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Parsai et al.

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(54) **DUAL-BRANCHED SHAPE MEMORY ALLOY ORGAN POSITIONER TO PREVENT DAMAGE TO HEALTHY TISSUE DURING RADIATION ONCOLOGY TREATMENTS**

(71) Applicant: **The University of Toledo**, Toledo, OH (US)

(72) Inventors: **E. Ishmael Parsai**, Toledo, OH (US);
Mohammad Elahinia, Toledo, OH (US)

(73) Assignee: **The University of Toledo**, Toledo, OH (US)

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(21) Appl. No.: **16/049,031**

(22) Filed: **Jul. 30, 2018**

Related U.S. Application Data

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(60) Provisional application No. 62/353,347, filed on Jun. 22, 2016.

(51) **Int. Cl.**
A61N 5/01 (2006.01)
A61N 5/10 (2006.01)
A61M 25/10 (2013.01)
A61B 17/00 (2006.01)

(52) **U.S. Cl.**
CPC *A61N 5/1014* (2013.01); *A61M 25/1002* (2013.01); *A61B 2017/00022* (2013.01); *A61N 2005/1094* (2013.01)

(58) **Field of Classification Search**
CPC A61M 29/02; A61M 25/04; A61M 25/10; A61M 2210/1085; A61M 25/0017; A61M 2202/0496; A61M 2205/0266; A61M 25/0074; A61M 25/0155; A61M 25/1011; A61M 27/008; A61M 2025/0213; A61M 2205/50; A61M 25/0026; A61M 2025/105; A61M 25/1018; A61M 25/10181; A61M 25/10184; A61M 25/1036; A61M 25/1038
See application file for complete search history.

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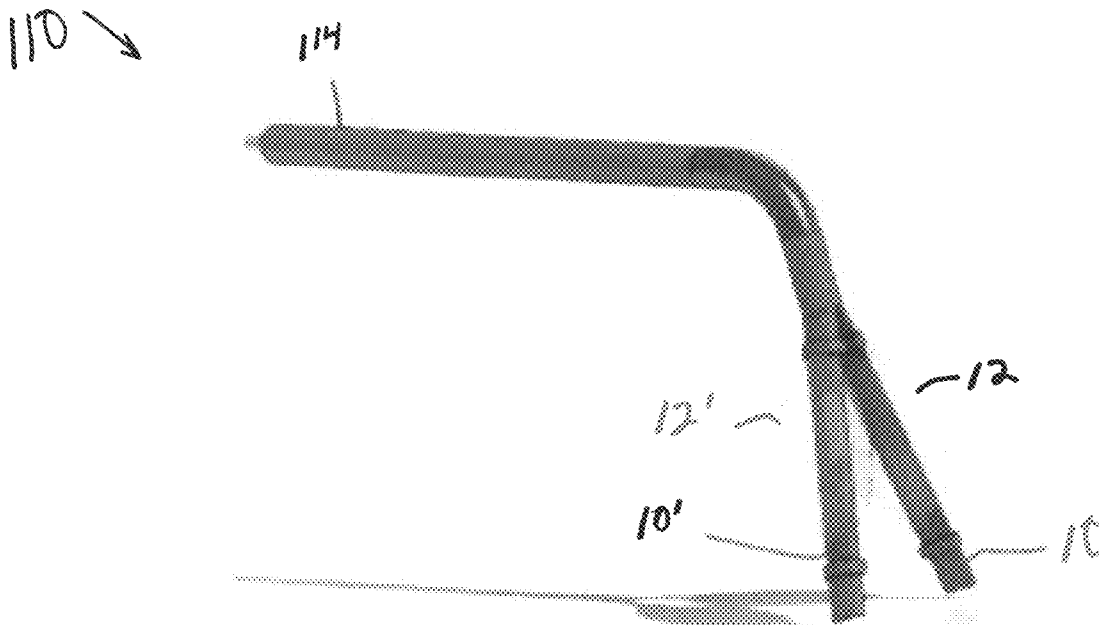
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Primary Examiner — Christine H Matthews
Assistant Examiner — Joshua Daryl D Lannu
(74) *Attorney, Agent, or Firm* — MacMillan, Sobanski & Todd, LLC

(57) **ABSTRACT**

Devices, systems, and methods for repositioning organs, such as the rectum, during radiation therapy treatments, are described.

