line.

[0033] According to another aspect, a method for sensing the shape of an elastic body and/or forces exerted on an elastic body can include securing a transmission line to the elastic body along its length. The transmission line can include a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body. The method also includes arranging the transmission line is to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body. The method also includes performing a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line. The method further includes combining the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

Drawings

[0034] Fig. 1A is a schematic representation of a transmission line that forms a part of the system, method, and apparatus for sensing the shape of elongated elastic bodies.

[0035] Fig. 1B is a schematic representation of equivalent circuits that the system, method, and apparatus uses to operates.

[0036] Fig. 2 is a chart representing the theoretical basis upon which the system, method, and apparatus operates.

[0037] Figs. 3A and 3B illustrate an example linear configuration of a transmission line sensor portion of the system and apparatus.

[0038] Fig. 4A is a graph illustrating an impedance profile for the sensor portion of the system and apparatus shown in Figs. 3A and 3B.

[0039] Figs. 4B-D are charts illustrating shape changes in the sensor portion of Figs. 3A-3B as sensed *via* the TDR sensing method implemented by the system and apparatus in comparison with those same shape changes sensed *via* camera.

[0040] Figs. 5A and 5B illustrate an example helical configuration of a transmission line sensor portion of the system and apparatus.

[0041] Fig. 6A is a perspective view illustrating the implementation of a transmission line sensor on an elongated elastic body.

[0042] Fig. 6B represents a portion of the system of Fig. 6A and shows certain parameters that form the basis of operation of the system.

[0043] Figs. 7A-7C illustrate the experimental results that prove the effectiveness of the system, method, and apparatus.

Description

[0044] Fig. 1 illustrates a system 10 including an apparatus in the form of a transmission line sensor, referred to herein as a transmission line 20 for sensing the shape of an elongated elastic member. Sensor electronics 30 are connected to the transmission line 20 and includes a signal generator 32 for generating a signal, such as a pulsed electrical signal, that is transmitted along the transmission line 20, which is composed of a signal wire 24 and a ground wire 26 arranged to run parallel to each other across a termination load 22. The sensor electronics 30 also include analyzer components 34, such as a vector network analyzer (VNA) or other components configured to sense changes in electrical impedance in the transmission line 20 using time domain reflectometry (TDR).

[0045] For purposes of illustration and explanation, Fig. 1A shows the transmission line 20 broken down into a plurality of sections along the length of the transmission line, where a change in impedance ΔZ can be measured. As shown in Fig. 1B, it is shown that each section can be represented by an equivalent *LCR* circuit. The segments and corresponding equivalent circuits shown in Figs. 1A and 1B illustrate that the *LCR* circuit can be analyzed and

solved at any point along the length of the transmission line 20, not just at the small number of discrete locations along its length. While the number of positions or spatial resolution of the analysis is discrete, it is limited only by the time resolution of the signal measurement device. The spatial resolution can therefore be so high as to be effectively continuous.

[0046] Because the transmission line 20 has a simple construction, *i.e.*, parallel wires 24, 26 electrically connected to a load 22, its properties do not vary when the transmission line is at steady-state. The system 10 relies on the principal that these properties will, however, vary in response to physical changes in the transmission line caused by external forces that distort or deform the spacing of the wires 24, 26. By securing the transmission line 20 to the surface of an elongated elastic member, such as a continuum device, sensed changes in transmission line impedance can be analyzed using TDR to detect the shape changes in the elastic member.

[0047] Fig. 2 illustrates this principal. As shown in the cross-section portion of Fig. 2, the transmission line 20 includes the wires 24, 26 arranged in parallel and separated by a distance $d(s)$, which varies at locations along its length. The sensor electronics 30 generate an incident signal pulse $V_{inc}(t)$ in the transmission line 20 across the load 22 and measures a reflected signal $V_r(t)$ in response to the pulse. As shown in the graph at the lower portion of Fig. 2, impedance in the transmission line 20 is affected by changes in the spacing between the wires. This is because changes in spacing produces changes in the effective LCR circuit (see Figs. 1A-B) at the location where the wire spacing is changed. The relative positions of the wires affects inductance L and capacitance C , which affects impedance Z .

[0048] Fig. 2 depicts the Time Domain Reflectometry (TDR) based shape sensing concept. The sensor electronics 30 (see Fig. 1A) perform TDR measurements *via* the analyzer 34, *e.g.*, a vector network analyzer or other components configured to perform this signal analysis. For example, in testing, a model 804/1 8 GHz vector network analyzer (VNA) from Copper Mountain

Technologies, of Indianapolis, Indiana, USA was used to analyze the reflected signal. The analyzer 34 collects the S_{11} reflection scattering coefficients (magnitude and phase) in the frequency domain by sweeping the frequency range, and then converts this into an equivalent time domain response to a step input using the Chirp-Z transform. There are dedicated TDR units that perform the measurement directly in the time domain, and these can be implemented in the system. For purposes of testing, the VNA was implemented due to its high dynamic range and accuracy.

[0049] Before using the sensor electronics 30 to detect changes in the transmission line 20, the transmission line is modeled so as to take into account any internal reflections caused by imperfections or irregularities in the wires 24, 26. This modeling effectively encodes the shape information of the transmission line 20, which is decrypted into an impedance profile first before it can be used. A non-uniform transmission line model is employed since the spacing between the conductors is expected to vary across the transmission line based on the deformations that the transmission line undergoes.

[0050] A known method is used to calculate the impedance profile $Z(t)$ of the transmission line 20 from the $V_r(t)$ measurement. The method can, for example, be the method described by Hsue *et al.* in Reconstruction of Nonuniform Transmission Lines from Time-Domain Reflectometry, *IEEE Transactions on Microwave Theory and Techniques*, Volume 45, Issue 1, January 1997. Hsue *et al.* discloses a technique to reconstruct the physical structures of a nonuniform transmission line from its time-domain or frequency-domain reflection (scattering) coefficient, taking into account the past history of reflection processes of nonuniform lines into consideration. This method takes the internal reflections within the transmission line into account, and calculates the reflection and transmission coefficients of the line based on the history of the reflected signal.

[0051] With $Z(t)$ obtained, the impedance formula for a lossless transmission line given below is used to calculate the spacing.

$$Z = \sqrt{\frac{L'}{C'}} \quad \text{Equation (1)}$$

In this equation, L' and C' are the inductance and the capacitance of the conductor pair per unit length. For parallel wire pair, these can be calculated by

$$L' = \frac{\mu}{\pi} \text{acosh}(d/D) \quad \text{Equation (2)}$$

$$C' = \frac{\pi\epsilon}{\text{acosh}(d/D)} \quad \text{Equation (3)}$$

where D is the wire diameter, and d is the spacing between wires. μ is the permeability and ϵ is the permittivity of the materials around the wire pair subjected to the electrical fields, respectively. As the materials surrounding the wire pair are ABS plastic and air, which are non-magnetic, the permeability, μ , is assumed to be equal to permeability of the free space, μ_0 , for the model. On the other hand, determining the permittivity, ϵ , is complicated since the composition of the surrounding area changes based on the wire spacing in terms of the ABS plastic and air amounts, which have may have different permittivity values. Thus, simply using a constant value for this would have increased the error in the experimental results. Instead, the permittivity value was calibrated experimentally using different constant wire spacing prototypes.

[0052] The permittivity is measured at different wire spacing configurations of the transmission line 20, and linear lines are fit between these points to obtain permittivity across all wire spacing values. The details of the calibration process are discussed in greater detail in the paragraphs below. With the permittivity ϵ calibrated, an impedance profile curve is generated using Equations 1-3 to relate impedance to wire spacing (see Fig. 2), and use that to convert $Z(t)$ measurements to the spacing between wires, $d(t)$ along the transmission line.

[0053] The only remaining thing left is to calculate the corresponding positions, s , along the transmission line 20 for every t . This calculation is not a trivial one with a constant signal speed assumption, as the travel speed of the

signal changes with ϵ and μ , and thus changes with wire spacing. The signal travel speed in the transmission line 20, $v(t)$, is given by

$$v = \sqrt{\frac{1}{L'C'}} = \sqrt{\frac{1}{\epsilon\mu}} \quad \text{Equation (4)}$$

[0054] The values for ϵ and μ , having already been calculated, are used to calculate the signal travel speed for each section. These speeds are integrated to determine the position along the transmission line for each section as:

$$s = \int_0^t v \, dt \quad \text{Equation (5)}$$

By substituting t with s , the wire spacing $d(s)$ is obtained, as well as impedance $Z(s)$, as a function of position along the transmission line.

