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(54) **Title:** STEERABLE INTRA-LUMINAL MEDICAL DEVICE

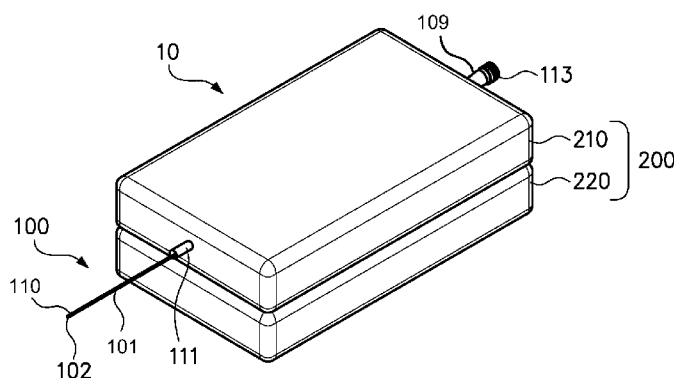


FIG. 1

(57) **Abstract:** The disclosure provides a flexible, narrow medical device (such as a micro-catheter or a guidewire) that is controllably moved and steered through lumens of a body. The medical device may include an electrically-actuatable bendable portion at a distal end, which may be provided by a polymer electrolyte layer, electrodes distributed about the polymer electrolyte layer, and electrical conduits coupled to the electrodes, such that the polymer electrolyte layer deforms asymmetrically in response to an electrical signal through one or more conduits. The disclosure further includes a controller for moving the device into and out of bodily lumens and for applying the electrical signal for steering the device. The device further includes methods of preparing the polymer electrolyte layer in tubular shape.



STEERABLE INTRA-LUMINAL MEDICAL DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application depends from and claims priority to U.S. Provisional Application No. 62/292,064 filed on February 7, 2016, which is fully incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

BACKGROUND OF THE INVENTION

Field of the Invention

[0003] The invention relates to a steerable intraluminal medical device and, more particularly, to a flexible, narrow medical device (such as a micro-catheter or a guidewire) introduced into and controllably moved through lumens of a body. The medical device may include an electrically-actuatable bendable portion at a distal, leading end that can be selectively manipulated for steering the medical device to a targeted anatomical location within a body.

Discussion of the Related Art

[0004] Intraluminal medical devices have various structures depending on the location within the body and the methods of treatment using the devices. Intraluminal devices generally include of a very slender and flexible tube that can be inserted into and guided through a lumen such as an artery or a vein, or a bodily passageway such as a throat, a urethra, a bodily orifice or some other anatomical passage. Examples of such medical

devices include syringes, endoscopes, catheters and micro-catheters, guide wires and other surgical instruments.

[0005] Some medical devices have a portion for being introduced into a body that generally comprises a flexible material that is easily bent by application of external force. In some medical devices, a distal, leading end (usually inserted first) may be selectively bent in a desired direction through manipulation of a steering mechanism by the user. The medical device can be inserted into a targeted lumen or bodily passage and moved to dispose a distal end of the medical device at a desired location in the body.

[0006] Surgical techniques for inserting and/or guiding a medical device into and/or through a lumen or passage in a body have been proposed in response to the rise in demand for minimally invasive surgical techniques. Many surgical techniques offer poor directional control or cumbersome manipulative components.

SUMMARY OF THE INVENTION

[0007] Embodiments of the steerable intraluminal medical device provide improved steering control and intra-body positioning of an actuation part (e.g., a micro-catheter or a guidewire) of a medical device wherein the actuation part is adapted to be introduced into a lumen or a bodily passage of a body and manipulated while being extended for movement into and through the lumen and/or bodily passage to dispose a distal end of the actuation part of the medical device at a desired anatomical location within the body. Embodiments of the medical device provide more precise control of movement and positioning of one or more manipulatable microsurgical components disposed at a distal, leading end of the actuation part of the medical device for performing a surgical procedure or other medical operation at the desired location within the body.

[0008] One embodiment of a medical device having an actuation part (e.g., a micro-catheter or a guidewire) for being moved into and/or through a lumen or a bodily passage comprises a slender, elongate and flexible portion having a distal end and a proximal end, an ionic electroactive polymer actuator comprising a polymer electrolyte layer disposed adjacent to the distal end of the elongate and flexible portion. The ionic electroactive polymer actuator, as will be discussed in greater detail below, is an actuator comprising a polymer electrolyte layer in which cations are free to migrate in response to an imposed electrical field. The electrical field is provided through energization of a plurality of angularly distributed electrodes disposed on the polymer electrolyte layer. The plurality of angularly distributed electrodes are one of embedded in, deposited on and secured against at least a portion of an exterior wall of the polymer electrolyte layer. Each of the plurality of electrodes may be connected to a source of electrical current through one or more electrically-conductive conduit such as, for example, a metal wire, being surrounded with the outer member and having a proximal end coupled to the source of electrical current and a distal end coupled to the electrode. Selective electrical energization of one or more of the plurality of electrodes causes the polymer electrolyte layer to deform as a result of contraction along a side or portion of the polymer electrolyte layer and/or swelling along a side or portion of the polymer electrolyte layer. It will be understood that cations within the polymer electrolyte layer will migrate towards an energized and anodic electrode, and away from an energized and cathodic electrode, while remaining within the matrix of the polymer electrolyte layer. This causes a portion adjacent to an energized anodic electrode to swell and a portion adjacent to an energized and cathodic electrode to contract, thereby causing the polymer electrolyte layer to bend. It will be understood that coordinated control of

electrical signals delivered to the electrodes through electrically-conductive conduits can produce bending in an intended direction. In some embodiments, the plurality of electrodes may be further electrically connected to a sensing member to sense changes in the electrical signal at each of the plurality of electrodes. Accordingly, the sensing member may detect whether the ionic electroactive polymer actuator deformed or not.

[0009] In one embodiment of the medical device, the ionic electroactive polymer actuator may comprise a plurality of angularly distributed electrodes equi-angularly distributed about the exterior wall of the polymer electrolyte layer. In one embodiment of the medical device, the ionic electroactive polymer actuator may be included in a bendable portion at the distal end of an actuation part (e.g., a micro-catheter or a guidewire) of the medical device. For example, but not by way of limitation, the bendable portion of the medical device may, in one embodiment, comprise three angularly-distributed electrodes that are separated, at their centerlines, one from the others by about 120 degrees (2.094 radians). As another example, but not by way of limitation, the bendable portion of the medical device may comprise eight angularly-distributed electrodes that are separated, at their centerlines, by about 45 degrees (0.785 radians). It will be understood that each of the plurality of electrodes occupies a circumferential span about the exterior wall of the polymer electrolyte layer, and that the “angular separation” may therefore be stated in terms of the centerlines of the electrodes instead of in terms of the adjacent edges of the electrodes, which will be much closer to the adjacent edge of the adjacent electrode. In some embodiments of the medical device, the electrodes are spaced in a manner to provide a substantial gap intermediate adjacent electrodes.

[0010] In a bendable portion at the distal end of an actuation part of another embodiment of the medical device, the ionic electroactive polymer actuator is provided in which the plurality of electrodes circumferentially distributed about the exterior wall of a polymer electrolyte layer are, along with at least a portion of an adjacent inner member of the elongate and flexible portion, surrounded by an outer member, coating, sheath or other barrier having a bore in which at least a portion of the plurality of electrodes and at least a portion of the polymer electrolyte layer surrounded by the electrodes are together disposed. The outer member, or an exterior wall of the outer member, may comprise a low-friction, hydrophilic and/or lubricious material that promotes smooth sliding engagement between the elongate and flexible portion of the medical device and an interior wall of a lumen or a bodily passage into which the actuation part of the medical device is introduced and through which the elongate and flexible portion of the medical device is extended to position a distal end of the actuation part of the medical device at a targeted location within a body. The outer member may comprise one or more materials including, but not limited to, nylon, polyurethane and/or a thermoplastic elastomer such as, for example, PEBAX[®], a polyether block amide material available from Arkema France Corporation of Colombes, France.

[0011] In one embodiment of the medical device, the plurality of electrically-conductive conduits that conduct electrical signals from a source of electricity to one or more of the plurality of electrodes to affect bending of the polymer electrolyte layer comprise a noble metal for superior chemical stability and corrosion resistance. For example, but not by way of limitation, the electrically-conductive conduits that deliver current to selected electrodes to actuate the polymer electrolyte layer may comprise highly conductive platinum, a platinum alloy, silver or a silver alloy, or they may comprise gold or a gold

alloy which, in addition to being chemically stable and corrosion resistant, is malleable and can be advantageously formed into very slender electrically-conductive conduits with very low resistance to bending.

[0012] In a relaxed or un-energized state, the polymer electrolyte layer of the ionic electroactive polymer actuator remains in its original form.

[0013] One embodiment of the elongate and flexible portion of the medical device includes an elongate, flexible inner member having a distal end, a proximal end, a radially interior bore with an axis, and a radially exterior wall, at least one ionic electroactive polymer actuator comprising polymer electrolyte layer having a bore, the polymer electrolyte layer secured adjacent to the distal end of the inner member with the bore of the polymer electrolyte layer aligned with the bore of the inner member, a plurality of electrodes circumferentially distributed about the at least one polymer electrolyte layer, and a plurality of electrically-conductive conduits, each having a proximal end and a distal end coupled to at least one of the plurality of electrodes, and an elongate and flexible center wire having a proximal end, a distal end and a diameter therebetween that is smaller than the diameter of the bore of the inner member to enable the distal end of the center wire to be introduced into the bore of the inner member and to then be pushed through the bore of the inner member to position the distal end of the center wire adjacent to the distal end of the inner member, a radially compressed and resilient spring member coupled to the distal end of the center wire, the compressed spring member sized, in an uncompressed or expanded configuration, for exceeding the diameter of the bore of the inner member in an expanded configuration and for fitting within and being positioned in the bore of the inner member by the center wire in a compressed configuration, wherein the polymer electrolyte layer

of the ionic electroactive polymer actuator deforms asymmetrically in response to the application of one or more electrical signals conducted from a source of electrical current (which may be further coupled to the proximal end of each electrically-conductive conduit) through at least one of the plurality of electrically-conductive conduits to at least one of the plurality of electrodes coupled to a distal end of the at least one of the plurality of electrically-conducting electrodes, and wherein the center wire can be used to position the spring member immediately adjacent to the distal end of the inner member with the inner member disposed within or immediately adjacent to an obstruction in a lumen into which the inner member is introduced, and wherein the spring member can be expanded from the compressed configuration to the expanded configuration to engage and grip the obstruction in the lumen by retracting the inner member while maintaining the center wire stationary relative to the inner member to cause the compressed spring member to be removed from the bore of the inner member and released from the radially compressed configuration to the expanded configuration within the obstruction to be gripped by the expanded spring member, thereby allowing the obstruction to be retrieved from the lumen by retrieving the center wire and the inner member together from the lumen. In one embodiment, the spring member is a coil spring having a plurality of coils aligned in a series. In another embodiment, the spring member includes a plurality of corrugated or sinusoidally shaped wires, each wire coupled at the apexes of the waves or peaks to the apexes of the waves or peaks of an adjacent wire to form a generally tubular or cylindrically shaped spring assembly. It will be understood that expandable spring elements of this type generally elongate as they radially expand from a radially compressed configuration to a radially expanded configuration.

[0014] One embodiment of the medical device includes an electrically insulating layer disposed within the bendable portion of the medical device. This insulating layer provides a flexible insulating boundary layer that contains but conforms to the polymer electrolyte layer as it deforms in response to an electrical field imposed by electrical signals conducted to the surrounding electrodes to provide advantageous steering of the medical device as it is positioned within a lumen or bodily passage.

[0015] The polymer electrolyte layer comprises an electrolyte (e.g., ionic liquid, but not limited to this) and a polymer selected from the group consisting of fluoropolymers and intrinsically conducting polymers. One embodiment of a method of preparing a tubular polymer electrolyte layer for use in providing an ionic electroactive polymer actuator in a bendable portion of a medical device comprises: providing a liquid dispersion of a base material selected from the group consisting of fluoropolymers and intrinsically conducting polymers, disposing the liquid dispersion on a substrate, curing the liquid dispersion of the selected base material to form a polymer film on the substrate, providing a mandrel, wrapping the polymer film onto the mandrel, and providing a heat-shrink tube, covering a portion of the mandrel wrapped in the polymer film with the heat shrink tube, and heating the heat-shrink tube to cause reflow the polymer film to form a tubular polymer electrolyte layer.

[0016] The polymer electrolyte layer may comprise, for example, but not by way of limitation, a polymer membrane containing an electrolyte (e.g., solvent such as, water or an ionic liquid). Alternately, the polymer electrolyte may comprise a porous polyvinylidene fluoride or polyvinylidene difluoride, a highly non-reactive thermoplastic fluoropolymer produced by the polymerization of vinylidene difluoride, and containing ionic liquid or salt water. Alternately, the polymer electrolyte may comprise a gel formed

by polyvinylidene fluoride or polyvinylidene difluoride, propylene carbonate and an ionic liquid.

[0017] In one embodiment of the method of preparing a tubular polymer electrolyte layer for use in providing an ionic electroactive polymer actuator in a bendable portion of a medical device, the material selected to use in forming the base material comprising fluoropolymers and/or intrinsically conducting polymers. For example, the material may be, one of Nafion® and Flemion®, which are perfluorinated ionomers. In another embodiment of the method, the material selected to use in forming the base material comprising one of polyvinylidene difluoride (PVDF) and/or one of a co-polymer thereof, for example, one of polyvinylidene difluoride-co-chlorotrifluoroethylene (P(VDF-CTFE)) and polyvinylidene fluoride-co-hexafluoropropylene (P(VDF-HFP)), which are fluoropolymers. In yet another embodiment of the method, the material selected to use in forming the base material comprising an intrinsically conductive polymer (ICP), for example, one of polyaniline (PANI), polypyrrole (Ppy), poly(3,4-ethylenedioxythiophene) (PEDOT) and poly(p-phenylene sulfide)(PPS). In yet another embodiment of the method of preparing a tubular polymer electrolyte layer, the material selected to use in forming the base material comprises a combination of two or more of the above listed and described base materials.

[0018] One embodiment of the method of preparing a tubular polymer electrolyte layer includes the step of dissolving the base material in a volatile solvent to form the liquid dispersion. The volatile solvents that may be used for this step include, but are not limited to, acetates, alcohol, chloroform, ether, aliphatic hydrocarbons, aromatic hydrocarbons, chlorinated hydrocarbons and ketones.

[0019] One embodiment of the method of preparing a tubular polymer electrolyte layer includes the step of disposing the liquid dispersion of the selected base material onto a solid substrate comprising one of polytetrafluoroethylene (PTFE) or glass. However, other solid substrates having non-stick surfaces may be substituted.

[0020] A first example of an embodiment of the method of preparing a tubular polymer electrolyte layer includes preparing a liquid dispersion of Nafion[®] in 10 to 20 wt. % alcohol, disposing the liquid dispersion on a flat PTFE substrate using a doctors' blade method to form a thickness of 15–25 μm , curing the liquid dispersion on the substrate at 68 °F (20 °C), removing volatile solvents by thermal treatment at 176 to 248 °F (80 to 120 °C), rolling the resulting Nafion[®] film around a stainless steel mandrel rod having an outside diameter of 0.025" (0.635 mm) by manually rotating the mandrel while translating the mandrel across the substrate to roll-up the Nafion[®] film into a tubular shape having an interior diameter and a wall thickness.

[0021] The resulting interior diameter and wall thickness of the resulting polymer tubing depend on the mandrel size, the thickness of the Nafion[®] film and the number of times the mandrel can be wrapped with the Nafion[®] film during the rolling step. The mandrel with the rolled Nafion[®] film is fitted into a fluorinated ethylene-propylene (FEP) heat-shrink sleeve and then heated at the recovery temperature of the heat-shrink material 392 to 446 °F (200 to 230 °C). During heating, the layers of the rolled Nafion[®] film are reflowed into a single homogenous polymer layer. After cooling and removing the heat-shrink tube and mandrel, a Nafion[®] tube having a homogenous morphology without traces of rolled layers. The tolerance of the wall thickness of the prepared Nafion tube is similar to commercially extruded Nafion tubing (+/- 10%) but is prepared without the

need for commercial extrusion equipment that can require a large amount of space and equipment.

[0022] A second example of an embodiment of the method is to prepare a PVDF tube, including the steps of providing a plurality of Poly[(vinylidene difluoride)-co-(chlorotrifluoroethylene)] (P(VDF-CTFE)) pellets, dissolving the pellets in acetone by heating and stirring the pellets in the acetone at about 122 °F (50 °C) for 4 hours. The prepared dispersion is disposed on a flat PTFE substrate using the doctors' blade. The substrate and dispersion disposed thereon are cured at 68 °F (20 °C) for 30 minutes and the resulting film is then peeled from the PTFE substrate. The prepared P(VDF-CTFE) film is vacuum dried at 172 °F (80 °C) to remove the residual solvent. The formed PVDF film of 15–25 µm in thickness is rolled around a stainless steel mandrel rod having an outer diameter of 0.025 inches (0.635 mm) by manually rotating the mandrel and translating the mandrel across the film. The mandrel with the rolled PVDF film thereon is fitted into a heat-shrink polymer tube (e.g., fluorinated ethylene-propylene (FEP)) and heated at a recovery temperature of the heat-shrink material 392 to 446°F (200 to 230 °C). The heating causes the layers of the rolled PVDF film to reflow into a single homogenous polymer tube wall. The heat-shrink tube is removed after cooling from the mandrel to remove the PVDF tube.

[0023] To further prepare an ionic electroactive polymer actuator, the prepared Nafion tube or PVDF tube may be further processed to deposit metal electrodes thereon (e.g., platinum or gold electrodes) using conventional methods such as an electrochemical process. Then, wires (e.g., gold wires) can be further integrated and embedded into the prepared metal electrodes using conducting paste or laser welding to serve as electrically-conductive conduits. Alternatively, in one embodiment, the prepared Nafion

tube or PVDF tube may be further processed to deposit carbon-based electrodes using a new reflow method provided and explained in further detail below for use in providing a tubular ionic electroactive polymer actuator. Then, wires (such as gold wires) can be further integrated and embedded into the prepared carbon-based electrodes during the reflow method to serve as electrically-conductive conduits.

[0024] In one embodiment, a method of preparing a tubular ionic electroactive polymer actuator of a medical device by disposing carbon-based electrodes on a polymer electrolyte layer with a heat-shrink tube using reflow process is provided. The method may comprise: providing a polymer electrolyte layer having a radially exterior wall, providing a mixture of a carbon-based conductive powder in a volatile solvent, providing a plurality of electrically-conductive conduits, each having a proximal end and a distal end, disposing the mixture on the exterior wall of the polymer electrolyte layer to form a carbon electrode layer thereon, contacting the distal end of each electrically-conductive conduit to the carbon electrode layer, providing a heat-shrink tube, covering the polymer electrolyte layer and the carbon electrode layer thereon with the heat-shrink tube, and heating the heat-shrink tube to cause reflow of the polymer electrolyte layer to form the ionic electroactive polymer actuator. In another embodiment of the method of preparing a tubular ionic electroactive polymer actuator of a medical device, the polymer electrolyte layer may be further impregnated with an electrolyte. For example, the electrolyte may be an ionic liquid including, but not limited to, 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF₄), 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-TFSI) or the combination thereof. In yet another embodiment of the method of preparing a tubular ionic electroactive polymer actuator of a medical device, a portion of the carbon electrode layer is further covered with one or

more metal layer to increase the electrical conductivity of the obtained carbon-based electrodes. The metal layer herein may be, for example, but are not limited to a gold layer, a platinum layer or the combination thereof.

[0025] In other embodiment of the method of preparing a tubular ionic electroactive polymer actuator of a medical device, the carbon-based conductive powder may be carbide-derived carbon, carbon nanotube, carbon aerogel, graphene, or the combination thereof. In some embodiments, the carbon-based conductive powder may optionally comprise fillers such as transition metal oxide powder, metal powder or the combination thereof. In some embodiments, the mixture of a carbon-based conductive powder is disposed on the exterior surface of the polymer electrolyte layer using brush coating or spray coating. In other embodiments, the carbon electrode layer is further micro-machined to form a plurality of electrodes after heating the heat-shrink tube.

[0026] In one embodiment of the medical device, an electrical controller is provided for controlling bending of the bendable portion by applying electrical signals to an ionic electroactive polymer actuator in the bendable portion. The electrical controller may be provided at the proximal end of the elongate, flexible portion and electrically connected to the electrically-conductive conduits for selectively controlling the electrical charges carried by the electrically-conducting conduits and imparted to the plurality of electrodes to manipulate the at least one ionic electroactive polymer actuator of the medical device. In another embodiment, the electrical controller may be further instructed by a master controller. The master controller may comprise a manipulatable control member for inputting the bending control signals to the at least one ionic electroactive polymer actuator for providing two degrees of freedom of bending through the electrical controller.

[0027] To steerably control the medical device, in some embodiments, the medical device further comprises a driving assembly for moving the medical device (e.g., the flexible, elongated member portion) lengthwise. The drive assembly includes: a first rotary drive member with a gripping surface, an adjacent second rotary drive member with a gripping surface disposed proximal to the gripping surface of the first rotary drive member, and at least one electrically powered motor coupled to controllably rotate at least one of the first rotary drive member and the second rotary drive member and wherein, the medical device is disposed intermediate and engaged by the gripping surface of the first rotary drive member and the gripping surface of the adjacent second rotary drive member so that rotation of one of the first rotary drive member and the second rotary drive member axially moves the medical device. In one embodiment of steerably controlling the medical device, clockwise rotation of the first rotary drive member and counterclockwise rotation of the adjacent second rotary drive member moves the medical device in a first direction; and counterclockwise rotation of the first rotary drive member and clockwise rotation of the adjacent second rotary drive member moves the medical device in a second direction opposite to the first direction. In another embodiment, the driving assembly may be also further instructed by the master controller that comprise a manipulatable control member for inputting advance and retract control signals to the drive assembly for providing one degree of freedom of translation. In some embodiments, the master controller may provide the bending control signals as well as the advance and retract signals.

[0028] In one embodiment of steerably controlling the medical device, the medical device may further comprise a case that includes: a first portion having a sealed interior portion containing the first rotary drive member, the second rotary drive member, a

proximal port through which the medical device passes, a distal port through which the medical device passes, and an interior cavity for storing windings of the medical device; and wherein the case further includes a second portion supporting the motor. In another embodiment, the second portion of the case and the first portion of the case are adapted for being coupled one to the other to operatively engage the motor with at least one of the first rotary member and the second rotary member. In other embodiments, the first portion may be disposable, for example, after use and contamination by bodily fluids contacted by the medical device.

[0029] In one embodiment, for remotely controlling/positioning the medical device when being introduced into and moving through a lumen of a human body, the medical device may further comprise: a transmitter coupled to the master controller for transmitting a signal corresponding to the manipulation of the master controller; and a receiver electrically connected to the drive assembly and the electrical controller for receiving the signal transmitted by the transmitter to the drive assembly and/or the electrical controller to correspond to the manipulation of the controller.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The appended illustrative drawings provide a further understanding of embodiments and are incorporated into and constitute a part of this application and, together with the written description, serve to explain the present invention. The appended drawings are briefly described as follows.

[0031] FIG. 1 is a perspective view showing one embodiment of a case for containing components used to controllably extend and retract an extendable actuation part of a medical device.

[0032] FIG. 2 is a perspective view of the elongate, flexible portion and a bendable portion disposed at the distal end of the actuation part of the embodiment of the medical device of FIG. 1.

[0033] FIG. 3 is the perspective view of the distal, bendable portion at the distal end of the actuation part of FIG. 2 illustrating the bending mode.

[0034] FIG. 4A is a cross-sectional view of the distal end of the bendable portion of FIGs. 2 and 3 illustrating a first selected set of four electrical signals applied to the four angularly-distributed electrodes disposed about the polymer electrolyte layer. The arrow indicates the direction of bend produced by the application of the illustrated set of electrical signals to the four individual electrodes.

[0035] FIG. 4B is the cross-sectional view of the distal end of the bendable portion of FIG. 4A revealing a second selected set of four electrical signals applied to the angularly distributed electrodes disposed about the polymer electrolyte layer. The arrow indicates the direction of bend produced by the application of the illustrated electrical signals to the four individual electrodes.

[0036] FIG. 5 is a perspective view of an alternative embodiment of a bendable portion and an elongate, flexible portion of an actuation part of a medical device of one embodiment having a plurality of individual electrodes separated both longitudinally and circumferentially. Each individual electrode is connected to an electrically-conductive conduit which provides an electrical signal to the electrode.

[0037] FIG. 6 is a block diagram schematically illustrating the systems and components that are used to use and control an embodiment of the medical device of FIGs. 1-4B.

[0038] FIG. 7 is a lengthwise sectional view of a distal end of an extendable and steerable actuation part of an embodiment of a medical device, including a distal, bendable portion and an elongate, flexible portion.

[0039] FIG. 8A is a perspective view of an upper case portion of the case of the embodiment of the medical device of FIG. 1 with the upper case portion of the case indicated in dotted lines to better reveal the components disposed therein.

[0040] FIG. 8B is a perspective view of a lower case portion of the case of the embodiment of the medical device of FIG. 1 with the lower case portion of the case indicated in dotted lines to better reveal the components disposed therein.

[0041] FIG. 9 is an elevational sectional view of an embodiment of a medical device provided by assembling of the upper case portion and the lower case portion of FIGs. 8A and 8B. The medical device is in wireless communication with a master controller.

