United States Patent Application Publication 20250262758
Kind Code A1
Publication Date August 21, 2025
Inventor(s) TAKAGI; KIYOSHI

CONTINUUM ROBOT CONTROL SYSTEM AND CONTROL METHOD, AND PROGRAM

Abstract

An object is to provide a mechanism that can ensure safe operation of a continuum robot. A block FTL calculates a target bending angle θ.sub.fFTL and a target rotational angle ζ.sub.fFTL Of a following bending section on the basis of a target bending angle θ.sub.1t and a target rotational angle ζ.sub.1t of a distal-most bending section and a displacement of a base. A switch unit **330** selects the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section obtained from the block FTL or a target bending angle θ.sub.1f and a target rotational angle ζ.sub.1f of the following bending section obtained from a block P.sub.1 corresponding to following operating means. A kinematic computing unit **340** computes, on the basis of the target bending angle and the target rotational angle, a drive displacement by which a driving unit drives a wire in the following bending section.

Inventors: **TAKAGI; KIYOSHI (Tokyo, JP)**

Applicant: **CANON KABUSHIKI KAISHA** (Tokyo, JP)

Family ID: **1000008574939**

Appl. No.: **19/196492**

Filed: **May 01, 2025**

Foreign Application Priority Data

JP	2020-109850	Jun. 25, 2020
JP	2021-100189	Jun. 16, 2021

Related U.S. Application Data

parent US continuation 18069127 20221220 parent-grant-document US 12318928 child US 19196492
parent WO continuation PCT/JP2021/023884 20210624 PENDING child US 18069127

Publication Classification

Int. Cl.: **B25J9/10** (20060101); **B25J13/08** (20060101); **B25J18/06** (20060101)

U.S. Cl.:

CPC **B25J9/104** (20130101); **B25J13/088** (20130101); **B25J18/06** (20130101);

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a Continuation of U.S. patent application Ser. No. 18/069,127, filed Dec. 20, 2022, which is a Continuation of International Patent Application No. PCT/JP2021/023884, filed Jun. 24, 2021, which is incorporated by reference herein in its entirety and which claims the benefit of Japanese Patent Application No. 2020-109850, filed Jun. 25, 2020, and Japanese Patent Application No. 2021-100189, filed Jun. 16, 2021, both of which applications are hereby incorporated by reference herein in their entireties.

TECHNICAL FIELD
[0002] The present disclosure relates to a control system and method for controlling a continuum robot that includes a bendable portion having a plurality of bending sections bent by being driven by a wire, and also relates to a program that causes a computer to function as the control system.
BACKGROUND ART
[0003] A continuum robot includes a bendable portion having a plurality of bending sections with a flexible structure. The shape of the continuum robot is controlled by deforming the bending sections. Such continuum robots have mainly two advantages over rigid-link robots composed of rigid links. One advantage is that continuum robots can move along curves in confined spaces where rigid-link robots may get stuck, and in environments where objects are scattered. The other advantage is that intrinsic softness of the continuum robots allows operation without damaging fragile objects. The operation does not necessarily require detection of external force that rigid-link robots require. With this feature, the continuum robots are expected to be applied in the field of medical instruments, such as endoscope sheaths and catheters, and in the field of robots for hazardous environments, such as rescue robots.
[0004] Patent Literature 1 describes a control method that enables characteristic motions of a continuum robot having a camera at the distal end of a bendable portion thereof (hereinafter referred to as “observation motion control”) with a simple operation by the operator. Examples of the observation motion control include moving the position of the distal end while keeping constant the direction of the line of sight of the camera, and changing the position and angle of the distal end in such a way that the line of sight of the camera always passes through a single distant point.
CITATION LIST
Patent Literature
[0005] PTL 1 International Publication No. 2017/003468
[0006] Specifically, for transition to the observation motion control from an initial bending attitude of the bendable portion, the method described in Patent Literature 1 algebraically determines the amount of additional bending of all bending sections of the bendable portion from the amount of

operation of an operating unit by the operator. In the control described in Patent Literature 1, therefore, even when the amount of operation of the operating unit by the operator is small, the amount of additional bending of each bending section may be controlled significantly, depending on the initial bending attitude of the bendable portion. Generally, the continuum robot can be moved along a narrow path in an object in a confined space by control (hereinafter referred to as "follow-the-leader control") that continuously transmits the bending attitude of the leading distal-most bending section to the following bending section along the length of each bending section. If the control described in Patent Literature 1 is performed in such a confined space, the continuum robot may accidentally come into contact with the object. This may damage the object or the continuum robot and it will be difficult to ensure safe operation of the continuum robot.