[0055] The method described in this section is not inherently a discrete algorithm. For numerical calculations, however, the method divides the transmission line into multiple discrete sections. The number of sections is determined by the time-resolution of the $V_r(t)$ signal, which is a function of maximum measurement frequency of the VNA and the number of points used for each measurement. Therefore, the spatial resolution of the method is only capped by the time resolution of the signal measurement device, and theoretically it can be used to sense deflections continuously.

Shape Sensing Proof-of-Concept with Planar Prototypes

[0056] In proof-of-concept study, the long flexible planar prototype transmission lines 50 shown in Figs. 3A and 3B were developed. Each transmission line 50 includes two parallel elastic rods 52 separated by a nominal gap 54. Each rod 52 is configured to carry or support one wire (not shown) of the transmission line, one for each wire, separated by a predetermined nominal gap. Ends 56 of the transmission line 50 are configured to interface with a mechanical device for supporting the transmission line and effecting the shape of the transmission line during testing, and also to electrically interface with the sensor electronics/VNA.

[0057] In one example configuration, the cross-sections of the rods 52 are rectangular with 3.0x6.8 mm (width x height) dimensions with a groove cutout for the wires at the top interior corners. 24 AWG copper wires are embedded in the grooves and secured them to the rods with thin tape. In one example configuration, the elastic rods 52 can be 3D printed from ABS, which provides the required elasticity for bending during testing. In the example configuration, for electrical connections, the wires can be soldered to coaxial SMA connectors at both ends 56 for connection to the sensor electronics/VNA and to the termination load, e.g., a 50 Ohm termination cap.

[0058] Permittivity ϵ calibrated impedance profile characteristics of the transmission line 50 as a function of wire separation is shown in Fig. 4A. In one round of prototype testing, the calibration was performed with 0.57 mm side-by-side and parallel at 1.5 mm, 3.0 mm, and 4.5 mm spacing, without deformation. To account for any assembly errors and unintentional deformations in the transmission line 50, wire spacing was measured and verified with a camera and checker board measurement setup. A photo of each planar transmission line 50 was taken with the checkerboard of known dimensions in plane with the wires. The position of each wire as a function of length was manually annotated using a graphical image annotation tool, such as Labelme, which is written in Python. These points were then converted from pixel to millimeter based on the checkerboard dimensions.

[0059] A cubic spline was implemented to smooth and interpolate continuously between the labelled points along the length of the wires. The average wire separation for each transmission line 50 was calculated and used for the calibration. The time domain measurements for S_{21} (transmitted signals across the transmission line) was obtained for all four transmission line configurations. The VNA was set to collect measurements between 400 kHz and 8 GHz range, with linear sweep using 400 kHz spacing. Using these transmitted signals, the time needed for signal to travel across each transmission line 50 with different spacing was obtained (measured at 50% magnitude rising edge). The travel time across the SMA connectors was also accounted for, which was

measured separately. Using the 200 mm length, the signal travel speed for each transmission line 50 was calculated.

[0060] By applying Equation 4, corresponding permittivities, ϵ , for the measured wire spacing values were obtained. These points were connected linearly to obtain a continuous permittivity ϵ profile, and the continuous curve that relates the impedance to wire spacing shown in Fig. 4A was generated. These curves were used to convert the TDR measured impedance values to the wire spacing along the transmission line, $d(s)$. Note that the transmission coefficient S_{21} is not inherently needed for the disclosed TDR shape sensing method. It is used only for the calibration of the permittivity ϵ profile.

[0061] After performing the calibration, the transmission line 50 was used to measure the shape of the planar prototypes in various deformed configurations. A transmission line 50 with a 1.5 mm nominal spacing between the rods 52 was selected. Spacers with different thicknesses were utilized to change the shape of the transmission line 50 at various locations along its length by altering the spacing between the rods 52 and, thus, the size of the gap 54. The different deformations are shown in Figs. 4B-D, which show the deformation of the transmission lines 50 schematically on the right side of the figures, and which show wire separation versus position on the left side of the figures.

[0062] As shown in Figs. 4B-D, the wire separation versus position sensed *via* the TDR shape sensing method described above is compared to actual values measured *via* camera and graphical analysis. This testing clearly shows that the system, method, and apparatus disclosed herein can sense displacement between the wires of the transmission lines 50 very accurately in a planar setting.

3D Shape Sensing

[0063] Fig. 6A illustrates an implementation of the system 10 in which the transmission line sensor 20 is used to sense the shape of an elongated elastic body in the form of a continuum device 40. As shown in Fig. 6A, the transmission line 20 is wrapped helically around the continuum device 40 along its length. The continuum device 40 forms a portion of a robotic system 12 in which the system

10 is implemented to detect its shape. The robotic system 12 includes the continuum device 40 and a controller 60, which includes a robot controller 62, for controlling the operation of the device. The continuum device 40 also includes a working end 42, which includes a tool 44, such as curettes, grippers, surgical lasers, graspers, retractors, scissors, imaging tips, cauterizing tips, ablation tips, morcelators, knives/scalpels, cameras, irrigation ports, suction ports, needles, probes, and tissue manipulators. The controller 60 can also control the operation of the tool 44. Additionally, the controller 60 can include a TDR controller or controller portion, that includes the sensor electronics for performing the shape sensing functions described herein.

[0064] When the continuum device 40 is deformed, *e.g.*, bent, as shown in Fig. 6A, strain occurs in the areas of the deformation/bend. The results of this strain is compression along the inside of the bend, and tension along the outside of the bend. Because the continuum device 40 is elastic, the tensioned portions of the continuum device cause an increase separation of the wires, and the compressed portions cause a decrease in separation, with the resulting changes in impedance as shown. The transmission line 20 thus acts as a strain sensor, sensing these separations as strain in the continuum device 40. In sensing the shape of the continuum device 40, the system, method, and apparatus essentially equates sensed strains in the device to the resulting shape of the device and/or the forces acting on the device to effectuate the change in shape.

[0065] By sensing the wire spacing as described above *via* TDR while taking into account the helical arrangement of the transmission line 20, the shape of the helical coil, and thus the continuum device 40, as well as the forces acting on the continuum device, can be determined. This is best understood with reference to Fig. 6A, in which d represents the diameter of the elastic member 40, p represents the pitch of the helically wound wires 24, 26, and θ represents the pitch angle of the helically wound wires. Fig. 6B shows the calculation of the pitch angle θ , along with wire spacing s_w and column c parameters.

[0066] Referring to Figs. 5A and 5B, a spring-like helical transmission line 70 was developed with double, helically coiled rods 72 with 1.5 mm nominal separation. The helical parameters of the transmission line 70 are diameter (d_c) = 100 mm, and pitch (p) = 40 mm. The cross-sectional dimensions for each rod and the print material was kept the same as the planar transmission lines discussed above in order to keep the permittivity ϵ characteristics the same. Calibration of the transmission line 70 therefore corresponds to that described above in regard to the planar transmission line 50. A base plate 74 and a top plate 76 are secured at opposite ends of the rods 72 and allow for the fixture of the helical transmission line 70 so that it can be deformed along the central axis into a complex 3D shape.

[0067] To calculate a TDR shape for the transmission line 70, time domain S_{11} signals were obtained for use according to the shape sensing method. At the same time, laser scanning was used to obtain actual measurements of the transmission line 70 for comparison and verification purposes. The laser scanning can, for example, be performed using a Faro Quantum^s FaroArm & ScanArm, from FARO Technologies, Inc, USA. The spacing between the rods 72, and thus the wire pairs, was calculated using TDR as described above with reference to the planar transmission line 50. The spacing between the wires 72 is a one dimensional measurement fundamentally, so the measurement and TDR methods do not change. Because, however, the transmission line 70 is helical, the TDR measurements need to be combined with a mechanics model for the helix in order to obtain the complete 3D shape of the transmission line. To do this, Cosserat rod modeling for continuum robots was utilized according to known methods to model the deflection behavior of the double helix prototype. See, for example, Rucker, E. C., Jones B. A., & Webster R. J., A Geometrically Exact Model for Externally Loaded Concentric-Tube Continuum Robots, *IEEE Transactions on Robotics*, volume 26 (5), 769-780 (2010).

[0068] The modeling of the helical transmission line 70 treats each helical rod as an individual inextensible and shearless flexible rod with a helical pre-curvature. The transmission line 70 is thus evaluated as a double helix. To

calculate the bending stiffness of the rods, experimentally determined values were developed according to known methods, such as those disclosed in Zou, R. et al., *Isotropic and Anisotropic Elasticity and Yielding of 3D printed material, Composites Part B: Engineering*, volume 99, pages 506-513, 2016).