[0042] FIG. 10 is a flowchart illustrating the steps of a method of performing surgery by use of the embodiment of an embodiment of the medical device illustrated in FIGs. 7A, 7B and 8.

[0043] FIG. 11 is a flowchart illustrating a method of imparting a bend to a bendable portion at the distal end of an actuation part of an embodiment of the medical device.

[0044] FIG. 12 is a modification of the block diagram of FIG. 6 illustrating the control system structure for an alternative embodiment of the medical device including an actuation part and a case.

[0045] FIG. 13 is a graph illustrating variance over time in an electrical signal applied to an electrode disposed with other electrodes to surround a polymer electrolyte layer of a bendable portion of an actuation part of an embodiment of a medical device.

[0046] FIGS. 14 is a cross-sectional view illustrating an alternative distribution of individual electrodes in recesses formed into a polymer electrolyte layer of a bendable portion of an actuation part of an embodiment of a medical device.

[0047] FIG. 15 is a cross-sectional view of an alternative configuration for a bendable portion of an actuation part of the medical device.

[0048] FIG. 16 is a flowchart illustrating a method of using a sensing member to monitor the performance of an embodiment of a medical device and of determining the impact of an external force on the performance of the embodiment of the medical device.

[0049] FIG. 17 illustrates an alternate embodiment of the case portion of the medical device for controllably advancing and withdrawing the actuation part of the medical device.

[0050] FIG. 18 is a perspective view of an alternative case with a guide barrel removed to reveal the positions of the components therein.

[0051] FIG. 19 is perspective view of an elongate, flexible portion of an actuation part of a medical device with a section of an outer member removed to reveal details of the components of the actuation part of this embodiment of the medical device.

[0052] FIG. 20 is cross-sectional view of an embodiment of an elongate, flexible portion of an actuation part of a medical device. The elongate, flexible portion may include electrically-conductive conduits and a metal reinforcing mesh or braid.

[0053] FIG. 21 is a cross-sectional view of an alternative embodiment of the elongate, flexible portion of an actuation part of the medical device in which each of the electrically-conductive conduits are embedded within a lumen structure and each electrically-conductive conduit and its lumen structure are together encased within the material of the outer member.

[0054] FIG. **22** a cross-sectional view of an alternative embodiment of the elongate, flexible portion of an actuation part of the medical device in which each of the electrically-conductive conduits are electrically insulated encased within a single, tubular insulation member that is surrounded by the outer member.

[0055] FIG. **23** is a modification of the block diagrams of FIGs. **6** and **12** illustrating a control system for an alternative embodiment of the medical device including an actuation part and a case.

[0056] FIG. **24** is an enlarged view of a portion of FIG. **5** showing an arrangement of four electrically-conductive conduits adhered to an exterior surface of the inner member of the elongate, flexible portion of a medical device.

[0057] FIG. **25** is an enlarged perspective view of an ionic electroactive polymer actuator that is included in the bendable portion of an actuation part of an alternate embodiment of the medical device.

[0058] FIG. **26** is an illustration of a distal end of an actuation part of an embodiment of a medical device with a spring member, in a radially compressed configuration, coupled to a center wire advanced through the bore of the actuation part to dispose the spring element adjacent to an obstruction in a lumen.

[0059] FIG. **27** is an illustration of the spring member in an expanded configuration, obtained by withdrawal of the bore of the actuation part while holding the center wire stationary, to expand and grip the obstruction for removal with the actuation part and the center wire.

[0060] FIG. **28** is an alternative embodiment of the spring member that can be used to implement the method illustrated by FIGs. **26** and **27**.

[0061] FIG. 29 is a perspective view of the elongate, flexible portion and a bendable portion disposed at the distal end of the actuation part of another embodiment of the medical device of FIG. 1.

[0062] FIG. 30 is the perspective view of the distal, bendable portion at the distal end of the actuation part of FIG. 29 illustrating the bending mode.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0063] Medical devices such as catheters or guidewires may be sufficiently slender for being inserted into a lumen such as an artery, a vein, a throat, an ear canal, a nasal passage, a urethra or any of a number of other lumens or bodily passages. These slender catheters (also referred to as micro-catheters) and guidewires, enable physicians to perform non-invasive surgery requiring a substantially shortened recovery period by preventing the need for cutting a subject or a patient to provide local access for performing a surgical procedure or medical operation. As used herein, the terms “subject” or “patient” refer to the recipient of a medical intervention with the device. In certain aspects, the patient is a human patient. In other aspects, the patient is a companion, sporting, domestic or livestock animal.

[0064] The following paragraphs describe certain embodiments of medical devices that can be used to perform or to enable the performance of surgical operations using the same, and methods that can be used to enable the preparation of such medical devices for same. It will be understood that other embodiments of medical devices and methods are within the scope of the claims appended herein below, and the illustration of such embodiments is not limiting of the present invention.

[0065] FIG. 1 is a perspective view showing one embodiment of a medical device **10** having a case **200** and an actuation part **100**. The medical device **10** of FIG. 1 includes an upper case portion **210** and a lower case portion **220** of the case **200**, the medical device **10** further including a flexible, elongate and slender actuation part **100** that comprises an elongate, flexible portion **101** to be extendable from the upper case portion **210** of the case **200** and a bendable portion **110** (FIG. 2) disposed at the distal end **102**. The elongate, flexible portion **101** comprises an inner member **120** (FIG. 2) that is sufficiently slender to can be inserted into a lumen (not shown) of a body (not shown). Also the inner member **120** is sufficiently flexible and substantially axially incompressible so that it can be advanced through a lumen having a winding pathway by pushing or driving the elongate, flexible portion **101** of the actuation part **100** forward after a distal end **102** of the actuation part **100** is introduced into the lumen of the body (not shown). The actuation part **100** further includes a proximal end **109**. The medical device **10** may be a micro-catheter having a bendable portion **110** that comprise an interior bore **140** (FIG. 2) to facilitate the movement of an elongate structure (not shown). In one embodiment, the elongate structure may be fed from the proximal end **109** through the interior bore **140** (FIG. 2) to and through the distal end **102** of the actuation part **100** of the medical device **10**. Alternatively, the medical device **10** may be a guidewire having a bendable portion **110** without an interior bore **140** (e.g., FIG. 29).

[0066] Optionally, the proximal end **109** of the actuation part **100** may include a fastener such as, for example, threads **113**, for use in securing a mating socket or other structure to the proximal end **109** of the actuation part **100**. Optionally, the upper case portion **210** of the case **200** of the medical device **10** may include a guide barrel **211** for

imparting a forward directional aspect to a distal portion **102** of the actuation part **100** that extends beyond the case **200**.

[0067] FIG. **2** is a perspective view of the elongate, flexible portion **101** and a bendable portion **110** disposed at the distal end **102** of the actuation part **100** of the embodiment of the medical device **10** (e.g., a micro-catheter) of FIG. **1**. The bendable portion **110** of the actuation part **100** includes an ionic electroactive polymer actuator comprising a polymer electrolyte layer **139** disposed adjacent to the inner member **120** of the elongate, flexible portion **101** and centrally to an angularly-distributed plurality of energizable electrodes **112**. Each of the plurality of electrodes **112** that surrounds the exterior wall **137** of the polymer electrolyte layer **139** is connected to a distal end **131** of an electrically-conductive conduit **130** through which an electrical signal or current may be supplied to the connected electrode **112**. The polymer electrolyte layer **139** includes a bore **140** through which other elongate structures may be inserted to position, control and/or actuate an effector or surgical tool or instrument disposed at the distal end of the elongate structure. The bore **140** of the polymer electrolyte layer **139** is, in a relaxed or de-energized condition, centered about an axis **141**. The bendable portion **110** of FIG. **2** is illustrated in the straight mode. The bendable portion **110** can be selectively and controllably deformed to a bent mode by selective energization of one or more of the plurality of electrodes **112**, as will be explained in further detail below.

[0068] In one embodiment of the medical device **10**, the ionic electroactive polymer actuator of the bendable portion **110** of FIG. **2** is an ionic polymer-metal composite (IPMC) actuator. In one embodiment of the medical device **10**, the ionic electroactive polymer actuator comprises a polymer electrolyte layer **139** made of a perfluorinated ionomer of Nafion[®] (Nafion[®] is available from E. I. DuPont de Nemours and Company)

that have superior ion transport properties. Alternately, other embodiments of the ionic electroactive polymer actuator of the medical device **10** may include a polymer electrolyte layer **139** that comprises a perfluorinated ionomer such as Aciplex™ (available from Asahi Kasei Chemical Corp. of Tokyo, Japan), Flemion® (available from AGC Chemical Americas, Inc. of Exton, Pennsylvania, USA) or fumapem® F-series (available from Fumatech BWT GmbH, Bietigheim-Bissingen, Federal Republic of Germany). In a preferred embodiment, the perfluorinated ionomer is Nafion®.

[0069] In one embodiment of the medical device **10**, the electrically-conductive conduits **130** may comprise one of platinum, gold, carbon, alloys thereof or a combination thereof. In other embodiments, the material for electrodes **112** may comprise carbon, such as carbide-derived carbon, carbon nanotubes, a composite of carbide-derived carbon or ionomer, and a composite of carbon nanotube and ionomer. A method according to one embodiment of disposing the carbon-based electrodes **112** onto the polymer electrolyte layer **139** will be discussed herein below.

[0070] Each of the plurality of electrodes **112** is connected to a distal end **131** of an electrically-conductive conduit **130** through which an electrical signal may be applied to the electrode **112** to which the conduit **130** is connected, thereby causing metal cations within the polymer electrolyte layer **139** to move in a direction determined by the applied electrical signal. This cation migration produced by the applied electrical signal causes the polymer electrolyte layer **139** to swell in the portion of the polymer electrolyte layer **139** disposed proximal to the anode and to bend or warp in the direction of the remaining unswelled portion. As a result, the magnitude and the direction of bending deformations of the polymer electrolyte layer **139** of the ionic electroactive polymer actuator can be controlled by strategically selecting the electrodes **112** to energize and

by adjusting the electrical signal applied through the electrically-conductive conduits **130** to the electrodes **112**.

[0071] As shown in FIG. 2, the polymer electrolyte layer **139** includes a circular bore **140**, and the plurality of electrodes **112** are angularly distributed about the circumference of the polymer electrolyte layer **139**.

[0072] FIG. 3 is a perspective view of the bendable portion **110** at the distal end **102** of the actuation part **100** of FIG. 2 illustrating the deformed or bending mode. The bendable portion **110** of the actuation part **100** of the medical device **10** is illustrated as having been actuated from the straight mode shown in FIG. 2 to the deformed or bent mode of FIG. 3 through the selective application of electrical signals to selected electrodes **112** to deform the polymer electrolyte layer **139**. The energization of selected electrodes **112** causes the bendable portion **110** to be deformed from the straight mode to the bent mode by application of an external force indicated by arrow **118**.

[0073] Alternately, in the event that the actuation part **100** is observed to be in a deformed mode in the absence of the application of one or more electrical signals to one or more of the plurality of the electrodes **112**, the magnitude of the observed deflection can be used to determine the magnitude and direction of an external force applied to the actuation part **100** or, alternately, in the event that the application of a known current to the electrodes **112** fails to produce an anticipated deformation of the bendable portion **110** of the actuation part **100**, the difference between the anticipated deformation and the actual deformation (if any) can be used as an indicator of the magnitude of an external force applied to the bendable portion **110** at the distal end **102** of the actuation part **100** of the medical device **10**.

[0074] FIG. **4A** is a cross-sectional view of the distal end **102** of the bendable portion **110** of the actuation part **100** of FIGs. **2** and **3** illustrating a first selected set of four electrical signals applied to four circumferentially distributed electrodes **112** disposed about the exterior wall **137** of the polymer electrolyte layer **139**. FIG. **4A** illustrates the electrical signals that may be applied to the plurality of angularly distributed electrodes **112** to impart bending of the bendable portion **110** of the actuation part **100** in the direction of the arrow **118**. It will be understood that the application of a positive charge on the electrodes **112** on the left and right sides of the bendable portion **110** of FIG. **4A**, in addition application of a positive charge to the electrode **112** at the top of FIG. **4A**, and further in addition to the application of a negative charge to the electrode **112** at the bottom of FIG. **4A**, may result in a different amount of deformation than would occur as a result of the application of a positive charge on the electrode **112** at the top of FIG. **4A** with a negative charge imparted to the remaining electrodes **112**. It will be understood that the user may select the plurality of electrical signals that produces the deformation desired by the user.

[0075] FIG. **4B** is the cross-sectional view of the distal end **102** of the bendable portion **110** of the extendable actuation part **100** of FIG. **4A** revealing a second selected set of four electrical signals applied to the circumferentially distributed electrodes **112** disposed about the polymer electrolyte layer **139**. FIG. **4B** illustrates the application of a positive charge to the electrode **112** at the top of the bendable portion **110** of FIG. **4B** and also to the electrode **112** at the right side of the bendable portion **110** of FIG. **4B**, and FIG. **4B** further illustrates the application of a negative charge to the electrode **112** at the bottom of FIG. **4B** and also to the electrode **112** at the left side of FIG. **4B**. The

deformation of the polymer electrolyte layer **139** resulting from the application of these electrical charges is in the direction of the arrow **118**.

[0076] It will be understood from FIGs. **4A** and **4B** that the distal end **102** of the bendable portion **110** of the actuation part **100** of the medical device **10** (e.g., a micro-catheter) can be bent in multiple directions and with varying degrees of deformation or deflection by strategic control of the electrical charges imparted to each of the individual electrodes **112**. Although the embodiment illustrated in FIG. **4A** and **4B** illustrates a bendable portion **110** including four electrodes **112**, it will be understood that the bendable portion **110** of the actuation part **100** of the medical device **10** may include fewer than four or more than four electrodes **112**, and such other embodiments will have differing deflection and deformation directional capacities.

[0077] FIG. **5** is a perspective view of an alternative embodiment of a bendable portion **110** of an actuation part **100** of a medical device **10** (e.g., a micro-catheter). FIG. **5** illustrates how the magnitude and direction of deflection and deformation of the polymer electrolyte layer **139** may be tailored by disposing a plurality of electrodes **112a**, **112b**, **112c** and **112d** at varying positions along the length of the bendable portion **110** of the actuation part **100**. By way of example and not by limitation, the bendable portion **110** of the actuation part **100** of FIG. **5** may include sixteen circumferentially and axially distributed electrodes **112a**, **112b**, **112c** and **112d** with the first set of four electrodes **112a** disposed proximal to the distal end **102** of the bendable portion **110** of the actuation part **100**, a second set of four electrodes **112b** disposed adjacent to the first set of electrodes **112a**, a third set of four electrodes **112c** disposed adjacent to the second set of electrodes **112b**, and a fourth set of electrodes **112d** disposed adjacent to the third set of electrodes **112c**. Each of the sixteen electrodes **112a**, **112b**, **112c** and

112d (four sets) disposed on the bendable portion **110** of the actuation part **100** of the medical device **10** is connected to one of sixteen electrically-conductive conduits **130a**, **130b**, **130c** and **130d**, each for delivering an energizing current to the respective electrodes. The embodiment of the bendable portion **110** of the actuation part **100** illustrated in FIG. **5** results in enhanced deformation of the bendable portion **110** due to reduced resistance to bending intermediate the axially-spaced apart sets of electrodes **112**.

[0078] FIG. **6** is a block diagram schematically illustrating the control system structure for the embodiment of the medical device **10** of FIGs. **1-4B**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The medical device **10** includes an actuation part **100** adapted for insertion into a lumen or bodily passage and a case **200** with a drive assembly **300** (see FIGs. **8A-9**) for advancing the elongate, flexible portion **101** and the bendable portion **110** of the actuation part **100** into and through a lumen or bodily passage and for selectively bending the bendable portion **110** at the distal end **102** of the actuation part **100**. FIG. **6** illustrates the control interaction between the case **200**, which contains both the drive assembly **300** for use in advancing the actuation part **100** into and through the lumen or bodily passage and an electrical controller **400** for selectively controlling the electrical charges carried by the electrically-conductive conduits **130** and imparted to the plurality of electrodes **112** to manipulate the bendable portion **110** of the actuation part **100** of the medical device **10**. The electrical controller **400** may comprise a processor (not shown) that calculates the values of an electrical signal applied to the electrodes **112**, in response to a user's input signals from the master controller **500**. The master controller **500**, which may be at a

location other than the location of the patient, is shown wirelessly, telephonically and/or via the Internet, communicating with the case **200** of the medical device **10** in FIG. **6**. It will be understood that, in one embodiment illustrated in FIG. **6**, the master controller **500** of the medical device **10** may be in the presence of a surgeon (operator or user) that is remote from the patient (body) and the medical device **10**. In that embodiment, the medical device **10** will include the master controller **500** or, alternately, an embodiment of the medical device **10** may not include a master controller **500** and may be used by a surgeon who is present in the operating room along with the patient and with the case **200**. The master controller **500** may include, for example, a joystick for enabling the user to input the bending control signals to the electrodes **112** of the bendable portion **110** for providing two degrees of freedom of bending through the electrical controller **400**, and a rolling input, such as, for example, a track ball or track wheel, for enabling the user to input advance and retract control signals to the drive assembly **300** for providing one degree of freedom of translation.

[0079] FIG. **7** is a lengthwise sectional view of an extendable and steerable intraluminal actuation part **100** of an embodiment of a medical device **10** (e.g., a micro-catheter), including a distal, bendable portion **110** and an elongate, flexible portion **101**.

[0080] FIG. **7** reveals the polymer electrolyte layer **139** and a plurality of surrounding electrodes **112**. Each electrode **112** is electrically coupled to an electrically-conductive conduit **130**. The bendable portion **110** is disposed adjacent to and aligned with the inner member **120** of the actuation part **100**. The elongate, flexible portion **101** may further comprise a protective outer member **150** to surround the inner member **120**, the electrically-conductive conduits **130**, the electrodes **112** and the polymer electrolyte layer **139**. The protective outer member **150** is adapted for low-friction sliding

engagement with the interior wall of a lumen or other bodily passage into which the actuation part **100** of the medical device **10** may be introduced. In an embodiment of a micro-catheter of the medical device **10**, the bore **140** provides a passage through which a surgical instrument such as, for example, an effector, a cutting implement, an imaging device (camera), a light source, a stint, a stint retriever or some other manipulatable surgical instrument can be passed and/or controlled by the user during surgery. Alternately, the bore **140** may form a fluid passage through which a drug, a radiation source or other material can be injected for precise placement in the body having the lumen or bodily passage. Although FIG. **7** illustrates an empty bore **140** in the elongate, flexible portion **101** of the actuation part **100**, this bore **140** is intended for multiple uses. It will be further understood that a surgical instrument positioned, controlled or introduced through the bore **140** of the actuation part **100** may be connected to an effector, instrument, tool or other implement disposed adjacent to the bendable portion **100**. It will be further understood that other devices for positioning a wire or other elongate slender device inserted into the bore **140** such as those described in relation to FIG. **6** may be used to position a wire or other device within the bore **140** without impairment of the function of devices used to position the actuation part **100** within the lumen.

[0081] FIGs. **8A** and **8B** together provide an exploded perspective view of an embodiment of a medical device **10**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**).

[0082] FIG. **8A** is a perspective view of an upper case portion **210** of the case **200** (see FIG. **1**) of the embodiment of the medical device **10** of FIG. **1** with the upper case

portion **210** indicated in dotted lines to better reveal the components of the medical device **10** disposed therein. In one embodiment of the medical device **10**, the upper case portion **210** may be disposable because it includes the actuation part **100** that is inserted into, and contaminated by, the lumen or bodily passage of the patient into which it is inserted and from which it is later withdrawn. The upper case portion **210** illustrated in FIG. **8A** includes a guide barrel **211** through which the distal end **102** of the actuation part **100** passes. The guide barrel **211** obscures an aperture (not shown) in the upper case portion **210** through which the actuation part **100** advances and withdraws. Similarly, the proximal end **109** of the actuation part **100** may pass through or may be fixedly disposed in an aperture **115**. The proximal end **109** of the actuation part **100** may further include threads **113** (FIG. **1**) for being paired with a mating socket or connection associated with a surgical instrument or tool. A cavity **215** within the upper case portion **210** may be used to store windings **116** formed in the length of the actuation part **100**. The windings **116** of the actuation part **100** do not include the bendable portion **110**, but do include the electrically-conductive conduits **130** and the inner member **120** (e.g., FIG. **7**), both components of the actuation part **100** that are used to supply, position and control the components that are part of or adjacent to the bendable portion **110**. The upper case portion **210** of FIG. **8A** further includes a drive assembly **300** including a first rotary drive member **330a** and an adjacent second rotary drive member **330b**. The actuation part **100** is shown passing intermediate the first rotary drive member **330a** and an adjacent second rotary drive member **330b**. It will be understood that clockwise rotation of the first rotary drive member **330a** and counterclockwise rotation of the adjacent second rotary drive member **330b** will withdraw the actuation part **100** from the lumen or bodily passage of the patient and into

the case **200**, and counterclockwise rotation of the first rotary drive member **330a** and clockwise rotation of the adjacent second rotary drive member **330b** will advance the actuation part **100** from the case **200** and into a lumen or bodily passage of the patient into which the distal end **102** of the actuation part **100** has been introduced.

[0083] FIG. **8B** is a perspective view of a lower case portion **220** of the case **200** (see FIG. **1**) of the embodiment of the medical device **10** of FIG. **1** with the lower case portion **220** indicated in dotted lines to better reveal the components of the medical device **10** disposed therein. In one embodiment of the medical device **10** in which the upper case portion **210** is disposable, the lower case portion **220** may be adapted for repeated and use, each use requiring pairing of a decontaminated lower case portion **220** with a new or refurbished upper case portion **210**. The shape of the lower case portion **220** corresponds to the shape of the upper case portion **210** of FIG. **8A** to facilitate the pairing of the lower case portion **220** with the upper case portion **210** to provide an assembled case **200**. The lower case portion **220** of FIG. **8B** includes components that have a low risk of contamination and those that are of a sufficient cost that they are useful for being refurbished, recycled and/or decontaminated after each use.

[0084] Components of the medical device **10** that are disposed in or on the lower case portion **220** are positioned to engage related components of the medical device **10** disposed in or on the upper case portion **210** to enable the coupling of these related components upon assembly of the upper case portion **210** of FIG. **8A** and the lower case portion **220** of FIG. **8B**. For example, but not by way of limitation, the drive assembly **300** of the upper case portion **210** of FIG. **8A** that engages and moves the flexible actuation part **100** may also engage a motor **310** through an intermediate worm

gear **320**. The motor **310** drives the worm gear **320** to controllably rotate a drive fitting **321** positioned to be received into a corresponding drive socket (not shown) formed in the first rotary drive member **330a** of the upper case portion **210** shown in FIG. **8A**. In the embodiment shown in FIGs. **8A** and **8B**, an interface device **420** enables the case **200** of the medical device **10** to receive control signals, for example, signals to advance or withdraw the actuation part **100** using drive assembly **300** or to impart bending to the distal end **102** of the actuation part **100** using the bendable portion **110** from a master controller **500** (FIG. **9**) used by a surgeon or operator (which includes for example other operators or users such as but not limited to medical practitioners, physicians, surgical technicians, nurses or assistants, veterinarians, etc.).

[0085] FIG. **9** is an elevational sectional view of an embodiment of a medical device **10** provided by assembling of the upper case portion **210** and the lower case portion **220** of FIGs. **8A** and **8B**. The windings **116** of the actuation part **100** of the medical device **10** are stored within the cavity **215** of the upper case portion **210** of the case **200**. The actuation part **100** of the medical device **10** extends from the proximal end **109** through the windings **116**, to the distal end **102** of the actuation part **100** that extends beyond the guide barrel **211** of the upper case portion **210**. FIG. **9** shows the manner in which the drive fitting **321** (see FIG. **8B**) engages a socket (not shown) in the first rotary drive member **330a** which cooperates with the second rotary drive member **330b** to controllably advance and withdraw the actuation part **100** from and back into the case **200** of the medical device **10**, respectively. Optionally, the upper case portion **210** includes a cavity wall **214** that separates the cavity **215** that houses the windings **116** of the actuation part **100** from the adjacent cavity **213** that houses the first rotary drive member **330a** and the second rotary drive member **330b** (FIG. **8A**) of the drive

assembly **300**. The medical device **10** of FIG. **9** further includes the electrical controller **400** disposed in the lower case portion **220** and used to receive command signals from the master controller **500** and to generate control electrical signals to the plurality of electrically-conductive conduits **130** (FIG. **2**) within the actuation part **100** to energize the plurality of electrodes **112** (e.g., FIG. **2**) to bend the bendable portion **110** (e.g., FIG. **2**) of the actuation part **110**. The electrical controller **400** relays the electrical currents through the interface **402** disposed in the lower case portion **220** to the current distributor **410** disposed in the upper case portion **210**. The current distributor **410** is the interface between the electrical controller **400** and the actuation part **100** of the medical device **10**. The proximal end **109** of the actuation part **100** of the medical device **10** is fixed relative to the upper case portion **210** to maintain a plurality of electrical feeder wires **411** extending between the current distributor **410** and the stationary proximal end **109** of the actuation part **100**. It will be understood that the distributor cavity **216** of the upper case portion **210** may be sealed to protect the feeder wires **411** and related terminals from contamination sources that may exist in the adjacent windings **116**.