SUMMARY OF INVENTION

[0007] One or more features of the present disclosure have been made in view of the issues described above. At least one object of the present disclosure is to provide at least one mechanism that may ensure safe operation of a continuum robot.

[0008] A continuum robot control system according to an aspect of the present disclosure is a system for controlling a continuum robot that includes a bendable portion having a plurality of bending sections bent by being driven by a wire, a base configured to support the bendable portion, and a driving unit configured to drive the wire. The continuum robot control system includes following calculating means, following operating means, following switching means, and computing means. The following calculating means calculates a target bending angle and a target rotational angle of a following bending section of the plurality of bending sections on the basis of a target bending angle and a target rotational angle of a distal-most bending section of the plurality of bending sections and a displacement of the base in a direction of movement of the continuum robot. The distal-most bending section is located farthest from the base, and the following bending section is located between the distal-most bending section and the base. The following operating means receives a target bending angle and a target rotational angle of the following bending section by being operated. The following switching means performs a switching operation for selecting the target bending angle and the target rotational angle of the following bending section obtained from the following calculating means or the target bending angle and the target rotational angle of the following bending section obtained from the following operating means. The computing means computes, on the basis of the target bending angle and the target rotational angle of the following bending section selected by the following switching means, a drive displacement by which the driving unit drives the wire in the following bending section.

[0009] Other aspects of the present disclosure include a continuum robot control method for the continuum robot control system, and a program that causes a computer to function as the continuum robot control system.

[0010] Further features of the present disclosure will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0011] FIG. **1** is a diagram illustrating an example of a general configuration of a continuum robot according to a first embodiment of the present disclosure.

[0012] FIG. **2** is a diagram illustrating details of one bending section of the continuum robot illustrated in FIG. **1**.

[0013] FIG. **3** is a diagram illustrating an example of a general configuration of an operating device for operating three bending sections of the continuum robot illustrated in FIG. **1**, according to the first embodiment of the present disclosure.

[0014] FIG. **4** is a diagram illustrating an example of a general configuration of a continuum robot control system according to the first embodiment of the present disclosure.
[0015] FIG. **5** is a diagram illustrating an example of how three wires (Wires a to c) for the n-th bending section, corresponding to three wires illustrated in FIG. **2**, are arranged in an xy plane.
[0016] FIG. **6** is a diagram illustrating an example of follow-the-leader control of the continuum robot according to the first embodiment of the present disclosure.
[0017] FIG. **7**A is a diagram illustrating an example of how a block FTL illustrated in FIG. **4** calculates a target bending angle of a following bending section, according to the first embodiment of the present disclosure.
[0018] FIG. **7**B is a diagram illustrating an example of how the block FTL illustrated in FIG. **4** calculates a target rotational angle of the following bending section, according to the first embodiment of the present disclosure.
[0019] FIG. **8**A is a diagram illustrating a first example of a result of simulation of a continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0020] FIG. **8**B is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0021] FIG. **8**C is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0022] FIG. **8**D is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0023] FIG. **8**E is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0024] FIG. **8**F is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0025] FIG. **9**A is a diagram illustrating a second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0026] FIG. **9**B is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0027] FIG. **9**C is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0028] FIG. **9**D is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0029] FIG. **9**E is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0030] FIG. **9**F is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0031] FIG. **10**A is a diagram illustrating a third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first

embodiment of the present disclosure.
[0032] FIG. **10**B is another diagram illustrating the third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0033] FIG. **10**C is another diagram illustrating the third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0034] FIG. **10**D is another diagram illustrating the third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0035] FIG. **10**E is another diagram illustrating the third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0036] FIG. **10**F is another diagram illustrating the third example of the result of simulation of the continuum robot control method by the continuum robot control system according to the first embodiment of the present disclosure.
[0037] FIG. **11** is a diagram illustrating an example of a general configuration of a continuum robot control system according to a second embodiment of the present disclosure.
[0038] FIG. **12**A is a diagram illustrating a first example of a result of simulation of a continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0039] FIG. **12**B is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0040] FIG. **12**C is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0041] FIG. **12**D is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0042] FIG. **12**E is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0043] FIG. **12**F is another diagram illustrating the first example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0044] FIG. **13**A is a diagram illustrating a second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0045] FIG. **13**B is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0046] FIG. **13**C is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0047] FIG. **13**D is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0048] FIG. **13**E is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second