[0069] The helical rods 72 are joined together at their ends with the base plate 74 and top plate 76. By taking into account the pose of the base plate 74 and the top plate 76 constraints, the deformed 3D shape of the overall body of the helical coil transmission line 70 can be calculated in various configurations. It is assumed that the rods 72 do not touch each other and, thus, interactions between the helical rods along their arc length are not taken into account. An additional function calculates the spacing c between the columns as a function of position along the helix for any configuration based on the Cosserat rod model.

[0070] This function is used to fit the mechanics model based spacing to the spacing data obtained via the TDR shape sensing method by iterating the top plate position/orientation while keeping the base plate position/orientation fixed. The data fitting can be performed by known methods, for example, using commercial applications, such as the `fsolve` function in Matlab, a software application, which is widely-known and available commercially from Mathworks, Inc. This transforms the TDR calculated wire spacing data into 3D shape sensing information for the whole prototype. To obtain the ground truth 3D shape data, the edge of the columns are manually segmented from the laser scanned point clouds.

[0071] The results of this testing is shown in Figs. 7A-7C. Fig. 7A depicts the laser-scanned (actual) shape of the helical transmission line 70, supported by the lower and upper plates 74, 76 through a fixture 80. As shown in Fig. 7B, the wire separation along the lengths of the wires 72 in both the TDR sensing and the fitted 3D model correspond substantially. The sensed shape resulting from the fitted 3D model is shown in Fig. 7C, which shows that the system, method, and apparatus can successfully sense the shape of a complex 3D elongated elastic body in various stretching and bending configurations. More specifically, the

system, method, and apparatus can successfully sense the shape of a continuum device in various stretching and bending configurations.

Force Sensing

[0072] The force and moment action on a continuum device and deflection of the continuum device are coupled problems, the system, method, and apparatus disclosed herein can also be used as a distributed load sensor. Using the system with calibrated stiffness values for the continuum device and sensor material, deflection measured *via* the TDR sensing methodology can be used to determine the external loads on the continuum device in a localized manner.

[0073] In this force sensing implementation, the mechanics model is used in conjunction with the TDR sensor to perform deflection-based force sensing. Given the stiffness values for the system, *i.e.*, the continuum device and the sensor that is affixed thereto, the model correlates external multidimensional forces acting on the device to the resulting multidimensional shape of the device. Accordingly, when multidimensional deflections are sensed *via* the TDR sensing methods implemented by the system and apparatus, the multidimensional force(s) acting on the continuum device can be estimated *via* the mechanics model.

[0074] Shape sensing and force sensing of the elastic body are coupled problems, linked by the stiffness of the elastic body. The shape modeling and force modeling, in effect, model the stiffness of the elastic body. Because the modeling effectively employs a stiffness model, both the shape of the elastic body and the forces acting on the elastic body can be determined at the same time. Thus, the system, method, and apparatus disclosed herein can have shape sensing implementations, force sensing implementations, or both shape and force sensing implementations.

[0075] From the above description of the invention, those skilled in the art will perceive improvements, changes and modifications. For example, although the system, method, and apparatus is disclosed herein in some examples as being used in conjunction with a continuum device in the form of a concentric tube

robot, the system, method, and apparatus can be implemented with other continuum and similar devices, such as flexible/actuatable endoscope-like tubes and other robotic devices/systems. Such improvements, changes and modifications within the skill of the art are intended to be covered by the appended claims.

Claims

1. A system for sensing the shape of an elastic body and/or forces acting on an elastic body, comprising:

a transmission line configured to be secured to the elastic body along its length, the transmission line comprising a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body, wherein the transmission line is configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body; and

sensor electronics operatively connected to the transmission line, wherein the sensor electronics are configured to:

perform a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line; and

combine the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

2. The sensing system recited in claim 1, wherein the mechanics model correlates the shape of the transmission line with the detected displacements, and the shape of the elastic body is determined as corresponding with the shape of the transmission line determined by the mechanics model in response to the detected displacements.

3. The sensing system recited in claim 1, wherein the mechanics model correlates strains on the elastic body and the transmission line as a whole with the detected displacements, and the external forces acting on the elastic body and transmission line as a whole are determined as corresponding with the strains and stiffness model for the elastic body.

4. The sensing system recited in claim 1, wherein the displacements of the conductive elements from the nominal spacing are correlated with strains along the length of the elastic body.

5. The sensing system recited in claim 4, wherein the mechanics model correlates the strains along the length of the elastic body with the shape of the elastic body.

6. The sensing system recited in claim 4, wherein the mechanics model correlates the strains along the length of the elastic body with external forces acting on the elastic body.

7. The sensing system recited in claim 1, wherein to perform the TDR function, the sensor electronics are configured to:

transmit a pulsed signal in the transmission line;

monitor the transmission line for a reflected signal in response to the pulsed signal;

detect *via* the reflected signal the displacements of the conductive elements from the nominal spacing; and

determine, *via* a signal travel speed function, a location along the length of the transmission line where the change in spacing occurred.

8. The sensing system recited in claim 7, wherein detecting a change in the displacements of the conductive elements from the nominal spacing comprises detecting a change in impedance of the transmission line.

9. The sensing system recited in claim 7, wherein detecting a change in the displacements of the conductive elements from the nominal spacing *via* the reflected signal comprises collecting reflection scattering coefficients in the frequency domain and converting the collected scattering coefficients into an equivalent time domain response.

10. The sensing system recited in claim 7, wherein determining the location where the change in spacing occurred comprises integrating the signal travel speed function.

11. The sensing system recited in claim 1, wherein the mechanics model comprises a Cosserat rod model configured to combine the detected displacements of the conductive elements from the nominal spacing with a mechanics model for the predetermined shape of the transmission line to determine the shape of the elastic body.

12. The sensing system recited in claim 1, wherein the elastic body has an elongated cylindrical configuration, and wherein the transmission line is configured as a helix that extends along the cylindrical elastic body.

13. The sensing system recited in claim 12, wherein the mechanics model comprises a mechanics model for the transmission line helix.

14. The sensing system recited in claim 12, wherein the cylindrical elastic body comprises a continuum device.

15. A continuum robot system comprising:
an actuatable continuum device;
a robot controller configured to robotically actuate the continuum device;
a transmission line secured to the continuum device along its length, the transmission line comprising a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body, wherein the transmission line is configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body; and

sensor electronics configured to perform time domain reflectometry (TDR) operatively connected to the transmission line, wherein the sensor electronics are configured to:

perform a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line; and

combine the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

16. A sensor for sensing strain along the length of a flexible elongated element, the strain sensor comprising:

a transmission line configured to be secured to the elastic body along its length, the transmission line comprising a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body, wherein the transmission line is configured to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body, wherein the sensor is configured to sense the strain *via* time domain reflectometry, which detects one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line.

17. A method for sensing the shape of an elastic body and/or forces exerted on an elastic body, comprising:

securing a transmission line to the elastic body along its length, the transmission line comprising a pair of conductive elements that are spaced nominally from each and extending along the length of the elastic body;

arranging the transmission line is to have a predetermined shape when secured to the elastic body so that the nominal spacing of the conductive elements changes in response to deformation of the elastic body;

performing a time domain reflectometry (TDR) function to detect one or more displacements of the conductive elements from the nominal spacing along the length of the transmission line; and

combining the detected displacements with a mechanics model to determine at least one of a shape of the elastic body and external forces acting on the elastic body.