[0086] In the embodiment of the medical device of FIG. **9**, the number of the plurality of feeder wires **411** provided to deliver electrical current from the electrical controller **400** to the electrically-conductive conduits **130** (e.g., FIG. **2**) will match the number of the plurality of electrically-conductive conduits **130**. An interface socket **415** may be disposed intermediate the interface **420** of the lower case portion **220** and the current distributor **410** of the upper case portion **210**. In one embodiment, the electrical controller **400** may include a wireless interface device **405** that is electrically connected

to the electrical controller **400** and drive assembly **300** enables the electrical controller **400** and drive assembly **300** to wirelessly communicate with the master controller **500**.

[0087] FIG. **10** is a flowchart illustrating the steps of a method **600** of performing surgery on a body of a patient using an embodiment of the medical device **10** illustrated in FIGs. **8A** and **8B**. The method **600** includes a step **610** of assembling the upper case portion **210** and the lower case portion **220** to form a case **200**, the step **620** of introducing the distal end **102** of the actuation part **100** into a lumen of the body, the step **630** of extending the actuation part **100** forward and into the lumen of the patient using the drive assembly **300**, the step **640** of detecting a branched or bending pathways of the lumen or bodily passage in which the actuation part **100** is disposed using an imaging device, the step **650** of bending the bendable portion **110** at the distal end **102** of the actuation part **100** of the medical device **10** to steer the actuation part **100** into a desired direction through the branched or bending pathways observed using an imaging device, and the step **660** of reaching the surgical site with the distal end **102** of the actuation part **100**.

[0088] Conventional techniques and methods known in the medical sciences may be used in conjunction with the methods and with the medical device **10**. For example, but not by way of limitation, the step **640** in FIG. **10** requires the surgeon to “detect branched and bending pathways” of the lumen of the body in which the actuation part **100** is introduced. More specifically, the surgeon or operator performing the method of FIG. **10** using the medical device **10** may view images of the lumen or bodily passage (pathway) in the body along which the distal end **102** of the actuation part **100** of the medical device **10** is pushed forward using radiography, magnetic resonance imaging, ultrasound, elastography, tactile imaging, photoacoustic imaging, tomography and other

imaging technologies and devices. It will be understood that an imaging device can be present in the room with the patient and that the output of the imaging device can be electrically transmitted to the surgeon or operator using a hardwired connection, for a surgeon who is nearby, and using telecommunications, such as but not limited to the Internet or wireless communications, for a surgeon or operator who is remotely located.

[0089] FIG. 11 is a flowchart illustrating a method 601 of controlling an embodiment of the medical device 10 and, more specifically, of imparting a bend to a bendable portion 110 at the distal end 102 of an actuation part 100 of an embodiment of the medical device 10 (e.g., a micro-catheter or a guidewire). Referring also to FIGs. 2 and 9, the method 601 includes the step 641 of generating a manipulation signal using the master controller 500 which will be received by the electrical controller 400 through the wireless interface device 405, step 642 of using the electrical controller 400 to determine the electrical signals to be applied to one or more of the plurality of electrodes 112 to obtain the desired direction and magnitude of bend of the bendable portion 110 of the distal end 102 of the actuation part 100 of the medical device 10, and step 643 of applying the determined electrical signals to be conducted over the electrically-conductive conduits 130 to one or more of the plurality of electrodes 112 to obtain the desired movement in the distal end 102 of the actuation part 100 of the medical device 10.

[0090] FIG. 12 is a modification of the block diagram of FIG. 6 illustrating the control system structure for an alternative embodiment of the medical device 10 including an actuation part 100 and a case 200 (e.g., FIG. 1). The medical device 10 herein may be a micro-catheter with an interior bore 140 (e.g., FIGs. 2-4B) or a guidewire without the interior bore 140 (e.g., FIG. 29). The actuation part 100 includes a bendable portion 110 and an elongate, flexible portion 101. The case 200 includes a drive assembly 300 and

electrical controller **400**, and further includes a sensing member **117**. The sensing member **117** is a bendable portion sensor that is electrically connected to the plurality of electrodes **112** of the bendable portion **110** to sense changes in the electrical signal at each of the plurality of electrodes **112**. More specifically, the sensing member **117** is individually electrically connected to each of the plurality of electrodes **112** to monitor changes in the potential at each of the plurality of electrodes **112**. Accordingly, the sensing member **117** detects deformation of the bendable portion **110** or the absence thereof based on changes in potential in each of the plurality of electrodes **112** over time.

[0091] For example, but not by way of limitation, as the bendable portion **110** and the elongate, flexible portion **120** of the actuation part **100** is advanced forward using the drive assembly **300** of the case **200**, the sensing member **117** detects whether the lumen or bodily passage through which the bendable portion **100** of the actuation part **100** is advanced is obstructed or whether there is a bend or obstruction in the lumen or bodily passage that is sufficient to prevent or impair forward movement of the actuation part **100**. Also, because an electrical signal is applied to each of the plurality of electrodes **112** by the electrical controller **400**, the sensing member **117** may determine whether the intended bending deformation corresponding to the plurality of electrical signals generated by the electrical controller **400** has occurred by receiving feedback about the electrical signal at each of the plurality of electrodes **112** and by comparing that feedback to the electrical signals assigned to each of the plurality of electrodes **112**.

[0092] The sensing member **117** is electrically connected to each of the electrically-conductive conduits **130** that supply electrical signals to each of the electrodes **112**. It will be understood that, just as the character and nature of an electrical signal delivered

to an energized electrode **112** determines the unimpaird deformation imparted to the polymer electrolyte layer **139** disposed adjacent to an energized electrode **112**, the actual deformation of the polymer electrolyte layer **139** can be compared to the electrical signal delivered to the adjacent electrodes to determine the direction and magnitude of an external force acting on the polymer electrolyte layer **139**.

[0093] FIG. **13** is a graph illustrating variance over time in an electrical current applied to a polymer electrolyte layer **139** of a bendable portion **110** of an actuation part **100** of an embodiment of a medical device **10**. FIG. **13** is a graph showing a change in electrical signal occurring at an electrode **112** monitored using the sensing member **117**. The solid line of FIG. **13** indicates the value of a sensed electrical signal at any one of a plurality of electrodes **112**. The dotted line of FIG. **13** indicates the value of an electrical signal that is applied to an electrode **112** to produce a bend in a desired direction and at a desired magnitude as determined using the electrical controller **400** and an input signal from the master controller **500**.

[0094] Changes in the electrode potential sensed by the sensing member **117** are caused by both an electrical signal applied to the plurality of electrodes **112** by the electrical controller **400** for bending control, and by external forces. Accordingly, the sensing member **117** may be used to determine the presence, direction and magnitude of an external force applied to the bendable portion **110** by taking into account how the electrical controller **400** performs bending control. As illustrated in FIG. **13**, an electrical signal is applied to an electrode **112** at a time designated as t_1 . As a result, the value of the electrical signal sensed by the sensing member **117** increases abruptly at time t_1 . Therefore, the sensing member **117** may determine the direction and magnitude of any external force that may be applied to the bendable portion **110** based on the difference

in the electrical signal, or ΔV , between the sensed value and ΔV_{th} , the value applied by the electrical controller **400**.

[0095] The sensing member **117** may be configured to determine the direction and/or the magnitude of an applied external force depending on whether the difference between the sensed value and the value applied by the master controller **500** exceeds a preset threshold value, ΔV_{th} . For example, the actuation part **100** may be subjected to a small amount of external force as the distal end **102** is brought into contact with a lumen wall or as it encounters sliding friction while being pushed forward along a lumen or bodily passage. Accordingly, it is possible to permit an expected small amount of external force during intraluminal movement of the actuation part **100** and to detect the application of a larger magnitude external force by determining whether an external force is applied or not based on a threshold value.

[0096] While FIG. **13** illustrates the value applied to the electrode upon bending and the value sensed at the electrode due to a deformation on the same scale, this is for ease of explanation and these values may vary in an actual situation, depending on the position of installation and the wire characteristics. In this case, using a method of calculation suitable for the wire characteristics, the application of an external force can be determined based on the value applied upon bending.

[0097] In this exemplary embodiment, an external force is sensed by using a plurality of four electrodes **112** used for bending control, without the addition of external force sensing electrodes to the bendable portion **110**. However, this is merely an example, and an external force may be sensed using various structures.

[0098] FIG. **14** is a cross-sectional view illustrating an alternative distribution of the plurality of electrodes **112** in a bendable portion **110** of an actuation part **100** of an

embodiment of a medical device **10**. The arrangement of the eight electrodes of the bendable portion **110** illustrated in FIG. **14** includes four (motive) electrodes **112** for responding to electrical signals generated by the electrical controller **400** (not shown) and an additional four sensing electrodes **112e** for sensing the deformation of the bendable portion **110** in which the eight electrodes are together disposed. The embodiment of the bendable portion **110** of FIG. **14** includes a polymer electrolyte layer **139** having an exterior wall **137** for disposing the electrodes **112** and **112e**.

[0099] FIG. **15** is a cross-sectional view of an alternative configuration for a bendable portion **110** of an actuation part **100** of an embodiment of the medical device **10**. FIG. **15** illustrates a polymer electrolyte layer **139** having an exterior wall **137** for disposing the electrodes **112**. Circumferentially intermediate each adjacent pair of electrodes **112** resides a strain gauge **114** that measures the strain applied to the bendable portion **110** of the actuation part **100** as a result of internal forces applied by the deformation of the polymer electrolyte layer **139** disposed adjacent one or more energized electrodes **112** and external forces applied to the bendable portion **110** as a result of physical interaction with the lumen or bodily passage through which the actuation part **100** of the medical device **10** is being advanced.

[00100] FIG. **16** is a flowchart illustrating a method of using a sensing member **117** to monitor the performance of an embodiment of a medical device **10** and of determining the impact of an external force on the performance of the embodiment of the medical device **10**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The sensing member **117** may be used to continuously monitor changes in electrical signal sensed at the plurality of electrodes **112** of the bendable portion **110**.

For example, the sensed value of the electrical signal may be the potential of each of the plurality of electrodes **112**.

[00101] The sensing member **117** may monitor changes in electrical signal induced by the user's bending. That is, the sensing member **117** receives information about the user's bending from the electrical controller **400** or the master controller **500** and the sensing member **117** then monitors changes in electrical signals induced by bending of the bendable portion **110**. Then, the sensing member **117** monitors changes in electrical signal induced by actual bending due to both internal and external forces and compares that change in the electrical signal to the isolated electrical signal indicating the intended bending.

[00102] When a change in signal (except for a change induced by bending) is sensed during monitoring, the sensing member **117** determines whether the change exceeds a preset threshold value or not, and if so, determines that an external force is applied. Furthermore, in this step, the direction of the external force or the amount of the external force may be calculated by combining information about changes at the electrodes **112**.

[00103] Once the application of an external force is detected, the step of informing the user of this is performed. In this exemplary embodiment, the sensing member **117** may send an external force generation signal to the master controller **500**, and issue an alarm message, an alarm sound, or haptic feedback to the user through the master controller **500**. In this case, the sensing member **117** may, through the master controller **500**, advise the user of both the direction and magnitude of an external force being applied to the bendable portion **110** and thereby enable the user to determine how to manipulate the bendable portion **110** for advancing beyond the obstacle

engaging the actuation part **100**, as well as the generation of the external force. It will be understood that if the actuation part **100** is advanced through a lumen or bodily passage with excessive force damage to contacted body tissues may occur. The capacity to detect the application of external force to the bendable portion **110** of the actuation part **100** of the medical device **10** enables the user to deactivate or slow the drive assembly **300** through the master controller **500**.

[00104] The embodiments of the medical device **10** illustrated in FIGs. **1**, **8A**, **8B** and **9** include a drive assembly **300** comprising a motor **310**, an intermediate worm gear **320** and a drive fitting **321** positioned to be received into a corresponding drive socket (not shown in FIG. **8A**) formed in the first rotary drive member **330a** of the upper case portion **210** shown in FIG. **8A**. It will be understood that the first rotary drive member **330a** and the second rotary drive member **330b** illustrated in FIG. **8B** are limited in the amount of surface contact between these drive components and the actuation part **100** engaged thereby. As a result of the limited amount of surface contact between the first rotary drive member **330a** and the second rotary drive member **330b** illustrated in FIG. **8B**, on the one hand, and the actuation part **100**, on the other hand, the resulting frictional force between the actuation part **100** and the first rotary drive member **330a** and the second rotary drive member **330b** are also limited. If the resistance to movement and advance of the actuation part **100** into or through a lumen or bodily passage is sufficiently high, then it may become difficult to smoothly and controllably move the actuation part **100** to the desired position for performing a planned surgery in the body.

[00105] FIG. **17** illustrates an alternate embodiment of the case **201** portion of the medical device **10** for controllably advancing and withdrawing the actuation part **100** of

the medical device **10**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The case **201** of the embodiment of the medical device **10** illustrated in FIG. **17** includes a drive assembly **300** that provides increased contact area between the drive members **431a** and **432a** and the actuation part **100** and, as a result, provides increased frictional force for moving the actuation part **100** against resistance to movement. A drive assembly **300** of the case **201** of FIG. **17** includes a guide barrel **411**, a motor **310a**, one or more intermediate worm gears **320a**, and the drive assembly **300** is operated by the motor **310a** working through the one or more worm gears **320a**. Like the case **200** illustrated in FIGs. **8A** and **8B**, the case **201** of FIG. **17** includes a case upper portion **211** and a case lower portion **221** adapted for engaging and being coupled with the case upper portion **211**. The motor **310a** and the one or more worm gears **320a** are disposed in the case upper portion **211** and a worm gear **320a** is positioned to dispose a drive fitting (not shown in FIG. **17**) disposed on the bottom of the worm gear **320a** into engagement with an inversely-shaped socket (not shown in FIG. **17**) on a drive shaft **432** that is a part of the drive assembly **300**. The drive assembly **300** includes a pair of drive spools **431a** and **432a** that are positioned one opposing the other on opposite sides of a pathway through the case lower portion **221** in which the actuation part **100** moves through the case lower portion **221**. Drive spool **431a** is coupled through a first belt **433** to an auxiliary spool **431b** and drive spool **432a** is coupled through a second belt **434** (not shown in FIG. **17**—see FIG. **18**) to an auxiliary spool **432b** (not shown in FIG. **17**—see FIG. **18**). The actuation part **100** passes intermediate belts **433** and **434** and is engaged by both of the belts **433** and **434**. The actuation part **100** is controllably pushed forward in the direction of arrow **439** or

withdrawn (in the opposite direction of the arrow **439**) by operation of the motor **310a** to drive the drive spools **431a** and **432a**. It will be understood that the contact area between the belts **433** and **434** and the actuation part **100** is substantially greater in the drive assembly **300** of the case **201** of the medical device **10** illustrated in FIG. **17** as compared to the contact area between the first rotary drive member **330a** and the second rotary drive member **330b** of the drive assembly **300** of the case **200** of the medical device **10** of FIG. **8A**. Optionally, belts **433** and **434**, on the one hand, and the mating drive spools **431a** and **432a**, on the other hand, may include a series of grooves (or other recesses) and/or ridges (or other protrusions), respectively, to promote non-slip engagement with the actuation part **100**. Optionally, a pair of worm gears **320a** may be disposed on opposite sides of a motor shaft **409** to evenly distribute torque from the motor **310a** to the drive spools **431a** and **431b**. Optionally, tensioners **431c** may be provided to enable the adjustment and maintenance of proper tension in the belts **433** and **434**. Optionally, the drive spools **431a** and **431b** may together be biased into engagement with the actuation part **100** to ensure non-slip frictional engagement between the belts **433** and **434** and the actuation part **100** to improve controllability and prevent slippage. Optionally, as will be seen in FIG. **18**, one of the drive spools **431a** and **431b** may be biased into engagement with the actuation part **100** for the same purposes.

[00106] FIG. **18** is a perspective view of the alternative case **201** of FIG. **17** with the guide barrel **411** removed to reveal the positions of the components therein. Drive spools **431a** and **431b** are seen straddling the actuation part **100** of the medical device **10** as they do in the embodiment of FIG. **17**. Additionally, the embodiment of the case **201** of the medical device **10** of FIG. **18** includes a tensioner **437b** disposed on the case

201 to move as permitted by a slot **435**. The tensioner **437b** shown in FIG. **18** is biased into engagement with a belt **434** using one or more springs **438** that maintain the tensioner **437b** engaged with the belt **434** to keep the belt **434** in non-slipping engagement with the drive spool **431b**.

[00107] FIG. **19** is a perspective view of an elongate, flexible portion **101** of an actuation part **100** of an embodiment of a medical device **10** with a section of an outer member **150** removed to reveal details of the interior of the actuation part **100** of this embodiment of the medical device **10**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The outer member **150** is shown to the right side of FIG. **19** but is removed from the left side of FIG. **19** to reveal the bendable portion **110** of the actuation part **100** including the inner member **120**, and the electrodes **112** circumferentially distributed about a polymer electrolyte layer **139**. Each electrode **112** is connected to an electrically-conductive conduit **130** that delivers an energizing electrical signal to one or more selected electrode(s) **112** to actuate the polymer electrolyte layer **139** to bend. FIG. **19** further illustrates a reinforcing mesh **121** comprising a wire or filament that is braided or wound radially intermediate the inner member **120** and the outer member **150** to provide enhanced structural rigidity and resistance to axial compression and enhanced resistance to torsional deformation of the actuation part **100** for improved control and steerability. It will be understood that the structure of the reinforcing mesh **121** may vary. Other embodiments of the actuation part **100** of the medical device **10** may include encircling coils of reinforcing wire (not shown) as opposed to braids or mesh. The material of the reinforcing mesh **121** may include, but is not limited to, stainless steel, tungsten or nylon. In one embodiment of

the actuation part **100** of the medical device **10**, the electrically-conductive conduits **130** through which electrical signals are delivered to the bendable portion **110** of the actuation part **100** comprise a plurality of very slender wires available from, among others, MK Electron Co., Ltd. of Gyeonggy-do, Korea. These wires may have a diameter of 25 μm , or 15 μm or less, and may comprise gold, gold-silver alloy or other highly conductive metals that demonstrate high chemical stability. These wires may be embedded in an insulating medium and may be of a multiple-layer braided construction.

[00108] FIG. **20** is cross-sectional view of an embodiment of an elongate, flexible portion **101** of an actuation part **100** of an embodiment of a medical device **10**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). It will be understood that the elongate, flexible portion **101** includes an inner member **120** and a reinforcing mesh **121**. An insulating layer **133** is disposed about the reinforcing mesh to isolate the reinforcing mesh **121** from the electrically-conductive conduits **130** to prevent electrical shorts. As shown in FIG. **20** the electrically-conductive conduits **130** are circular in cross-section and are formed within a space defined within the insulating layer **133** between the outer member **150** and the reinforcing mesh **121**. The elongate, flexible portion **101** illustrated in FIG. **20** further includes an insulation coating **134** to further insulate the electrically-conductive conduits **130** from the outer member **150** and also from the reinforcing mesh **121**.

[00109] FIG. **21** is a cross-sectional view of an alternative embodiment of the elongate, flexible portion **101** of the actuation part **100** of an embodiment of the medical device **10** having an inner member **120**, a reinforcing mesh **121** and electrically-conductive conduits **130**. The medical device **10** herein may be a micro-catheter with an interior

bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The elongate, flexible portion **101** of FIG. **21** illustrates that the electrically-conductive conduits **130** and one or more lumens **135** around each electrically-conductive conduit **130** are together encapsulated or encased within the material of the outer member **150**. The lumens **135** herein may be placed longitudinally within the outer member **150**. Each lumen **135** defines an interior space **135a** passing through the outer member **150** and an exterior wall **135b**. Each electrically-conductive conduit **130** may be correspondingly placed through the each interior space of each lumen **135**, so that each electrically-conductive conduit **130** can be insulated by the exterior wall **135b** of each lumen **135** to prevent electrical shorts.

[00110] FIG. **22** a cross-sectional view of an alternative embodiment of the elongate, flexible portion **101** of the actuation part **100** of an embodiment of the medical device **10** having an inner member **120**, a reinforcing mesh **121** and an outer member **150**. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g., FIG. **29**). The embodiment of the elongate, flexible portion **101** of FIG. **22** further includes a tubular insulation member **127** surrounding the reinforcing mesh **121** to further insulate the electrically-conductive conduits **130** from the reinforcing mesh **121**.

[00111] FIG. **23** is a modification of the block diagrams of FIGs. **6** and **12** illustrating a control system **502** for an alternative embodiment of the medical device **10** including an actuation part **100** and a case **200**. FIG. **23** illustrates a system for remotely controlling a medical device **10** having an actuation part **100** introduced within a lumen or passage of the body of a patient. The medical device **10** herein may be a micro-catheter with an interior bore **140** (e.g., FIGs. **2-4B**) or a guidewire without the interior bore **140** (e.g.,

FIG. 29). The system **502** comprises a local communication member **501** that remotely communicates with the remote master controller **500**. The surgeon, operator or user uses the master controller **500** to remotely operate the medical device **10** that includes the actuation part **100**, the drive assembly **300** in the case **200** of the medical device, and the electrically-conductive conduits **130** that carry electrical signals to the bendable portion **110**. FIG. 23 illustrates that the surgeon, operator or user may remotely control the medical device **10** from a remote location using the master controller **500** and the local communication member **501**, and that the master controller **500** and the local communication member **501** may communicate through telephonic systems, Bluetooth, wireless 802.11 communication and/or the Internet.

[00112] In an alternative embodiment of the medical device **10**, the electrically-conductive conduits **130** are embedded in a radially exterior surface **122** of the inner member **120**, as discussed in connection with FIG. 24.

[00113] FIG. 24 is an enlarged view of a portion of FIG. 5 and illustrates a plurality of four electrically-conductive conduits **130a**, **130b**, **130c** and **130d** disposed within a plurality of four parallel and spaced-apart channels **123**, **124**, **125** and **126** formed into the exterior surface **122** of the inner member **120**. It will be understood that the four electrically-conductive conduits **130a**, **130b**, **130c** and **130d** are each isolated one from the others by the barrier portions **129** of the exterior surface **122** disposed intermediate each pair of adjacent channels **123**, **124**, **125** and **126**.

[00114] While FIGs. 2-5 and 7 illustrate embodiments of the bendable portion **110** of the actuation part **100** of the medical device **10**, it will be understood that other embodiments may be easier to fabricate or may provide improved responsiveness to the electrical signals generated to manipulate and steer the intraluminal the medical

device **10** to the targeted location within a body. The discussion that follows relates to an embodiment of the bendable portion **110** of the actuation part **100** of the medical device **10** that provides additional benefits.

[00115] FIG. **25** is an enlarged perspective view of an alternative tubular polymer electrolyte layer **139A** that is included in a bendable portion **100** of an actuation part **100** of an alternate embodiment of the medical device **10** (e.g., a micro-catheter). FIG. **25** shows a bendable portion **110** having a plurality of electrodes **112** circumferentially distributed about the exterior wall **137** of a polymer electrolyte layer **139**. The electrodes **112** in FIG. **25** are each coupled to an electrically-conductive conduit **130** for transmitting one or more electrical signals from an electrical source (not shown in FIG. **25**) to the electrodes **112**. The bendable portion **110** of FIG. **25** includes electrodes **112** that may extend radially further from an axis **141** of the bendable portion **110** (in a relaxed condition) than the exterior wall **137** of the tubular polymer electrolyte layer **139A** intermediate adjacent pairs of electrodes **112**. The configuration of the bendable portion **110** illustrated in FIG. **25** is the result of a method for making the bendable portion **110**, which is discussed in detail below.

[00116] The alternate embodiment of the bendable portion **110** illustrated in FIG. **25** is made by forming a tubular polymer electrolyte layer **139A** from a polymer, such as Nafion[®], available from The Chemours Company of Wilmington, Delaware, USA. The exterior wall **137** of the tubular polymer electrolyte layer **139A** is pre-conditioned by roughening the exterior wall **137** using an abrasive such as, for example, sandpaper, or by an abrasive process such as, for example, sandblasting, followed by cleaning the roughened exterior wall **137** of the tubular polymer electrolyte layer **139A** using a reducing agent such as, for example, a hydrogen peroxide (H₂O₂) solution and/or a

sulfuric acid (H_2SO_4) solution, and de-ionized water. The now-roughened and cleaned exterior wall **137** of the tubular polymer electrolyte layer **139A** is then deposition-plated with a conductive metal such as, for example, platinum. It will be understood that common methods of depositing a solid coating or layer onto a substrate may be used. In one embodiment of the method, an electroless chemical deposition process is used to deposit platinum onto the roughened and cleaned exterior wall **137** of the tubular polymer electrolyte layer **139A**. The roughened and cleaned tubular ionic electroactive polymer **139A** is impregnated in a complex platinum salt solution such as, for example, a solution including $[\text{Pt}(\text{NH}_3)_4]\text{Cl}_2$, for several hours at about 68 °F (20 °C). That impregnation step is followed by a reduction process using an aqueous solution containing a reducing agent such as, for example, sodium borohydride (NaBH_4), during which the platinum ions in the polymer are chemically reduced to metallic form at the exterior wall **137** of the tubular polymer electrolyte layer **139A**.