embodiment of the present disclosure.
[0049] FIG. **13**F is another diagram illustrating the second example of the result of simulation of the continuum robot control method by the continuum robot control system according to the second embodiment of the present disclosure.
[0050] FIG. **14** is a diagram illustrating an example of a general configuration of a continuum robot control system according to a third embodiment of the present disclosure.
[0051] FIG. **15**A is a diagram illustrating an example of a result of simulation of a continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0052] FIG. **15**B is another diagram illustrating the example of the result of simulation of the continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0053] FIG. **15**C is another diagram illustrating the example of the result of simulation of the continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0054] FIG. **15**D is another diagram illustrating the example of the result of simulation of the continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0055] FIG. **15**E is another diagram illustrating the example of the result of simulation of the continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0056] FIG. **15**F is another diagram illustrating the example of the result of simulation of the continuum robot control method by the continuum robot control system according to the third embodiment of the present disclosure.
[0057] FIG. **16** is a diagram illustrating an example of a general configuration of a continuum robot control system according to a fourth embodiment of the present disclosure.
[0058] FIG. **17** is a diagram illustrating an example of a general configuration of an operating device for operating the three bending sections of the continuum robot illustrated in FIG. **1**, according to a fifth embodiment of the present disclosure.
[0059] FIG. **18** is a diagram illustrating an example of a general configuration of a continuum robot control system according to a sixth embodiment of the present disclosure.

DESCRIPTION OF EMBODIMENTS

[0060] Hereinafter, embodiments of the present disclosure will be described with reference to the drawings.

First Embodiment

[0061] A first embodiment of the present disclosure will now be described.
[0062] FIG. **1** is a diagram illustrating an example of a general configuration of a continuum robot **100** according to the first embodiment of the present disclosure. FIG. **1** illustrates a base **140** and a bendable portion **170** as components of the continuum robot **100**.
[0063] The bendable portion **170** is a component including a plurality of bending sections **171** to **173** bent by being driven by wires. Specifically, FIG. **1** illustrates n (three) bending sections: the bending section **171** corresponding to (n−2), the bending section **172** corresponding to (n−1), and the bending section **173** corresponding to n. FIG. **1** also illustrates a bending angle θ.sub.n and a rotational angle In of the bending section **173**, a bending angle θ.sub.n-1 and a rotational angle ζ.sub.n-1 of the bending section **172**, and a bending angle θ.sub.n-2 and a rotational angle ζ.sub.n-2 of the bending section **171**. The base **140** is a component that supports the bendable portion **170**. The base **140** includes internal actuators (not shown in FIG. **1**) serving as driving units that drive the respective wires for the bending sections **171** to **173**. FIG. **1** also illustrates an xyz coordinate system that has an origin O at a predetermined position (e.g., center position) of an upper surface **141** of the base **140**, with a z direction being the direction of movement of the continuum robot **100**

(e.g., direction of forward movement) and x and y directions being orthogonal to the z direction and orthogonal to each other. The continuum robot **100** is thus capable of moving in the z direction as well as allowing a bending motion of the plurality of bending sections **171** to **173** of the bendable portion **170**. In FIG. **1**, a displacement Z.sub.b of the base **140** is illustrated as an index that represents the amount of movement (amount of forward movement) of the continuum robot **100** in the z direction.

[0064] Of the plurality of bending sections **171** to **173** constituting the bendable portion **170**, the bending section **173** is the distal-most bending section farthest from the base **140** in FIG. **1**. The bending section **172** (and the bending section **171** as well) is a following bending section disposed between the bending section **173** (distal-most bending section) and the base **140** and configured to follow the bending section **173** (distal-most bending section) as the continuum robot **100** moves forward. During forward movement of the continuum robot **100**, the bending section **173** (distal-most bending section) is a leading bending section.