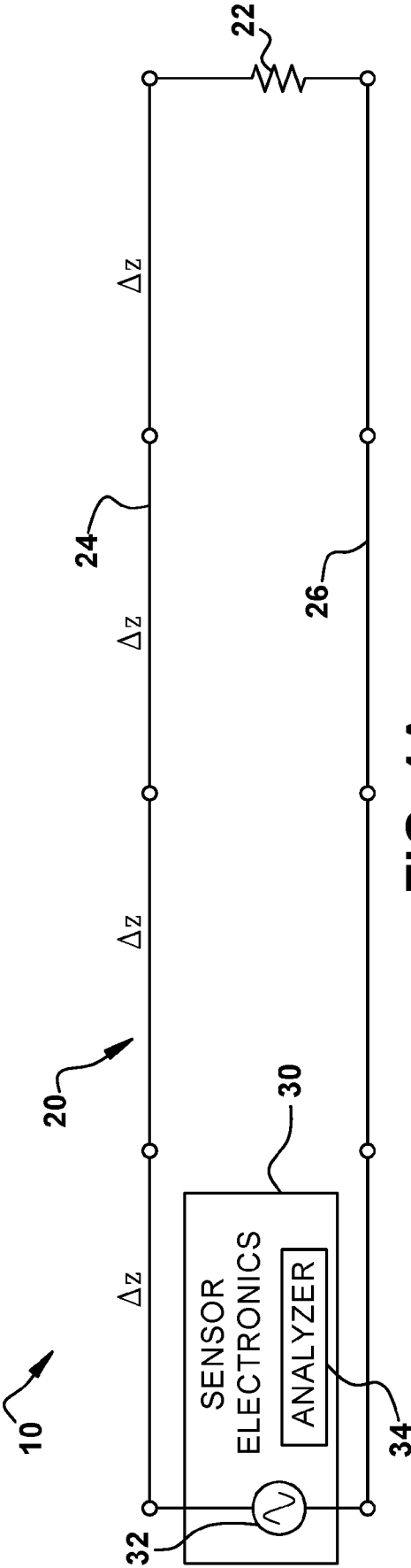


FIG. 1A

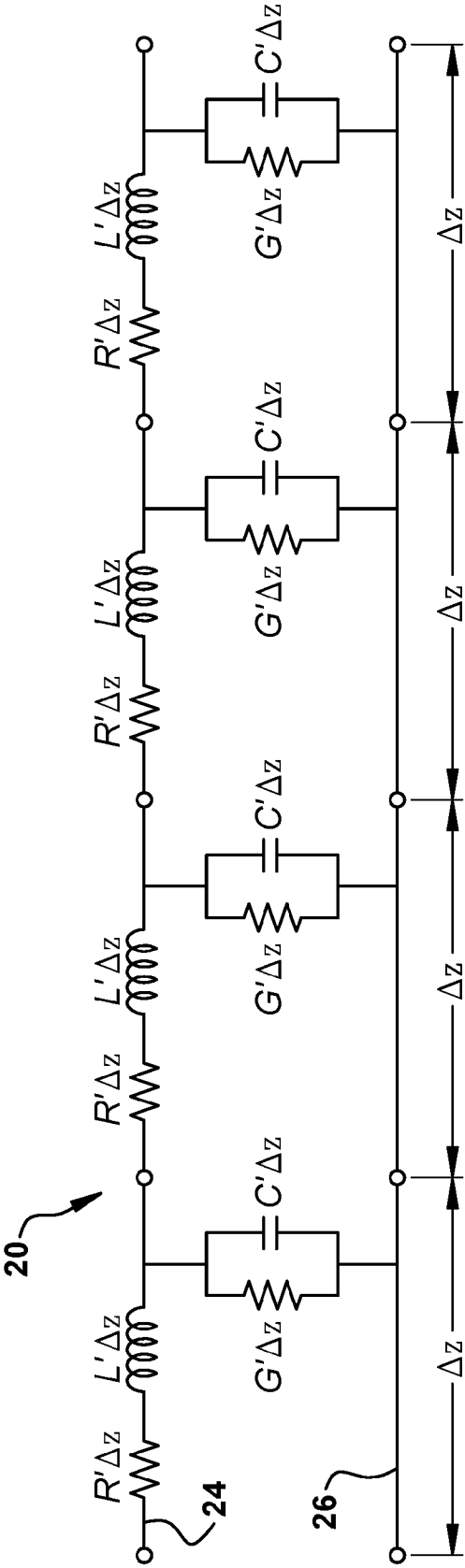


FIG. 1B

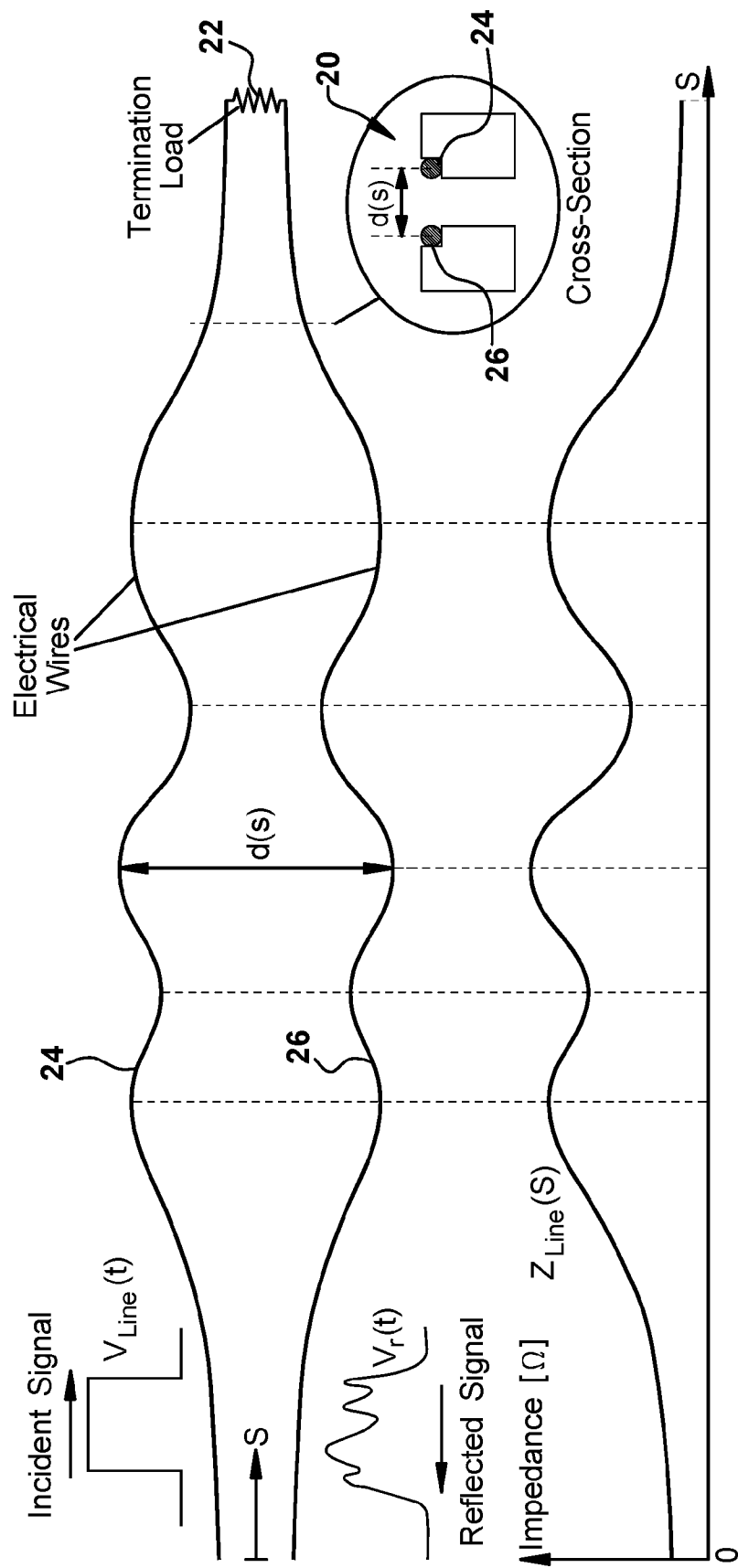


FIG. 2

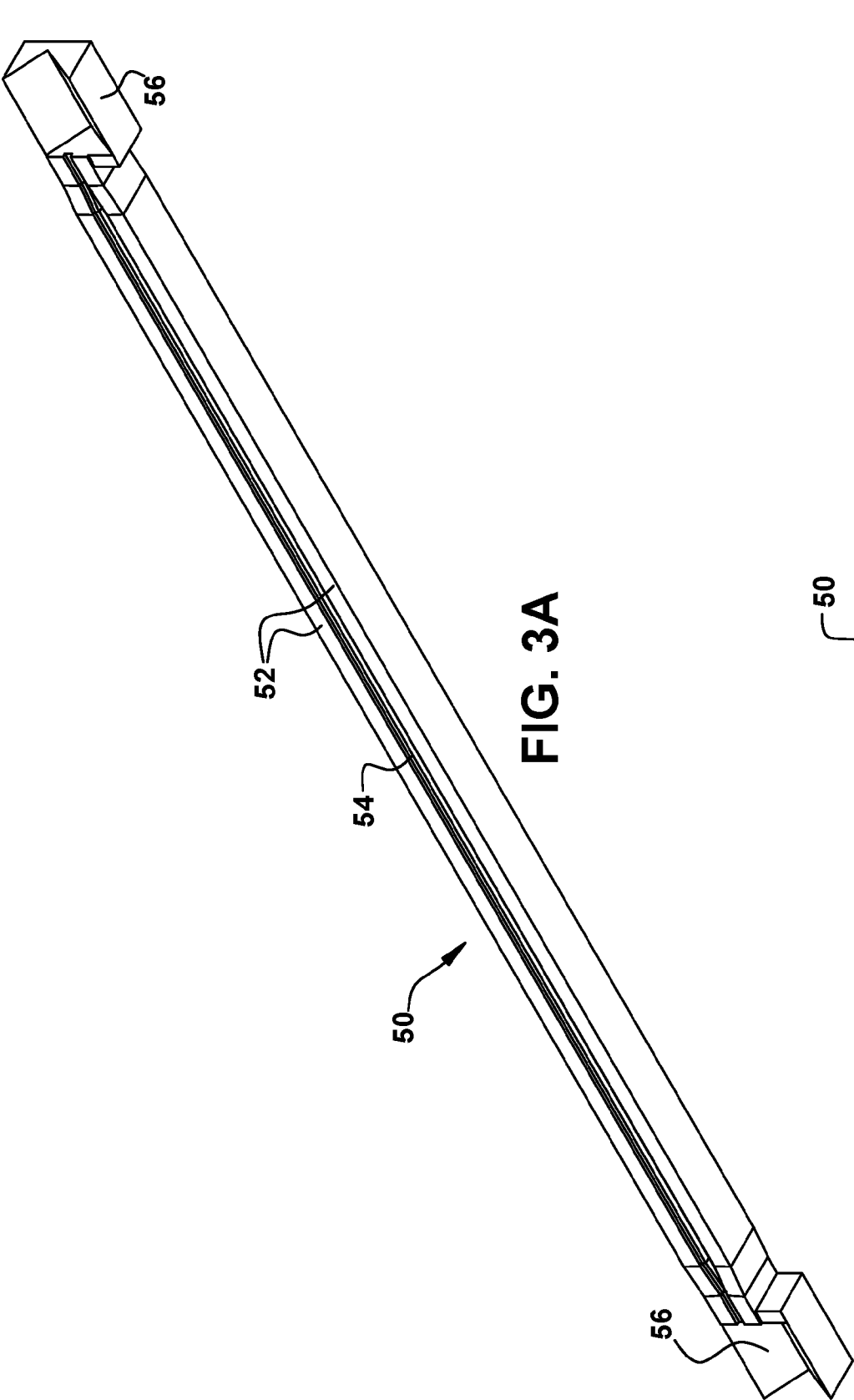