[00117] After an additional cleaning with a reducing agent such as, for example, sulfuric acid, and deionized water, the exterior wall **137** of the now platinum-coated tubular polymer electrolyte layer **139A** may be further plated with a thin layer of gold (Au) using a conventional electrochemical deposition process to increase the thickness and electrical conductivity of the presently undivided metal electrodes **112** that will be ultimately formed onto the exterior wall **137** of the tubular polymer electrolyte layer **139A**. Following the gold deposition processes, the circumferentially continuous sleeve-shaped platinum and gold-coated exterior wall **137** of the tubular polymer electrolyte layer **139A** can be sectored into four circumferentially-distributed and isolated metal electrodes **112** using a micro-machining process. More specifically, a computer-controlled milling machine with a micro end-mill tool may be used to mechanically

remove a thin layer of platinum-gold material and, optionally, a small portion of the underlying exterior wall **137** of the tubular polymer electrolyte layer **139A** at a depth of, for example, twenty to forty (20 to 40) microns. In FIG. **25**, the plurality of milled grooves **136** indicate where the previously circumferentially continuous platinum-gold electrode has been sectored into plurality of metal electrodes **112**, each coupled to an electrically-conductive conduit **130**. FIG. **25** shows four equally sized and circumferentially distributed metal electrodes **112** centered 90° apart on the exterior wall **137** of the tubular polymer electrolyte layer **139A**. The bendable portion **110** illustrated in FIG. **25** can be manipulated by selectively introducing energizing electrical signals into the metal electrodes **112** by way of the conduits **130** to provide actuation. In a final step, the finished tubular polymer electrolyte layer **139A** with sectored platinum-gold electrodes **112** is cleaned and ion-exchanged into a desired cationic form (typically using lithium ions) by soaking in a metal-salt solution such as, for example, lithium chloride. During this final soaking process, the hydrogen ions (H⁺) in the tubular polymer electrolyte layer **139A** are exchanged with lithium ions (Li⁺).

[00118] A embodiment of a method of disposing the carbon-based electrodes **112** on the tubular polymer electrolyte layer **139A** is also provided. In one example, the bendable portion **110** illustrated, e.g., in FIG. **25**, is made by forming carbon-based electrodes **112** on a tubular polymer electrolyte layer **139A** from a polymer, such as Nafion® using a reflow process. Since the electrode integration by the reflow process involves high temperature treatment, the exemplary example provided below herein is a wet assembly method applicable with thermally stable and non-volatile electrolytes such as ionic liquids.

[00119] In this exemplary example, the tubular polymer electrolyte layer **139A** is pre-conditioned by roughening its exterior wall **137** using an abrasive (e.g., sandpaper) or by an abrasive process (e.g., sandblasting), followed by being cleaned using a reducing agent, for example, a hydrogen peroxide (H₂O₂) solution and/or a sulfuric acid (H₂SO₄) solution, and de-ionized water, but not limited to this. The roughened and cleaned tubular polymer electrolyte layer **139A** is further deposition-plated with a carbon-based conductive powder, such as carbide-derived carbon, carbon nanotube, carbon aerogel, graphene, or the combination thereof.

[00120] In this exemplary example, one or more electrolytes are then incorporated in the cleaned tubular polymer electrolyte layer **139A** which is first dried under vacuum (30 in Hg) at about 100 to about 140 °C for several hours to remove humidity. Thereafter, the dried tubular polymer electrolyte layer **139A** is impregnated with an ionic liquid (such as EMI-BF₄ or EMI-TFSI, but not limited to this) by soaking in respective ionic liquid at elevated temperature for several hours.

[00121] In this exemplary example, after being ionic liquid-impregnated, a layer of carbon-based electrodes **112** are fabricated directly onto the tubular polymer electrolyte layer **139A** as follows. The conductive powder material of carbide-derived carbon (or other carbon allotrope (e.g., carbon nanotube, carbon aerogel, graphene) or the mixture thereof, but not limited to this) is dispersed in a volatile solvent of isopropanol (or the like). In an alternative embodiment, the conductive powder may further comprise fillers such as transition metal oxide powder (such as MnO₂ or RuO₂) or metal powder (such as Pt or Au). Ionic polymer (Nafion) dispersion in alcohol (or PVDF) is further added in the above-mentioned conductive powder dispersion for a binder. The mixture is homogenized by a treatment in an ultrasonic bath. The prepared conductive powder

dispersion is then directly applied onto the tubular polymer electrolyte layer **139A** using a conventional brush or spray coating technique to form a layer of carbon-based electrode **112**. Volatile solvents are evaporated by a mild heating process after the desired thickness of the layer of carbon-based electrode **112** is achieved.

[00122] The electrical conductivity of the obtained layer of carbon-based electrode **112** is often inadequate to ensure proper electromechanical functionality for the ionic electroactive polymer actuator. In this exemplary example, the electrical conductivity of the obtained layer of carbon-based electrode **112** may be increased by further attaching Au microwire onto the surface of the obtained layer or by embedding Au wire in the obtained layer. Additionally, Au foil with a thickness of 50-150 nm may be rolled around the tubular polymer electrolyte layer **139A** to serve as a highly conductive current collector.

[00123] Then, in this exemplary example, the layer of carbon-based electrode **112** is integrated with the tubular polymer electrolyte layer **139A** by a reflow process. In this process, the heat-shrink polymer tube such as fluorinated ethylene-propylene (FEP) is fitted over the tubular polymer electrolyte layer **139A** and heated up to a recovery temperature of the heat-shrink material. The supplied heat and applied compressive load by the heat-shrink tube may cause reflow of the ionic polymer from the tubular polymer electrolyte layer **139A**, so that the layer of carbon-based electrode **112** and Au foil are thermally bonded with the tubular polymer electrolyte layer **139A**. After this reflow process, the heat shrink tube is removed and the layer of carbon-based electrode **112** is sectored into four isolated carbon-based electrode sectors **112** using a micromachining process, where the computer-controlled milling machine with micro end-mill tool is used to mechanically remove a thin layer of carbon-Au composite and

the tubular polymer electrolyte layer **139A** at a depth of 30–50 microns. This process creates four equally sized carbon-based electrode sectors **112** at every 90° on the tubular polymer electrolyte layer **139A** which can be independently controlled by electrical power to achieve two degrees-of-freedom actuation.

[00124] In another example, the bendable portion **110** illustrated, e.g., in FIG. **25**, is made by forming carbon-based electrodes **112** on a tubular polymer electrolyte layer **139A** from a polymer, such as Nafion® using a reflow process. This example is directed to a dry assembly applicable with both volatile (such as aqueous) and non-volatile (ionic liquids) electrolytes. The tubular polymer electrolyte layer **139A** (Nafion®, DuPont) is provided and pre-conditioned as described above. To prepare a layer of carbon-based electrodes **112** onto the conditioned the tubular polymer electrolyte layer **139A**, the conductive powder material of carbide-derived carbon (or other carbon allotrope, e.g., carbon nanotube, carbon aerogel, graphene, or mixtures thereof) is dispersed in a volatile solvent of isopropanol (or the like). In some embodiments, the conductive powder may further comprise transition metal oxide powders (such as MnO₂ or RuO₂, but not limited to this) or metal powder (Pt or Au, but not limited to this).

[00125] In this exemplary example, ionic polymer (Nafion) dispersion in alcohol (or PVDF) is further added in the conductive material dispersion for a binder. The mixture is homogenized by a treatment in an ultrasonic bath. Next, the prepared conductive powder dispersion is directly applied onto the tubular polymer electrolyte layer **139A** using a brush or spray coating technique after being ionic liquid-impregnated. Volatile solvents are evaporated by a mild heating process until the desired thickness of the layer of carbon-based electrodes **112** is achieved.

[00126] The electrical conductivity of the obtained layer is often inadequate to ensure proper electromechanical functionality for the ionic electroactive polymer actuator. In terms of this, in this exemplary example, the electrical conductivity of the obtained layer of carbon-based electrodes **112** may be increased by attaching Au microwire onto the surface of the layer of carbon-based electrodes **112** or by embedding Au wire in the layer of carbon-based electrodes **112**. Then, the layer of carbon-based electrodes **112** is integrated with the tubular polymer electrolyte layer **139A** by a reflow process. In this process, the heat-shrink polymer tube such as fluorinated ethylene-propylene (FEP) is fitted over the tubular polymer electrolyte layer **139A** and heated up to a recovery temperature of the heat-shrink material. The supplied heat and applied compressive load by the heat-shrink tube cause reflow of the ionic polymer, so that the layer of carbon-based electrodes **112** and Au foil are thermally bond with the tubular polymer electrolyte layer **139A**. After reflow process, the heat shrink tube is removed. Additionally, the electrical conductivity of the layer of carbon-based electrodes **112** may be further increased by applying a thin layer of Pt thereon using the electroless chemical deposition and subsequent electrochemical deposition of Au.

[00127] Then, in this exemplary example, the obtained layer of carbon-based electrodes **112** is sectored into four isolated electrode sectors **112** using a micromachining process, where the computer-controlled milling machine with micro end-mill tool is used to mechanically remove a thin layer of carbon-based electrodes **112** and the tubular polymer electrolyte layer **139A** at a depth of 30–50 microns. This process thus creates four equally sized electrode sectors **112** at every 90° on the surface of the tubular polymer electrolyte layer **139A** which can be independently controlled by electrical power to achieve two degrees-of-freedom actuation.

[00128] Finally, in this exemplary example, the electrolyte is incorporated in the cleaned tubular polymer electrolyte membrane layer **139A**. First, the tubular polymer electrolyte layer **139A** is dried under vacuum (30 in Hg) at 100–140 °C for several hours to remove humidity. Thereafter, the dried tubular polymer electrolyte layer **139A** is impregnated with an ionic liquid (such as EMI-BF₄ or EMI-TFSI) by soaking in respective ionic liquid at elevated temperature for several hours.

[00129] In another embodiment, the flexible and elongate portion **101** of the medical device **10** (see FIGs. **1**, **7**, **8A**, **8B**, **17**, **19** and **25**) used to move the bendable portion **110** as described above can be formed using conventional processes known in the art. Alternately, an inner member **120** may comprise a polytetrafluoroethylene (PTFE) material, a reinforcing mesh **121** (see FIG. **19**), which may be a braided wire or a coiled wire, and an outer member **150** are placed over a slender rod or a pin to be used as a mandrel. Four electrically-conductive conduits **130**, which may comprise gold wires having a small diameter of, for example, 25 μm, are aligned with and secured along the length of the insulating tube using an adhesive such as, for example, an epoxy adhesive or, more specifically, a photo-activated (for example, such as a ultraviolet light-activated) adhesive. An outer member **150**, which functions as a sheath or a jacket comprising a resilient material such as, for example, PEBA[®], available from Arkema of Colombes, France, is sheathed over inner member **120** and the electrically-conductive conduits **130** adhered thereto. The inner member **120**, the reinforcing mesh **121** (which may be, for example, braided wire or coiled wire), the tubular insulation member **127** and the outer member **150** may be assembled using a reflow process. For subsequent coupling with the polymer electrolyte layer **139**, the inner member **120** is left longer in length than the outer member **150**, resulting in an extended portion of the inner member

120 that extends further beyond the distal end of the outer member **150**. A polymer electrolyte layer **139** is placed over the extended portion of the inner member **120** and moved proximal to the distal end of the outer member **150** and the electrically-conductive conduits **112** are connected to the four electrodes **112** formed onto the exterior of the polymer electrolyte layer **139** using epoxy, followed by a reflow process.

[00130] The polymer electrolyte layer **139** may have an outer diameter of, for example, one millimeter (1 mm), a length of, for example, twenty millimeters (20 mm). It will be understood that the size may vary with the intended application. The polymer electrolyte layer **139** may be clamped in a vertical cantilever configuration using a custom-made connector clamp with four spring-loaded prong contacts that attach to each electrode **112** formed on the polymer electrolyte layer **139** (see FIG. 25). The free-length of the polymer electrolyte layer **139** may be up to eighteen millimeters (18 mm) or more. Electrical wires from the clamp may be connected to a custom-made controller device. A digital microscope camera such as, for example, a Plugable[®] USB 2.0, may be used to record images of the actuation of the polymer electrolyte layer **139**.

[00131] In one embodiment of the medical device **10** (e.g., a micro-catheter), the bore **140** of the inner member **120** can be used to guide an inserted center wire **270** having an effector attached thereto to a predetermined position within a lumen of the body. For example, but not by way of limitation, FIG. 26 illustrates a distal end **102** of an actuation part **100**, comprising: a radially interior bore **140**, at least one polymer electrolyte layer **139**, the polymer electrolyte layer **139** secured adjacent to the distal end **102** of the actuation part **100** in alignment with the inner member **120**. A plurality of electrodes **112** are circumferentially distributed about the at least one polymer electrolyte layer **139** and connected to a source of electrical current through a plurality of electrically-conductive

conduits **130**, each having a proximal end coupled to the source of electrical current (not shown) and a distal end coupled to at least one of the plurality of electrodes **112**. An elongate and flexible center wire **270** having a proximal end (not shown), a distal end **272** and a diameter **279** therebetween that is smaller than the diameter of the bore **140** of the inner member **120** of the actuation part **100** is introduced into the bore **140** of the actuation part **100** with a spring member **271** connected to the distal end **272** of the center wire **270**. The spring member **271** is radially compressed to the state illustrated in FIG. 26 to enable it to be introduced, while connected to the distal end **272** of the center wire **270**, into the bore **140** of the actuation part **100**. The spring member **271** and the center wire **270** are pushed through the bore **140** of the actuation part **100** until the spring member **271** is in the bore **140** of the bendable portion **110** at the distal end **102** of the actuation part **100** to position the distal end **272** of the center wire **270** adjacent to the distal end **102** of the actuation part **110**. The spring member **271** is a radially compressible and resilient spring member **271** coupled to the distal end **272** of the center wire **270**. The spring member **271** is sized for exceeding the diameter **279** of the bore **140** of the actuation part **100** in an expanded configuration and for fitting within and being positioned in the bore **140** of the actuation part **100** by the center wire **270** in a radially compressed configuration as shown in FIG. 26. The center wire **270** can be used to advance, in the direction of arrow **291**, and to position the spring member **271** immediately adjacent to the distal end **102** of the actuation part **100** with the actuation part **100** disposed within or immediately adjacent to an obstruction **293** in a blood vessel (lumen) **290** into which the actuation part **100** is introduced.

[00132] The spring member **271** can be expanded to engage and grip the obstruction **293** in the blood vessel **290** by retracting the actuation part **100** in the direction of arrow

292 while maintaining the center wire **270** stationary to cause the actuation part **100** to be withdrawn from a surrounding position about the spring member **271**, thereby causing the spring member **271** to be released from the radially compressed configuration to the expanded configuration shown in FIG. **27**. FIG. **27** illustrates how the obstruction **293** is gripped by the expanded spring member **271**, thereby allowing the obstruction **293** to be retrieved in the direction of the arrow **292** from the blood vessel **290** by retrieving the center wire **270** and the actuation part **100** together from the blood vessel **290**.

[00133] In one embodiment, the spring member **271** is a coil spring having a plurality of coils **296** in a series as shown in FIG. **26**. In another embodiment, the spring member **271** includes a plurality of corrugated or sinusoidally shaped wires **294** as shown in FIG. **28**, each coupled at the apexes of the waves or peaks **295** to the apexes of the waves or peaks **295** of an adjacent wire **294** to form a generally tubular or cylindrically shaped spring assembly **271A**, as shown in FIG. **28**. It will be understood that expandable spring elements of this type generally elongate as they radially expand from a radially compressed configuration to a radially expanded configuration.

[00134] FIG. **29** is a perspective view of the elongate, flexible portion **101** and a bendable portion **110** disposed at the distal end **102** of the actuation part **100** of another embodiment of the medical device **10** of FIG. **1**. Unlike a micro-catheter (e.g., the medical device shown in FIGs. **2-4B**), FIG. **29** illustrates a medical device **10** without an interior bore that may, for example, be a guidewire. The bendable portion **110** of the actuation part **100** includes an ionic electroactive polymer actuator comprising a polymer electrolyte body **139B** disposed adjacent to the inner member **120** of the elongate, flexible portion **101** and centrally to an angularly-distributed plurality of

energizable electrodes **112**. Each of the plurality of electrodes **112** that surrounds the exterior wall **138** of the polymer electrolyte body **139B** is connected to a distal end **131** of an electrically-conductive conduit **130** through which an electrical signal or current may be supplied to the connected electrode **112**. To increase the function of the guidewire (e.g., support, steering, tracking, visibility, tactile feedback, lubricity, and/or trackability), it will be understood that the elongate, flexible portion **101** may optionally further comprise a protective outer member (not shown, such as a cover and/or coating) to surround the inner member **120** while a helical coil may be optionally further covered over the protective outer member. The bendable portion **110** of FIG. **29** is illustrated in the straight mode, which can be selectively and controllably deformed to a bent mode by selective energization of one or more of the plurality of electrodes **112**, as explained above.

[00135] FIG. **30** is the perspective view of the bendable portion **110** at the distal end **102** of the actuation part **100** of FIG. **29** illustrating the deformed or bending mode. The bendable portion **110** of the actuation part **100** of the medical device **10** is illustrated as having been actuated from the straight mode shown in FIG. **29** to the deformed or bent mode of FIG. **30** through the selective application of electrical signals to selected electrodes **112** to deform the polymer electrolyte body **139B**. The energization of selected electrodes **112** causes the bendable portion **110** to be deformed from the straight mode to the bent mode by application of an external force indicated by arrow **118**. It will be understood that the medical device **10** in FIG. **29** and **30**, as a guidewire, may be used to navigate vessels to reach a lesion or vessel segment. Once the bendable portion **110** of the medical device **10** arrives at its destination, it acts as a

guide so that larger catheters having a bore for passing through the guidewire can rapidly follow for easier delivery to the treatment site.

[00136] In some embodiments a medical device **10** comprises an elongate flexible portion **101** that comprises an outer tubular layer; an inner tubular layer, wherein a space is formed between the outer tubular layer and the inner tubular layer; a support layer positioned within the space, wherein the support layer comprises: a braided wire, a coil or the combination thereof being covered on an outer surface of the inner tubular layer; a bendable portion **110** provided at a distal end **102** of the elongate flexible portion **101**, comprising an ionic electroactive polymer layer, that is bendable in a desired direction in response to an applied electrical signal, wherein the ionic electroactive polymer layer comprises: an ionomer tubular layer comprising an electrolyte and a plurality of electrodes placed in contact with the ionomer tubular layer; and a transmitting member which comprises a plurality of wires respectively arranged along the space of the flexible elongate member and electrically connecting the electrodes. In some embodiments the wires further comprise an insulating layer.

[00137] In some embodiments a medical device comprises a flexible elongated member; and a bending member provided at a distal end of the flexible elongated member, made from an electroactive polymer, and bendable in a desired direction in response to an applied electrical signal, wherein the bending member comprises a main body made of an ionic electroactive polymer and a plurality of electrodes placed in contact with the main body. In some embodiments the outer surfaces of the flexible elongated member and the bending member are coated with a hydrophilic material.

[00138] In some embodiments the bendable portion **110** further comprises an encapsulation layer covering the bendable portion **110**. In some embodiments the

flexible inner member **120** and the bendable portion **110** are coated with a hydrophilic material and/or the bendable portion **110** further comprises a tubular insulation member **127** between the reinforcing mesh and electrically-conducting conduit **130**. In some embodiments the outer tubular member further comprises a plurality of insulation layers. In some embodiments each wire passes through each insulation layer respectively. In some embodiments, the electrodes are selected from the group consisting of Pt electrodes, Au electrodes, carbon electrodes, or the combination thereof. In some embodiments the carbon electrodes are selected from the group consisting of carbide-derived carbon, carbon nanotube, graphene, a composite of carbide-derived carbon and ionomer, and a composite of carbon nanotube and ionomer. In some embodiments, the electrodes are symmetrically arranged along the circumference of the ionic electroactive polymer layer and in some embodiments there are four electrodes.

[00139] In some embodiments the device further comprises an electrical controller that transmits electrical signals through the electrically-conducting conduit **130** to the electrodes and inducing bending of the bendable portion **110**. In some embodiments the electrical controller is configured to generate electrical signals in response to user manipulation such that the bendable portion **110** responds to user manipulation. In some embodiments the medical device is a catheter or a guide wire.

[00140] In some embodiments, the device further comprises a drive assembly configured to move the flexible inner member **120** lengthwise. In some embodiments the drive assembly is configured to come into partial contact with the surface of the flexible inner member **120** using a friction-based mechanism that acts between the drive assembly and the surface.

[00141] In some embodiments, the drive assembly comprises at least a pair of rotary drive members **330a**, **330b** and a motor **310** that operates the rotary drive members **330a**, **330b**. The flexible inner member **120** is arranged to pass between the pair of rotary drive members **330a**, **330b** and is moved along lengthwise with the operation of the rotary drive members **330a**, **330b**.

[00142] In some embodiments the pair of rotary drive members **330a**, **330b** comprise spools rotatably placed, and the flexible inner member **120** is placed to be movable between the pair of spools by the rotation of the spools. In some embodiments the drive system comprises a pair of belts that are arranged on either side of the flexible inner member **120**, and the flexible inner member **120** is placed to be movable between the pair of belts by the operation of the belts.

[00143] In some embodiments the medical device further comprises: an upper case portion **210** that accommodates the flexible inner member **120**; and a lower case portion **210** that is detachable from the upper case portion **210**, wherein some or all parts of the drive assembly and the electrical control member are placed in the lower case portion **210**. In some embodiments, the moving parts are arranged in the upper case portion **210**. In some embodiments the drive assembly further comprises: a current distributor **410** electrically connecting the wires and being inside the upper case portion **210**; an interlocking part for transmitting driving force from the motor **310** to the moving parts, being provided in the lower case portion **210**; and an interface device **420** being connected to the electrical controller and provided in the lower case portion **210**. In some embodiments the upper case portion **210** and the lower case portion **210** are fastened together, the worm gear **320** of the lower case portion **210** is connected to the moving parts of the upper case portion **210** to transmit the driving force, and the

interface device **420** of the lower case portion **210** is connected to the current distributor **410** of the upper case portion **210** to transmit electrical signals from the electrical controller to the wires. Some embodiments further comprise a sensing member that senses an electrical signal at the bendable portion **110** when a deformation occurs to the bending member. In some embodiments the bendable sensing member **117** is configured to determine whether an external force is applied to the bendable portion **110** or not, considering an electrical signal generated by bending control from the electrical control member, out of electrical signals sensed at the bending member. Some embodiments further comprise a master controller that remotely instructs the electrical controller and the drive assembly. In some embodiments the medical device is a catheter in which the flexible inner member **120** and the bendable portion **110** have a conduit inside and in some embodiments the medical device is a guide wire. In some embodiments the bendable portion **110** further comprises an encapsulation layer being covered the bending member. In some embodiments the outer surfaces of the flexible inner member **120** and the bendable portion **110** are coated with a hydrophilic material. In some embodiments the medical device the wires further comprise an insulation layer. In some embodiments the bendable portion **110** further comprises a tubular insulation member **127** between the reinforcing mesh and electrically-conducting conduit **130**. In some embodiments the outer tubular member further comprises a plurality of insulation layers. In some embodiments each wire passes through each insulation layer respectively. In some embodiments the electrodes are Pt electrodes, Au electrodes, carbon electrodes or the combination thereof. In some embodiments the ionic electroactive polymer layer further comprises carbon-based electrodes consisting of carbide-derived carbon, carbon nanotube, graphene, a composite of carbide-derived

carbon and ionomer, and a composite of carbon nanotube and ionomer. In some embodiments the electrodes are symmetrically arranged along the circumference of the ionic electroactive polymer layer. In some embodiments there are four electrodes.

[00144] In some embodiments the electrical controller is configured to generate electrical signals, and the drive assembly is configured to move the flexible inner member **120** in response to user manipulation.

[00145] In some embodiments a system for remotely controlling the positioning of a medical device within the body of a patient comprises: a remote control member that comprises a master controller that remotely instructs the medical device to be positioned within the body of the patient; and a local communication member configured to communicate a control signal between the remote control member and the medical device. In some embodiments the communication member wirelessly transmits information using Bluetooth or wireless 802.11 communication over the internet. In some embodiments the system drive assembly is configured to come into partial contact with the surface of the flexible inner member **120** and move the flexible inner member **120** based on a friction-based mechanism acting between the drive assembly and the surface. In some embodiments the system drive assembly comprises at least a pair of rotary drive members **330a**, **330b** and a motor **310** that operates the rotary drive members **330a**, **330b**, and the flexible inner member **120** is arranged to pass through between the pair of rotary drive members **330a**, **330b** and moves lengthwise along with the operation of the rotary drive members **330a**, **330b**.

[00146] In some embodiments of the system the pair of rotary drive members **330a**, **330b** comprises a pair of spools that are rotatably placed, and the flexible inner member **120** is placed to be movable between the pair of spools by the rotation of the spools. In

some embodiments the system the pair of rotary drive members **330a**, **330b** comprises a pair of belts that are arranged on either side of the flexible inner member **120**, and the flexible inner member **120** is placed to be movable between the pair of belts by the operation of the belts. In some embodiments the system further comprises an upper case portion **210** that accommodates a tubular flexible inner member **120**; and a lower case portion **210** that is placed to be detachable from the upper case portion **210**, wherein some or all parts of the drive assembly and the electrical controller are placed in the lower case portion **210**. In some embodiments the system the rotary drive members **330a**, **330b** are arranged in the upper case portion **210**. In some embodiments the system the drive assembly further comprises: a current distributor **410** electrically connecting the wires and being inside the upper case portion **210**; a worm gear **320** for transmitting driving force from the motor **310** to the moving parts, being provided in the lower case portion **210**; and a interface device **420** being connected to the electrical controller and provided in the seconding module. In some embodiments of the system the upper case portion **210** and the lower case portion **210** are fastened together, the worm gear **320** of the lower case portion **210** is connected to the rotary drive members **330a**, **330b** of the upper case portion **210** to transmit the driving force, and the interface device **420** of the lower case portion **210** is connected to the current distributor **410** of the upper case portion **210** to transmit electrical signals from the electrical controller/processor to the wires.