10 Claims, 23 Drawing Sheets
(17 of 23 Drawing Sheet(s) Filed in Color)



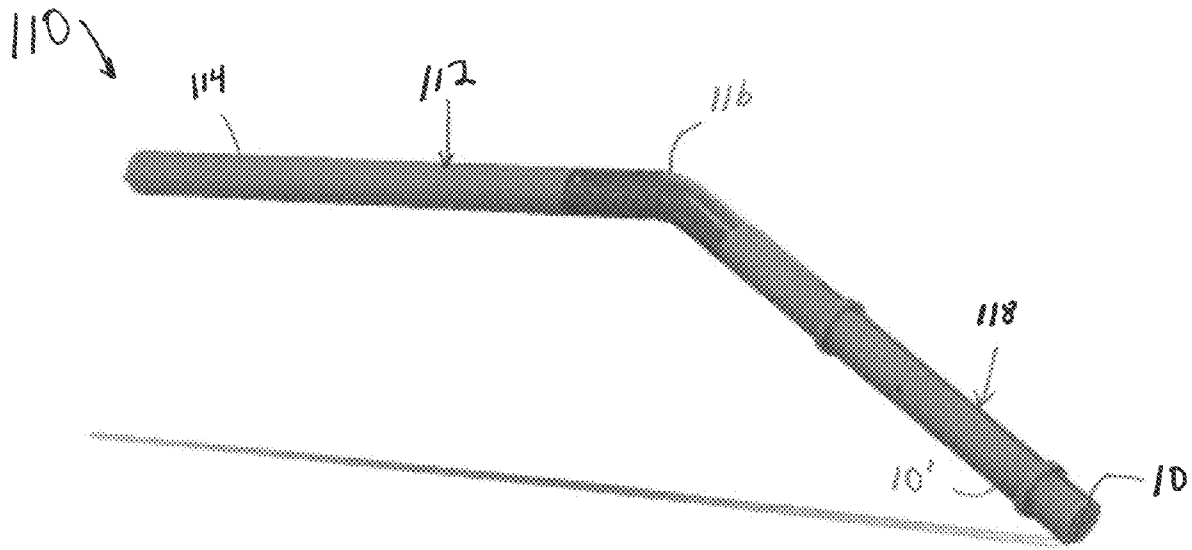


FIG. 1A

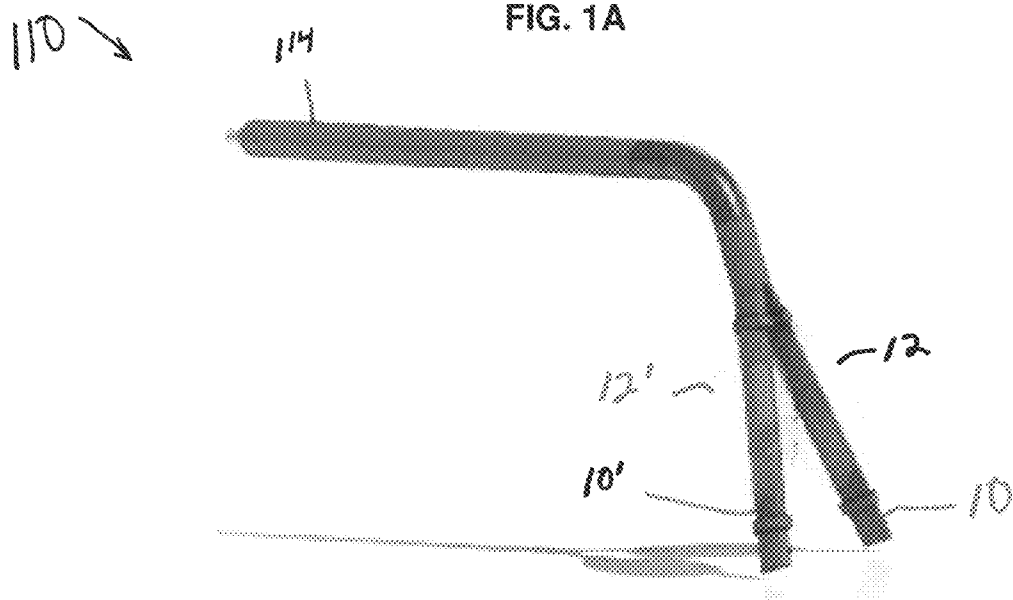


FIG. 1B

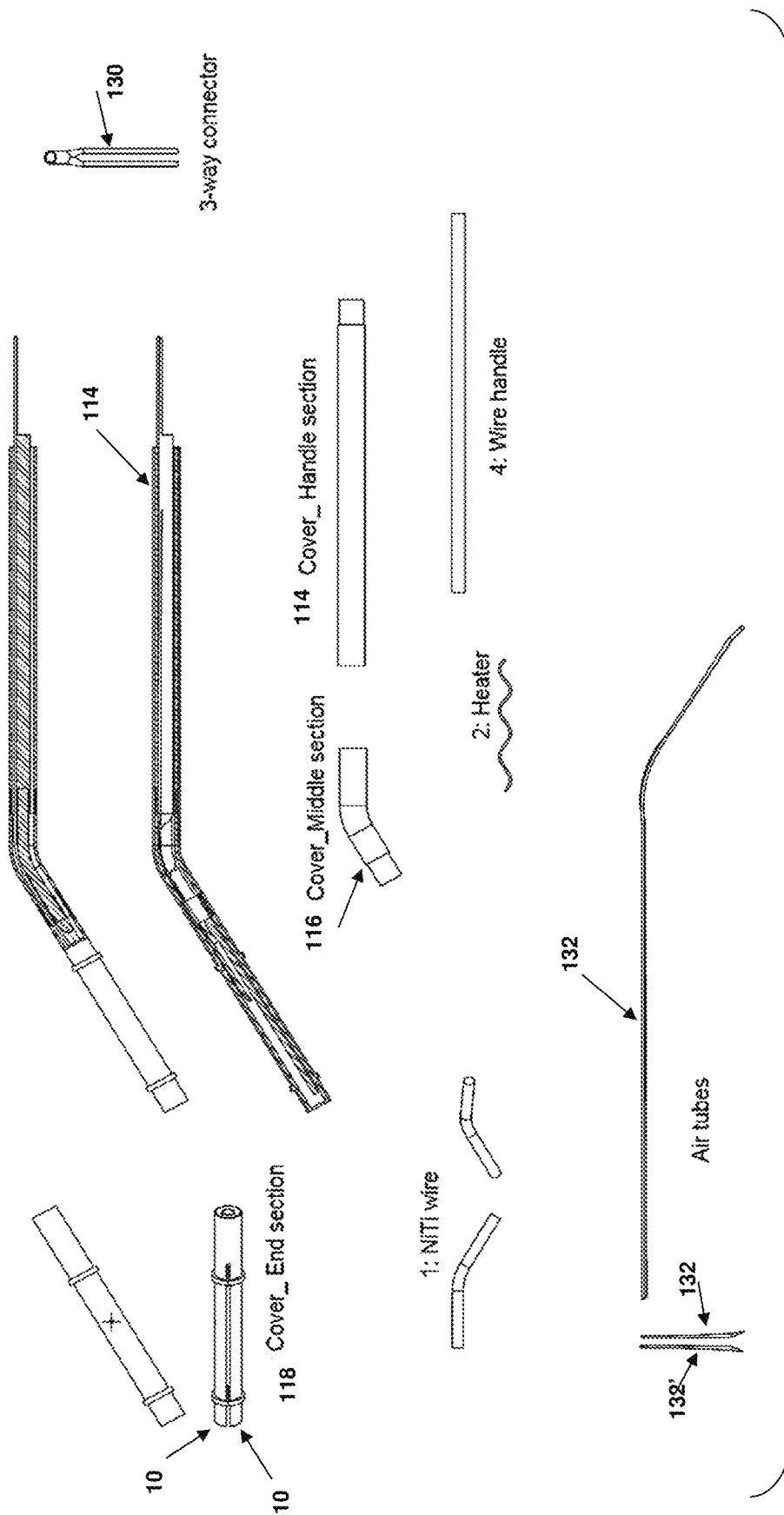


FIG. 1C

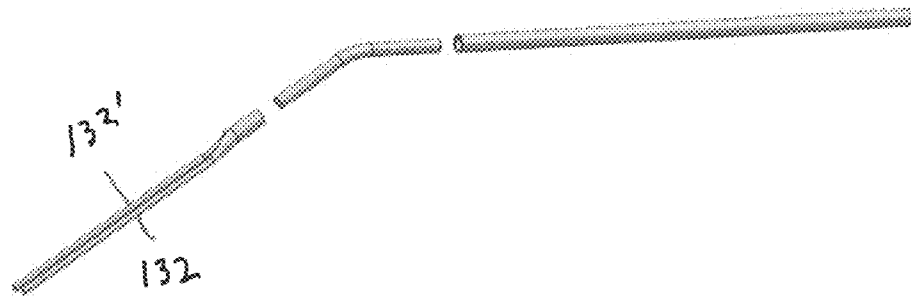


FIG. 1D

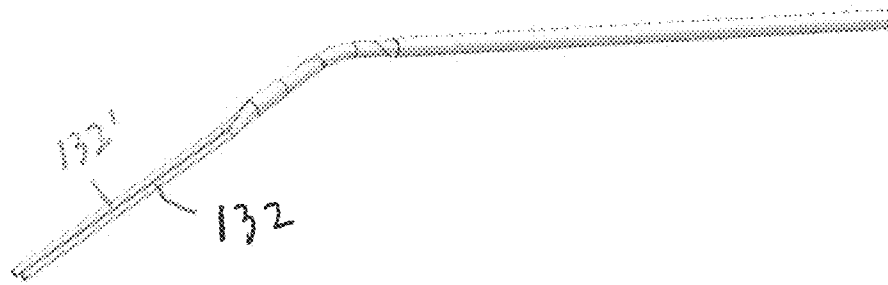


FIG. 1E

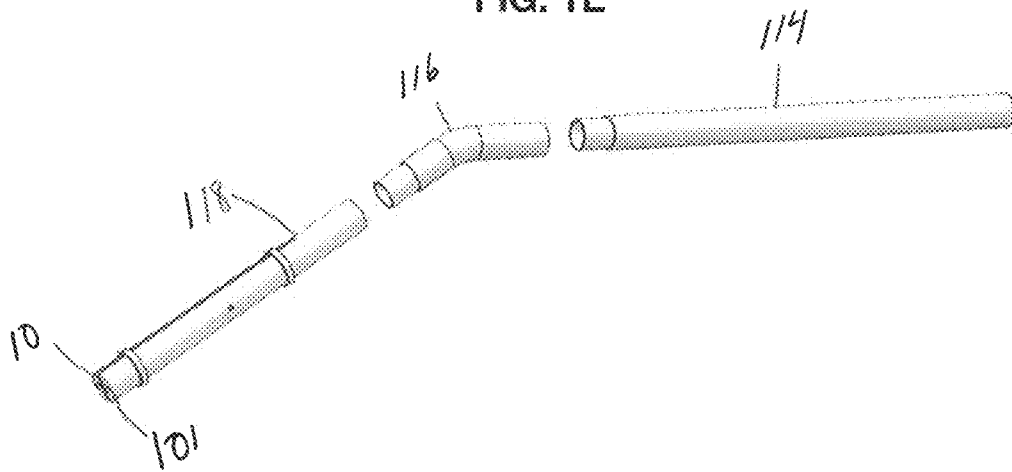


FIG. 1F

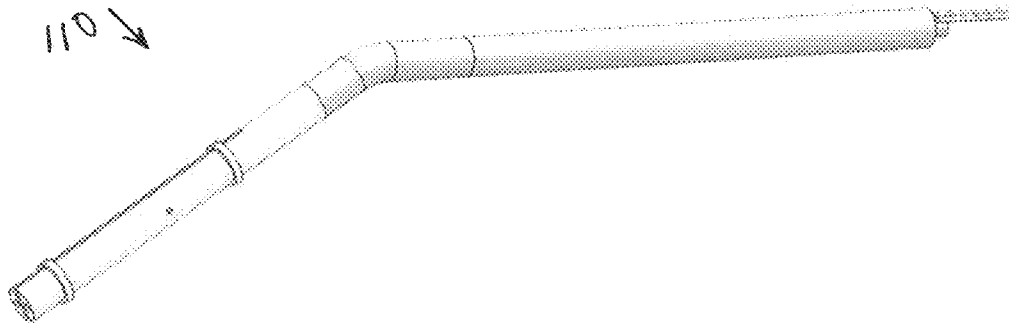


FIG. 1G

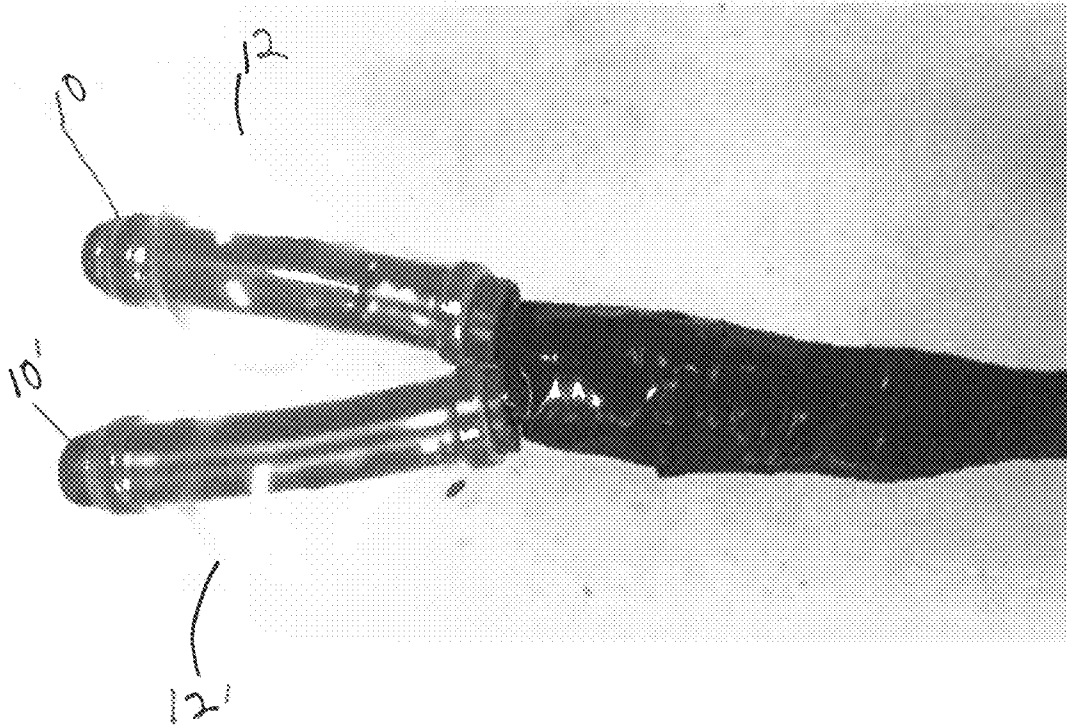


FIG. 1H

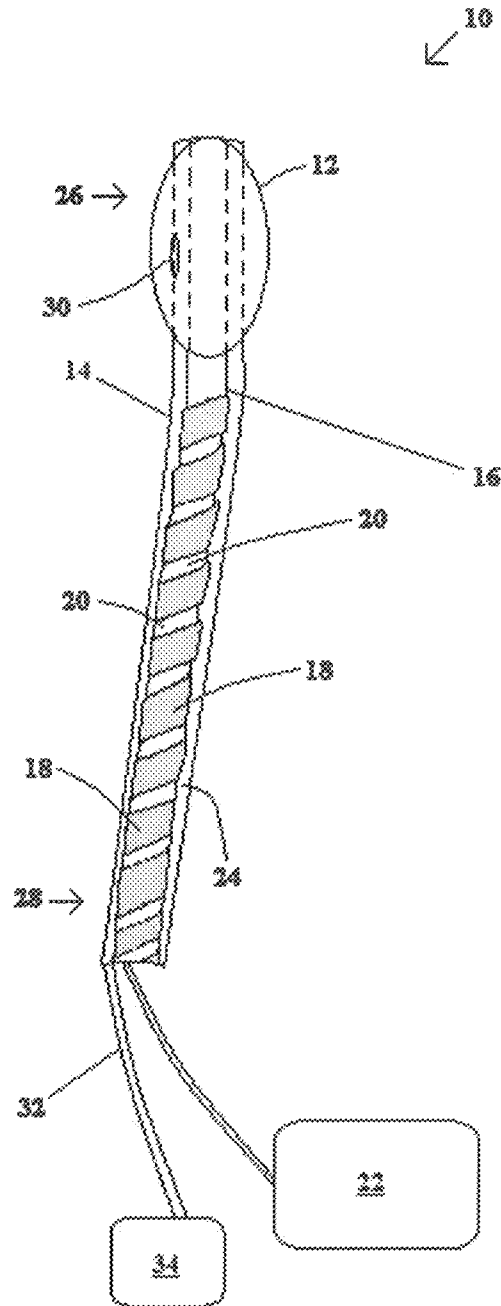


FIG. 11

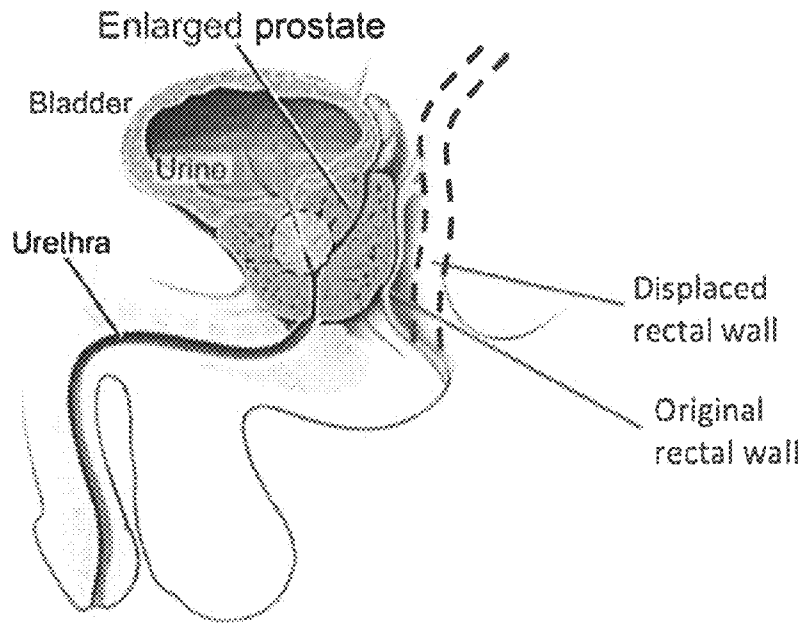


FIG. 1J

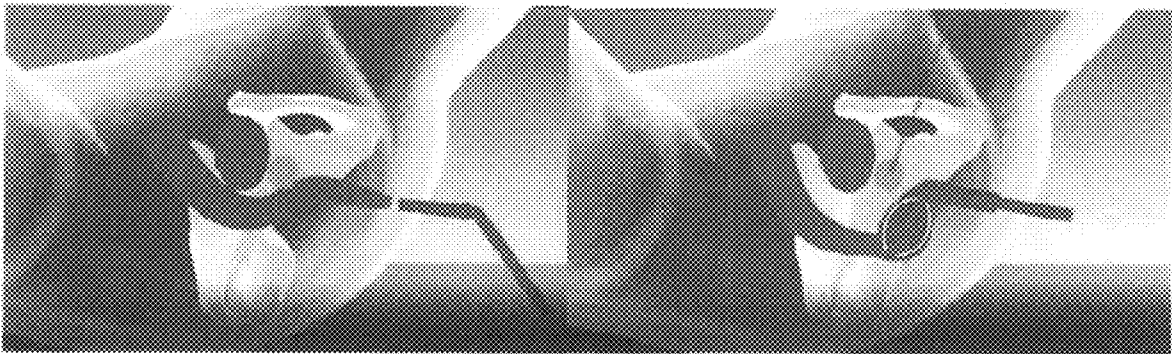


FIG. 1K

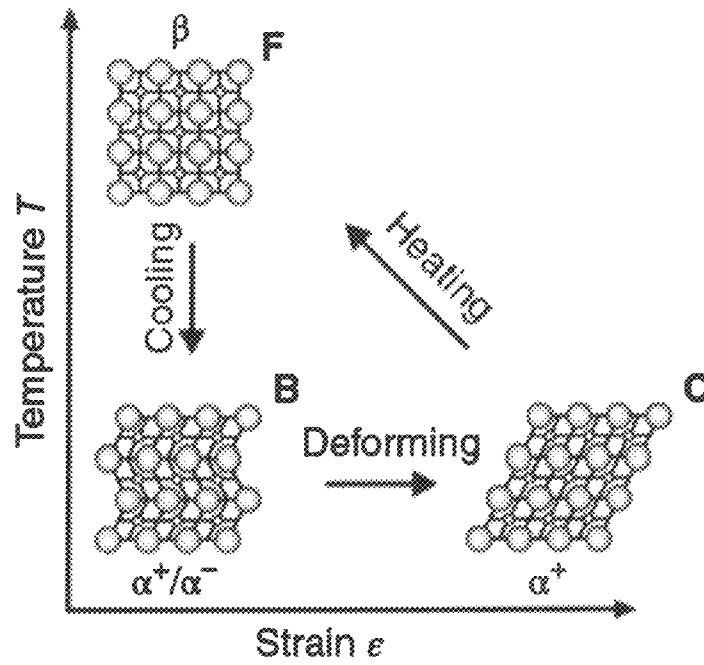


FIG. 2A

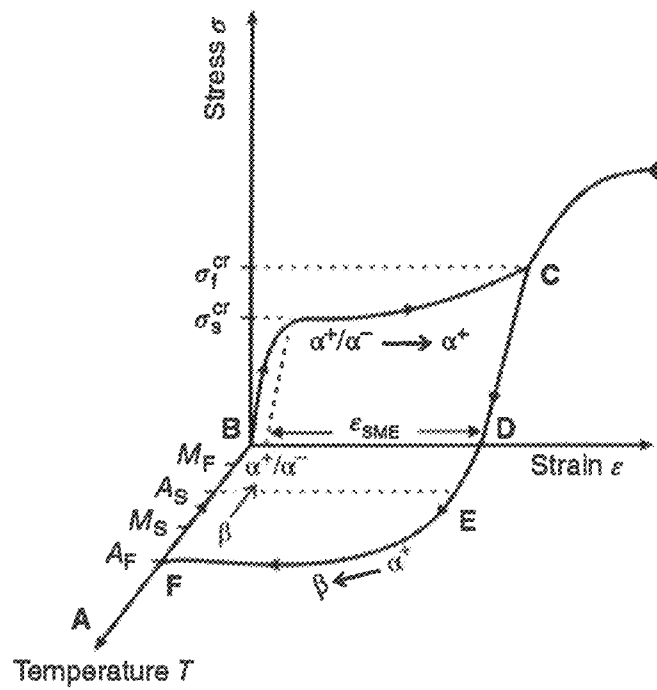


FIG. 2B

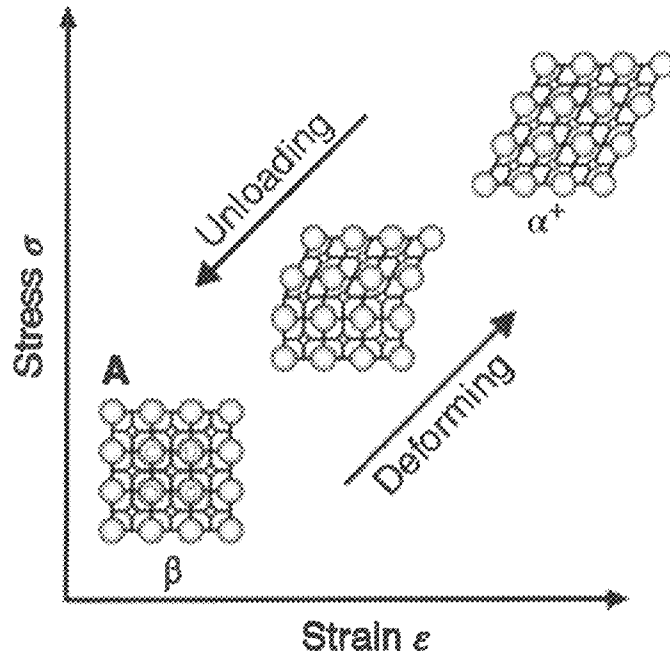


FIG. 3A

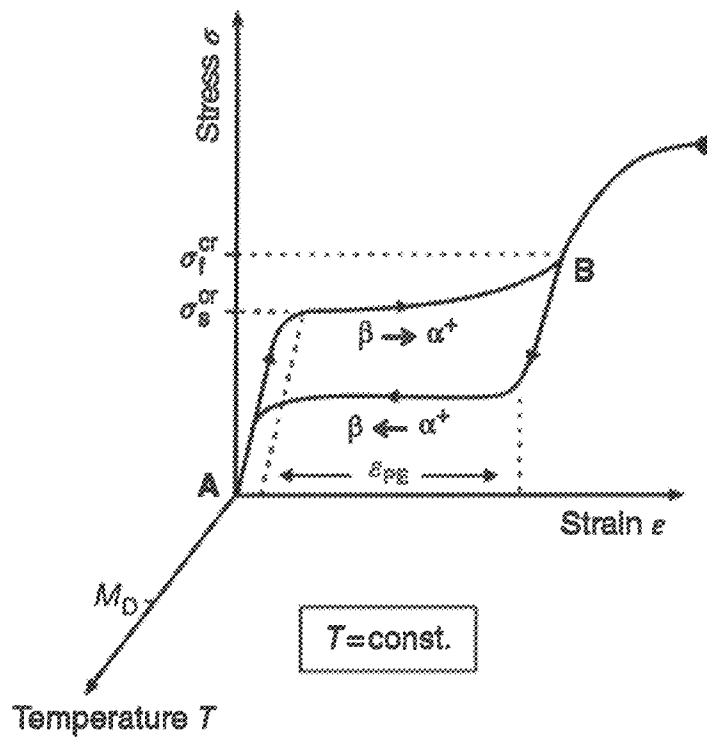


FIG. 3B

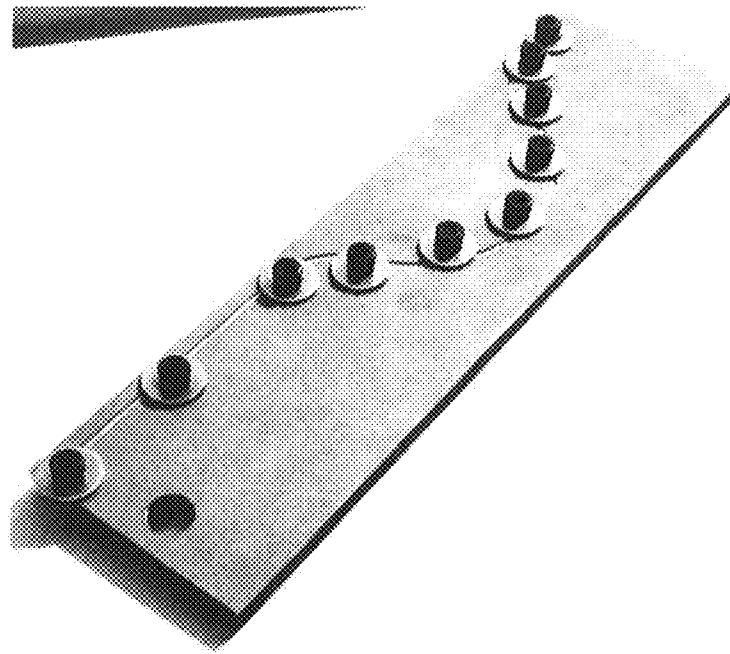


FIG. 4

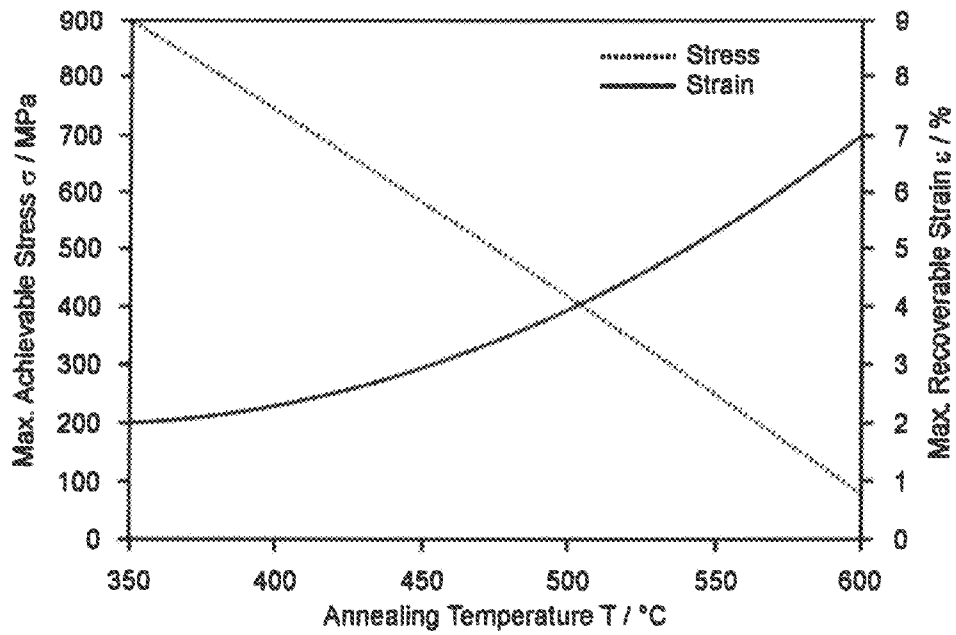


FIG. 5

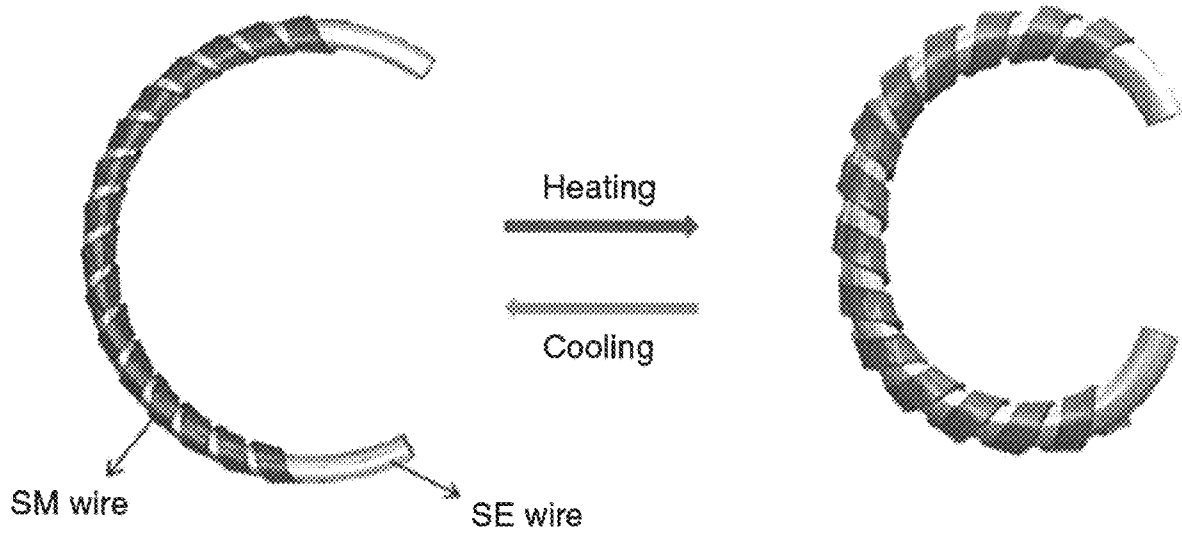


FIG. 6A