FIG. 3A

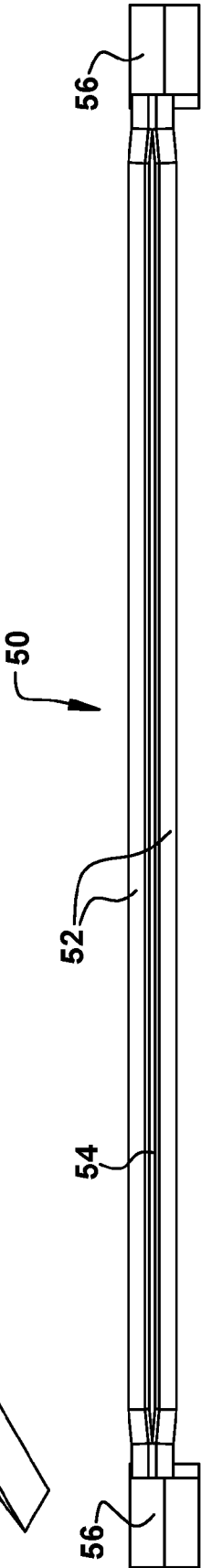


FIG. 3B

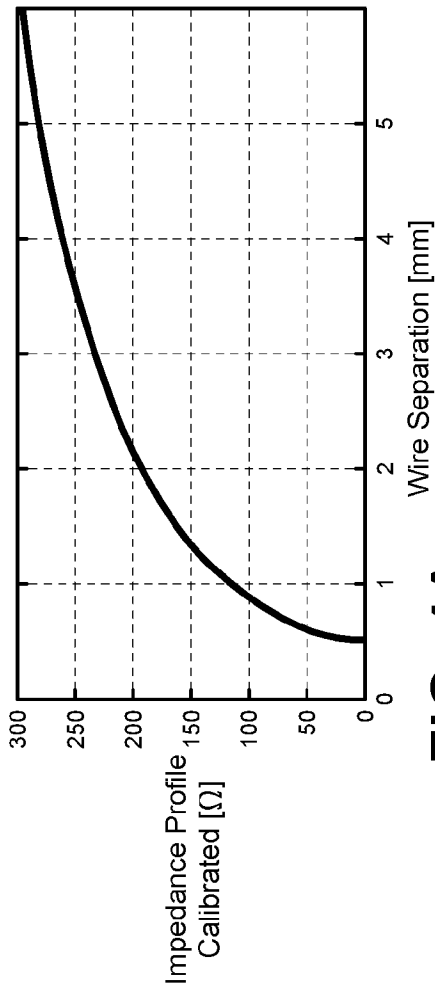


FIG. 4A

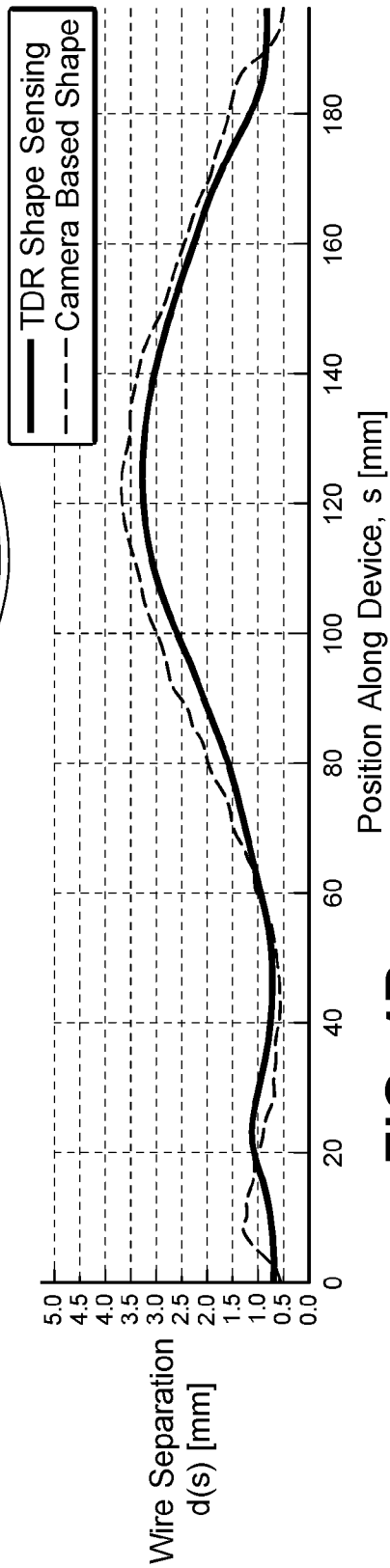
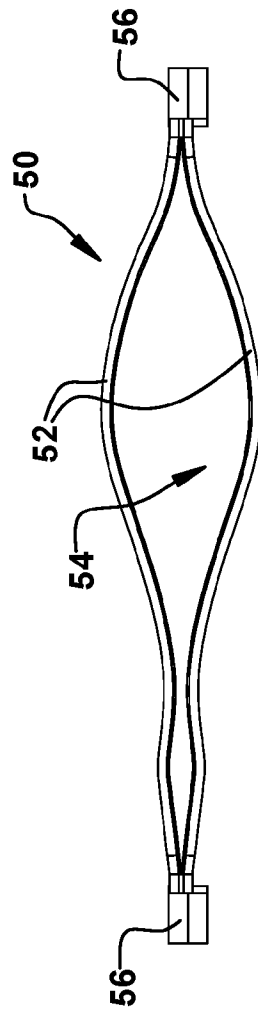