[0065] FIG. **2** is a diagram illustrating details of the bending section **171** of the continuum robot **100** illustrated in FIG. **1**. That is, FIG. **2** illustrates in detail the configuration of the bending section **171** at a proximal end closest to the base **140**. In FIG. **2**, the same elements as those in FIG. **1** are denoted by the same reference numerals and their detailed description will be omitted. In FIG. **2**, the bending angle of the bending section **171** is denoted by θ.sub.1, the rotational angle of the bending section **171** is denoted by ζ.sub.1, and the radius of curvature of the bending section **171** (corresponding to a line segment connecting points O and w1 in FIG. **2**) is denoted by ρ.sub.1.

[0066] The continuum robot **100** includes wires **111**, **112**, and **113** connected to connection points **121**, **122**, and **123**, respectively, in a distal end **160** of the bending section **171**. The wires **111**, **112**, and **113** are pushed and pulled by actuators **131**, **132**, and **133**, respectively, inside the base **140**, so that the attitude (bending shape) of the continuum robot **100** is controlled. The actuator **131** is a driving unit for driving the wire **111**, the actuator **132** is a driving unit for driving the wire **112**, and the actuator **133** is a driving unit for driving the wire **113**.

[0067] The continuum robot **100** includes wire guides **161** to **164** for guiding the wires **111** to **113** in the bending section **171**. The wire guides **161** to **164** may be a plurality of members discretely arranged, or may be constituted by a continuum member, such as a bellows or mesh member. The wire guides **161** to **164** are secured to the wire **111** at fixed points **150** to **153**. In FIG. **2**, the central axis of the continuum robot **100** is indicated by a broken line.

[0068] In the present embodiment, the wires **111**, **112**, and **113** are referred to as Wire a, Wire b, and Wire c, respectively, counterclockwise in the xy plane.

[0069] Specifically, in the example illustrated in FIG. **2**, the wire **111** corresponds to Wire a, and the drive displacement of the wire **111** pushed and pulled by the actuator **131** in the bending section **171** is denoted by l.sub.p1a. Also, in the example illustrated in FIG. **2**, the wire **112** corresponds to Wire b, and the drive displacement of the wire **112** pushed and pulled by the actuator **132** in the bending section **171** is denoted by l.sub.p1b. Also, in the example illustrated in FIG. **2**, the wire **113** corresponds to Wire c, and the drive displacement of the wire **113** pushed and pulled by the actuator **133** in the bending section **171** is denoted by l.sub.p1c.

[0070] FIG. **2** illustrates in detail the configuration of the bending section **171** alone. The bending section **172** and the bending section **173** illustrated in FIG. **1** are configured similarly to the bending section **171** illustrated in FIG. **2**. That is, the bending section **172** and the bending section **173** each include wires corresponding to the wires **111** to **113**, actuators corresponding to the actuators **131** to **133**, a distal end corresponding to the distal end **160**, and wire guides corresponding to the wire guides **161** to **164**. The drive displacements of Wires a to c that drive the n-th bending section are denoted in a generalized way by l.sub.pna, l.sub.pnb, and l.sub.pnc.

[0071] FIG. **3** is a diagram illustrating an example of a general configuration of an operating device **200** for operating the three bending sections **171** to **173** of the continuum robot **100** illustrated in FIG. **1**, according to the first embodiment of the present disclosure. In the following description, the operating device **200** according to the first embodiment illustrated in FIG. **3** is referred to as an "operating device **200-1**".

[0072] As illustrated in FIG. **3**, the operating device **200-1** includes a first operating unit **210** for operating the first bending section **171**, a second operating unit **220** for operating the second bending section **172**, and a third operating unit **230** for operating the third bending section **173**.

[0073] Components **231** to **233** of the third operating unit **230** are components related to the bending angle θ.sub.n of the third bending section **173** (distal-most bending section). Specifically, the operating lever **231** is an operating lever for the bending angle θ.sub.n of the third bending section **173** and is driven by the motor **232**. The angle of rotation of the operating lever **231** is detected by the angular sensor **233**. The motor **232** and the angular sensor **233** are secured to a housing (not shown) of the operating lever **231**. Also, components **234** to **236** of the third operating unit **230** are components related to the rotational angle ζ.sub.n of the third bending section **173** (distal-most bending section). Specifically, the operating lever **234** is an operating lever for the rotational angle ζ.sub.n of the third bending section **173** and is driven by the motor **235**. The angle of rotation of the operating lever **234** is detected by the angular sensor **236**. The motor **235** and the angular sensor **236** are secured to a housing (not shown) of the operating lever **234**. The third operating unit **230** thus corresponds to distal-most operating means that is operated, for example, by the operator and receives the target bending angle θ.sub.n and the target rotational angle ζ.sub.n of the third bending section **173** (distal-most bending section).