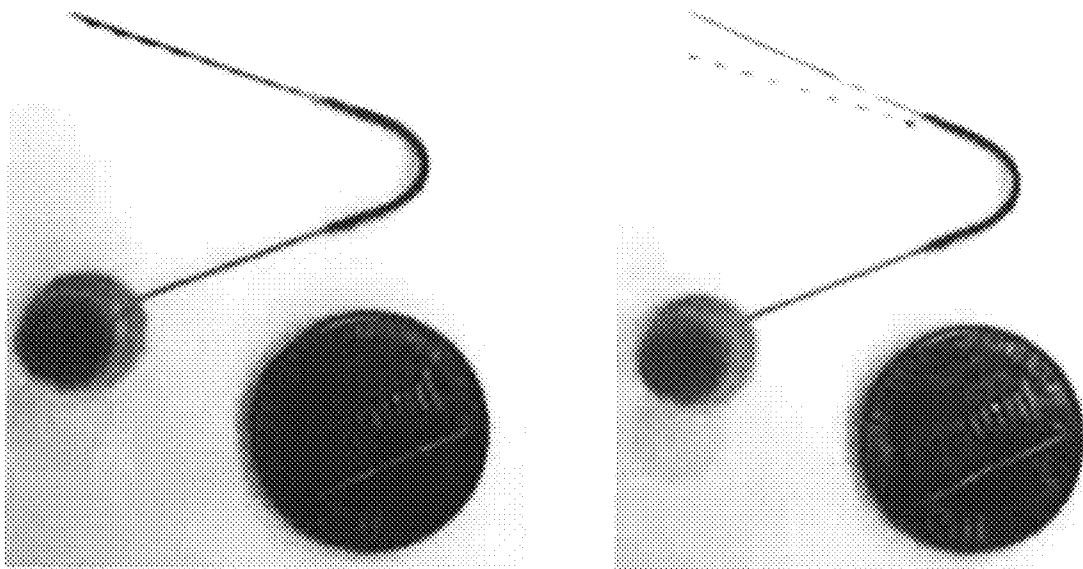
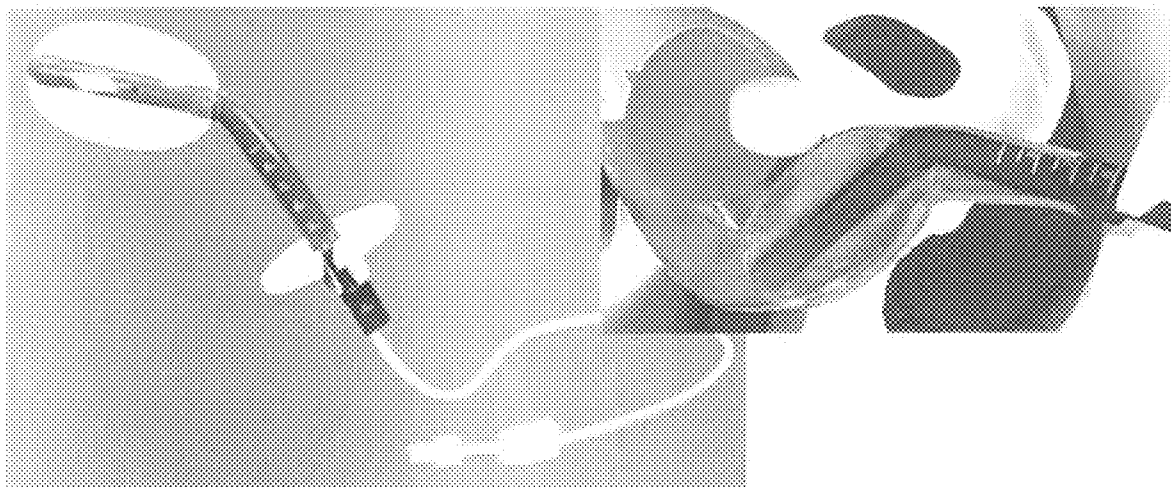


FIG. 6B



PRIOR ART FIG. 7A

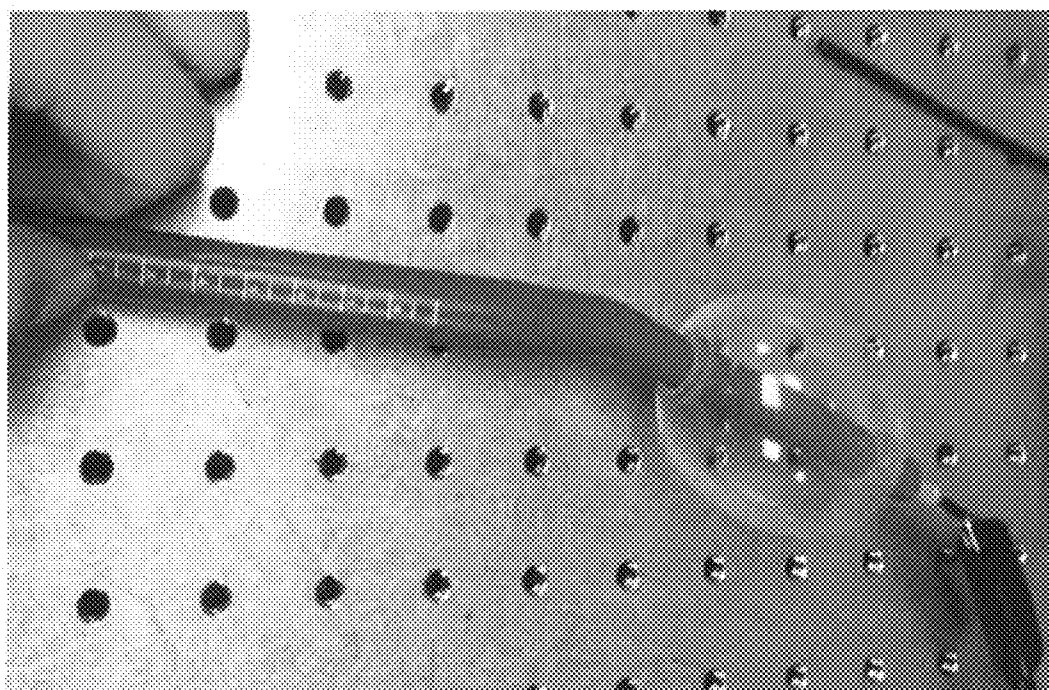


FIG. 7B

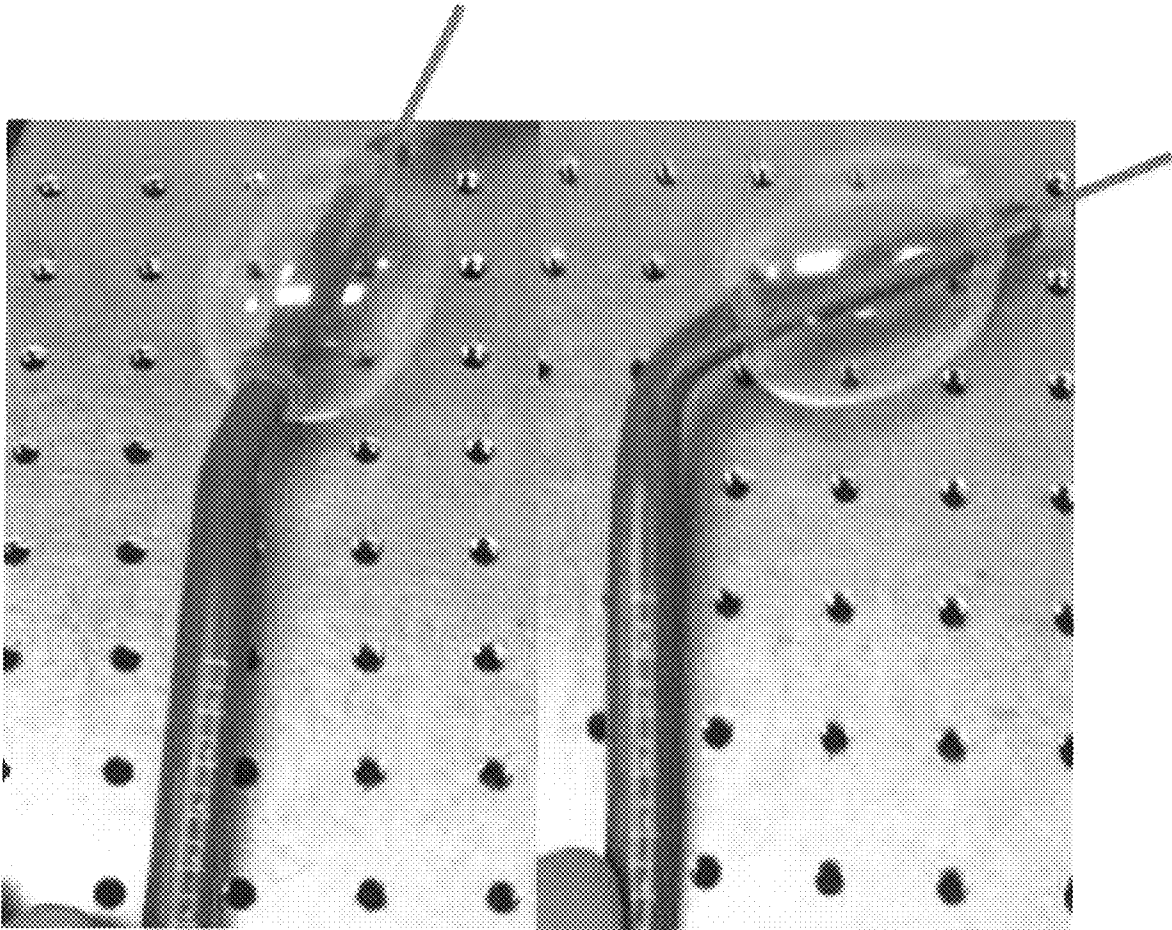


FIG. 7C

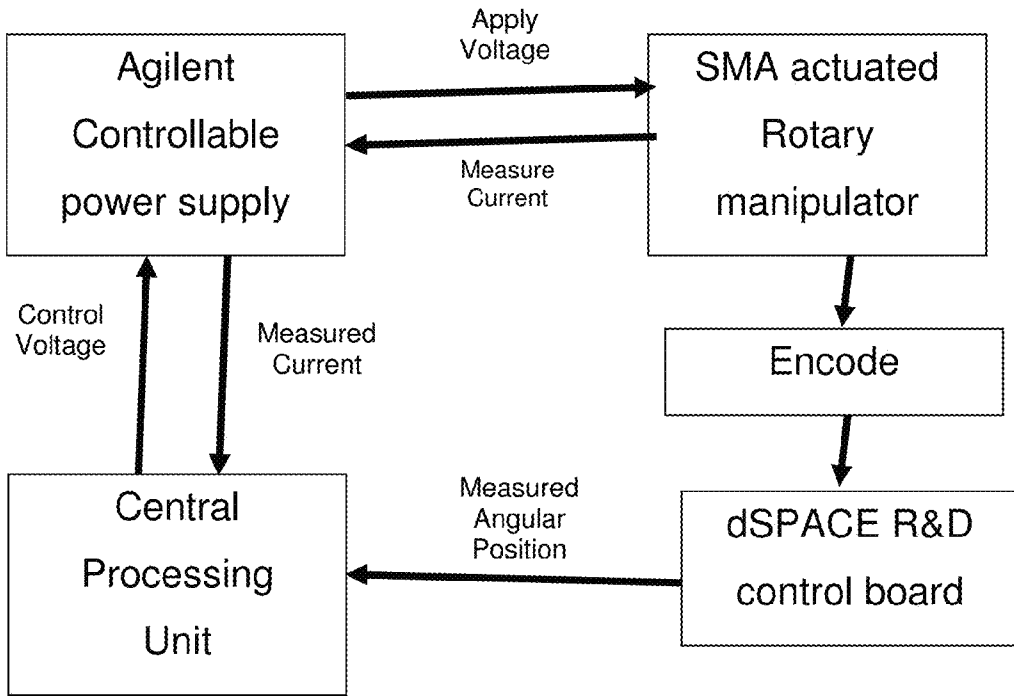


FIG. 8

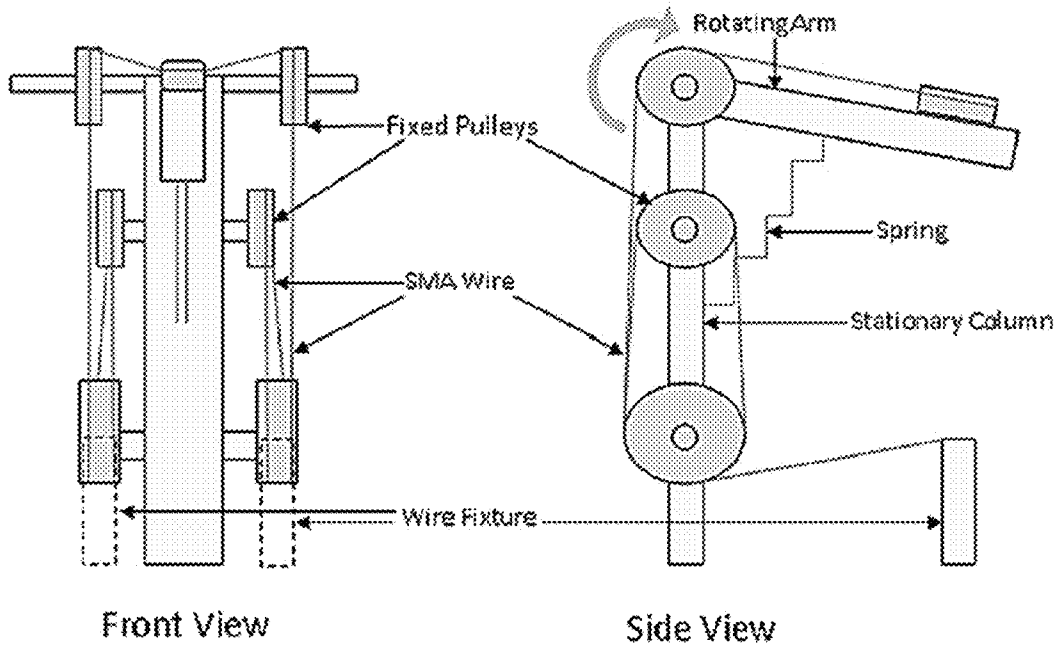


FIG. 9

Table 1. Parameters describing SMA-actuated rotary manipulator.

Parameters	Value	Unit
SMA wire's mass per unit length	$1.14e^{-4}$	kg/m
SMA wire's cross-sectional area	$4.71e^{-4}$	m^2
Initial length of SMA wire	0.90	M
SMA wire's initial strain	0.04	
SMA wire's initial stress	150.00	MPa
Ambient temperature	20.00	$^{\circ}C$
SMA wire's initial martensite fraction	1.00	
Austenite start temperature	68.00	$^{\circ}C$
Austenite final temperature	78.00	$^{\circ}C$
Martensite start temperature	52.00	$^{\circ}C$
Martensite final temperature	42.00	$^{\circ}C$
Payload mass	57.19	G
Moving link mass	19.70	G
Bias spring stiffness	3.87	N/m
Maximum resistance	57.25	Ω
Minimum resistance	47.50	Ω

SMA: shape memory alloy.