FIG. 4B

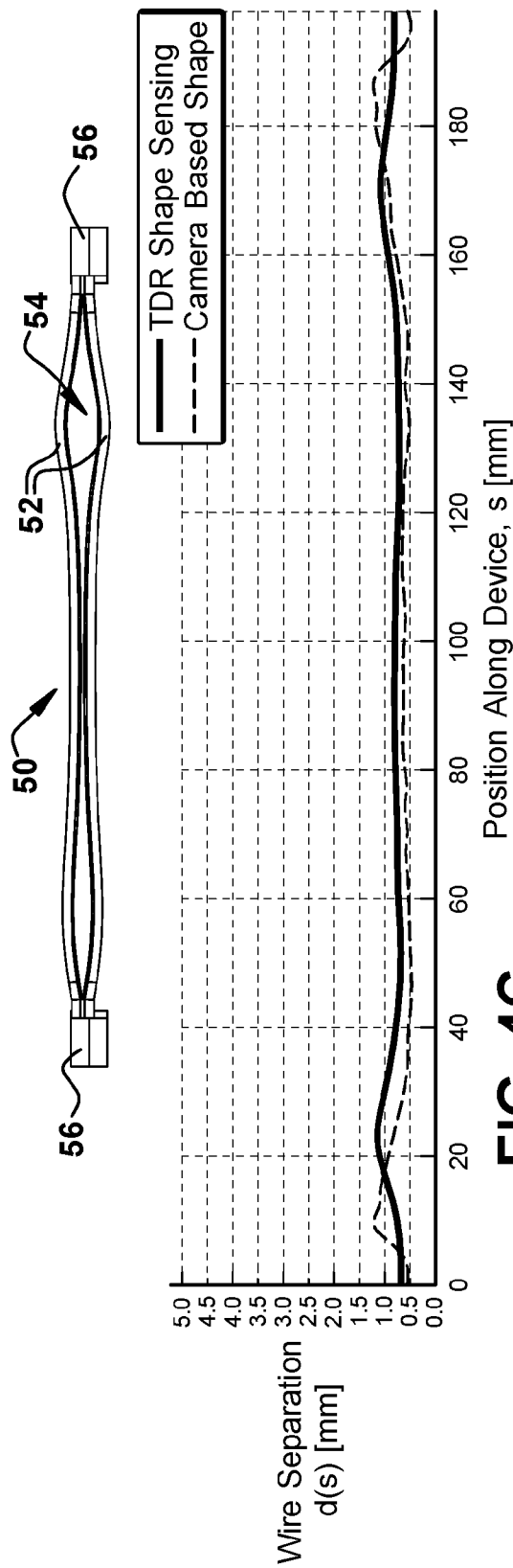


FIG. 4C

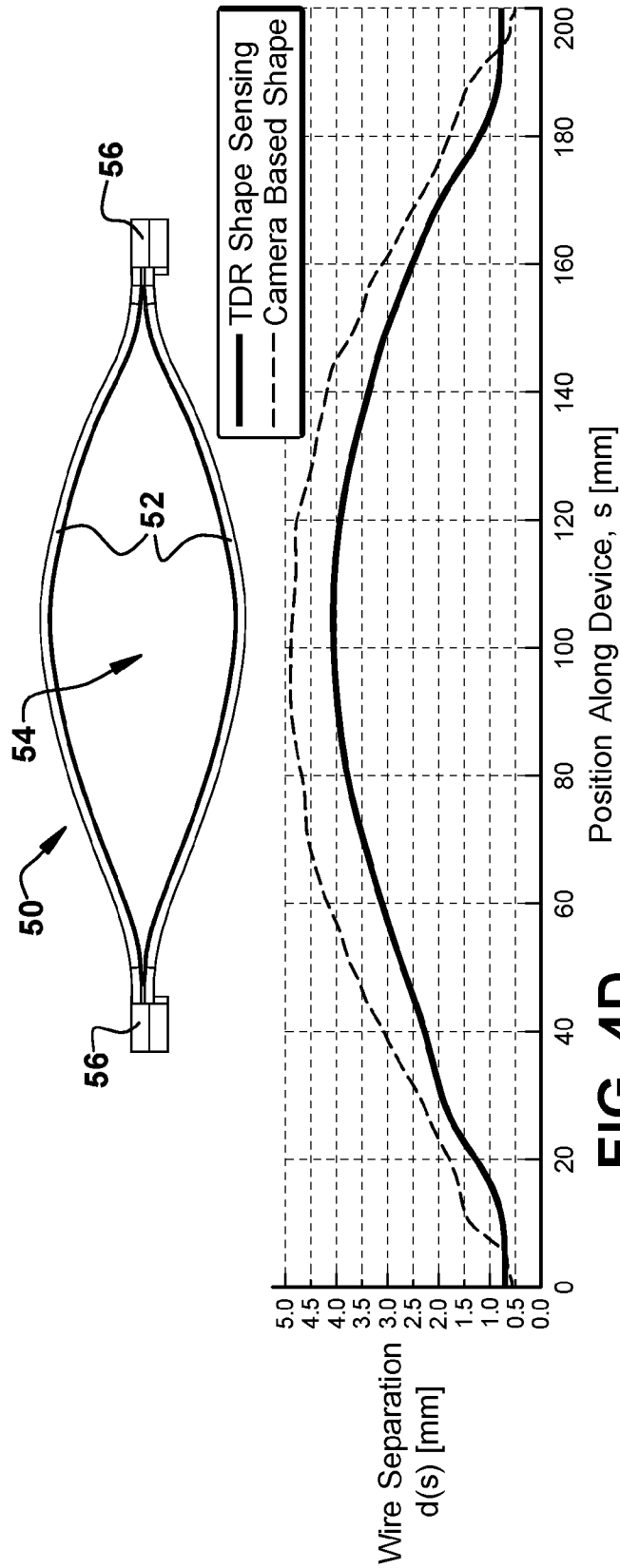


FIG. 4D

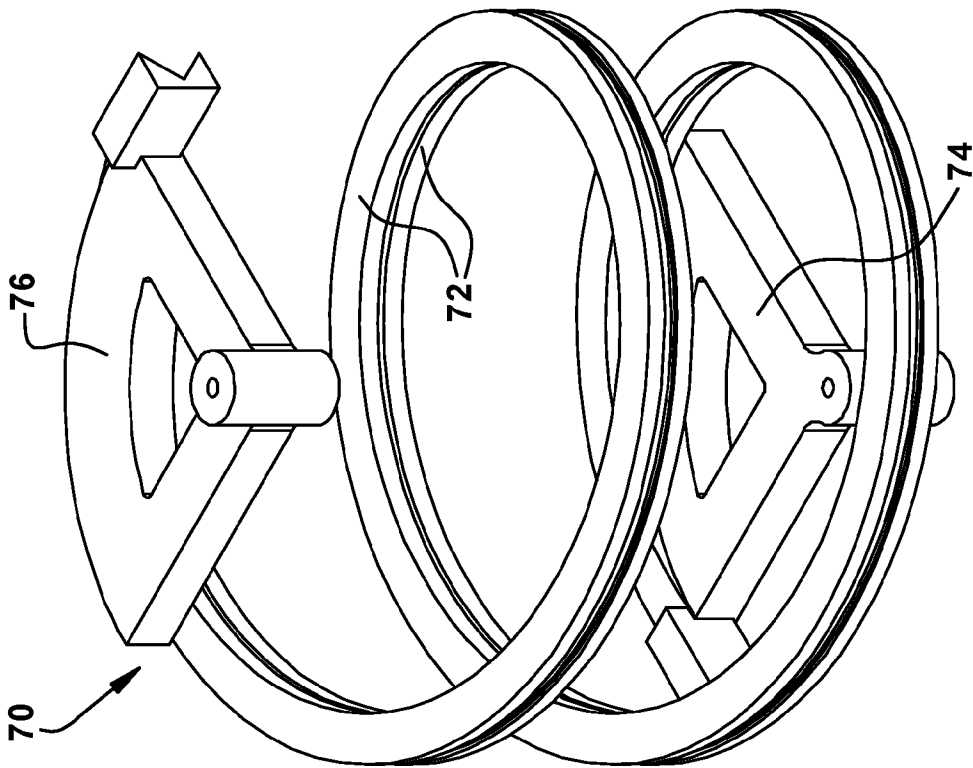