[00147] In some embodiments the system further comprises a sensing member **117** that senses an electrical signal at the bendable portion **110** when a deformation occurs to the bending member. In some embodiments the sensing member **117** is configured to determine whether an external force is applied to the bendable portion **110** or not,

considering an electrical signal generated by bending control from the electrical control member, out of electrical signals sensed at the bending member. In some embodiments the system further comprises a master controller that remotely instructs the electrical controller and the drive assembly. In some embodiments of the system the medical device is a catheter in which the flexible inner member **120** and the bendable portion **110** have a conduit inside. In some embodiments the medical device is a guide wire. In some embodiments of the system the bendable portion **110** further comprises an encapsulation layer being covered the bending member. In some embodiments of the system the outer surfaces of the flexible inner member **120** and the bendable portion **110** are coated with a hydrophilic material. In some embodiments the system the wires further comprise an insulation layer. In some embodiments of the system the bendable portion **110** further comprises a tubular insulation member **127** between the reinforcing mesh and electrically-conducting conduit **130**. In some embodiments of the system the outer tubular member further comprises a plurality of insulation layers. In some embodiments of the system each wire passes through each insulation layer respectively. In some embodiments of the system the electrodes are Pt electrodes, Au electrodes, carbon electrodes or the combination thereof. In some embodiments of the system the ionic electroactive polymer layer further comprises carbon-based electrodes consisting of carbide-derived carbon, carbon nanotube, graphene, a composite of carbide-derived carbon and ionomer, and a composite of carbon nanotube and ionomer. In some embodiments of the system the electrodes are symmetrically arranged along the circumference of the ionic electroactive polymer layer. In some embodiments of the system there are four electrodes. In some embodiments of the system the electrical controller is configured to generate electrical signals, and the drive assembly is

configured to move the flexible inner member **120** in response to user manipulation. In some embodiments, the inner member **120** is tubular. In some embodiments the ionomer tubular layer comprising an electrolyte is a polymer electrolyte layer **139**. In some embodiments the ionic electroactive polymer layer comprises a polymer electrolyte layer **139** and a plurality of electrodes **112**.

[00148] Certain embodiments include methods for preparing the bendable portion **110** of a device comprising the steps of: providing a polymer electrolyte layer **139** and a mandrel against an inner surface of the ionomer tube; forming a carbon electrode layer on an outer surface of the polymer electrolyte layer **139**, wherein a mixture of a carbon-based conductive power is applied onto the outer surface of the polymer electrolyte layer **139**; attaching an electrically-conducting conduit **130** on the carbon electrode layer, wherein the electrically-conducting conduit **130** comprises a plurality of wires respectively being electrically connected to the carbon electrode layer; providing a heat-shrink tubular layer covered around the carbon electrode layer and the polymer electrolyte layer **139**; heating the heat-shrink polymer to cause reflow of the ionic electroactive polymer from the polymer electrolyte layer **139**, so that the carbon electrode layer and the polymer electrolyte layer **139** are thermally bonded; and removing the heat-shrink tubular layer and the mandrel to form the bending member.

[00149] In some embodiments the method further comprises the steps of: forming a platinum layer on the carbon electrode layer; forming a gold layer on the platinum layer; micromachining the carbon electrode layer to be sectored into a plurality of carbon electrodes; and incorporating electrolytes into the bending member, wherein the bendable portion **110** is dried to remove humidity and impregnated with an ionic liquid. In some embodiments the platinum layer is disposed on the carbon electrode layer

using electroless chemical deposition. In some embodiments the gold layer is disposed on the platinum layer using electrochemical deposition. In some embodiments a computer-controlled milling machine with a micro end-mill tool is used to mechanically remove a thin layer from the carbon electrode layer and the polymer electrolyte layer **139** at a predetermined depth. In some embodiments the predetermined depth is about 30 to about 50 microns.

[00150] In some embodiments the method for preparing a bendable portion **110** of a medical device, comprises steps of: providing a mandrel against an outer surface of a polymer electrolyte layer **139** comprising at least a ionic electroactive polymer; incorporating electrolytes into the bending member, wherein the bendable portion **110** is dried to remove humidity and impregnated with an ionic liquid; forming a carbon electrode layer on the polymer electrolyte layer **139**, wherein at least a carbon-based conductive power is dispersed in a volatile solvent to form an a mixture of the carbon electrode and the mixture is applied onto the polymer electrolyte layer **139** to form a carbon electrode layer; attaching an electrically-conducting conduit **130** on the carbon electrode layer, wherein the electrically-conducting conduit **130** comprises a plurality of wires respectively being electrically connected to the carbon electrode layer; disposing a heat-shrink polymer around the carbon electrode layer and the polymer electrolyte layer **139**; heating the heat-shrink polymer, the carbon electrode layer and the polymer electrolyte layer **139** to cause reflow of the ionic electroactive polymer from the polymer electrolyte layer **139**, whereby the carbon electrode and the polymer electrolyte layer **139** are thermally bonded; and removing the first heat shrink material and the mandrel to form the bending member. Some embodiments further comprise the steps of: micromachining the carbon electrode layer to be sectored into a plurality of carbon

electrodes. While in other embodiments a computer-controlled milling machine with micro end-mill tool is used to mechanically remove a thin layer from the carbon electrode layer and the polymer electrolyte layer **139** at a predetermined depth, for example a predetermined depth is about 30 to about 50 microns.

[00151] In some embodiments the bendable portion **110** is dried to remove humidity, and then is impregnated with an ionic liquid. In some embodiments the drying occurs under vacuum at about 100 to about 140°C. In some embodiments the ionic liquid is 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF₄), 1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-TFSI) or a combination thereof. In some embodiments the ionic electroactive polymer is an ionic polymer-metal composite (IPMC). In some embodiments the ionic polymer-metal composite (IPMC) is Nafion. In some embodiments of the method the carbon-based conductive powder is selected from carbide-derived carbon, carbon nanotube, carbon aerogel, graphene, or the combination thereof. In some embodiments the carbon-based conductive powder further comprises: transition metal oxide powder or metal powder or the combination thereof. In some embodiments the transition metal oxide powder comprises: MnO₂, RuO₂ or the combination thereof. In some embodiments the metal powder comprises: Pt, Au or the combination thereof. In some embodiments attaching a electrically-conducting conduit **130** on the carbon electrode layer further comprises a step of attaching a gold foil layer covered the polymer electrolyte layer **139**.

[00152] In some embodiments of the method at least one carbon-based conductive powder is dispersed in a volatile solvent to form a mixture that is applied onto outer surface of the polymer electrolyte layer **139** to form a carbon electrode layer. In some embodiments the mixture is applied onto the polymer electrolyte layer **139** using brush

coating or spray coating to form a carbon electrode layer. In some embodiments the volatile solvent is isopropanol. In some embodiments the polymer electrolyte layer **139** is pretreated to roughen and clean the outer surface thereof. In some embodiments the outer surface of the polymer electrolyte layer **139** is roughened by a mechanical treatment, such as, but not limited to sandpapering or sandblasting. In some embodiments wherein the outer surface of the polymer electrolyte layer **139** is cleaned with hydrogen peroxide (H_2O_2), sulfuric acid (H_2SO_4) solutions, and de-ionized (DI) water.

[00153] Some embodiments provide a method for preparing a polymer electrolyte layer **139** in tubular shape for a bendable portion **110** of a device, comprising steps of: providing a liquid dispersion of a base material that is selected from the group consisting of ionic polymer, fluoropolymer and intrinsically conductive polymer; casting the liquid dispersion on a substrate; forming a polymer film on the substrate by curing the liquid dispersion; providing a mandrel, wherein the mandrel is further rolled around with the polymer film being removed from the substrate; and providing a heat-shrink tube to cover the rolled polymer film around the mandrel, and heating the heat-shrink tube to cause reflow of the rolled polymer film to form a polymer electrolyte layer **139**. In some embodiments the ionic polymer comprises Nafion or Flemion. In some embodiments the fluoropolymer comprises Poly[(vinylidene difluoride)-co-(chlorotrifluoroethylene) (PVDF) or the co-polymer thereof. In some embodiments the co-polymer comprises Poly(vinylidene difluoride-co-chlorotrifluoroethylene) (P(VDF-CTFE)) or Poly(vinylidene fluoride-co-hexafluoropropylene) (P(VDF-HFP)).

[00154] In some embodiments the intrinsically conductive polymer comprises: polyaniline (PANI), polypyrrole (Ppy), poly(3,4-ethylenedioxythiophene) (PEDOT), or

poly(p-phenylene sulfide) (PPS). In some embodiments the bendable portion **110** is an electroactive polymer actuator. In some embodiments the medical device is a catheter. In some embodiments the substrate is a PTFE plate or a glass plate. In some embodiments the heat-shrink tube is a fluorinated ethylene-propylene (FEP) tube. In some embodiments the heat-shrink tube is heated at a temperature of 200 to 230 °C.

[00155] It is to be noted that various modifications or alterations can be made to the above-described exemplary embodiments of the invention without departing from the technical features of the invention as defined in the appended claims.

We claim:

1. A medical device, comprising:

an elongate, flexible portion having a distal end and a proximal end;

at least one ionic electroactive polymer actuator, the actuator comprising:

at least one polymer electrolyte layer secured adjacent to the distal end of the elongate, flexible portion and

a plurality of electrodes circumferentially distributed about the at least one polymer electrolyte layer; and

a plurality of electrically-conductive conduits, each having a proximal end and a distal end coupled to at least one of the plurality of electrodes;

wherein the at least one polymer electrolyte layer deforms asymmetrically in response to the application of an electrical signal through at least one of the plurality of electrically-conductive conduits to at least one of the plurality of electrodes.

2. The medical device of claim 1, wherein the at least one polymer electrolyte layer comprises an electrolyte and a polymer selected from the group consisting of fluoropolymers and intrinsically conducting polymers.

3. The medical device of claim 2, wherein the fluoropolymers are perfluorinated ionomers, polyvinylidene difluoride (PVDF) or co-polymer thereof.

4. The medical device of claim 2, wherein the intrinsically conducting polymers comprise polyaniline (PANI), polypyrrole (Ppy), poly(3,4-ethylenedioxythiophene) (PEDOT), poly(p-phenylene sulfide) (PPS) or the combination thereof.

5. The medical device of claim 1, wherein each of the plurality of electrodes comprises one of platinum, gold, carbon and a combination of two or more of platinum, gold and carbon.
6. The medical device of claim 5, wherein each of the plurality of electrodes comprises one of carbide-derived carbon, carbon nanotube, graphene, a composite of carbide-derived carbon and ionomer, and a composite of carbon nanotube and ionomer.
7. The medical device of claim 1, wherein the plurality of electrodes is circumferentially distributed by equal angles about the at least one polymer electrolyte layer.
8. The medical device of claim 1, wherein the elongate, flexible portion further comprises:
 - an elongate, flexible inner member having a proximal end and a distal end disposed to couple with the at least one polymer electrolyte layer, and
 - an outer member surrounding the inner member and the plurality of electrically-conductive conduits.
9. The medical device of claim 8, wherein the inner member and the at least one polymer electrolyte layer further form a bore, and the polymer electrolyte layer is secured adjacent to the distal end of the inner member with the bore of the polymer electrolyte layer aligned with the bore of the inner member.

10. The medical device of claim 1, wherein each of the electrically-conductive conduits is electrically isolated one from the others.
11. The medical device of claim 8, wherein the outer member comprises a plurality of lumens embedded within the outer member, each lumen having an interior space longitudinally along the outer member for passing through each of the plurality of electrically-conductive conduits.
12. The medical device of claim 1, wherein each of the plurality of electrically-conductive conduits further comprise an insulation coating covered thereon.
13. The medical device of claim 8, further comprising at least one wire helically or interweavingly wrapped around the inner member intermediate the proximal end and the distal end to provide enhanced rigidity and strength.
14. The medical device of claim 13, further comprising an insulation member surrounding the at least one wire.
15. The medical device of claim 1, further comprising an electrical controller provided at the proximal end of the elongate, flexible portion and electrically connected to the electrically-conductive conduits for selectively controlling the electrical charges carried by the electrically-conducting conduits and imparted to the plurality of electrodes to manipulate the at least one ionic electroactive polymer actuator of the medical device.

16. The medical device of claim 15, further comprising a master controller having a manipulatable control member for inputting the bending control signals to the at least one ionic electroactive polymer actuator for providing two degrees of freedom of bending through the electrical controller.

17. The medical device of claim 15, further comprising a drive assembly configured to move the medical device lengthwise, the drive assembly including:

 a first rotary drive member with a gripping surface;

 an adjacent second rotary drive member with a gripping surface disposed proximal to the gripping surface of the first rotary drive member; and

 at least one electrically powered motor coupled to controllably rotate at least one of the first rotary drive member and the second rotary drive member;

 wherein the medical device is disposed intermediate and engaged by the gripping surface of the first rotary drive member and the gripping surface of the adjacent second rotary drive member so that rotation of one of the first rotary drive member and the second rotary drive member axially moves the medical device.

18. The medical device of claim 17, wherein clockwise rotation of the first rotary drive member and counterclockwise rotation of the adjacent second rotary drive member moves the medical device in a first direction; and counterclockwise rotation of the first rotary drive member and clockwise rotation of the adjacent second rotary drive member moves the medical device in a second direction opposite to the first direction.

19. The medical device of claim 17, further comprising a master controller having a manipulatable control member for inputting the bending control signals to the at least one ionic electroactive polymer actuator for providing two degrees of freedom of bending through the electrical controller and/or for inputting advance and retract control signals to the drive assembly for providing one degree of freedom of translation.

20. The medical device of claim 17, further comprising a case that includes:

a first portion having a sealed interior portion containing the first rotary drive member, the second rotary drive member, a proximal port through which the medical device passes, a distal port through which the medical device passes, and an interior cavity for storing windings of the medical device; and

a second portion supporting the motor.

21. The medical device of claim 20, wherein the second portion of the case and the first portion of the case are adapted for being coupled one to the other to operatively engage the motor with at least one of the first rotary member and the second rotary member.

22. The medical device of claim 1, further comprising a sensing member electrically connected to the plurality of electrodes to sense changes in the electrical signal at each of the plurality of electrodes.

23. The medical device of claim 19, further comprising:

a transmitter coupled to the master controller for transmitting a signal corresponding to the manipulation of the master controller; and

a receiver electrically connected to the drive assembly and the electrical controller for receiving the signal transmitted by the transmitter to the drive assembly and/or the electrical controller to correspond to the manipulation of the master controller.

24. A method of preparing a polymer electrolyte layer in tubular shape, comprising:

providing a substrate having a flattened surface;

providing a mandrel having a diameter of a desired size for the polymer electrolyte layer;

providing a volume of a liquid dispersion of a base material selected from the group consisting of fluoropolymers and intrinsically conducting polymers;

disposing the liquid dispersion on the substrate;

curing the liquid dispersion of the selected base material to form a cured polymer film having a thickness of between 10 microns and 50 microns on the substrate;

wrapping the polymer film onto a portion of the mandrel to provide a generally tubular sleeve formed of a plurality of wraps of the polymer film; and

providing a heat-shrink tube;

covering a portion of the mandrel and the generally tubular sleeve thereon with the heat shrink tube; and

heating the heat-shrink tube to cause reflow of the polymer film to form a homogenous tubular polymer electrolyte layer.

25. The method of claim 24, wherein the fluoropolymers comprise perfluorinated ionomers, polyvinylidene difluoride (PVDF) or co-polymers thereof.
26. The method of claim 24, wherein the intrinsically conducting polymers comprise one or more of polyaniline (PANI), polypyrrole (Ppy), poly(3,4-ethylenedioxythiophene) (PEDOT), poly(p-phenylene sulfide) (PPS), polyvinylidene fluoride, polyvinylidene difluoride or propylene carbonate.
27. The method of claim 24, wherein the heat shrink tube is a fluorinated ethylene-propylene (FEP) tube.
28. The method of claim 24, wherein the heat-shrink tube is heated at a temperature of 200 to 230 °C.
29. A method for preparing an ionic electroactive polymer actuator of a medical device in tubular shape, comprising :
- providing a polymer electrolyte layer having an exterior wall;
 - providing a mixture of a carbon-based conductive powder in a volatile solvent;
 - providing a plurality of electrically-conductive conduits, each having a proximal end and a distal end;
 - disposing the mixture on the exterior wall of the polymer electrolyte layer to form a carbon electrode layer thereon;
 - contacting the distal end of each electrically-conductive conduit to the carbon electrode layer;

providing a heat-shrink tube;

covering the polymer electrolyte layer and the carbon electrode layer thereon with the heat-shrink tube; and

heating the heat-shrink tube to cause reflow of the polymer electrolyte layer to form the ionic electroactive polymer actuator.

30. The method of claim 29, wherein the polymer electrolyte layer is further impregnated with an electrolyte.

31. The method of claim 29, wherein the electrolyte comprises an ionic liquid including one or more of 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF₄), 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-TFSI), or the combination thereof.

32. The method of claim 29, wherein a portion of the carbon electrode layer is further covered with one or more metal layers.

33. The method of claim 29, wherein after heating the heat-shrink tube, the carbon electrode layer is further micromachined to form a plurality of electrodes.

34. The method of claim 29, wherein the carbon-based conductive powder comprises carbide-derived carbon, carbon nanotube, carbon aerogel, graphene, or a combination thereof.

35. The method of claim 29, wherein the carbon-based conductive powder further comprises transition metal oxide powder, metal powder, or a combination thereof.

36. The method of claim 29, wherein the mixture is disposed on the exterior wall of the polymer electrolyte layer using a brush coating or spray coating.

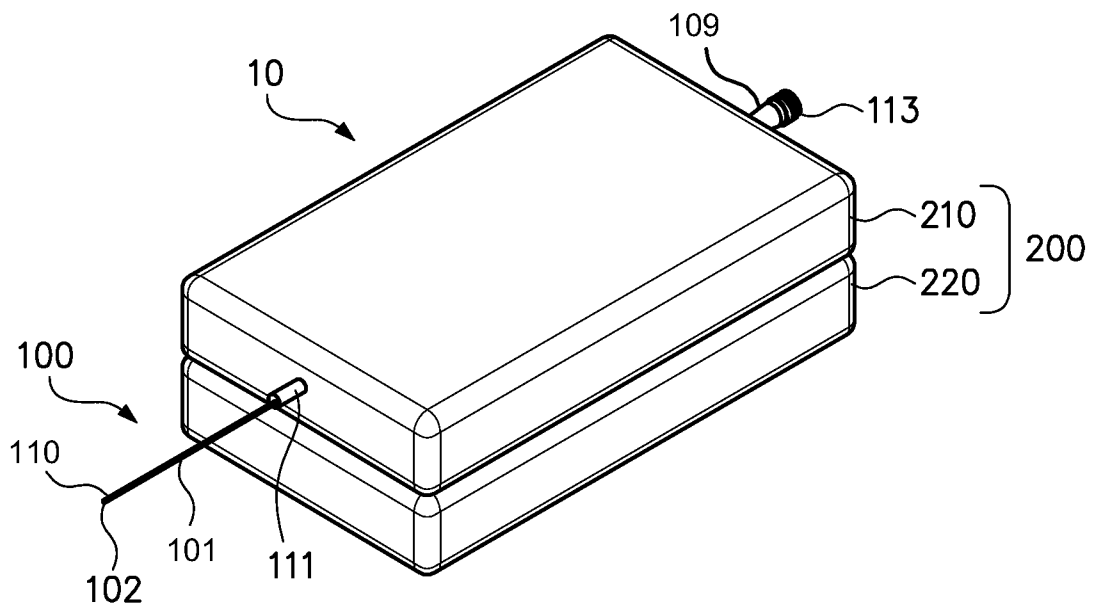


FIG. 1

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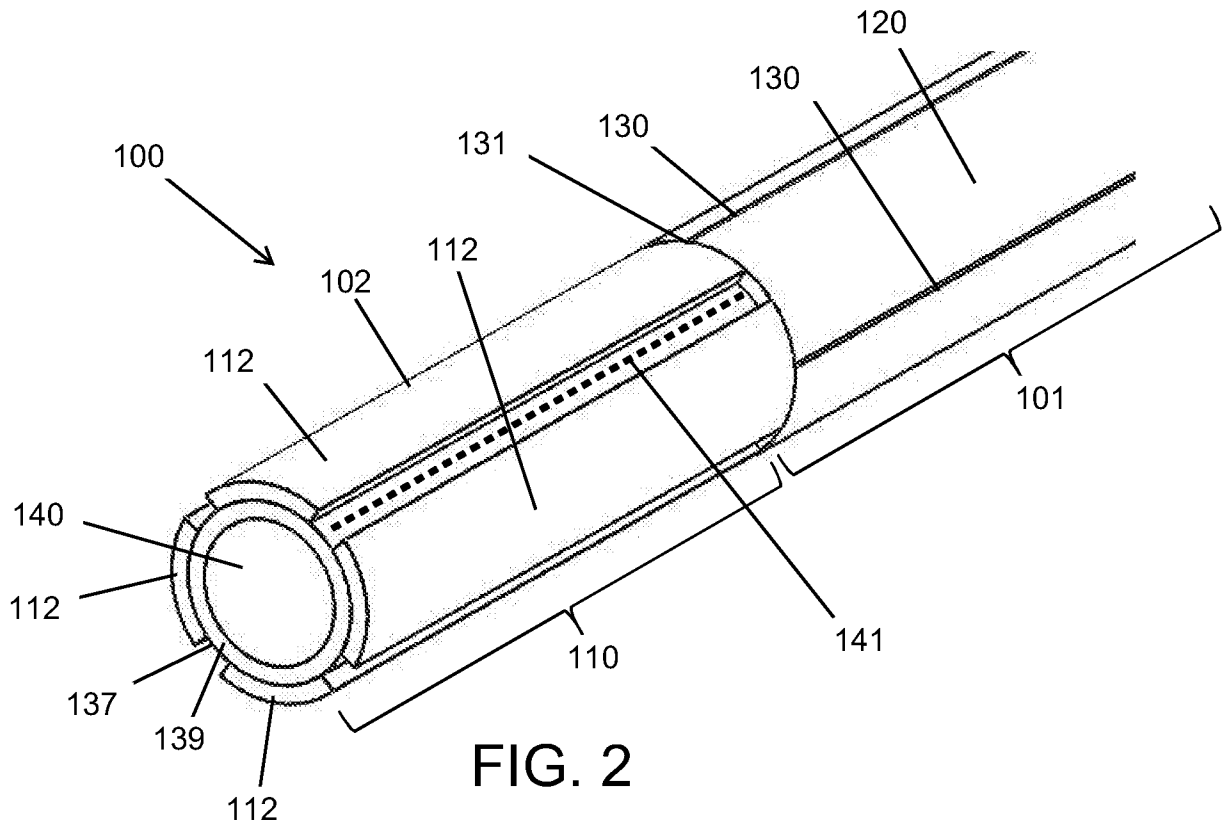