FIG. 10

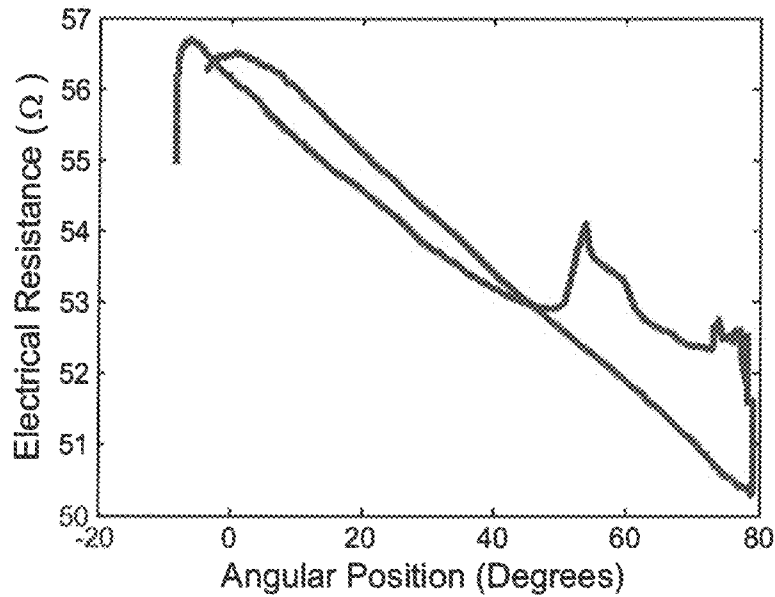


FIG. 11

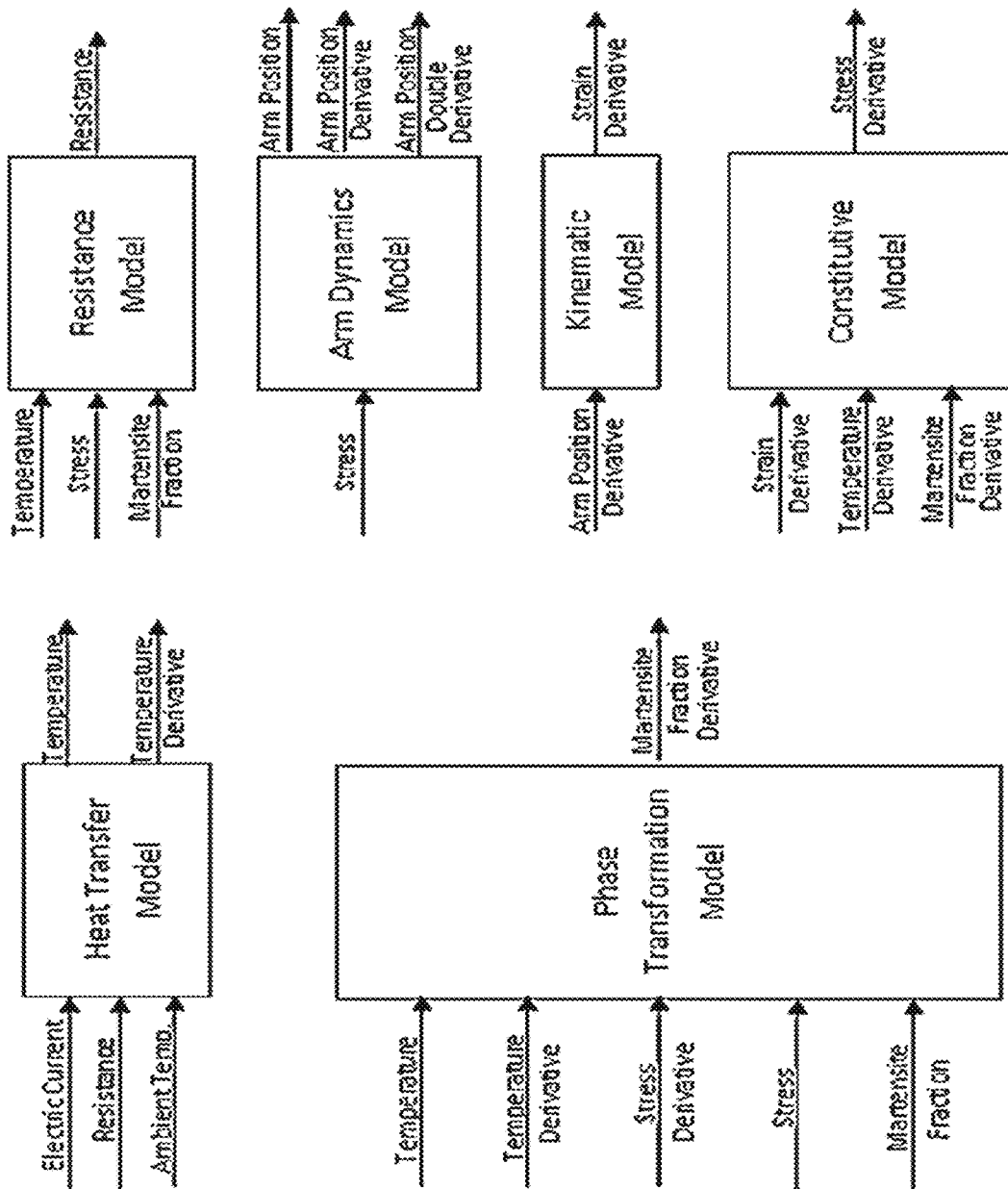


FIG. 12

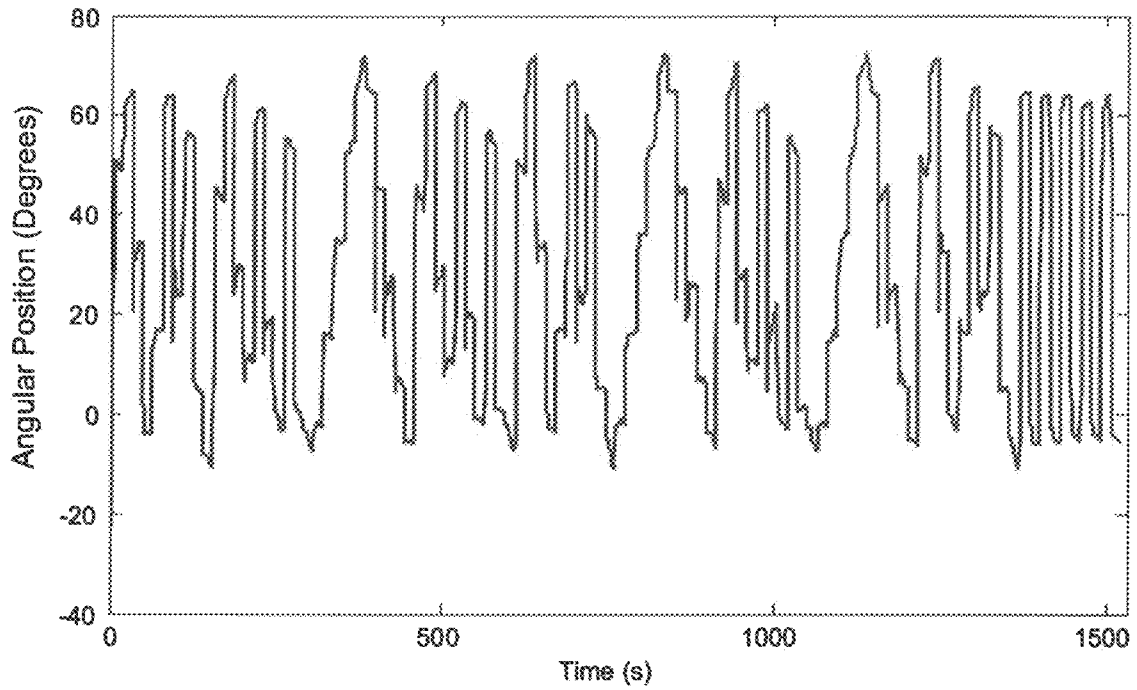


FIG. 13

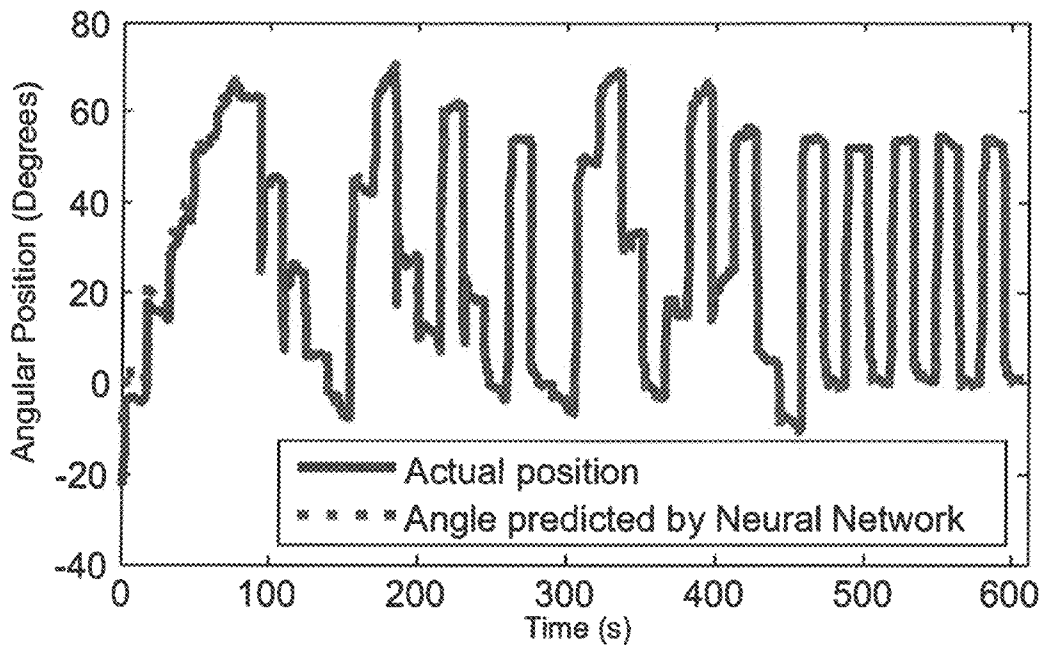


FIG. 14

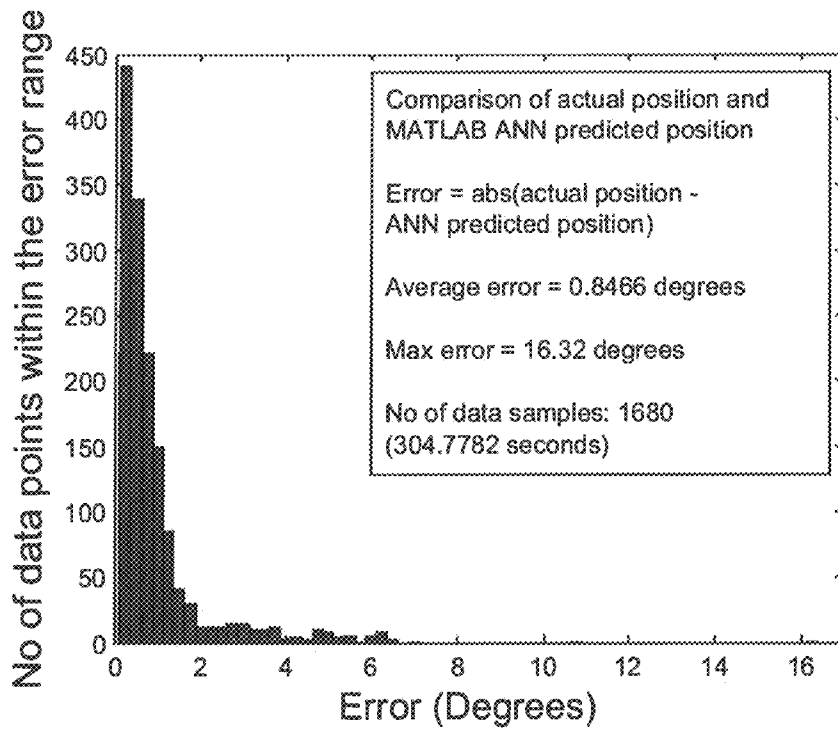


FIG. 15A

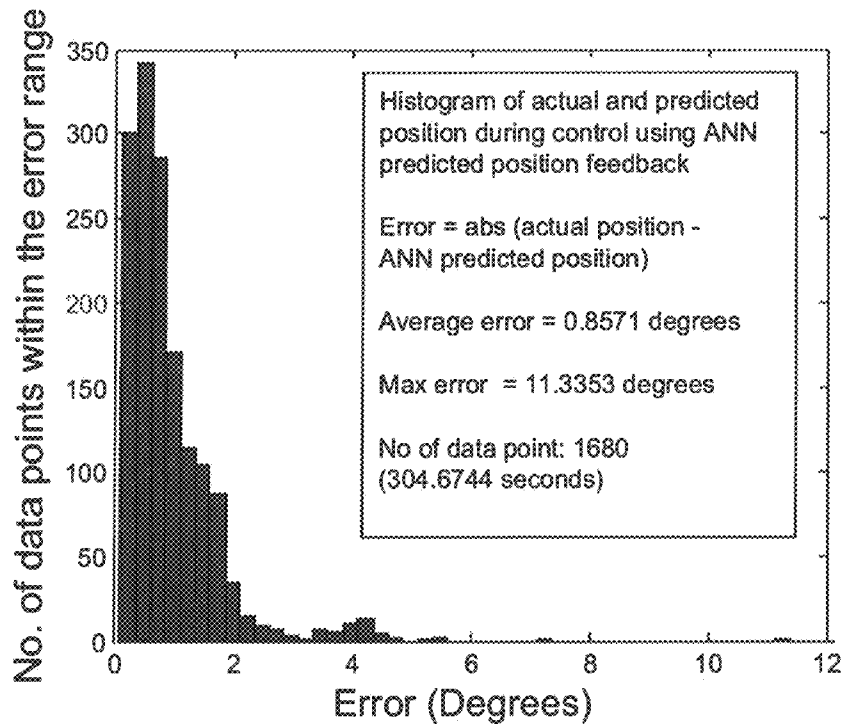


FIG. 15B

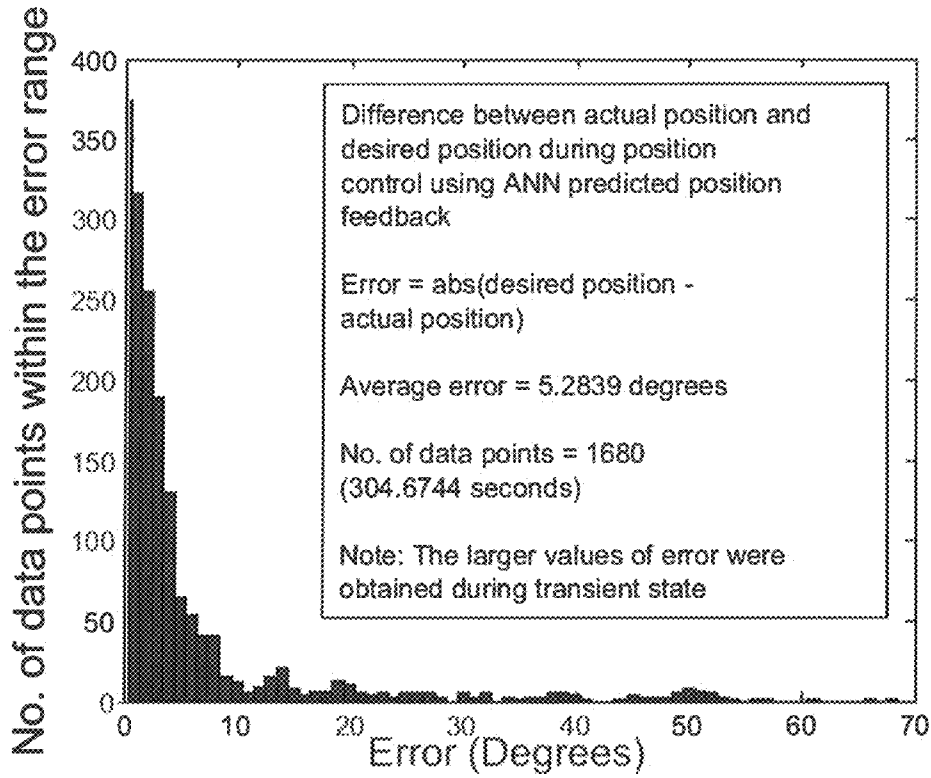


FIG. 15C

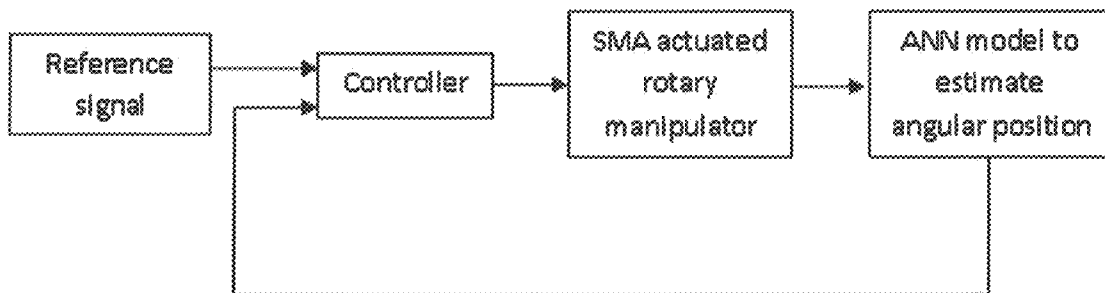


FIG. 16

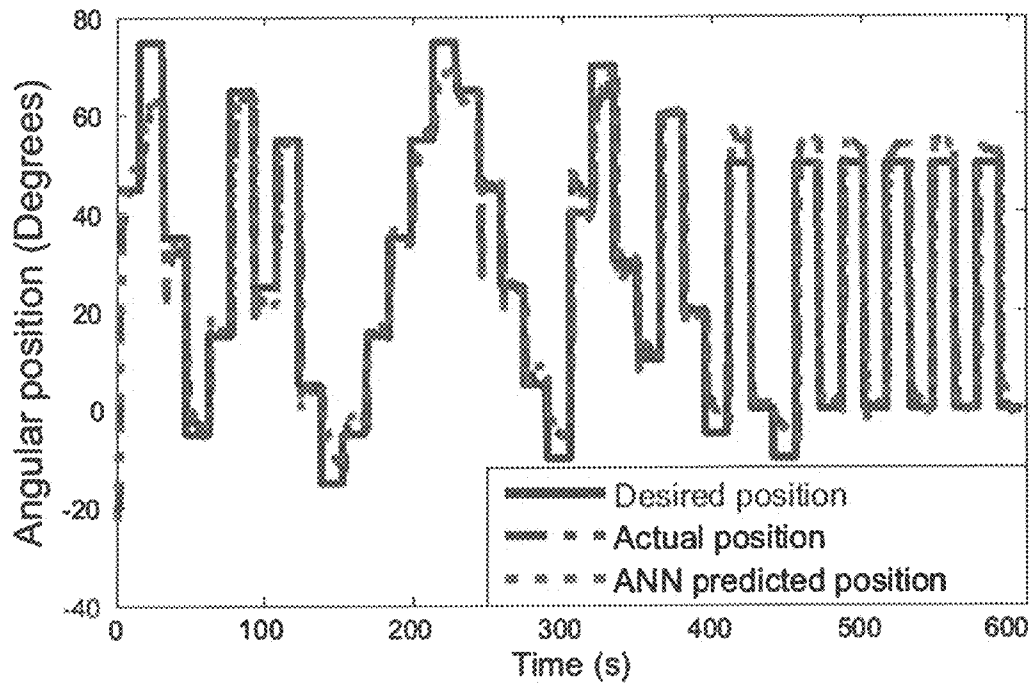


FIG. 17

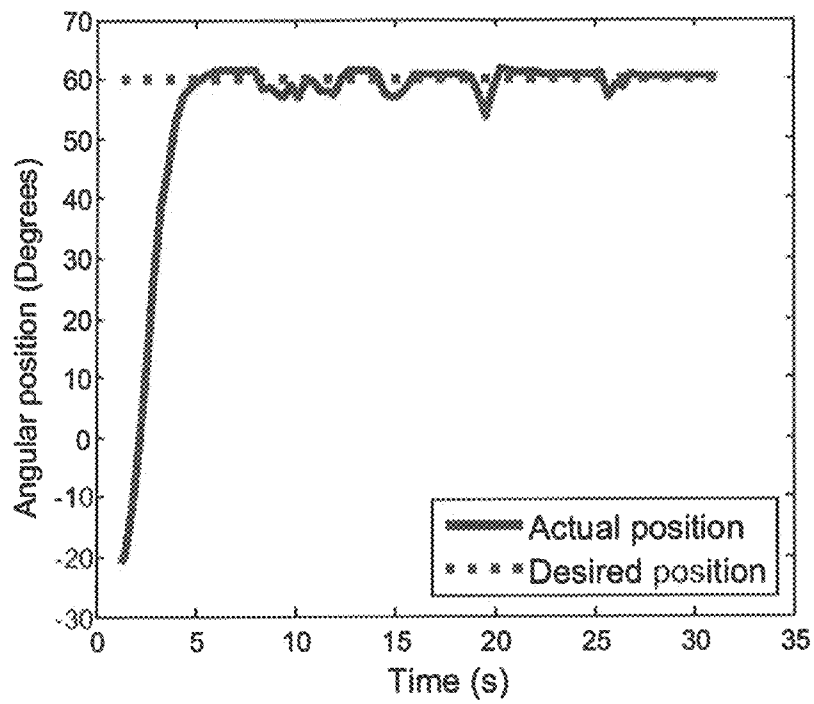


FIG. 18

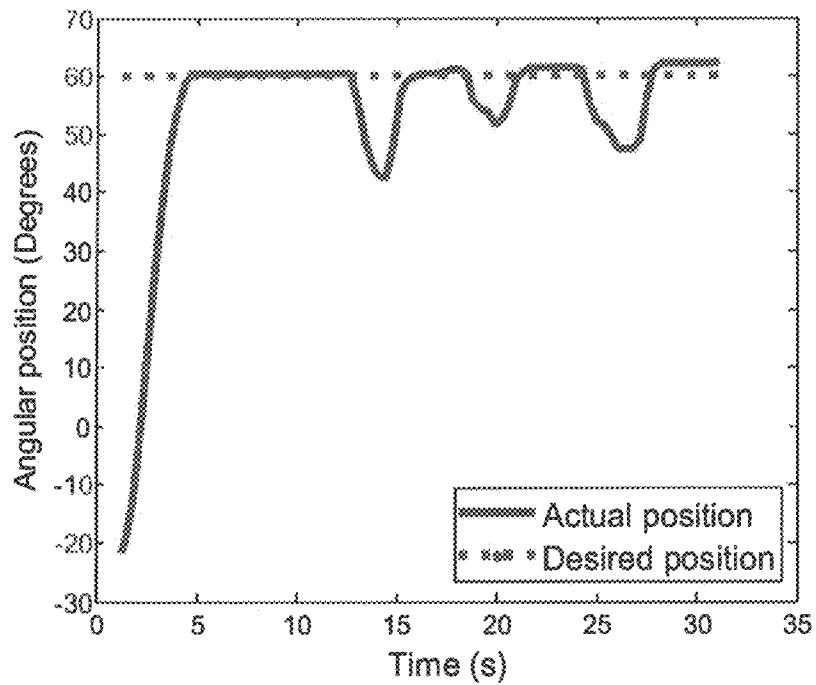


FIG. 19

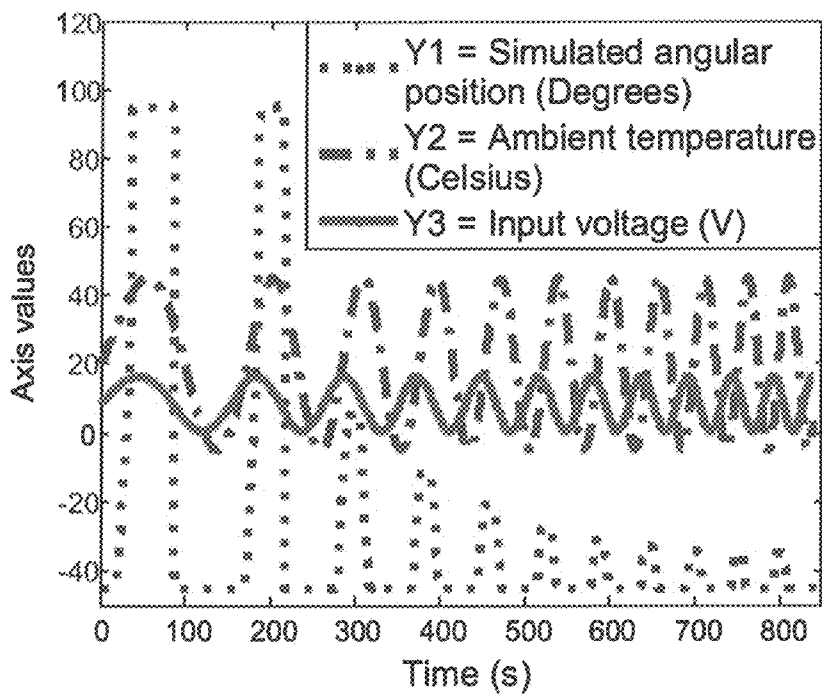


FIG. 20

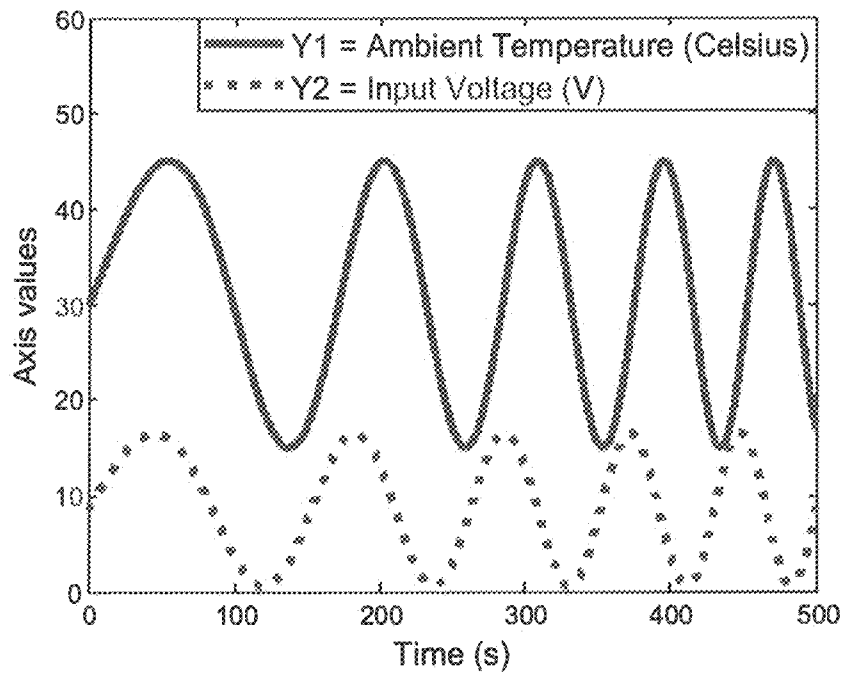


FIG. 21

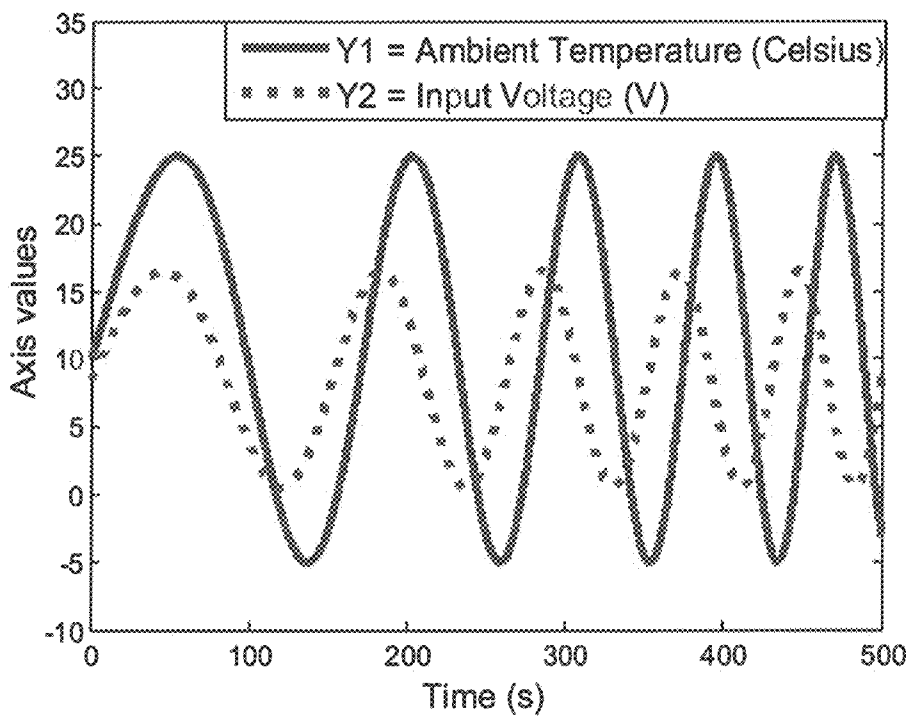


FIG. 22

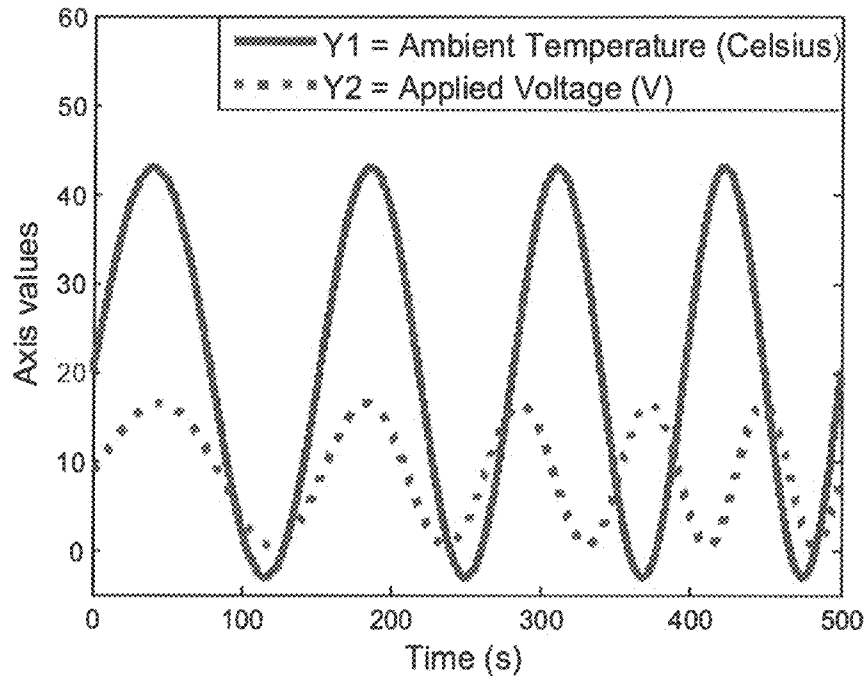


FIG. 23

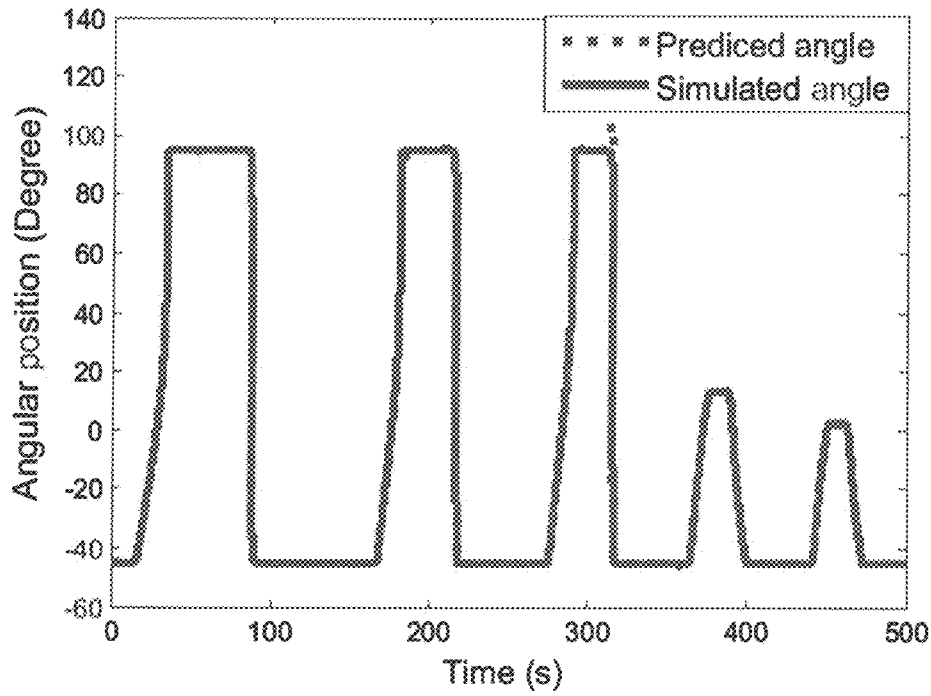


FIG. 24

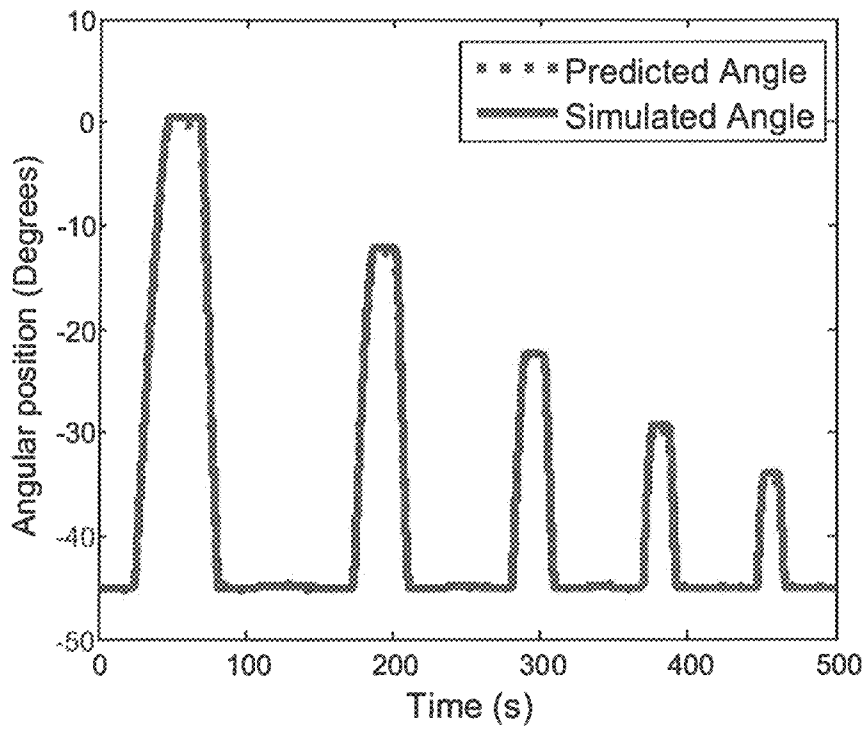


FIG. 25

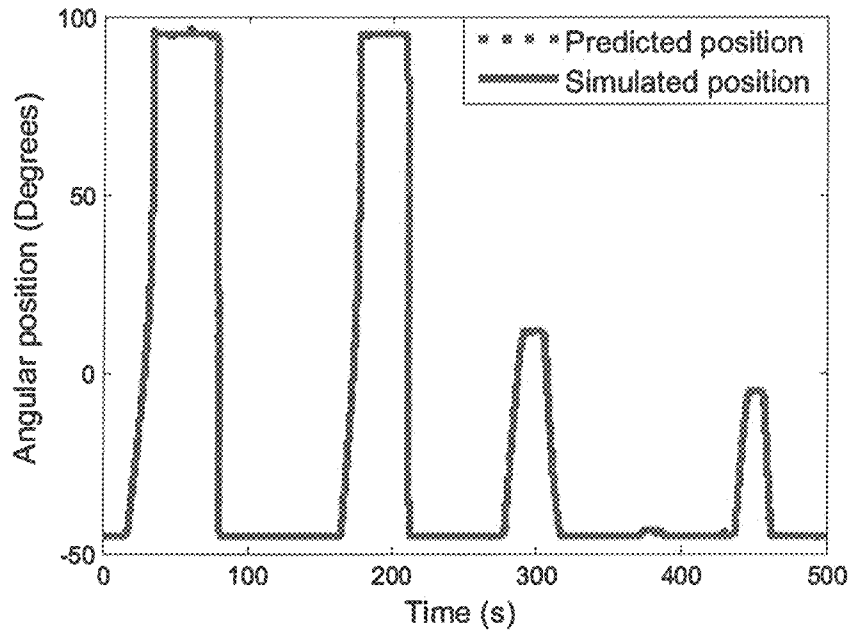


FIG. 26

**DUAL-BRANCHED SHAPE MEMORY
ALLOY ORGAN POSITIONER TO PREVENT
DAMAGE TO HEALTHY TISSUE DURING
RADIATION ONCOLOGY TREATMENTS**

RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Ser. No. 15/630,606, filed Jun. 22, 2017, which claims priority to U.S. Provisional Application Ser. No. 62/353,347 filed under 35 U.S.C. § 111(b) on Jun. 22, 2016, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH

This invention was made with no government support. The government has no rights in this invention.

BACKGROUND OF THE INVENTION

During the course of radiation therapy, radiation-induced chronic morbidities may be observed in nearby critical structures. For younger patients and for patients with longer life expectancy, RT-induced second malignancies will likely increase. Curative doses of radiation in many instances may lead to good disease control but cause radiation-induced chronic morbidities in treatment areas. These include interstitial capillary injury of the myocardium leading to an increased incidence of coronary artery disease, cardiomyopathy, and pulmonary interstitial fibrosis, which could occur during lung or breast treatments. These toxicities are dose related, and reducing the radiation damage to nearby critical structures is highly desirable and very relevant to the patient's quality of life.