FIG. 5A

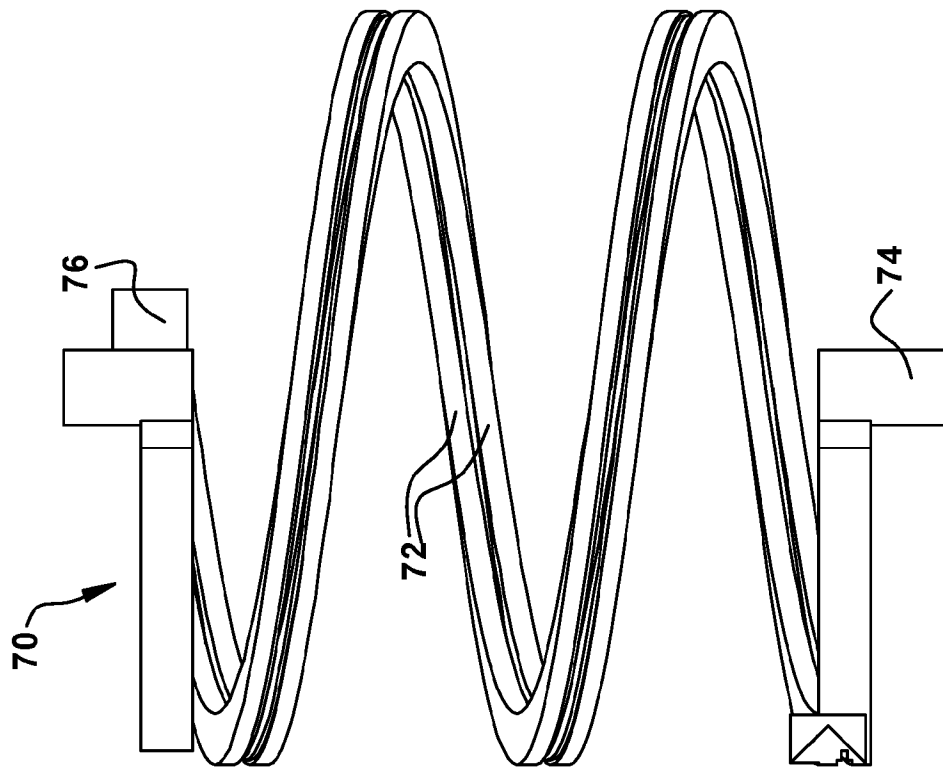


FIG. 5B

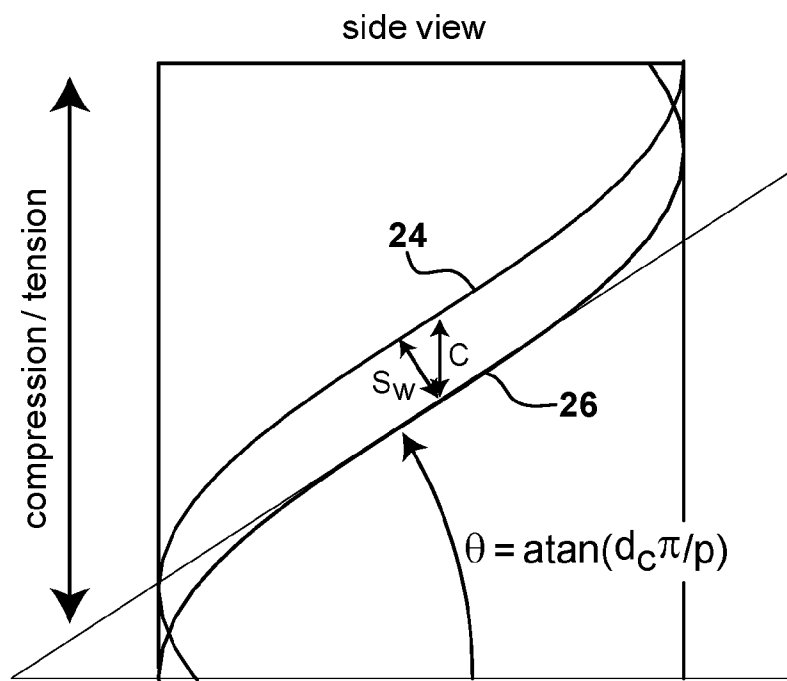
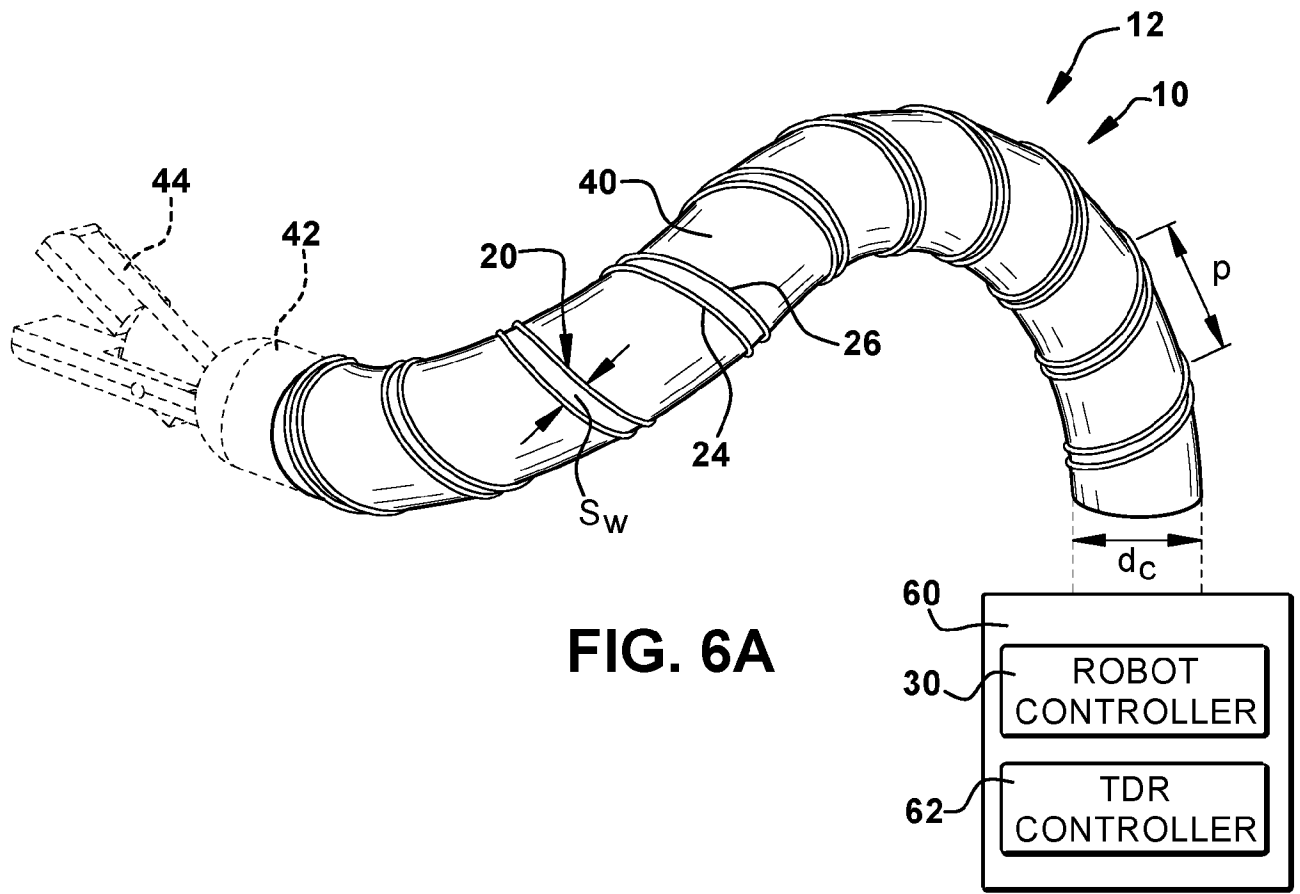