FIG. 2

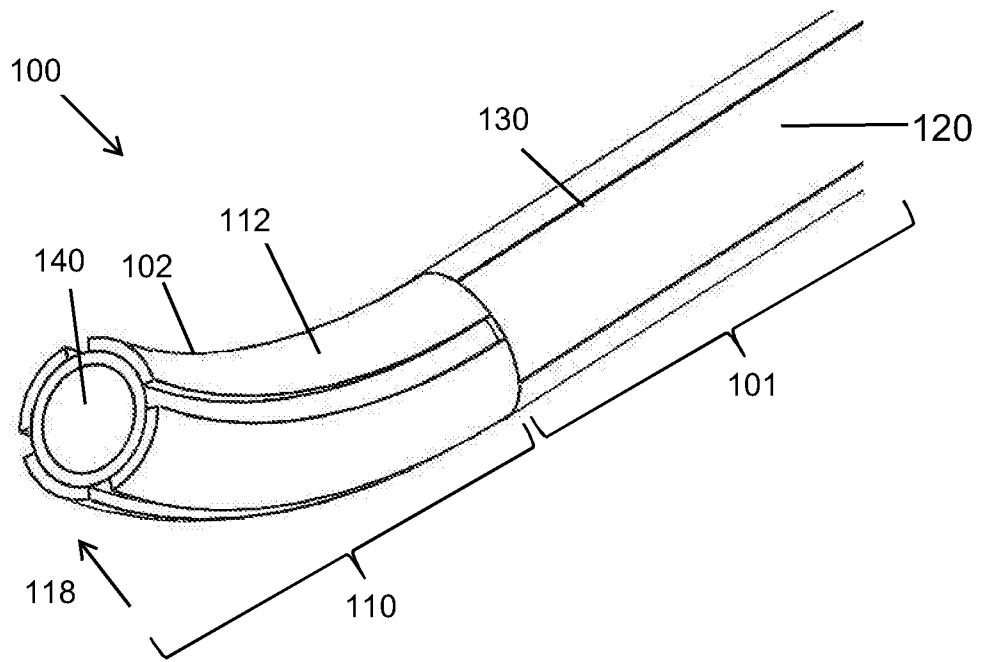


FIG. 3

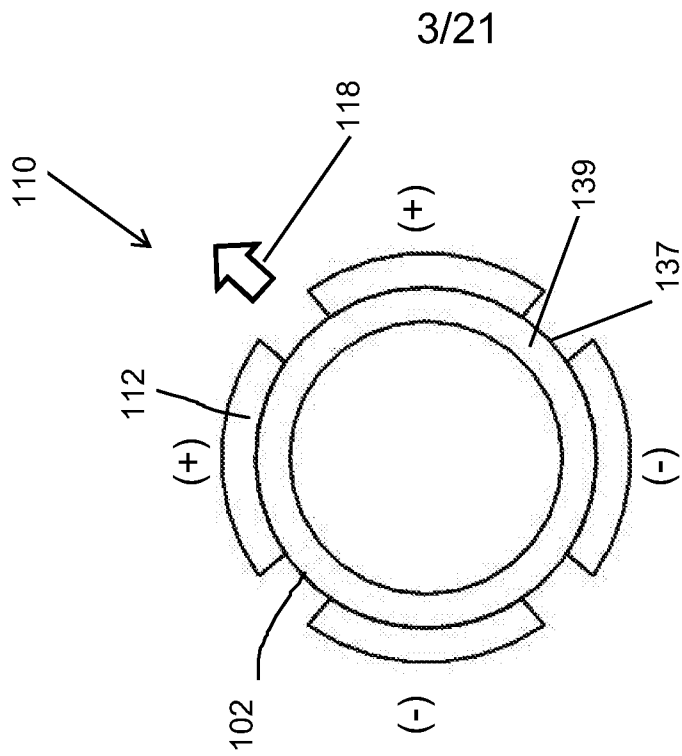


FIG. 4B

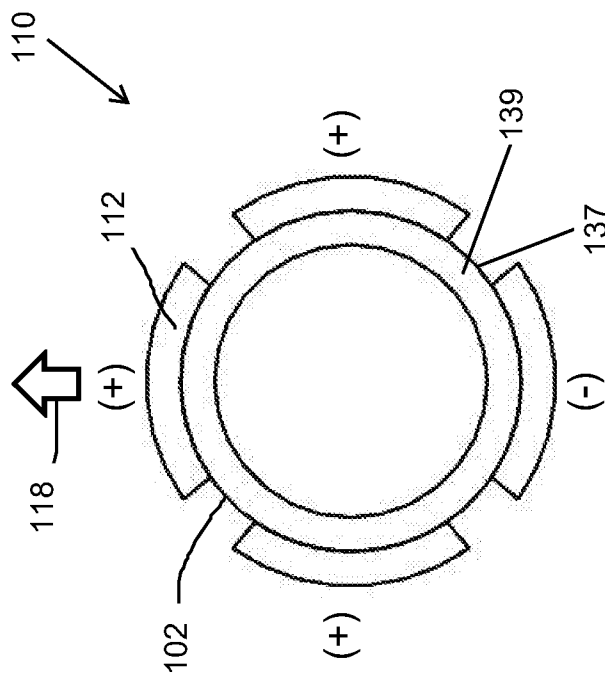


FIG. 4A

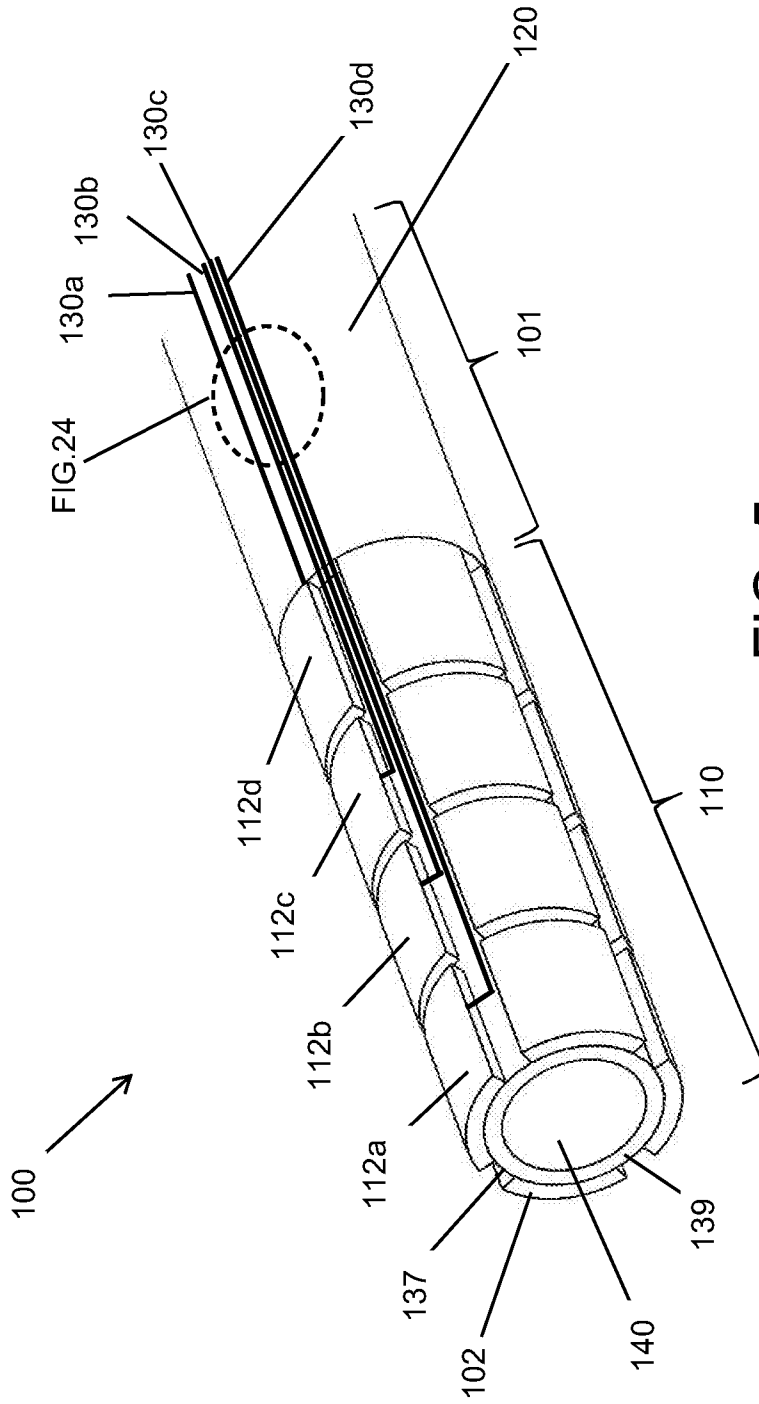


FIG. 5

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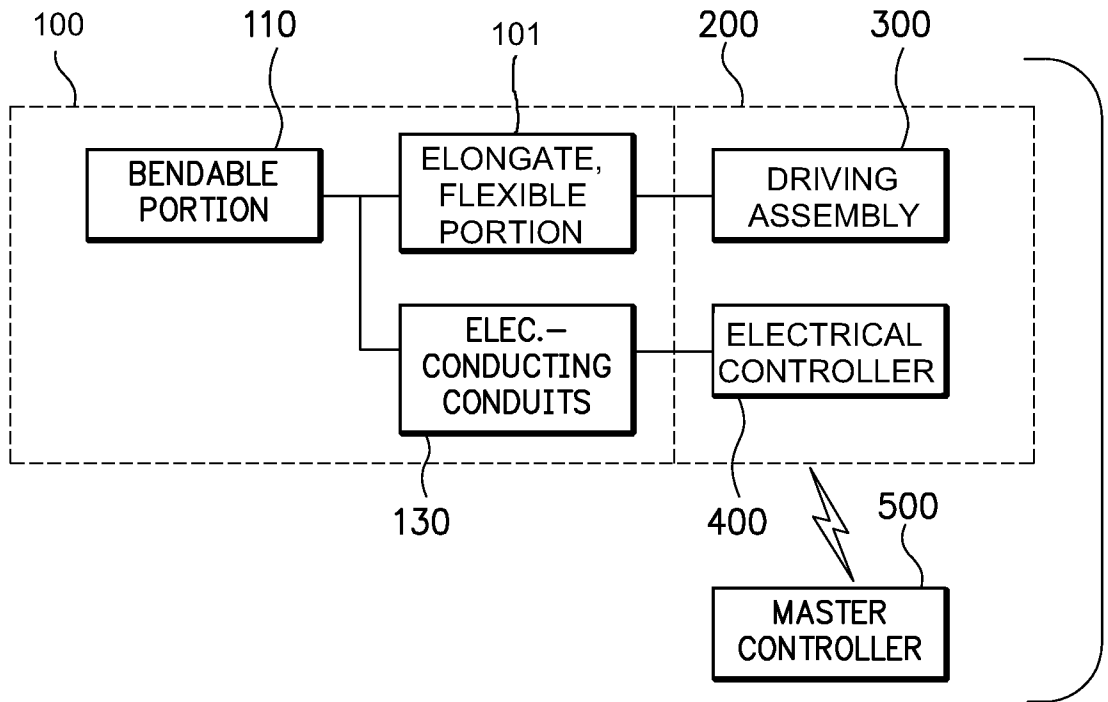


FIG. 6

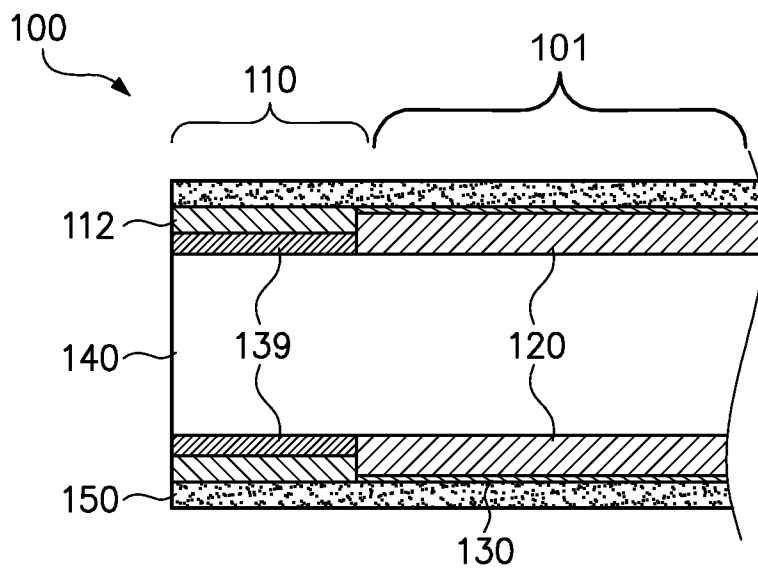
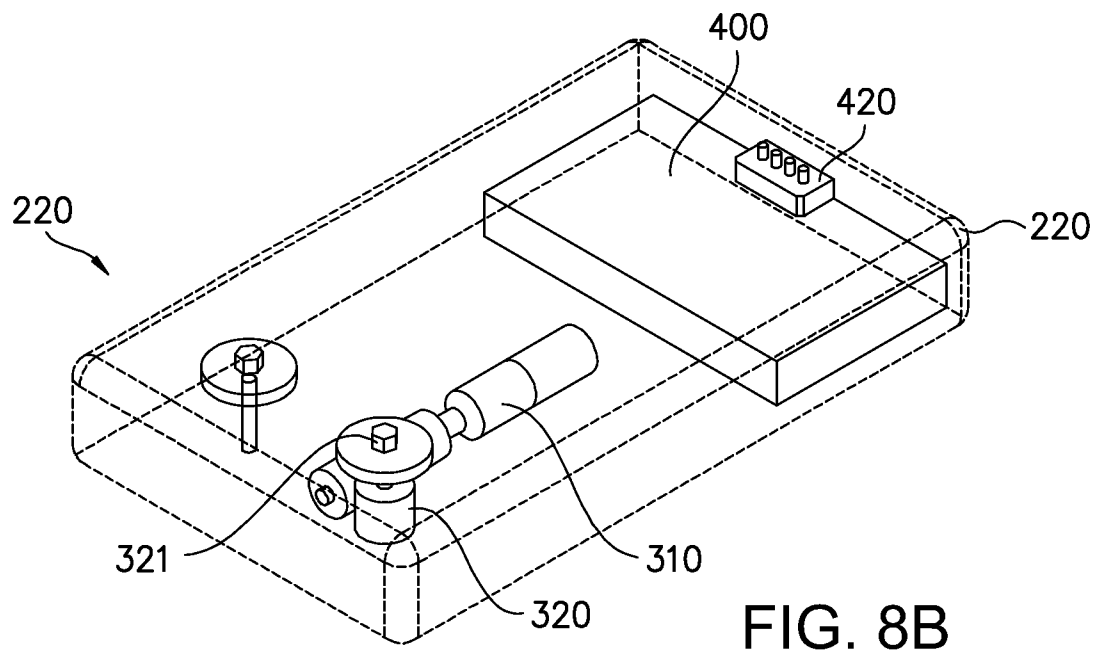
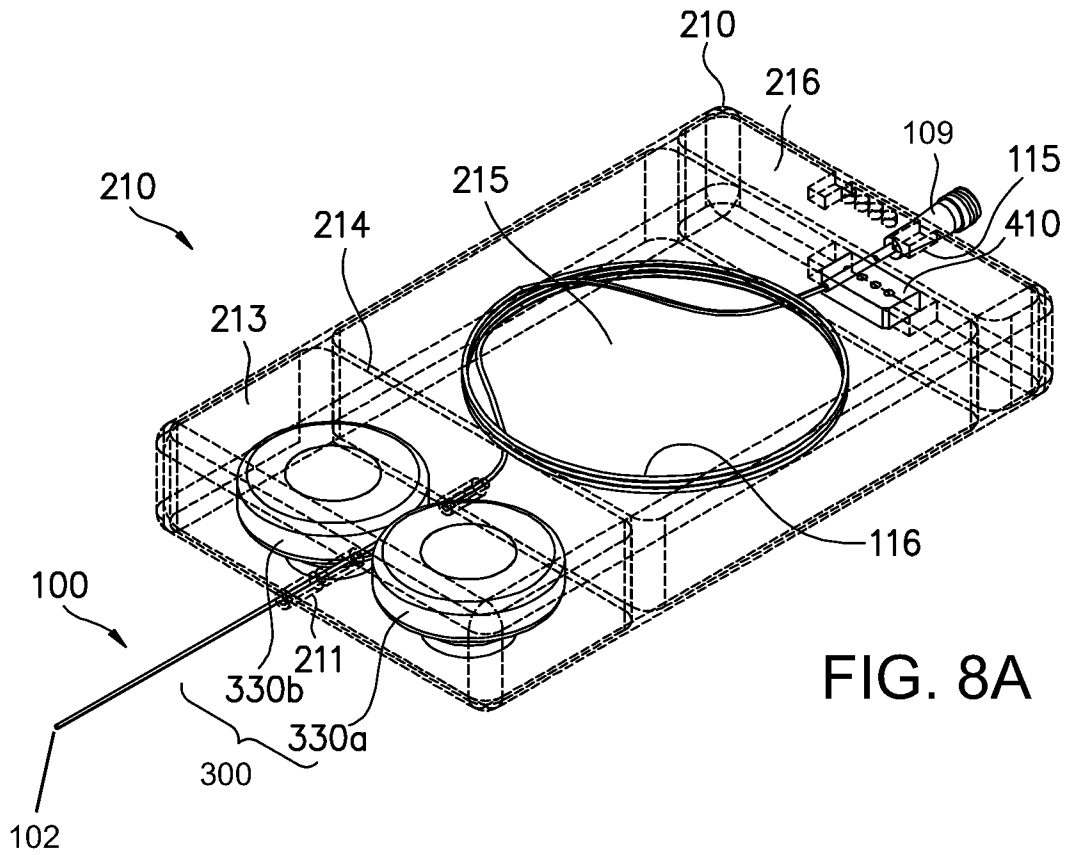


FIG. 7



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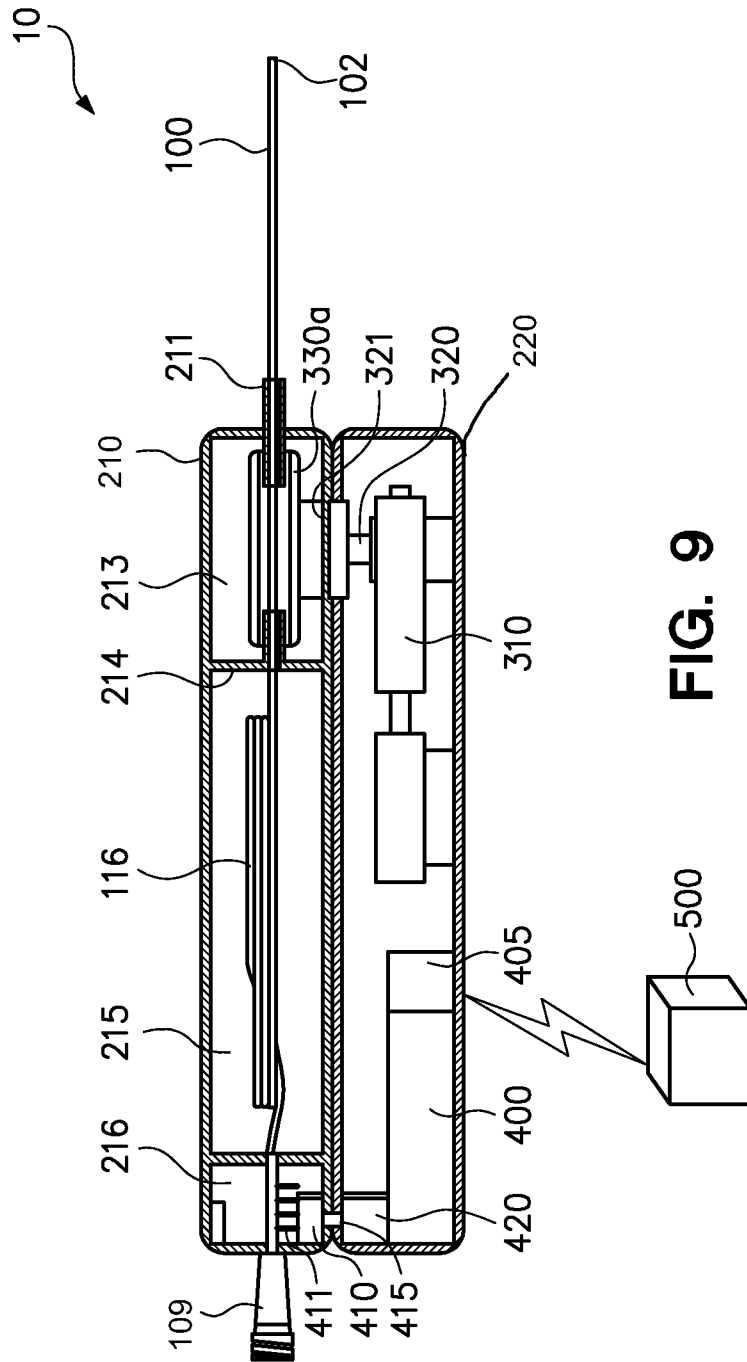


FIG. 9

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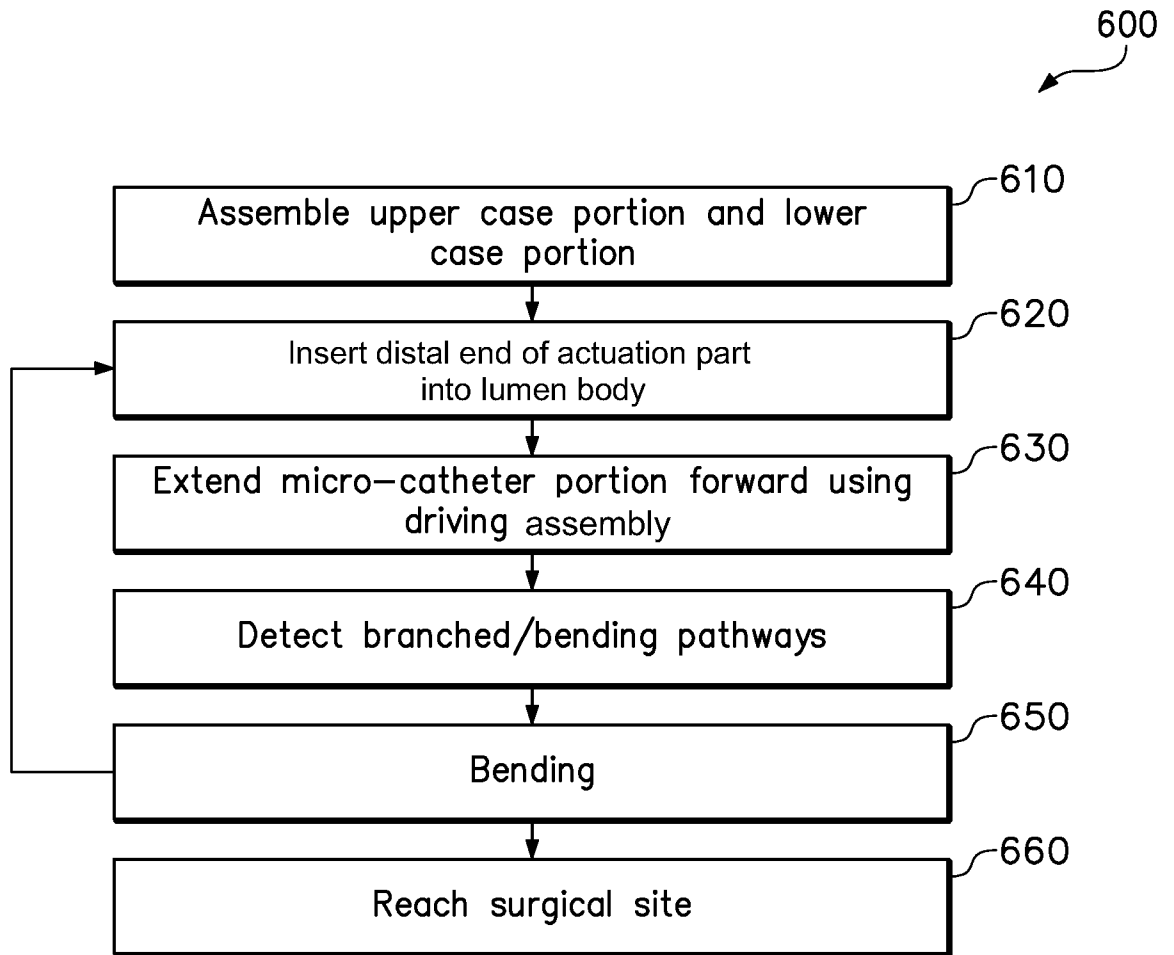


FIG. 10

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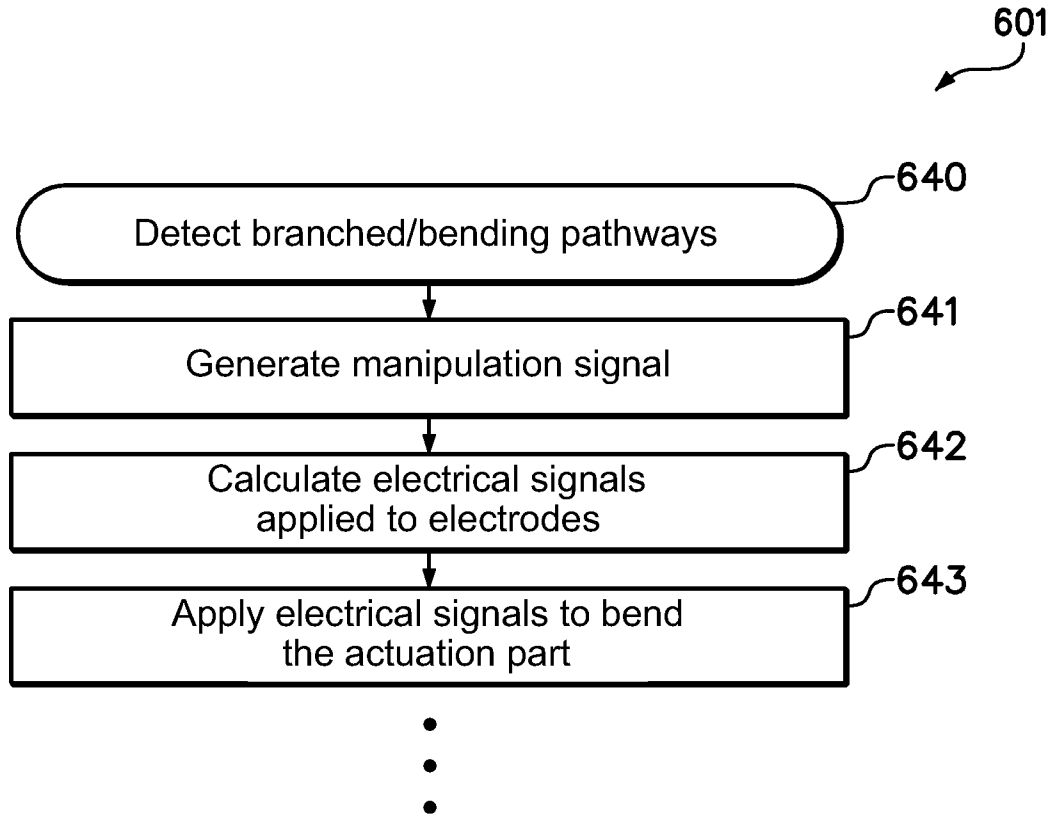