There is a large body of data in literature on tissue tolerances which shows it is important to respect the tolerance of critical structures such as the heart, lungs, esophagus, etc., and reduce associated morbidities while improving the quality of life. In most clinical situations, the radiation oncologist compromises the upper level of achieving specific tumoricidal dose to the tolerance doses of the nearby normal tissues. With the advent of Intensity-Modulated Radiation Therapy (IMRT) as a new radiation modality, some relief in sparing critical organs has been achieved as this technique has the potential to increase the therapeutic ratio. However, with newer treatments of stereotactic body radiotherapy (SBRT) for many disease sites, where in a smaller number of fractions a much larger dose per fraction is delivered, there are times when normal tissue located in the vicinity or path of the beam has to be sacrificed.

As an example, for cancers of the pelvis such as prostate cancer, the rectum is a key dose-limiting structure. Increased rectal dose can lead to acute proctitis, potential serious late toxicities, chronic irritation, bleeding, and ulceration. Currently, there is no easy or effective solution to place a distance between the rectum and the field of radiation. This is true for conventional EBRT, image-guided IMRT, and high dose rate (HDR) brachytherapy. Lowering dose to rectal tissue in newer modalities, such as SBRT with low fractionation and much higher dose per fraction, is of even greater importance. SBRT has rapidly gained acceptance in the radiation oncology community for a number of excellent incentives from the patient's point of view, including a non-invasive treatment, and a shorter treatment course compared to conventional EBRT. From the physician's perspective,

SBRT of prostate offers cancer control rates equivalent to those of brachytherapy, conventional external beam IGRT, or surgery.

With HDR treatment of prostate, cervical, and endometrial cancer as well, where a strong radioactive source is often positioned to dwell in the vicinity of the rectum, displacing the anterior rectal wall even a short distance is highly desirable.

No minimally invasive device currently exists that relocates the rectum away from the field of radiation. A known method involves the injection of a biodegradable spacer between the prostate and the rectum. However, the biodegradable spacer is a gel that takes an average of 6 to 12 months to absorb after the injection. Furthermore, with current prostate fixation methods, such as a rectal balloon, the rectum wall anterior is still exposed to higher doses of radiation than desired.

It would be advantageous to discover devices, systems, and methods for repositioning critical structures, such as the rectum, during radiation therapy treatments.