FIG. 6B

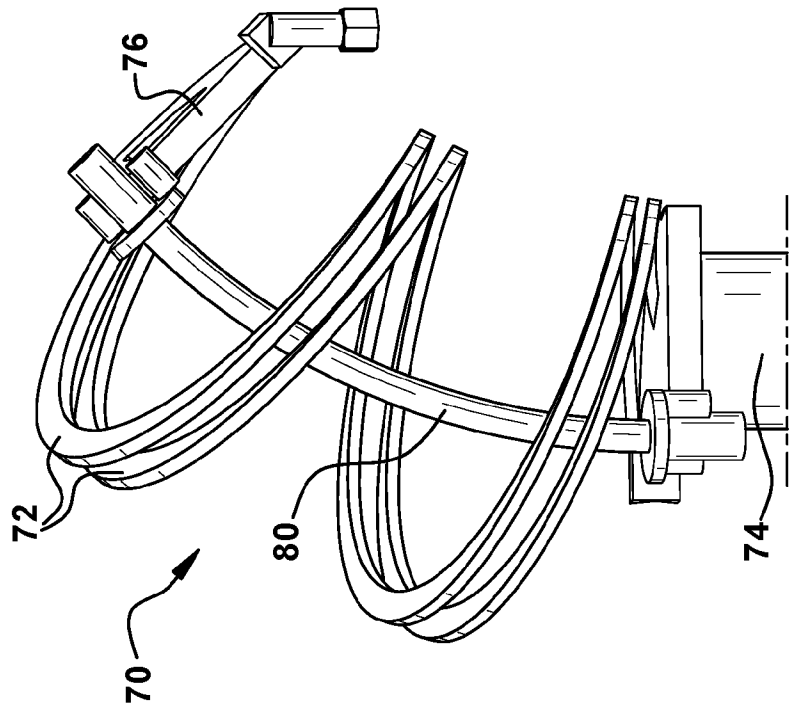


FIG. 7A

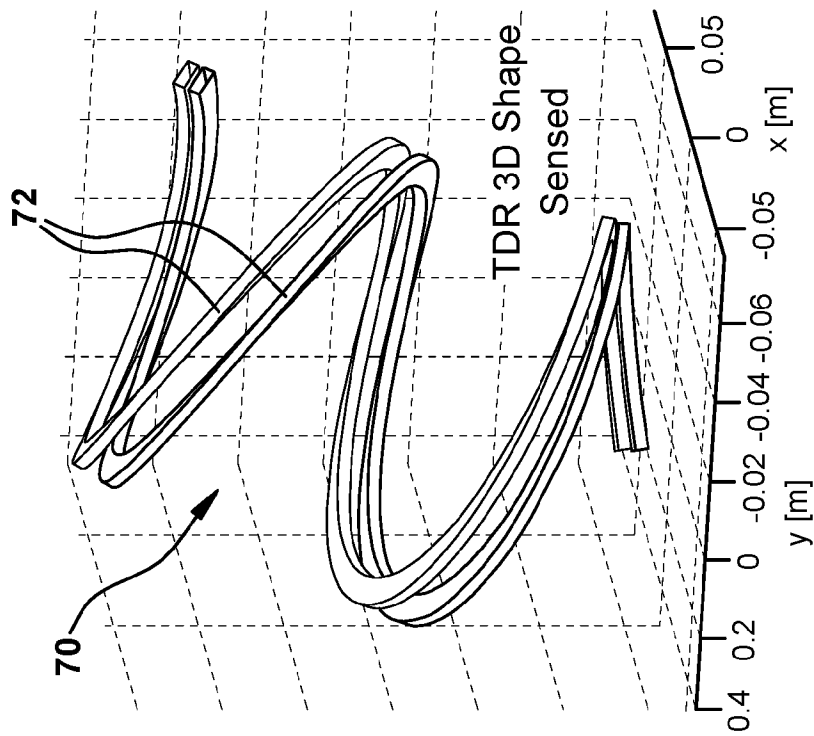


FIG. 7B

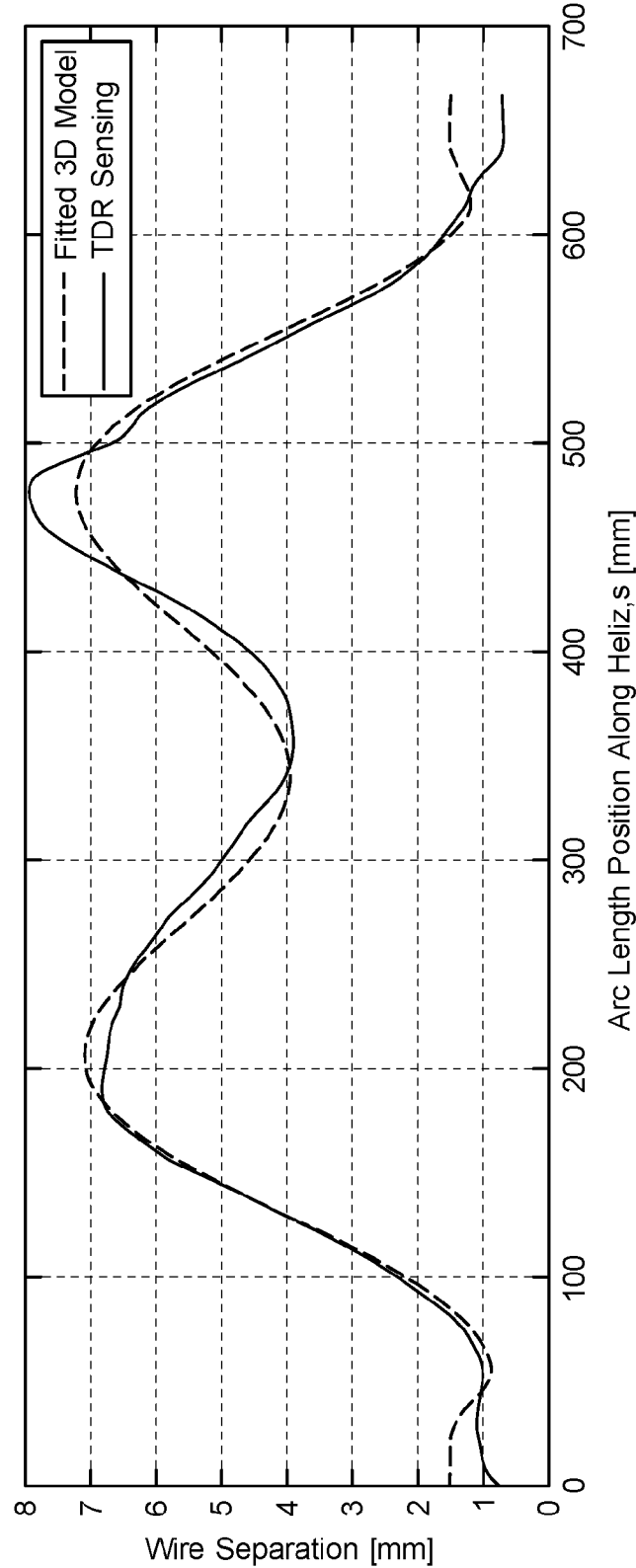


FIG. 7C

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2023/015547

A. CLASSIFICATION OF SUBJECT MATTER INV. G01M5/00 G01L1/14 A61B34/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G01M G01L A61B G01N		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SCHEUERMANN A ET AL: "On the Feasibility of Pressure Profile Measurements With Time-Domain Reflectometry", IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, IEEE, USA, vol. 58, no. 2, 1 February 2009 (2009-02-01), pages 467-474, XP011233090, ISSN: 0018-9456, DOI: 10.1109/TIM.2008.928876	1-14,16, 17
Y	abstract figures 1-4,9,10-13 I. INTRODUCTION II. STEP RESPONSE CALCULATION III. RECONSTRUCTION ALGORITHM V. PROTOTYPE DEVELOPMENT V. CONCLUSION ----- -/-	15
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 28 July 2023		Date of mailing of the international search report 07/08/2023
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Mouanda, Thierry

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2023/015547

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2011/059889 A1 (INTUITIVE SURGICAL OPERATIONS [US]) 19 May 2011 (2011-05-19) abstract figures 1-3 paragraphs [0003], [0038] - [0073] -----	15
A	MA CEYI ET AL: "Crosstalk Prediction of Cables Based on Cosserat Elastic Rod Theory", 2019 28TH WIRELESS AND OPTICAL COMMUNICATIONS CONFERENCE (WOCC), IEEE, 9 May 2019 (2019-05-09), pages 1-4, XP033581446, DOI: 10.1109/WOCC.2019.8770610 [retrieved on 2019-07-23] abstract figure 1 table 1 I. INTRODUCTION II. COSSERAT ELASTIC ROAD MODEL -----	11
A	RENYUAN TONG ET AL: "Design of elastic helical Time Domain Reflectometry cable for distributed tensile deformation monitoring", ARTIFICIAL INTELLIGENCE, MANAGEMENT SCIENCE AND ELECTRONIC COMMERCE (AIMSEC), 2011 2ND INTERNATIONAL CONFERENCE ON, IEEE, 8 August 2011 (2011-08-08), pages 3887-3890, XP031962772, DOI: 10.1109/AIMSEC.2011.6009868 ISBN: 978-1-4577-0535-9 abstract figures 2, 4, 5, 6, 8, 10, 11 II. ELASTIC HELICAL TDR CABLE III. TDR TEST IV. CONCLUSIONS -----	1, 12-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2023/015547

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2011059889 A1	19-05-2011	US 2011118749 A1	19-05-2011
		WO 2011059889 A1	19-05-2011