FIG. 11

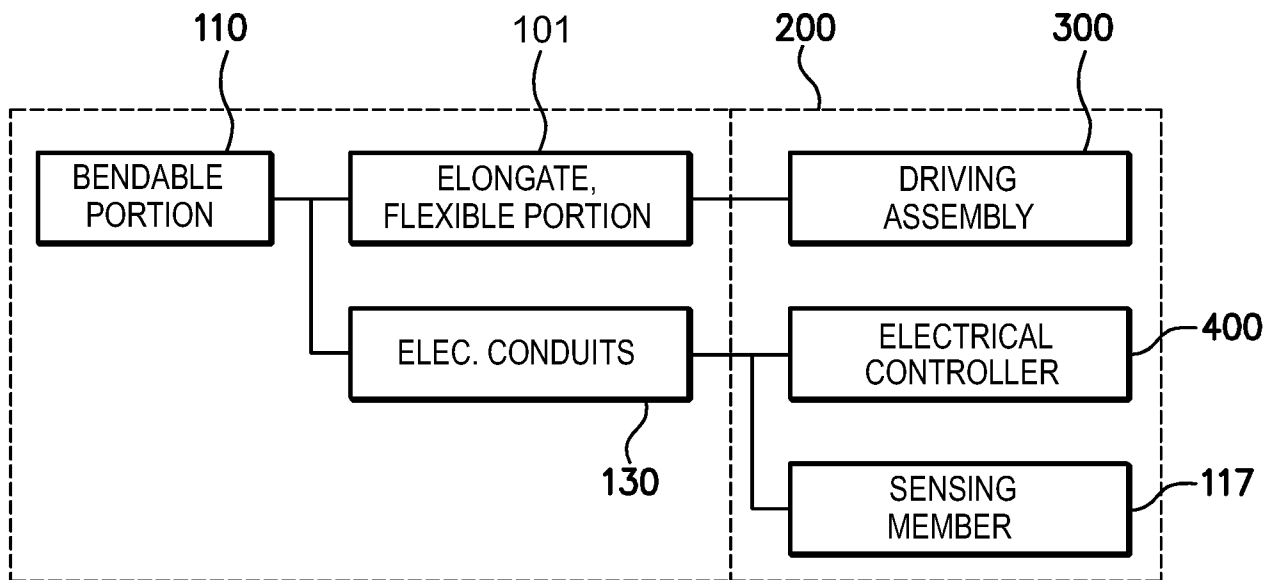


FIG. 12

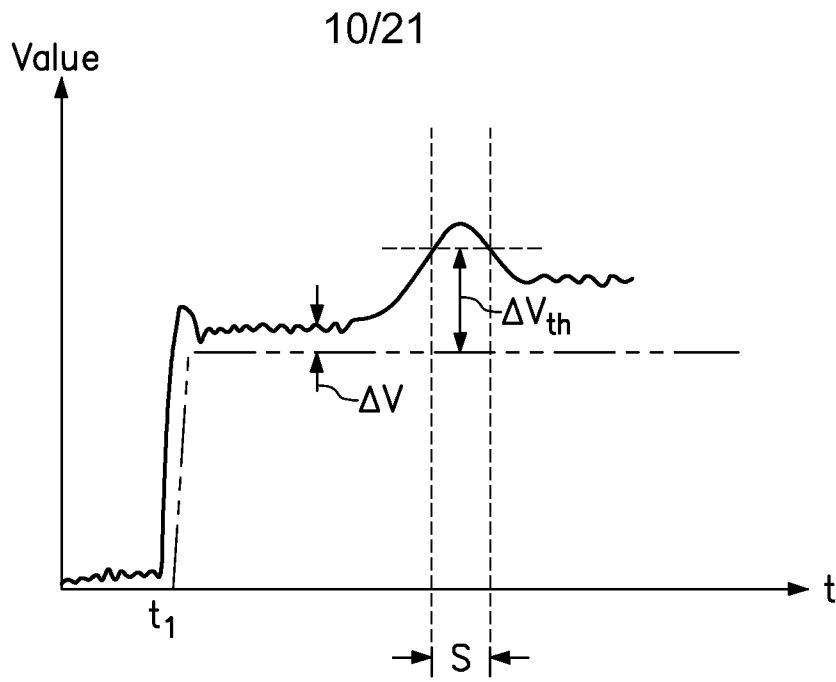


FIG. 13

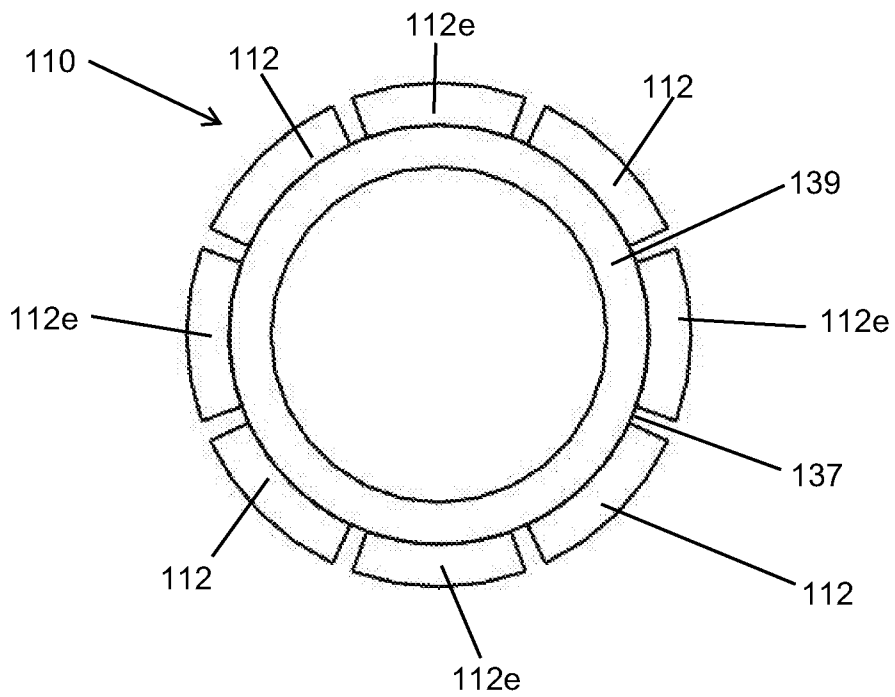


FIG. 14

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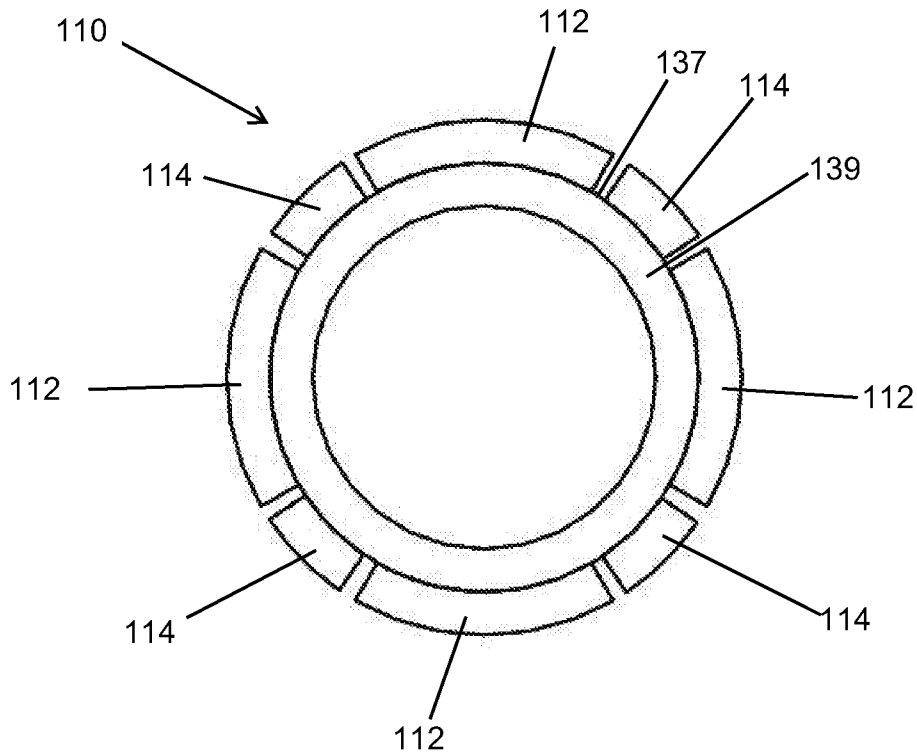


FIG. 15

700

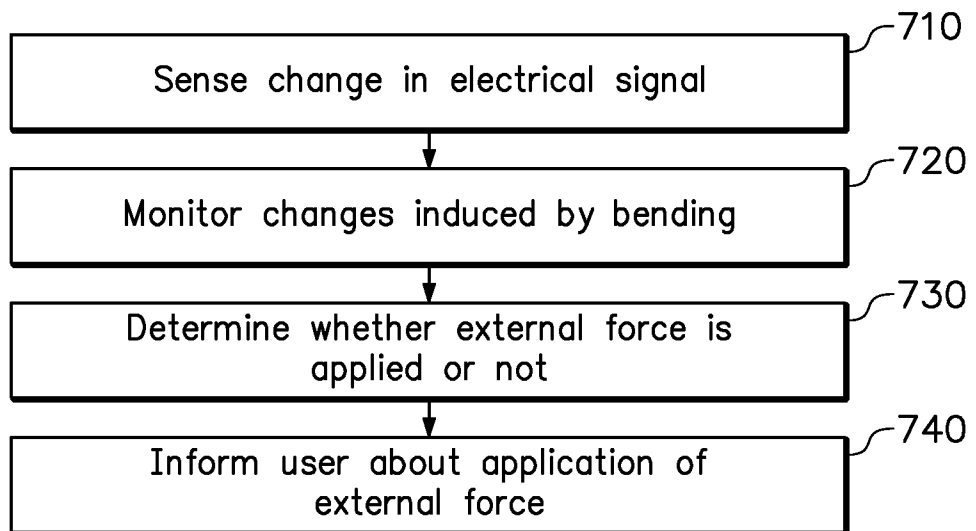


FIG. 16

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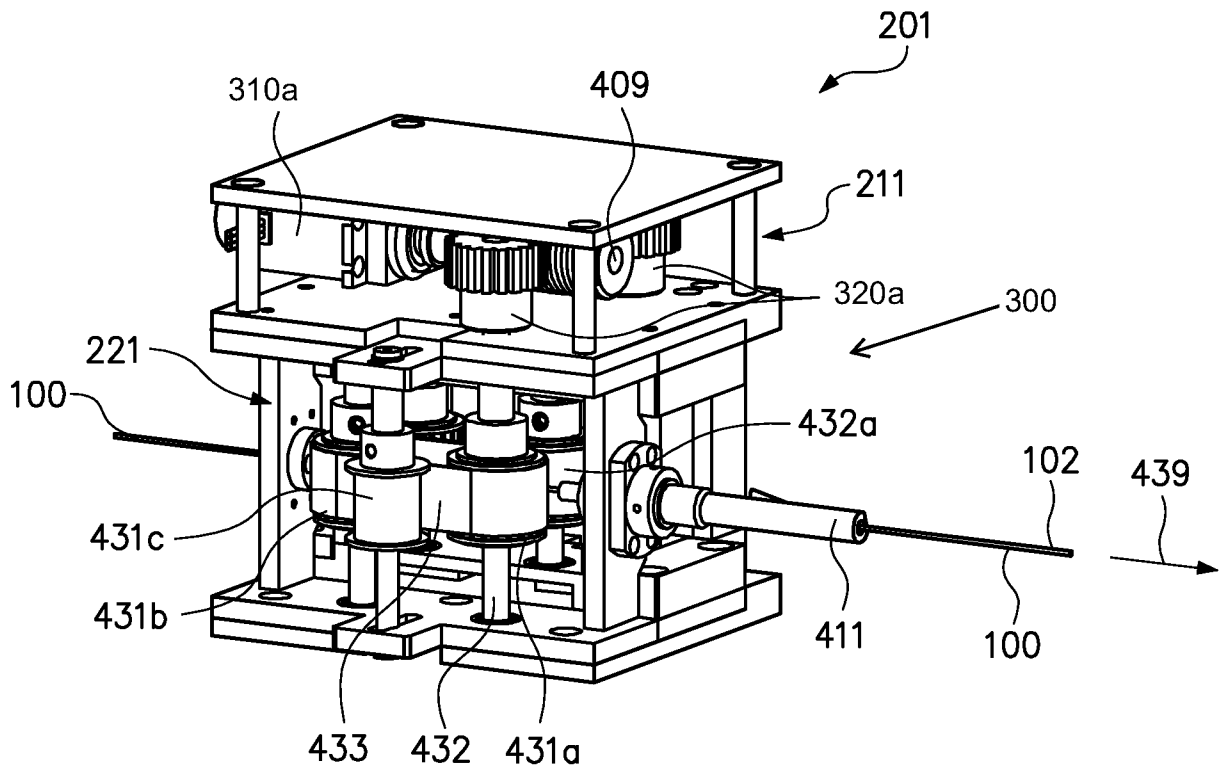


FIG. 17

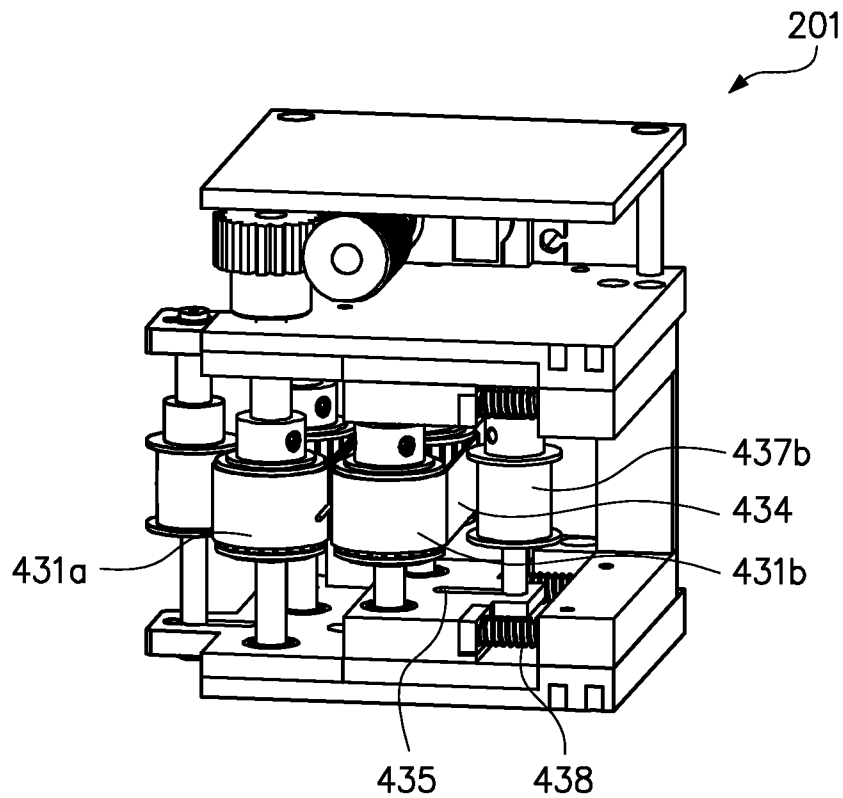


FIG. 18

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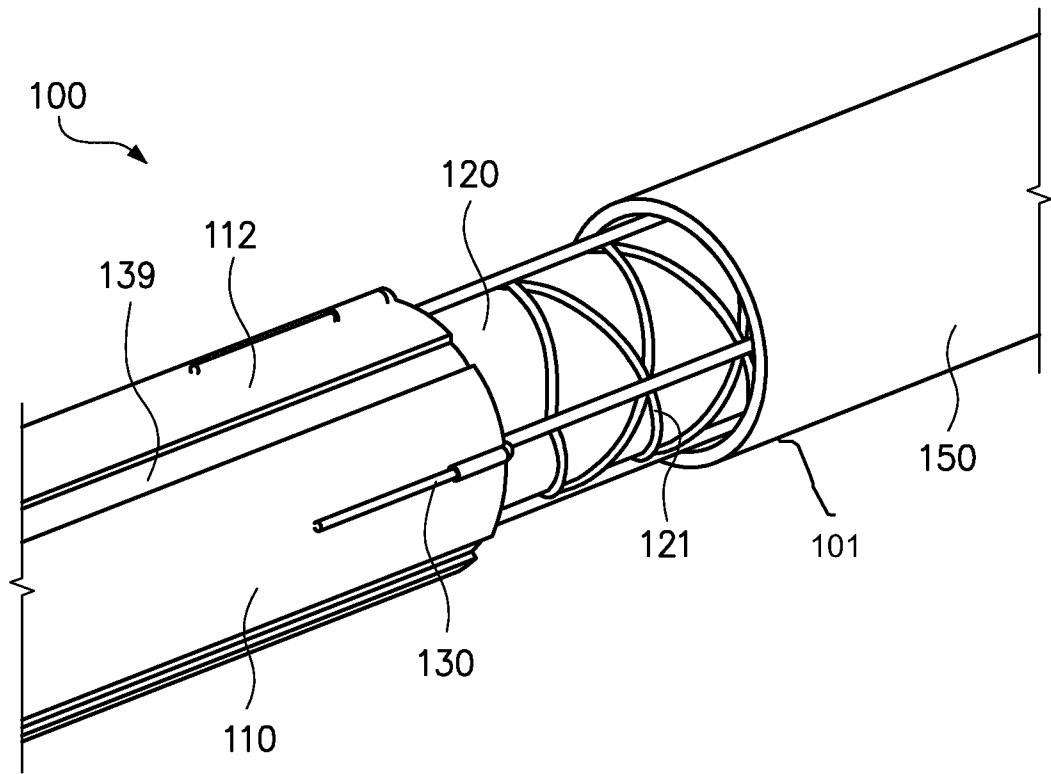