SUMMARY OF THE INVENTION

Provided is a dual-branched organ repositioner device that includes a first inflatable balloon mounted on a first bendable tube defining a first lumen, and a second inflatable balloon mounted on a second bendable tube defining a second lumen. Each lumen houses an assembly of a shape memory (SM) element and a superelastic (SE) element. The SM element comprises a first shape memory alloy and has a first shape set form. The SE element comprises a second shape memory alloy and has a second shape set form. Each bendable tube and lumen bends upon shape transformations of the assembly. The assembly has an equilibrium shape between the first shape set form and the second shape set form. In some embodiments, the SM element is disposed around the SE element. In other embodiments, the SE element is disposed around the SM element. In certain embodiments, the dual-branched organ repositioner device comprises a plurality of inflatable balloons mounted on the bendable tube.

In certain embodiments, upon cooling the dual-branched organ repositioner device deforms toward the second shape set form, and heating drives the dual-branched organ repositioner device toward the first shape set form. In certain embodiments, the SM element is a round wire and the SE element is a flat wire, where the round wire is wrapped around the flat wire. In certain embodiments, the SM element is a round wire and the SE element is a flat wire, where the flat wire is wrapped around the round wire. In certain embodiments, the first shape memory alloy comprises a NiTi alloy. In certain embodiments, the second shape memory alloy comprises a NiTi alloy. In certain embodiments, the first shape memory alloy and the second shape memory alloy are different NiTi alloys. In certain embodiments, the device further includes a controller in electrical communication with the SM element and the SE element, where the controller is configured to apply a voltage in the dual-branched organ repositioner device.

Also provided is a method of administering a radiation therapy to a prostate, the method comprising using the dual-branched organ repositioner device described herein to displace a rectum away from a prostate with respect to a radiation beam path, and then administering a radiation therapy to the prostate through the radiation beam path. In certain embodiments, the dual-branched organ repositioner device comprises a controller that monitors electrical resis-

tance in the dual-branched organ repositioner device to determine an actuation state of the dual-branched organ repositioner device.

Also provided is a method of repositioning an organ, the method comprising inserting an dual-branched organ repositioner device into an anatomical location, where the dual-branched organ repositioner device comprises an assembly of an SM element and an SE element, the SM element and the SE element comprising memory shape alloys, and actuating the assembly to cause the dual-branched organ repositioner device to reposition an organ near the anatomical location. In certain embodiments, the actuation is caused by cooling the assembly. In certain embodiments, the actuation is caused by heating the assembly. In certain embodiments, the method further includes monitoring the actuation of the assembly by measuring electrical resistance in the assembly. In certain embodiments, the actuation is controlled using an artificial neural network. In certain embodiments, the method further includes administering a radiation therapy to or nearby the anatomical location.

Also provided is a method of repositioning an organ for a radiation treatment, the method comprising positioning an dual-branched organ repositioner device in a first configuration in an anatomical location, cooling or heating the dual-branched organ repositioner device to deform the organ repositioner into a second configuration, wherein deformation into the second configuration causes the dual-branched organ repositioner device to reposition an organ at or near the anatomical location, and sensorlessly monitoring the deformation of the organ repositioner device by measuring electrical resistance in the organ repositioner. In certain embodiments, the method further comprises administering a radiation treatment to or nearby the anatomical location. In certain embodiments, the dual-branched organ repositioner device comprises an assembly of two memory shape alloys. In particular embodiments, the assembly comprises a super-elastic element and a shape memory element.

BRIEF DESCRIPTION OF THE DRAWINGS

The 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. 1A: Schematic illustration of a dual-branched organ repositioning device in a non-actuated mode.

FIG. 1B: Schematic illustration of a dual-branched organ repositioning device in an actuated mode.

FIG. 1C: Exploded schematic illustration of a dual-branched organ repositioning device.

FIG. 1D: Exploded schematic illustration of portions of a dual-branched organ repositioning device.

FIG. 1E: Schematic illustration of an assembled view of the FIG. 1D.

FIG. 1F: Exploded schematic illustration of cover sections of a dual-branched organ repositioning device.

FIG. 1G: Schematic illustration of an assembled view of FIG. 1F.

FIG. 1H: Photograph of a distal portion of a dual-branched organ repositioning device.

FIG. 1I: Schematic illustration, partially in cross-section and partially in phantom, of one embodiment of one branch of a dual-branched organ repositioner device designed for rectal repositioning.

FIG. 1J: Schematic illustration of position of prostate in relation to rectum before insertion of dual-branched repositioning device (Left); and illustration of position of prostate in relation to rectum after insertion of dual-branched repositioning device (right).

FIG. 1K: Schematic illustration of the relative anatomical positions of the prostate, rectum, and bladder, and the benefits of repositioning of the rectum using a dual-branched repositioning device.

FIGS. 2A-2B: Shape memory effect path in stress-strain-temperature space.

FIGS. 3A-3B: Schematic diagrams of superelasticity: effect of load on crystalline structure (FIG. 3A), and stress-strain-temperature plot (FIG. 3B).

FIG. 4: Photograph of a shape-setting jig used for securing the NiTi wire during the heat treatment.

FIG. 5: Schematic showing the correlation of annealing temperature for shape setting ($t=30$ min) of a NiTi actuator, and maximum achievable stress of this actuator in case of suppressed deformation and maximum recoverable strain in case of free shape recovery, respectively.

FIG. 6A: An antagonistic superelastic wire and shape memory flat wire wrapping creates a bistable actuation mechanism. Low temperature (left) and high temperature (right) stable forms provide the close and open forms of the actuator.

FIG. 6B: An antagonistic superelastic flat wire wrapped around a shape memory wire creates a two-way actuation with repeatable actuation between two stable positions: low-temperature (left) and high-temperature (right) positions. A penny is shown for scale.

PRIOR ART FIG. 7A: Conventional endorectal balloon (ERB) that can stabilize the rectum and the prostate during the radiation therapy of the prostate.

FIG. 7B: Color photograph of an organ repositioner device that includes an endorectal balloon. The organ repositioned device can move the inflated rectum away from the prostate and out of the radiation beam path.

FIG. 7C: Color photographs of an organ repositioner device with two shapes: shape 1 (left) and shape 2 (right). In this example, the device has 55° of rotation from the initial configuration. Blue lines are shown as guides to illustrate the degree of rotation.

FIG. 8: Block diagram of the experimental setup described in the Examples herein.

FIG. 9: Diagram showing components of SMA-actuated 1-DOF rotary manipulator.

FIG. 10: Table 1, displaying parameters describing SMA-actuated rotary manipulator.

FIG. 11: Relationship between electrical resistance and angular position during open-loop experiment.

FIG. 12: Submodels that are combined to simulate the functionality of 1-DOF rotary manipulator. The input for the combined manipulator model is input voltage and ambient temperature while the output of the model is the manipulator position.

FIG. 13: Complex data used to train the artificial neural network (ANN) as described in the Examples.

FIG. 14: Comparison of actual manipulator position and position predicted by ANN.

FIGS. 15A-15C: Histogram of difference between actual and ANN-predicted angular positions using MATLAB-trained ANN (FIG. 15A), histogram of difference between actual and ANN-predicted positions during control experiment (FIG. 15B), and histogram of difference between desired and actual positions during control experiment (FIG. 15C).

FIG. 16: Block diagram showing the working principle of position sensor-less control of SMA-actuated rotary manipulator using ANN-predicted position.

FIG. 17: Comparison of desired, actual, and ANN-predicted positions during control experiment.

FIG. 18: Effect of mechanical disturbance, induced by manually tapping the rotary manipulator.

FIG. 19: Effect of thermal disturbance, induced by manually blowing air onto the SMA actuator.

FIG. 20: Variation of input voltage, ambient temperature, and simulated manipulator angle when collecting data for ANN training.

FIG. 21: Variation of ambient temperature and input voltage when simulating in the first scenario.

FIG. 22: Variation of ambient temperature and input voltage when simulating in the second scenario.

FIG. 23: Variation of ambient temperature and input voltage when simulating in the third scenario.

FIG. 24: Comparison of simulated angle and ANN-predicted angle in the first scenario.

FIG. 25: Comparison of simulated angle and ANN-predicted angle in the second scenario.

FIG. 26: Comparison of simulated angle and ANN-predicted angle in the third scenario.

DETAILED DESCRIPTION OF THE INVENTION

Throughout this disclosure, various publications, patents, and published patent specifications are referenced by an identifying citation. The disclosures of these publications, patents, and published patent specifications are hereby incorporated by reference into the present disclosure in their entirety to more fully describe the state of the art to which this invention pertains.

In the treatment of prostate cancer using radiation therapy (RT), one persisting challenge is reducing radiation dose to critical surrounding structures such as the rectum while delivering an effective ablative dose to the target. Planning and delivery of RT for prostate cancer must always carefully account for rectal dose. The rectum serves as a key dose-limiting structure; increased rectal dose can lead to acute proctitis and potential serious late toxicities, including chronic irritation, bleeding, or ulceration. The increasing use of hypofractionated regimens for prostate radiotherapy, in which higher doses per fraction are delivered over a smaller total number of treatment sessions, makes achieving a lower rectal dose of even greater importance. This problem currently has no effective solution.

Provided is an dual-branched organ repositioner device which, in some embodiments, is designed and fabricated to physically move the rectum away from the path of a direct radiation beam during external beam and brachytherapy treatments.

FIGS. 1A-1G illustrate an embodiment of a dual-branched organ repositioner device **110** designed for rectal repositioning. Using the dual-branched organ repositioner device **110**, the rectal wall can be shifted away from the source of radiation, or from the vicinity of the radiation field, resulting in a lower dose to the rectum. When actuated, the dual-branched organ repositioner device **110** assumes a pre-defined shape that can apply pressure to the posterior wall of the rectum, resulting in displacement of the entire rectum posteriorly, away from the target volume.

The dual branched organ repositioner device **110** includes a main assembly **112** that has a proximal handle section **114**, an angled middle section **116**, and a branched end **118**. The

branched end **118** is comprised of a first branch repositioner device **10**, and an opposing second branch repositioner device **10'**. The repositioner devices **10**, **10'** are further explained below in detail with respect to FIG. 11.

FIG. 1A shows the first branch and second branch repositioner devices **10**, **10'** in a closed, or initial position, which allows for insertion of the branched end **118** into a patient.

FIG. 1B shows the first and second repositioner devices **10**, **10'** in an open or activated, position. The first branch repositioner device **10** includes a first balloon **12**. The second branch repositioner device **110'** includes a second balloon **12'**. FIG. 1B also shows that the middle section **116** has been activated a more acute position.

The dual-branched device **110** has two shapes here called shape **1** (FIG. 1A) and shape **2** (FIG. 1B). The device **110** is in shape **1** (30 degree) at time of insertion. After insertion the dual-branched device **110** gradually changes to shape **2** (75 degree) via heating by heater and two balloons, **12**, **12'** start to inflate and separate the first and second branches **10**, **10'**.

The dual branched device **110** maintains shape **2** during the treatment session via a controller. Before removal the first and second branch repositioner device **10**, **10'** are retracted, and the dual-branched device **110** reverts back to shape **1** for easy removal. The shape changes are the result of temperature variation. The temperature of the surface of the device does not exceed the safe temperature of 40° C. The movement between the shape **1** and shape **2** is gradual to minimize the risk of injury. The maximum deflection of the device is limited to not cause any injury.

The rectal retractor is useful for prostate treatment. The length of interest for rectum is about 20 cm. That starts from posterior part of the external anal sphincter muscle to about where the rectosigmoid junction begins. The prostate, which is typically the organ that is intended for irradiation, is usually located in the middle of this length. The each of the first and second branch repositioner devices **10**, **10'** moves the wall of the rectum from where the prostate gland is by 2 cm in average. In the 20 cm long device, the prostate is located at about 10 cm from the anus. The displacement takes place in starting from the 5 cm point to 10-12 cm point along the dual-branched device **110**. In addition to fully grabbing the rectum the first and second branched repositioner devices **10**, **10'**, each with inflatable balloons **12**, **12'** at their ends, aids the dual-branched device **110** to move the rectum from the two sides of the tail bone.

For grabbing the larger area of rectum, the first and second branched repositioner devices **10**, **10'** open up after insertion via inflation of the first and second balloons **12**, **12'**. Before insertion, the branched repositioner devices **10**, **10'** are parallel and can stick to each other. After placing the device **110** in the right position inside the rectum, the first and second balloons **12**, **12'** start to inflate via the air tubes **132**, **132'** that are connected to an air supply outside of the body of patient. Inflating the balloons **12**, **12'** allows the branches **10**, **10'** to move away from each other and to create a desired distance between the ends of the branches.

The volume of the balloons **12**, **12'** and the size of the first and second branches **10**, **10'** are designed according to standards for biomedical devices. The tube of the device **110** can be made of silicon, which is a biocompatible and high temperature resistance material. Silicon is the good insulator material as well.

FIG. 1C is an exploded, partially in cross-section, view showing various sections of the device **110**. The device **110** includes a three-way connector **130** which provides air to first and second air supply lines **132** and **132'**. Cover handle section **114** is a tube which is a cover for a wire handle and

the air tubes together. The air tubes are used to inflate the balloons which are mounted at the end of the branched repositioner devices. In this embodiment, only the actuator section is made of NiTi wire and two ends of NiTi wires are hard and lightweight plastics.

When the device **110** is the shape **1** position, it has an angle of about 30 degrees. After actuation via the heater, the angle is increased to about the 75 degrees which is the shape **2** position. FIG. **1D** is an exploded schematic illustration of the handle end **114**, air supply lines **132**, **132'**, the middle section **116** and the branched ends **118** of the dual-branched organ repositioning device **110**. The middle section **116** is made of NiTi and the handle end **114** and branched ends **118** are made of plastic. FIG. **1E** is a schematic illustration of an assembled view in FIG. **1D**.

FIG. **1F** is an exploded schematic illustration of cover sections of the dual-branched organ repositioning device. FIG. **1G** is a schematic illustration of an assembled view of FIG. **1F**. The cover can be three separate pieces that facilitates the process of assembling.

FIG. **1H** is a photograph of one prototype of the distal end of the dual-branched organ repositioning device **110**.

The functionality of the device **110** is achieved by using the properties of a shape memory alloy and one small size high electrical resistance heater, as further explained below in reference to FIG. **1I**.

FIG. **1J** is a schematic illustration of position of prostate in relation to rectum before insertion of dual-branched repositioning device (Left); and illustration of position of prostate in relation to rectum after insertion of dual-branched repositioning device (right).

FIG. **1K** is a schematic illustration of the relative anatomical positions of the prostate, rectum, and bladder, and the benefits of repositioning of the rectum using a dual-branched repositioning device.

Heating takes place by passing controlled current through an electrically high resistance coil that is wrapped around the SMA element. In this embodiment, at low temperatures the SMA wire is in shape **1**. When heated the device assumes shape **2**. This shape is maintained for the duration of the treatment via defining set point for the controller. At the end, the wire is cooled by switching off the circuit and the device is removed.

Further, in this embodiment, only a small portion (56 mm) of the NiTi wire for the moving part of the device **110** is needed. Two ends of the NiTi wire are made of hard light weight plastics.

The NiTi wire needs to heat up above A_f to bend and stay in the shape **2**. Since the length of the NiTi wire is small, the heater for actuating the NiTi wire can be small as well. This length is about 30 mm, and the current and voltage for turning on the heater is less than 1 amp and 3 volts respectively. The actuation of the NiTi can be take place via any normal battery.

A controller monitors the temperature of the surface of the device **110**. When the temperature of the surface goes above the set point temperature of the controller, the circuit will be off by controller. When the temperature goes below the set point, then the controller will on the switch of the circuit. In this way, the device **110** will stay on the shape **2** position during the radiation therapy session and also the temperature will never goes above the safe temperature (**40C**). The controller is connected to the sensitive thermocouple to monitor the temperature.

The dual-branched organ repositioning device **110** allows for the delivery of an ablative SBRT dose to a tumor, or to escalate the dose when needed. Moving the rectum away

even a short distance, such as 1 cm, from the plane of radiation dramatically relax the prescription dose limitation. The dual-branched organ repositioner device **110**, by lowering the rectal dose in a convenient and easily reproducible manner, can serve an integral role in shorter-course treatment regimens, allowing dose escalation in a safe manner. Minimizing the radiation dose to adjacent critical structures reduces the risk of treatment-related toxicities, and can greatly influence a patient's quality of life after treatment.

It is understood that, though rectal repositioning is described through the application for ease of illustration, the device **110** and methods described herein can be utilized to reposition many other organs or anatomical structures. With respect to the rectum in particular, the dual-branched organ repositioner device **110** represents a shift in paradigm, as the current means of limiting rectal dose during prostate radiotherapy all fall far short of achieving permanent dosimetric gains. None of the current approaches appear to be practical and/or widely feasible in all clinical settings. Existing approaches to minimize rectal dose entail: utilizing the effect of gravity, using rectal balloons (which displaces the posterior wall of the rectum at the expense of exposing further the anterior wall), or the recently adapted invasive procedure by some clinics of insertion of temporary, gel-like dissolvable substrates in the region between the rectum and prostate, creating a few mm of space.

In one embodiment, the first and second dual-branched repositioning device **10**, **10'** can be as shown in FIG. **1I**. Each organ repositioner device **10**, **10'** includes an inflatable endo-rectal balloon **12** mounted on a bendable tube **14** which defines a lumen **24**. The tube **14** has a proximal end **26** and a distal end **28**. The balloon **12** is mounted on the proximal end **26** of the tube **14**. In some embodiments, the dual-branched organ repositioner device includes multiple balloons **12**, such as semispherical balloons, mounted on the tube **14**. The organ repositioner device **10** can include an opening **30** at the proximal end **26** of the tube **14** connected to an air supply line **32** configured to deliver air from an air source **34** so as to inflate the balloon **12**. It is understood that the air source **34** need not be external to the device; rather, the air source **34** can be a small cartridge that fits inside the lumen **24**. Alternatively, the air supply line **32** can be connected to any source of pressurized air.

The lumen **24** houses an assembly **16** of the SM element **18** and the SE element **20** formed together. The SM element **18** has a first shape set form, and the SE element **20** has a second shape set form. Either the SM element **18** is formed around the SE element **20**, or the SE element **20** is formed around the SM element **18**. For example, the SM element **18** can be a wire wrapped around the SE element **20** wire, or vice versa.

Though FIG. **1I** depicts the assembly **16** as extending the length of the lumen **24**, from the proximal end **26** to the distal end **28**, the assembly **16** need not extend through the entire lumen **24**. Rather, it is only important that the assembly **16** extend through enough of the lumen **24** so as to cause the bendable tube **14** to bend upon actuation of the assembly **16**. In other words, the bendable tube **14** bends upon shape transformations of the assembly **16**.