FIG. 19

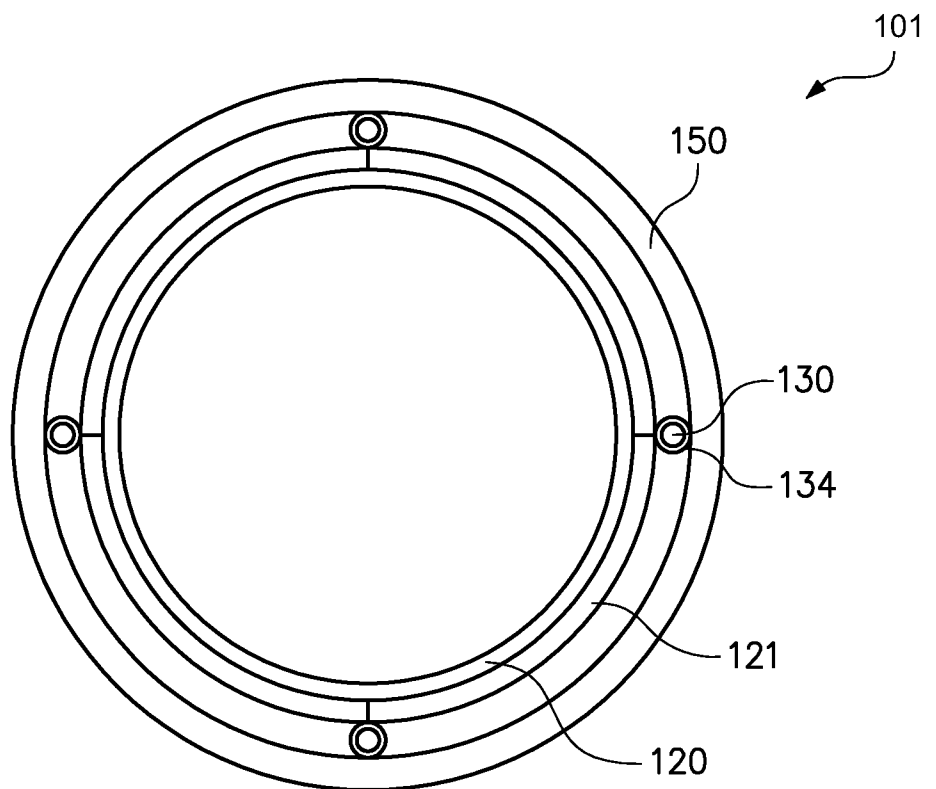


FIG. 20

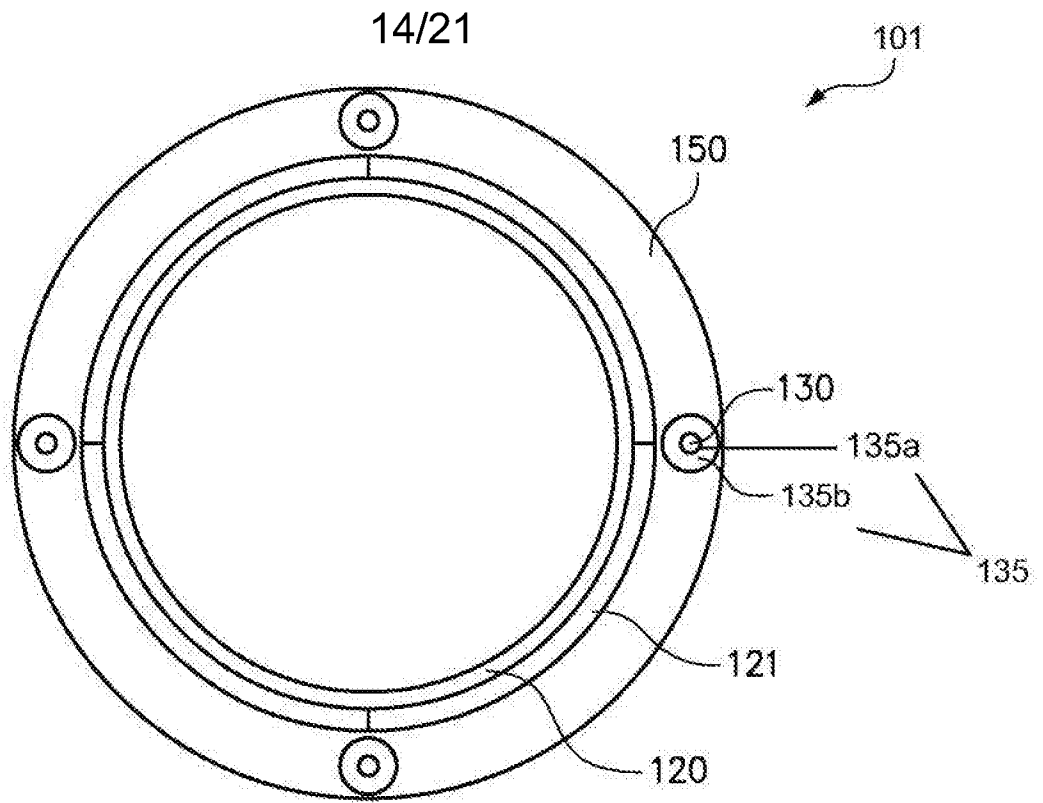


FIG. 21

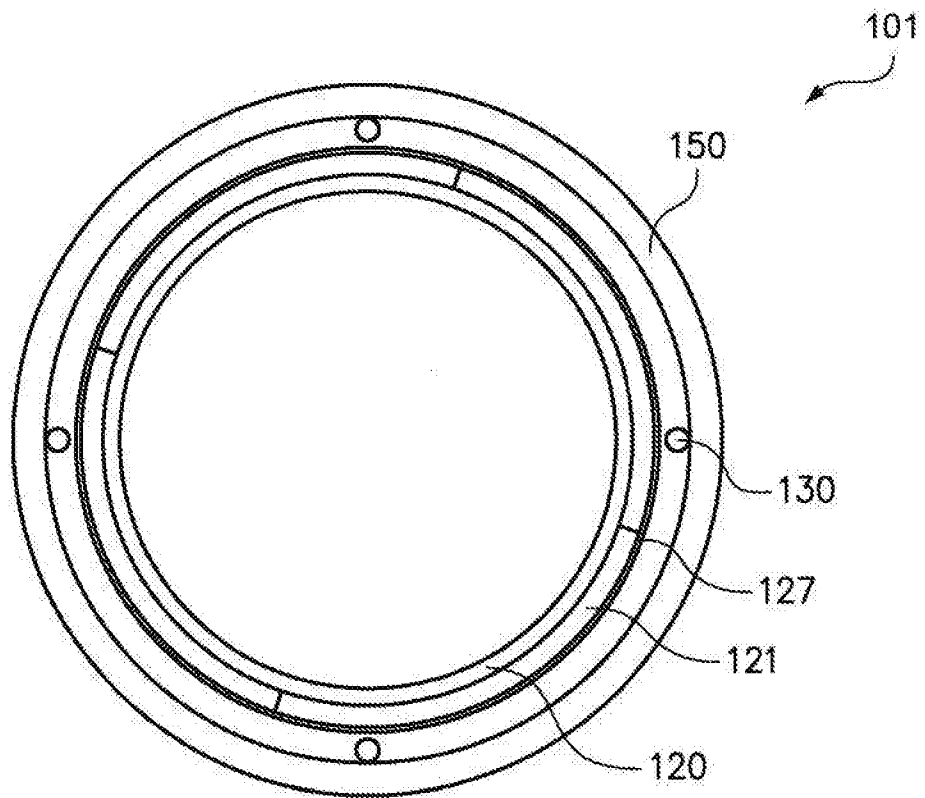


FIG. 22

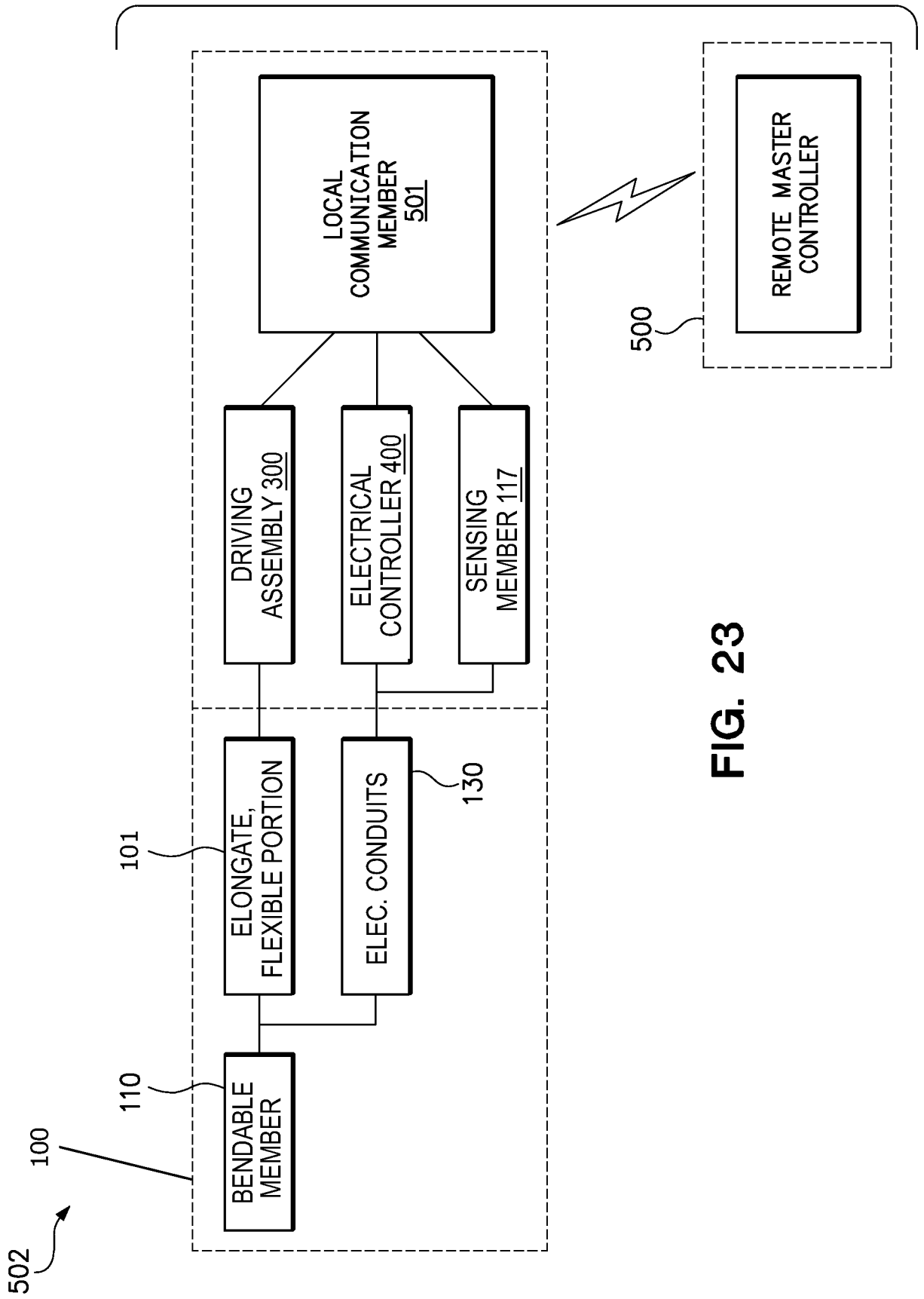


FIG. 23

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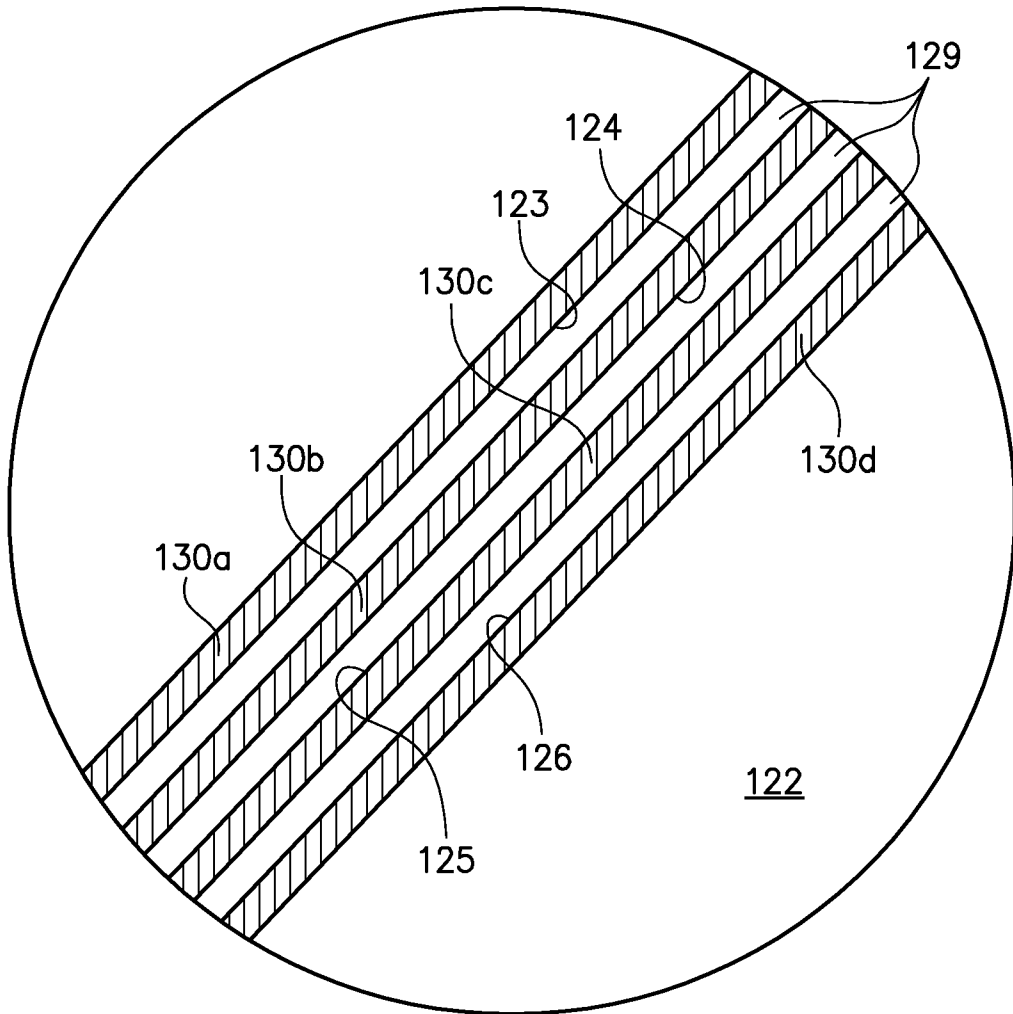
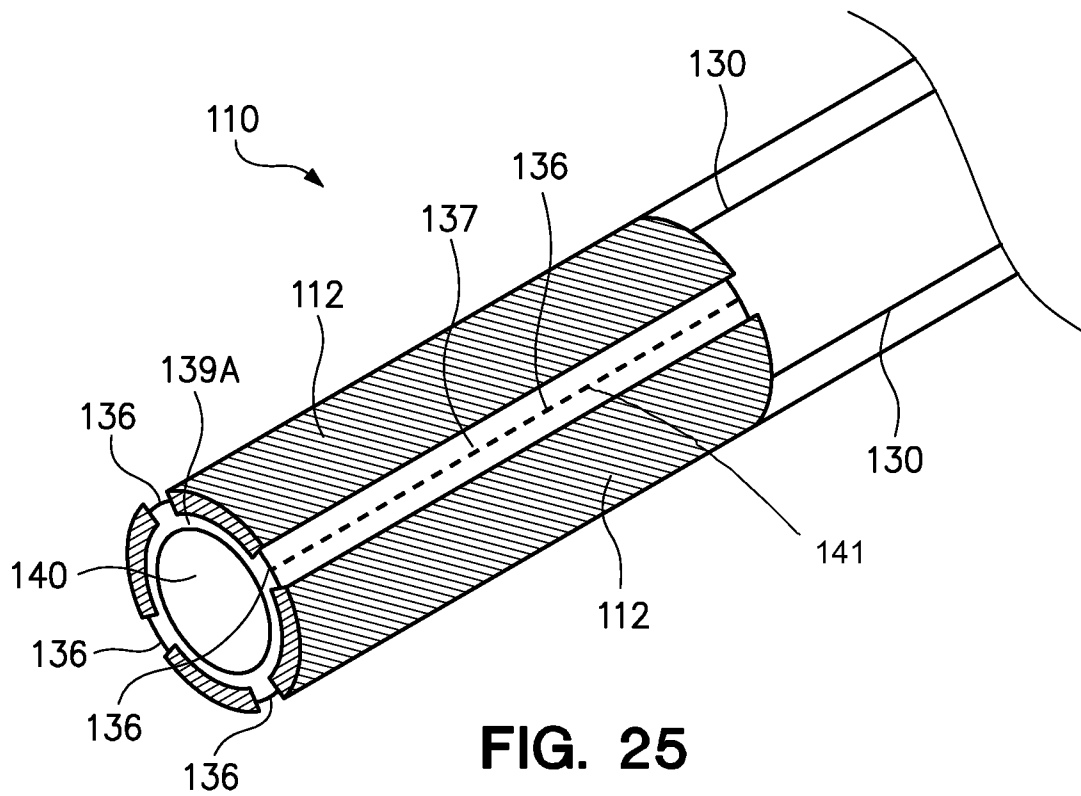


FIG. 24



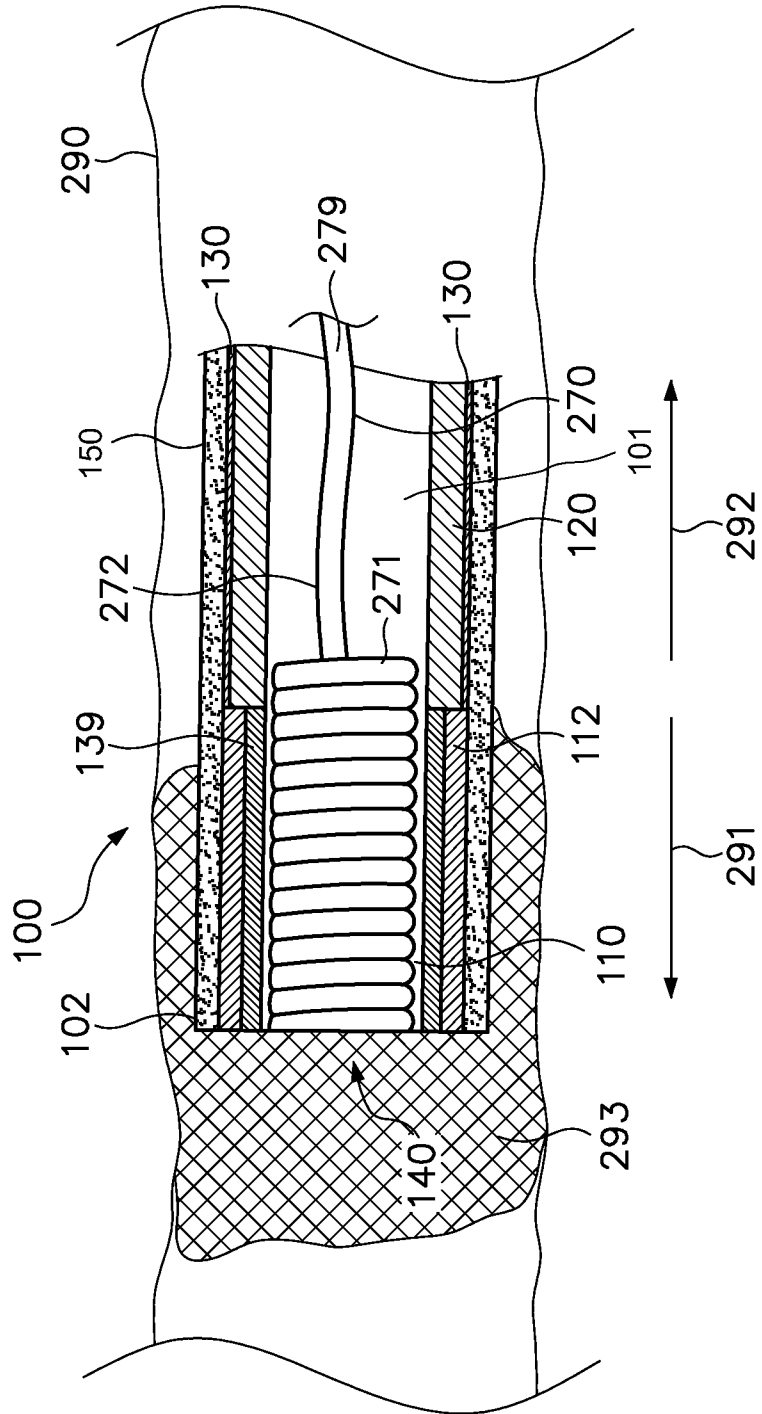


FIG. 26

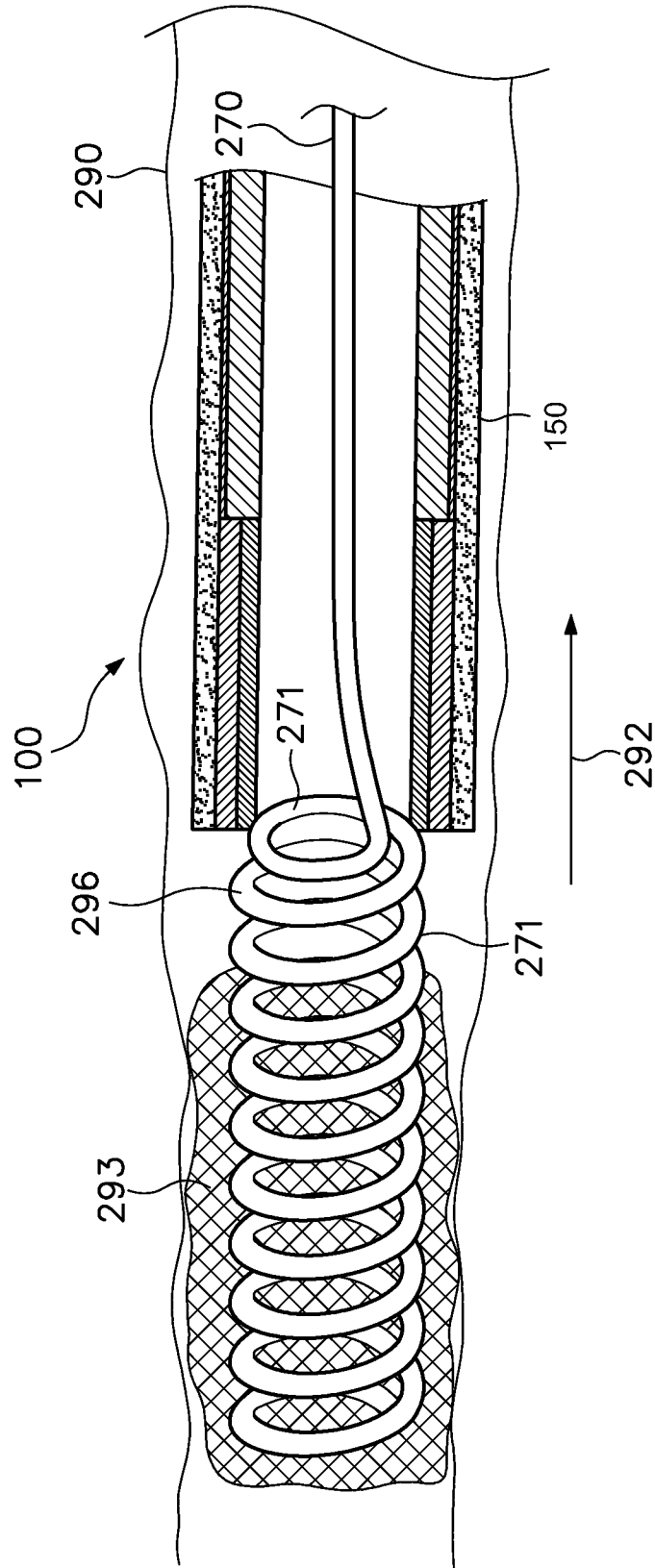


FIG. 27

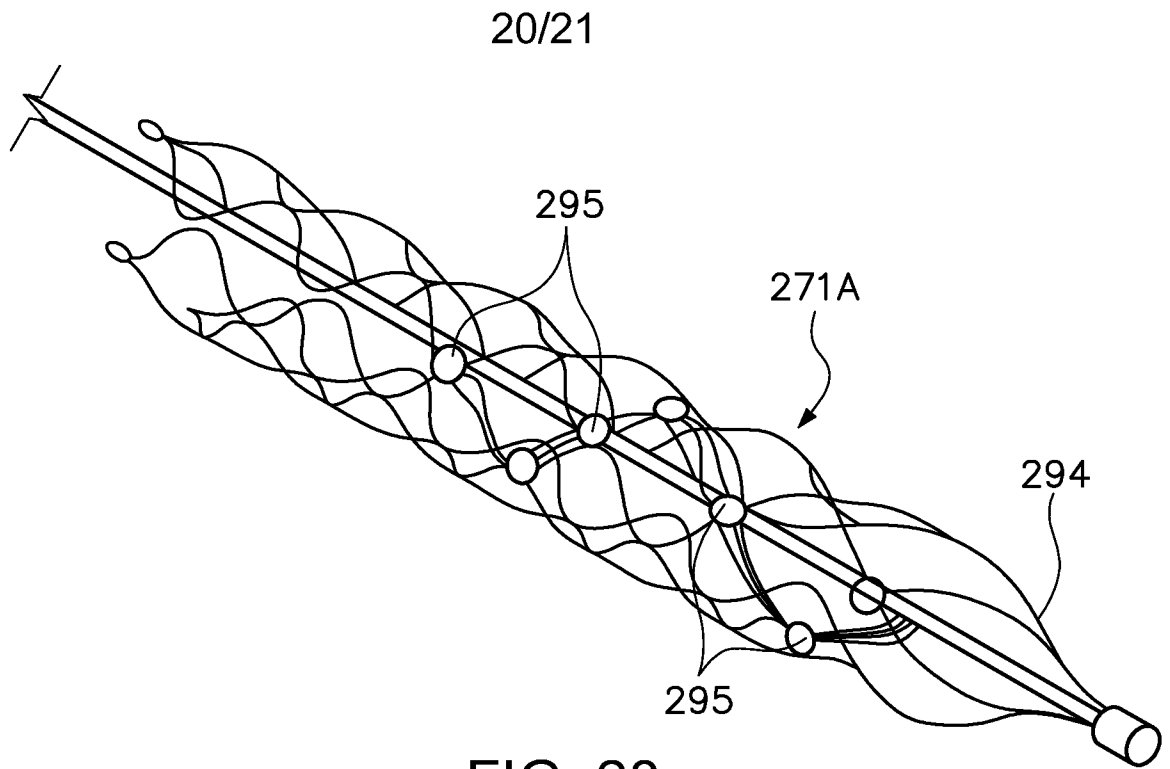


FIG. 28

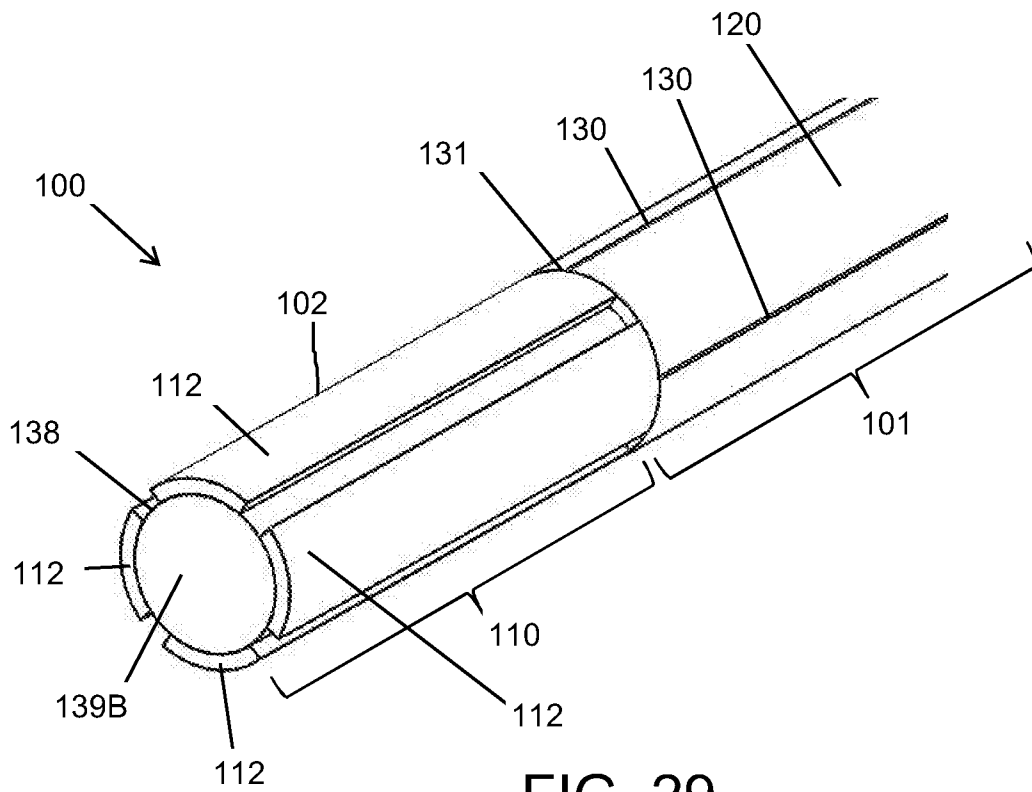


FIG. 29

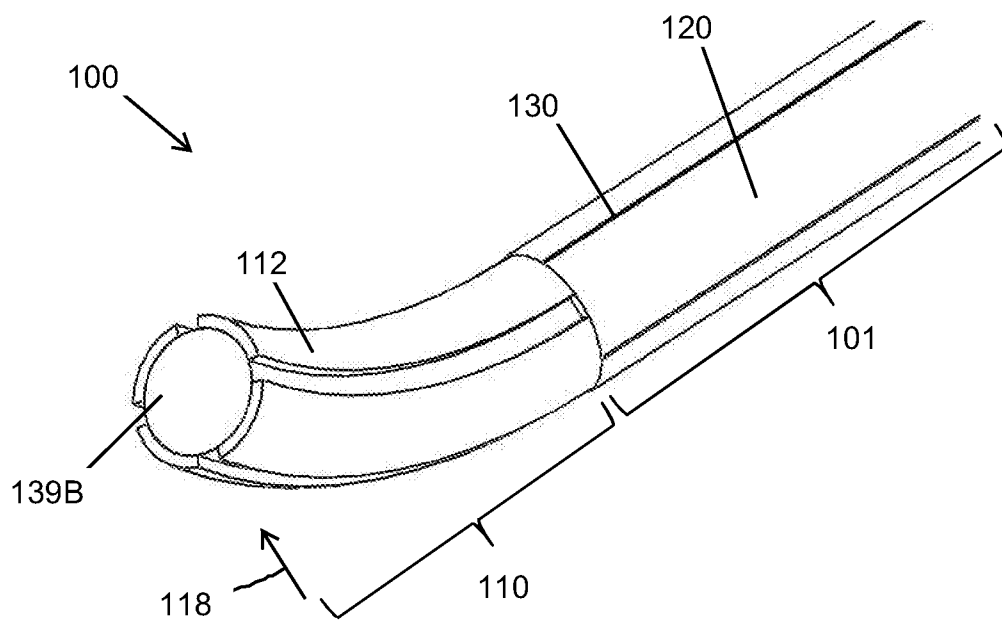


FIG. 30

A. CLASSIFICATION OF SUBJECT MATTER**A61M 25/01(2006.01)i, A61M 25/00(2006.01)i, A61L 29/14(2006.01)i**

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)

A61M 25/01; A61M 36/12; A61B 1/00; A61M 31/00; H01L 41/29; A61M 25/092; H01L 41/047; A61M 25/00; H02N 1/00; A61L 29/14

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: catheter, steerable, electrolyte, conductive, wire, electrode, metal, migration, deflect, iontophoretic, signal, deform, flow, bend, advance, rotary, retract

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A		24-36
Y	US 2013-0253424 A1 (THE BOARD OF REGENTS OF THE NEVADA SYSTEM OF HIGHER EDUCATION, ON BEHALF OF THE UNIVERSITY OF NEVADA) 26 September 2013 See paragraphs [0035]-[0088]; claims 1-18; figures 1A-19.	1-23
Y	US 2013-0035537 A1 (WALLACE, D. T. et al.) 07 February 2013 See paragraphs [0081]-[0152]; figures 1-21.	17-21, 23
A	US 2003-0006669 A1 (PEI, Q. et al.) 09 January 2003 See the whole document.	1-36
A	US 2007-0250036 A1 (VOLK, A. K. et al.) 25 October 2007 See the whole document.	1-36

 Further documents are listed in the continuation of Box C. See patent family annex.

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search

12 May 2017 (12.05.2017)

Date of mailing of the international search report

15 May 2017 (15.05.2017)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

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Information on patent family members

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