The assembly **16** has an equilibrium shape between the first shape set form and the second shape set form. Upon heating and/or cooling, such as through an electrical current, the assembly **16** is actuated and the bendable tube **14** bends accordingly. The organ repositioner device **10** can utilize the preformed bend in the endorectal balloon device for actuation. In the example shown, the organ repositioner device bends 55° from the initial configuration. Alternatively, the

bendable tube **14** could be made to bend at an additional or alternative location upon actuation of the assembly **16**. The bending of the bendable tube **14** can reposition the desired organ into the desired location, such as away from the path of a radiation beam. For example, in use for repositioning a rectum during a prostate treatment, the proximal end **26** of the organ repositioner device **10** is inserted in the rectal cavity, where the balloon **12** is then inflated to stabilize the prostate, and the assembly **16** is actuated. Actuation of the assembly **16**, by heating or cooling (whether by active control or through passive heating/cooling caused by body temperature), causes the bendable tube **14** to bend and exert a pushing force on the rectal wall, thereby repositioning the rectum as desired.

The organ repositioner device **10** can further include a controller **22** for controlling the actuation of the assembly **16** as described below. The controller **22** is in electrical communication with the SM element **18** and the SE element **20**. The controller **22** can apply a voltage in the device **10**, and can determine the state of actuation by measuring electrical resistance in the device **10**. The controller **22** is generally configured to apply a voltage to the device in a closed loop feedback based on the measured electrical resistance. By heating and/or cooling and measuring the resistance of the device **10**, remote device displacement of an organ is possible with the device. Electronic circuitry on the controller **22** can give an indication of a safe range of displacement based on the feed value of the resistance. Changing the power input manually can allow safe and optimal dislocation of rectal tissue away from the field of radiation. The controller **22** can be configured to monitor the electrical resistance in the device, determine the actuation state of the device based on the measured actuation state, and control the voltage as necessary based on the determined actuation state.

In general, the organ repositioner device includes components made of shape memory alloys (SMAs). Shape memory alloys are a class of smart materials that can recuperate their initial shape after being deformed mechanically. SMAs are distinguished from conventional metallic materials by their ability to restore their shape after large deformations, which can significantly exceed the actual elastic deformability of the material. This is referred to as shape memory effect (SME), characteristic as demonstrated in FIG. 2A. SME is the ability of these alloys to recover a certain amount of unrecovered strain upon heating, which takes place when the material is loaded such that the structure reaches the detwinned martensite phase and then unloaded while the temperature is below the austenite start temperature (A_s). SME occurs because of the transformation between martensite and austenite phase when subjected to thermomechanical changes. Heating the material at this stage to austenite will lead to strain recovery, and the material will regain its original shape. Shape memory alloys can thus recover their original shape by heating above the austenite transformation temperature when subjected to deformation at low temperature. The combined stress-strain-temperature diagram as shown in FIG. 2B illustrates this phenomenon. At lower temperature, the soft martensite phase is observed, which can be easily deformed. When this deformed SMA is heated beyond transformation temperature, phase transformation takes place, and austenite phase is obtained. After this phase transformation, the original shape is recovered. This property enables the shape memory alloy to be used as a unique actuator.

SMAs are useful in positioning surrounding tissue out of the area affected by a treatment. In most radiation oncology applications, the use of a shape memory alloy actuation can

be beneficial in sparing the surrounding normal tissues and critical structures by simply relocating the structure away from the path of the external beam or place distance between the structure and source of radiation in cases of brachytherapy. Implementation of this device as an organ positioner in conjunction with IMRT and SBRT allows for dose escalation and significant dose reduction to normal tissues. Another example is during atrial fibrillation radio frequency ablation, where dysfunctional cells are ablated by heat and can cause thermal injury to the nearby tissue, namely the esophagus. By inserting an SMA-based repositioner device in the esophageal tube, surgeons can shift the esophagus away from the affected area.

A non-limiting example of a shape memory alloy is nitinol (NiTi). Nitinol is a binary alloy of nickel and titanium. Nitinol is implantable and capable of shape-setting via crystalline phase transformation in various geometries. Nitinol has one of the highest force-to-mass ratios of shape memory alloys. For example, a nitinol wire of radius 0.254 mm can lift as much as 7.257 kg. This, combined with other desirable properties such as maintainability and reliability with clean and silent actuation, makes nitinol an ideal actuator for various application. Nitinol is already accepted and used in the medical device community, for example as cardiovascular stents. Though nitinol is described for exemplary purposes herein, it is understood that the organ repositioning device can utilize shape memory alloys other than nitinol.

Nitinol exhibits both the shape memory effect and superelasticity (SE). As mentioned above, shape memory is the ability to undergo deformation at one temperature, then recover the original, undeformed shape upon heating above its transformation temperature. Superelasticity, on the other hand, occurs at a narrow temperature range just above the material's transformation temperature. In contrast to the thermally activated effects, in superelasticity, no temperature change is required. Instead, an external mechanical load can be used to induce phase transformation. In this phenomenon, the detwinned and favorably oriented martensite variants directly transform from the austenitic phase. As shown in FIG. 3, the superelastic behavior takes place at temperatures above the austenite finish temperature (A_f) where the material is fully austenitic. As shown in FIG. 3B, loading the material from point A initially induces elastic deformation of the austenite phase. Further loading leads to stress-induced formation of the detwinned martensite crystal and the macroscopically elastic-like deformation of this structure to point B. The transformation strain generated during this forward transformation from austenite to martensite is fully recovered in the reverse transformation. This takes place during the unloading from point B, which involves an initial elastic recovery of martensite followed by the transformation to austenite and finally the elastic recovery of austenite to point A. At this point, the strain is completely recovered. Thus, for superelasticity, no heating is necessary to cause the undeformed shape to recover, and the material exhibits more elasticity than ordinary metal.

By varying the atomic percentage of nickel and titanium in the alloy, the resulting shape memory alloy can be made to be either an SM element or an SE element. As described herein, an organ repositioner device includes an assembly of an SM element and an SE element. In general, certain nitinol alloys can exhibit shape memory or superelastic behavior, or both. Although nitinol is essentially a binary alloy with nickel and titanium, some superelastic and/or shape memory Ni:Ti alloys can contain additional elements, such as cobalt or vanadium. In addition, some other alloys exhibit shape

memory or superelastic behavior or, like some Ni:Ti alloys, both shape memory and superelasticity. Some examples of these alloys are: AgCd, AuCd, AuCu, CuAlNi, CuAuZn, CuSn, CuZn, CuZnSi, CuZnSn, CuZnAl, CuZnGa, CuZnXe, InTi, NiAl, FePt, FePd, FeMn, Fe₃Be, Fe₃Pt, FeNiTiCo, and MnCu. Some polymers and other materials have also been shown to exhibit shape memory or superelastic behavior, or both. It is understood that the organ repositioner device described herein can utilize any combination of these materials, so long as the device includes an assembly of a shape memory element and a superelastic element. NiTi is especially useful, however, for actuation and motion control applications because NiTi can be easily heated by passing an electrical current while offering several advantages for system miniaturization such as high power-to-mass ratio, maintainability, reliability, and clean and silent actuation.

Semi-finished SMAs such as wires require a shape set configuration to reveal the demanded functional properties before being used in their desired application. This configuration is accomplished by a special heat treatment called shape setting. The objective of this treatment is to improve the shape recovery behavior since cold-worked NiTi does not exhibit shape memory properties, and to establish the geometrical shape, which is memorized in the shape memory operations. For this heat treatment, the semi-finished product such as a wire or a sheet is cold-formed on a jig into the final product shape, as shown in FIG. 4.

This cold-deformation requires a significant amount of deformation beyond the recoverable limit because of the large springback effect in NiTi or superelastic shape recovery. In this constrained shape the NiTi has to be fixed tightly on the jig, for example with screws or by using a tight fit. The suppression of free recovery results in the buildup of stresses within the material, which later will relax in the course of the following shape setting heat treatment. The shape setting heat treatment can be performed at moderate conditions but the temperature should be about 350-450° C. higher than the austenite-finish temperature of the alloy. Temperature and duration may vary slightly to account for the desired application and geometry (wire, strip, ribbon, sheet, etc.) but both significantly affect the shape recovery properties, mechanical behavior, and transformation temperatures of the material.

As shown in FIG. 5, shape setting at low temperatures results in low recoverable strains, but if the deformation is suppressed high forces can be achieved because work hardening effects are mostly retained. In addition, shape setting at low temperatures also results in higher fatigue life. In contrast, shape setting at higher temperatures results in higher recoverable strains but achievable forces and fatigue life decrease.

Each branch of the dual-branched organ repositioner device has two shapes, which can be referred to for purposes of illustration as shape 1 and shape 2. The following explains a non-limiting example of the functionality of the device. The device is in shape 1 at the time of insertion. Thus, before insertion, the SMA in the device is unactuated (i.e., martensitic phase). After insertion, the device gradually changes to shape 2 (its pre-determined shape, i.e., austenite phase), either by active or passive heating or cooling. The SMA in the device is actuated in order to move the rectum away from the radiation field. The device maintains shape 2 during the treatment session. In some cases, the actuation causes the repositioner device to be positioned next to the posterior wall of the rectum. The repositioner device pushes the posterior rectum wall, which in turn moves the anterior

rectum wall towards the posterior wall. Before removal, the organ repositioner device reverts back to shape 1 for easy removal. The shape changes are the result of temperature variation, which can be actively controlled via electric current or passively caused by body temperature. The temperature of the surface of the device does not exceed the safe temperature of 40° C. The motion is gradual to minimize the risk of injury. The maximum deflection of the device is limited to not cause any injury. Optionally, the device can be marked for reference such that the device is inserted with the markings pointed towards the posterior rectal wall, for ease of use.

The length of interest for the rectum is about 20 cm. That starts from posterior part of the external anal sphincter muscle to about where the rectosigmoid junction begins. The prostate, which is typically the organ that is intended for irradiation, is usually located in the middle of this length. In some embodiments, the organ repositioner device moves the wall of the rectum from where the prostate gland is by about 2 cm, though it is understood that the ideal length varies based on the patient's anatomy. In the 20 cm long device, the prostate is generally located at about 10 cm from the anus. In some embodiments, the displacement takes place starting from about the 5 cm point to about the 10-12 cm point along the rectal repositioner device.

The functionality of the organ repositioner device is achieved by combining the properties of a shape memory and/or a superelastic element as explained below. Active heating can take place either by directly passing a controlled current through the device or by passing controlled current through an external heating element that is wrapped around the SMA elements.

One embodiment is based on combining a superelastic round wire and a flat shape memory wire by wrapping the flat wire around the round wire. In this embodiment, the shape memory flat wire is shape set to assume shape 2 and the round superelastic wire is shape set to shape 1. At low temperature the assembly assumes shape 1 and at high temperature the assembly assumes shape 2. At an intermediate temperature, the assembly has an equilibrium shape between shape 1 and shape 2. In this configuration, the assembly is heated for the duration of the treatment but not for insertion and removal. Another embodiment is based on combining a superelastic round wire and a flat shape memory wire by wrapping the flat wire around the round wire. In this embodiment, the shape memory flat wire is shape set to assume shape 1 and the round superelastic wire is shape set to shape 2. At low temperature the assembly assumes shape 2, and at high temperature shape 1. At an intermediate temperature, the assembly has an equilibrium shape between shape 1 and shape 2. In this configuration, the assembly is heated for insertion and removal. The skilled person will recognize that the combination of an SM element and an SE element is versatile and customizable in many different ways.

The variation of electrical resistance is significant during phase transformation. By using the variation in electrical behavior during the phase transformation to determine the strain of SMA, the need of an external sensor in a feedback control is eliminated. While heating the wire, the resistance of the actuator can be monitored to measure the level of displacement in the device. Light indicators on a control unit can show the level of displacement based on the value of the electrical resistance. This is an additional assurance measure as imaging techniques are used to ensure the proper positioning for treatment. In some embodiments, a controller unit adjusts the level of current to the SMA actuator. The

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controller can have two modes of operation: manual and automatic. In the automatic mode, the operator selects the level of displacement needed. The control unit can adjust the current applied to the actuator to achieve the desired level of displacement while monitoring the electrical resistance of the SMA elements. In the manual mode, the operator adjusts the current applied to the SMA elements to achieve the desired level of displacement by continuously monitoring the electrical resistance.

In some embodiments, the repositioner device employs both of the two properties of SMAs: shape memory effect and superelasticity. An SM member when combined with an SE element creates an antagonistic actuator. The SM segment controls the actuation function, while the system is designed and operated in a way that the SE element provides the opposing actuation force and stroke. Actuation generally works best between two temperatures, referred to for ease of reference as a high temperature and a low temperature. The SE member is always in the austenite phase; that is, its austenite finish temperature is lower than both the high temperature and the low temperature. On the other hand, the SM element is initially in its martensite phase, which transforms to austenite at high temperature. To this end, the SM material should be selected such that its martensite finish temperature is below the low temperature and its austenite finish temperature is below the high temperature. The geometry of the SE and SM components and their memorized shape are set such that in low temperature, the memorized shape of the SE element is stronger and the assembly moves toward the SE element, which is designed to be the low-temperature (inactive) form of the actuator. At the high temperature, the SM segment exceeds its austenite temperature and deflects the assembly toward its memorized shape that is designed to be the high temperature (active) configuration of the device.

FIG. 6A illustrates an assembly that combines a superelastic round wire with a flat shape memory wire. In this embodiment, the SM element is a flat wire and the SE element is a ring shaped round wire. By wrapping the flat wire around the round SE member, an antagonistic actuator is formed. When the two members are assembled at a low temperature, they apply force on each other in a way that the SM wire tends to close the ring. Depending on the material properties, geometry, and the memorized shape of each of the two components, an equilibrium shape will be obtained at the low temperature. The left side of FIG. 6A displays the equilibrium or neutral position of the assembly at low temperature. By heating the SM element either by changing the thermal environmental conditions or by resistive heating, the assembly moves toward the shape set form of the SM member, which tends to close the ring, as shown on the right side of FIG. 6A. By cyclic heating and cooling, these two configurations can be repeated. It is understood, however, that the actuation stroke and shape generally depend on the geometry, material properties, and shape set forms of the SM and SE elements; thus, numerous actuation configurations are possible with the antagonistic actuator created by an assembly of SM and SE elements.

FIG. 6B shows a similar configuration where an actuator is created from a flat superelastic wire, which is wrapped around a SM wire to create a bidirectional bistable actuation.

To make an assembly such as shown in FIGS. 6A-6B, the two elements are shape set in the desired configurations that they should assume. When the two elements are in contact in the final assembly, the antagonistic actuator assumes a neutral position. At high temperatures, the SM element transforms to austenite, meaning the flat wire becomes

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stiffer. The higher stiffness should be sufficient to deform the superelastic round wire. At higher temperatures, the stiffness of the SM flat wire should be greater than the stiffness of the round SE wire. On the other hand, at the low temperature, the stiffness of the round SE wire should be greater than the stiffness of the SM wire. As soon as the SM wire is heated, it starts to actuate.

The organ repositioner device can be created by an assembly of SE and SM elements used as an alternative insert to existing endo-rectal devices. As shown in PRIOR ART FIG. 7A, a commercially available rectal positioner device is a balloon-based marker used for prostate fixation and to localize the rectum during the radiation treatment. However, this device has the potential to increase the chance of rectal toxicity as it causes the anterior rectal wall to be pushed against the prostate, which is the target, and in the direct field of the radiation. As an example of application, the repositioner device described herein can be an insert of the device shown in PRIOR ART FIG. 7A to provide the desired functionality of moving the rectal wall away from the prostate during the radiation therapy treatments.

FIGS. 7B-7C show photographs, and FIG. 1A shows an illustration, of an embodiment of the organ repositioner device where an assembly of SM and SE elements is an insert of an endorectal balloon device such as that shown in PRIOR ART FIG. 7A. As seen from FIG. 1A and FIGS. 7B-7C, the organ repositioner device 10 includes an inflatable endo-rectal balloon 12 mounted on a bendable tube 14 which defines a lumen 24. The tube 14 has a proximal end 26 and a distal end 28. The balloon 12 is mounted on the proximal end 26 of the tube 14. In some embodiments, the organ repositioner device includes multiple balloons 12, such as semispherical balloons, mounted on the tube 14. The organ repositioner device 10 can include an opening 30 at the proximal end 26 of the tube 14 connected to an air supply line 32 configured to deliver air from an air source 34 so as to inflate the balloon 12. It is understood that the air source 34 need not be external to the device; rather, the air source 34 can be a small cartridge that fits inside the lumen 24. Alternatively, the air supply line 32 can be connected to any source of pressurized air.

The lumen 24 houses an assembly 16 of the SM element 18 and the SE element 20 formed together. The SM element 18 has a first shape set form, and the SE element 20 has a second shape set form. Either the SM element 18 is formed around the SE element 20, or the SE element 20 is formed around the SM element 18. For example, the SM element 18 can be a wire wrapped around the SE element 20 wire, or vice versa. Though FIG. 1A depicts the assembly 16 as extending the length of the lumen 24, from the proximal end 26 to the distal end 28, the assembly 16 need not extend through the entire lumen 24. Rather, it is only important that the assembly 16 extend through enough of the lumen 24 so as to cause the bendable tube 14 to bend upon actuation of the assembly 16. In other words, the bendable tube 14 bends upon shape transformations of the assembly 16.

The assembly 16 has an equilibrium shape between the first shape set form and the second shape set form. Upon heating and/or cooling, such as through an electrical current, the assembly 16 is actuated and the bendable tube 14 bends accordingly. As seen from the photographs in FIGS. 7B-7C, the organ repositioner device 10 can utilize the preformed bend in the endorectal balloon device for actuation. In the example shown in FIG. 7C, the organ repositioner device bends 55° from the initial configuration. Alternatively, the bendable tube 14 could be made to bend at an additional or alternative location upon actuation of the assembly 16. The

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bending of the bendable tube **14** can reposition the desired organ into the desired location, such as away from the path of a radiation beam. For example, in use for repositioning a rectum during a prostate treatment, the proximal end **26** of the organ repositioner device **10** is inserted in the rectal cavity, where the balloon **12** is then inflated to stabilize the prostate, and the assembly **16** is actuated. Actuation of the assembly **16**, by heating or cooling (whether by active control or through passive heating/cooling caused by body temperature), causes the bendable tube **14** to bend and exert a pushing force on the rectal wall, thereby repositioning the rectum as desired.

The organ repositioner device **10** can further include a controller **22** for controlling the actuation of the assembly **16** as described below. The controller **22** is in electrical communication with the SM element **18** and the SE element **20**. The controller **22** can apply a voltage in the device **10**, and can determine the state of actuation by measuring electrical resistance in the device **10**. The controller **22** is generally configured to apply a voltage to the device in a closed loop feedback based on the measured electrical resistance. By heating and/or cooling and measuring the resistance of the device **10**, remote device displacement of an organ is possible with the device. Electronic circuitry on the controller **22** can give an indication of a safe range of displacement based on the feed value of the resistance. Changing the power input manually can allow safe and optimal dislocation of rectal tissue away from the field of radiation. The controller **22** can be configured to monitor the electrical resistance in the device, determine the actuation state of the device based on the measured actuation state, and control the voltage as necessary based on the determined actuation state.

As noted above, a shape memory alloy's resistance changes during transformation. In fact, the variation of electrical resistance during phase transformation is significant. Therefore, the change in resistance and other electrical properties can be used to sense the deformation of the material. The variation in electrical behavior during the phase transformation can be used to determine the strain of the shape memory alloy. In other words, the actuation state can be monitored by measuring the electrical resistance in the device. This eliminates the requirement of external sensors in a feedback control. Despite this ability of shape memory alloys, the phase transformation exhibits hysteresis behavior which acts as a drawback in using this self-sensing property in an SMA-based actuator.

There are two ways for modeling hysteresis. In the first method, a mathematical model is developed to model phase transformation and hysteresis behavior. Various phenomenological models have been proposed for this purpose. However, these constitutive models are based on experimentally determined parameters and approximations, which may not be suitable for online control system. Others have applied the Preisach model to capture hysteresis in SMA. However, these models involve complex equations with multiple parameters that are difficult to implement in a control scenario.

An alternative method is based on machine learning (ML) techniques, where experimental data are collected. An artificial neural network (ANN) is an example ML technique that is useful for SMA hysteresis modeling. As demonstrated in the Examples herein, an artificial neural network can accurately model the relationship between the electrical properties and manipulator position. However, it is understood that the device need not be used with an ANN.

The NiTi shape-setting can be optimized through cooling and heating the core alloy. The device may include an

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electronic circuit designed to induce the reversible NiTi austenitic transformation. In use, the motion of the repositioner device can be fully controlled in order to safely relocate the rectum during radiation treatment. Passive heating from the body can be utilized to cause the actuation. Alternatively, active heating can be applied to the device through an electrical current. As another alternative, the device can be fabricated such that cooling, instead of heating, causes the desired actuation. In such cases, the device can be heated prior to insertion, and allowed to cool inside the body to cause the desired actuation. The SMA materials provide great flexibility for customization of the device.

The organ repositioner device can be made in varying lengths of from about 10 cm to about 40 cm. The organ repositioner device can be manufactured to accommodate different rectal sizes through the use of expandable balloons in the distal part of the actuator, and is clinically comfortable during insertion and removal, as the device remains very flexible pre-actuation. The device can be marked at, for example, 1 cm intervals to provide a convenient reference to compensate for film or digital imaging magnification. When used for rectal repositioning, the device may or may not be used with an anus locator during X-ray imaging. The location of the device and the location of the organ being treated can be determined using conventional OBI device or even MV imaging onboard most accelerators.

Examples

This Example describes a system for controlling the methodology of a shape memory alloy-actuated rotary manipulator using the feedback signal from the artificial neural network model, thus eliminating the need for any external position sensor. The control methodology using a variable structure control technique was experimentally tested under different conditions. Also, the effect of environmental temperature on the ability of artificial neural network (ANN) to predict manipulator position was analyzed using phenomenological model simulations. It is concluded that this system gives a robust performance with a small tolerance (less than 5°) and can operate well even when the ambient temperature changes considerably.

A robust position control methodology was developed using an internal feedback from ANN. An accurate ANN model was used to determine the manipulator angle from the electrical properties of SMA. First, the ANN-determined position was used as a feedback signal to control the SMA-actuated rotary manipulator. The control system was experimentally tested under various scenarios to determine the robustness of the proposed system. Then, the effect of ambient temperature was analyzed as it was found to play an important role in SMA actuation control. To analyze this, an approximate phenomenological model was used to simulate the rotary manipulator system, and the effect of ambient temperature on the performance of ANN is analyzed.

Device Design

The experimental setup consisted of an SMA-actuated rotary manipulator, an Agilent E3631A controllable power supply, a dSPACE DS1104 board, and a central processing unit, the block diagram of which is shown FIG. 8. In this Example, a binary nickel-titanium alloy (nitinol) wire was used as an SMA actuator. A single degree-of-freedom bias-type manipulator used in this Example is shown in FIG. 9. In a bias-type manipulator, the upward force was generated by the SMA actuator, while the return force was generated by the bias spring. A 0.9-mm nitinol wire was used to actuate the rotary manipulator. The nitinol wire was connected from

the wire fixture, passing through the three pulleys on one side, then through the arm pulley, then through the three pulleys on the other side, and finally connected to the other wire fixture. Also, two different grooves were provided in lower pulleys; hence, the wires did not overlap. A list of parameters that describe the SMA-actuated rotary manipulator and their values is provided in Table 1 (FIG. 10). The actuation of SMA wire was controlled by adjusting the temperature through controlled joule heating by varying the electric current. The cooling took place through natural convection. The power supply was remotely controlled by a MATLAB program to apply a specific voltage. The amount of current passing through the SMA wire was also measured at that instant and was recorded. A position encoder was attached to the manipulator to measure the position of the manipulator arm. The position of the manipulator arm was measured, and the data were obtained in real time in MATLAB workspace through dSPACE DS1104 R&D board. The data of voltage and current were used to calculate the resistance of the wire, using ohms law. Thus, all the data were obtained in MATLAB workspace based on which further processing was done. FIG. 11 shows the relationship between electrical resistance and angular position during an open-loop experiment, where the voltage was increased linearly and then decreased in a similar fashion.

ANN Design

An ANN is a type of ML technique, which can be used to model a system based on data obtained from that system. ANN is an information processing system which is inspired from biological neural system's capability to learn from observation. A trained ANN can generalize any arbitrary input-output relationship. The two main components of an ANN are the neurons and the link between the neurons. The neuron acts as a processing element and is represented by a mathematical function called the activation function. These neurons are arranged in multiple layers, and this structure is commonly referred to as multilayer perceptron (MLP). The other important component of ANN is the link between the neurons. Each of these connections has a real valued parameter called weight associated with them. Once the training is complete, the values of weight vector are frozen, and the final weight vector encodes the input-output relationship. ANN has been used to model the hysteresis behavior of SMA. In this Example, the neural network toolbox of MATLAB was used to develop the ANN model. The inputs to ANN were electrical resistance of SMA, rate of change of current, and voltage applied. The output assigned to ANN was angular position of the rotary manipulator (in degrees). The Levenberg-Marquardt (LM) algorithm was used for training this ANN model. This algorithm is designed to approach second-order training speed without having to compute the Hessian matrix. The LM algorithm can be visualized as a combination of gradient descent algorithm and Newton's algorithm, thus having the advantages of both methods. The designing of ANN, method of weight initialization, and training was performed using known guidelines. The weight initialization was done using Nguyen-Widrow initialization algorithm. The hidden layer size was determined using network growing principle, whereas a single hidden layer was selected based on the universal approximation theorem. Early stopping mechanism was used to determine the number of epochs during training and to avoid over-fitting. Using the above techniques, the final design of ANN was obtained as 3 input layer neurons, 21 hidden layer neurons, and 1 output layer neurons.

Control Design

The control of SMA-actuated rotary manipulator was done using a modified variable structure control (VSC) algorithm. This algorithm was modified to include an integrator term. The logic of variable structure control-proportional-integral (VSC-PI) algorithm is given as follows:

$$u = \begin{cases} V_{high} & \text{if } \frac{s}{\phi} > 1 \\ V_{low} & \text{if } \frac{s}{\phi} < -1 \\ K_p \left(\frac{s}{\phi} \right) + K_i \left(\frac{s}{\phi} \right) dt & \text{if } 1 \geq \frac{s}{\phi} \geq -1 \end{cases}$$

where the boundary layer, K_p is the controller proportional gain, K_i is the integral gain, and s is defined as follows:

$$s = \left(\frac{d}{dt} (\theta_d - \theta) \right) + \lambda (\theta_d - \theta)$$

where θ is the angular position of the manipulator predicted by ANN, θ_d is the desired angular position of the manipulator, and λ is the slope of sliding surface in phase plane which is determined experimentally. A boundary layer is the region around the switching surface $s=0$, where a different control law (PI control law in this case) applies, thereby resulting in smoother control. The thickness of boundary layer is the region where this control law applies. The values of all the above control parameters were obtained experimentally. An SMA actuator has a very slow actuation speed. The VSC algorithm, described above, provides fast actuation, especially when the manipulator arm is away from the desired point, compared to conventional linear algorithms. The other advantages of VSC algorithm in actuating SMA-actuated rotary manipulator include robust control and insensitivity to unmodeled system dynamics. This algorithm was implemented using a MATLAB program.

Effect on Ambient Temperature

The effect of environmental temperature on SMA actuation and control is significant partly because resistance of the material is affected by the temperature. Moreover, in a bias-type actuator, the cooling of nitinol occurs by convection. Hence, it becomes important to analyze the performance of ANN when the environmental temperature is varied. To do this, an approximate phenomenological model was used to simulate the working of SMA-actuated rotary manipulator. The model used contains a number of submodels as shown in FIG. 12, and was implemented in MATLAB-Simulink environment. Signals were differentiated or integrated using the Simulink function as per the requirement. For training the ANN model, the Simulink model was simulated under varying ambient temperature conditions and open-loop position control. The values of resistance, rate of change of electric current, voltage applied, and manipulator angular position were recorded at each time step. These data were processed, and the ANN was trained by a method described below. The ANN was then tested with data from the same Simulink model when simulated under different ambient temperature conditions. The performance of ANN was evaluated based on its ability to predict the angular position under varying ambient temperature conditions. The results are described in the following section.

Results

ANN Training

This analysis was started by developing a robust ANN design which was able to accurately relate the electrical properties of SMA actuator and the manipulator angular position. The ANN was tested in complex situations. The SMA-actuated rotary manipulator was controlled using VSC-PI algorithm with position feedback from encoder, and the manipulator was made to track a complex signal. The position data collected from this experiment are shown in FIG. 13. These data were then used to train the ANN. The training was repeated a number of times to escape the problem of local minima associated with gradient-based approaches, and the model giving best performance is selected for further experiments.

ANN Testing

A similar experiment as described in the training section was performed, and the data from this experiment were used to test the developed ANN. The results of this testing are shown in FIG. 14. The analysis of error, that is, difference between actual and predicted positions, is presented as histogram, as shown in FIG. 15A. From the results, it is observed that the ANN is able to produce a good average accuracy of close to 0.8° .

Control System

Then, the developed ANN was used to provide position feedback in a control scenario as described in the block diagram shown in FIG. 16. The effect of control parameters ϕ and K_f was found to be significant. The use of nonzero K_f helped in reducing the steady-state error. A sufficiently large value of ϕ was needed to provide stable operation as the ANN output had small fluctuation.

Experiments

Then, the control system using ANN-predicted position feedback was tested under different conditions. First, the system was tested by making it to track a complex signal. The result of these experiments, with a comparison of desired, actual, and predicted positions, is shown in FIG. 17. The ANN prediction error analysis, that is, difference between actual and predicted positions, is shown in a form of histogram in FIG. 15B. The control error analysis, that is, difference between actual and desired positions, is shown as a histogram in FIG. 15C. From the results, it is observed that the prediction error accuracy was close to 0.8° , and the control error accuracy was close to 5° , which is good considering no external sensors are used. The system was also made to track simpler signals such as square wave, multi-step input, and staircase signal. An average control accuracy of 2° - 3° was obtained in these experiments. The control system was also tested by subjecting it to thermal and mechanical disturbances. The thermal disturbance was introduced by blowing air onto the system when the system was tracking a particular angular position. This cooled the SMA wires at a faster rate, and thus, the error was observed. Similarly, the mechanical disturbance was introduced by manually tapping the rotary arm when the system was tracking an angular position. This caused the arm to move down further, thereby introducing error in the system. However, as soon as the disturbances were removed, the system returned to the desired position. Thus, it was found that the system was able to reject these small disturbances, even though the ANN was not trained in these scenarios, as shown in FIGS. 18-19.

Effect of Ambient Temperature

The ANN was tested by varying the ambient temperatures. For this, ANN was developed from simulation as explained in section "Effect of ambient temperature." The simulation data were obtained using a chirp-sine input voltage (i.e. a sine wave with uniformly varying frequencies) with amplitude=8 V, bias=8.5 V, and angular frequency varying from 0.005 to 0.02 rad/s. At the same time, the ambient temperature was varied using a chirp-sine input voltage with amplitude=25V, bias=20V, and frequency from 0.004 to 0.02 rad/s. Thus, the simulation was performed with ambient temperature varying from 25° C. to 45° C. The simulation was performed for 750 s, and the recorded data were used for training an ANN. The values of applied voltage, ambient temperature, and simulated manipulator position are shown in FIG. 20. The ANN was then tested in three scenarios. First, the data were obtained by performing simulation at high ambient temperature range, that is, from 15° C. to 45° C. In the second simulation, the temperature range was varied from 25° C. to 15° C. In both the cases, the frequency variation was at the same rate as used in the training data. The variation of input voltage and ambient temperature during these two simulations is shown in FIGS. 21-22, respectively. In the third simulation, the temperature was varied from 23° C. to 43° C., and the angular frequency of the sine wave was varied from 0.006 to 0.01 rad/s, as shown in FIG. 23. The ANN test results for these three scenarios are shown in FIGS. 24-26, respectively. The average prediction error, that is, the difference between simulated angle and ANN-predicted angle, in these three test cases was 0.09° , 0.17° , and 0.15° , respectively. From the results, it is observed that the ANN is able to differentiate the ambient temperature variations if such data are included in training. In the first scenario, few data points with high prediction error are observed. This could be overcome by collecting more data point in those regions when training the ANN.

CONCLUSION

In this Example, a successful attempt has been made to develop a technique for sensorless position control of SMA-actuated rotary manipulator using ANN. First, an ANN was developed that can estimate the angular position using available electrical signals, so that the requirement of any external position sensors is eliminated. This ANN was then tested in different scenarios with varying complexities. The designed ANN was able to estimate the angular position accurately (average accuracy of 0.8°). The accuracy was good during both major and minor hysteresis loops, even though the complex thermomechanical relationship between stress and temperature altered the transformation temperature significantly at various instances of operation. The ANN was then used in VSC-PI control algorithm for sensorless control of SMA-actuated rotary manipulator. Multiple experiments were performed, where the rotary manipulator was made to track different reference signals of varying complexities. The SMA actuator was able to track the signals with an average accuracy of 5° . Also, as the SMAs have slow actuation speed, they had a larger response time. Since these values were also included in average error calculation, the value of steady-state error was concluded to be less than 5° . The system was also subjected to external disturbances and was found to be robust. The performance of ANN was not affected by the speed of actuation but was sensitive to large change in pre-stress and load on the manipulator. This is because the training data included scenarios with different speeds of actuation while only one

prestress and load condition was used. Thus, by incorporating variation of pre-stress in training data, the model could be made more robust to load and pre-stress changes. Thus, it is concluded that the design can be implemented in any scenario where a small tolerance of error (around 5°) is acceptable. Then, the developed ANN was tested under varying ambient temperatures. For this, a simulation model was used to generate data, and an ANN was trained. The ANN was then tested in three scenarios, and accurate prediction results were obtained in all the three cases. The ANN was able to operate with good accuracy under the test condition of varying ambient temperature ranges of 25° C. to 45° C. with varying frequencies. Thus, it is concluded that the ANN is robust to ambient temperature changes if trained with proper data.

Certain embodiments of the devices, systems, and methods disclosed herein are defined in the above examples. It should be understood that these examples, while indicating particular embodiments of the invention, are given by way of illustration only. From the above discussion and these examples, one skilled in the art can ascertain the essential characteristics of this disclosure, and without departing from the spirit and scope thereof, can make various changes and modifications to adapt the compositions and methods described herein to various usages and conditions. Various changes may be made and equivalents may be substituted for elements thereof without departing from the essential scope of the disclosure. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof.

What is claimed is:

1. An dual organ repositioner device comprising:

a first inflatable balloon mounted on a first bendable tube defining a first lumen,

a second inflatable balloon mounted on a second bendable tube defining a second lumen,

each lumen housing an assembly of a shape memory (SM) element and a superelastic (SE) element, wherein the SM element comprises a first shape memory alloy and has a first shape set form, and the SE element comprises a second shape memory alloy and has a second shape set form;

wherein each bendable tube bends upon shape transformations of the assembly, and the assembly has an equilibrium shape between the first shape set form and the second shape set form.

2. The dual-branched organ repositioner device of claim 1, wherein upon cooling the dual-branched organ repositioner device deforms toward the second shape set form, and heating drives the dual-branched organ repositioner device toward the first shape set form.

3. The dual-branched organ repositioner device of claim 1, wherein the SM element is a round wire and the SE element is a flat wire, wherein either the round wire is wrapped around the flat wire or the flat wire is wrapped around the round wire.

4. The dual-branched organ repositioner device of claim 1, wherein the first shape memory alloy comprises a NiTi alloy.

5. The dual-branched organ repositioner device of claim 1, wherein the second shape memory alloy comprises a NiTi alloy.

6. The dual-branched organ repositioner device of claim 1, wherein the first shape memory alloy and the second shape memory alloy are different NiTi alloys.

7. The dual-branched organ repositioner device of claim 1, further comprising a controller in electrical communication with the SM element and the SE element, wherein the controller is configured to apply a voltage in the dual-branched organ repositioner device.

8. The dual-branched organ repositioner device of claim 1, wherein the dual-branched organ repositioner device comprises a plurality of inflatable balloons mounted on each bendable tube.

9. A method of administering a radiation therapy to a prostate, the method comprising:

using the dual-branched organ repositioner device of claim 1 to displace a rectum away from a prostate with respect to a radiation beam path; and administering a radiation therapy to the prostate through the radiation beam path.

10. The method of claim 9, wherein the dual-branched organ repositioner device comprises a controller that monitors electrical resistance in the dual-branched organ repositioner device to determine an actuation state of the dual-branched organ repositioner device.

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