[0074] Components **221** to **223** of the second operating unit **220** are components related to the bending angle θ.sub.n-1 of the second bending section **172** (following bending section). Specifically, the operating lever **221** is an operating lever for the bending angle θ.sub.n-1 of the second bending section **172** and is driven by the motor **222**. The angle of rotation of the operating lever **221** is detected by the angular sensor **223**. The motor **222** and the angular sensor **223** are secured to a housing (not shown) of the operating lever **221**. Also, components **224** to **226** of the second operating unit **220** are components related to the rotational angle ζ.sub.n-1 of the second bending section **172** (following bending section). Specifically, the operating lever **224** is an operating lever for the rotational angle ζ.sub.n-1 of the second bending section **172** and is driven by the motor **225**. The angle of rotation of the operating lever **224** is detected by the angular sensor **226**. The motor **225** and the angular sensor **226** are secured to a housing (not shown) of the operating lever **224**. The second operating unit **220** thus corresponds to second following operating means that is operated, for example, by the operator and receives the target bending angle θ.sub.n-1 and the target rotational angle ζ.sub.n-1 of the second bending section **172** (second following bending section).

[0075] Components **211** to **213** of the first operating unit **210** are components related to the bending angle θ.sub.n-2 of the first bending section **171** (following bending section). Specifically, the operating lever **211** is an operating lever for the bending angle θ.sub.n-2 of the first bending section **171** and is driven by the motor **212**. The angle of rotation of the operating lever **211** is detected by the angular sensor **213**. The motor **212** and the angular sensor **213** are secured to a housing (not shown) of the operating lever **211**. Also, components **214** to **216** of the first operating unit **210** are components related to the rotational angle θ.sub.n-2 of the first bending section **171** (following bending section). Specifically, the operating lever **214** is an operating lever for the rotational angle ζ.sub.n-2 of the first bending section **171** and is driven by the motor **215**. The angle of rotation of the operating lever **214** is detected by the angular sensor **216**. The motor **215** and the angular sensor **216** are secured to a housing (not shown) of the operating lever **214**. The first operating unit **210** thus corresponds to first following operating means that is operated, for example, by the operator and receives the target bending angle θ.sub.n-2 and the target rotational angle ζ.sub.n-2 of the first bending section **171** (first following bending section).

[0076] As described above, for the bending sections **171** to **173**, the operating device **200-1** includes the operating levers **211**, **221**, and **231** for the respective bending angles θ and the operating levers **214**, **224**, and **234** for the respective rotational angles ζ. In the present embodiment, when a continuum robot control system **300** (to be described with reference to FIG. **4**) controls the bending angle θ or the rotational angle ζ of the continuum robot **100** to any target angle, the operating levers **211**, **221**, and **231** or the operating levers **214**, **224**, and **234** are controlled to provide the same angle as the target angle.

[0077] The operating levers **211**, **221**, and **231** and the operating levers **214**, **224**, and **234** each include a sensor (not shown) that detects contact by the operator. The sensor for each of the operating levers **211**, **221**, and **231** and the operating levers **214**, **224**, and **234** may be a push-button switch, or may be a sensor that detects capacitance. There may be an operation button (not shown) for controlling the displacement z.sub.b of the base **140**, or may be a plurality of switches (not shown) for changing the motion mode.

[0078] FIG. **4** is a diagram illustrating an example of a general configuration of the continuum robot control system **300** according to the first embodiment of the present disclosure. In the following description, the continuum robot control system **300** according to the first embodiment illustrated in FIG. **4** is referred to as a "continuum robot control system **300-1**". Specifically, FIG. **4** is a block diagram illustrating a control system for switching between follow-the-leader control and observation motion control.

[0079] In the continuum robot control system **300-1** illustrated in FIG. **4**, a block P.sub.s represents the continuum robot **100** to be controlled (or more specifically, an actuator serving as a driving unit, corresponding to the actuators **131** to **133** illustrated in FIG. **2**). In FIG. **4**, an output l.sub.p from the block P.sub.s is a vector representing the drive displacement of a wire. Also, in the continuum robot control system **300-1** illustrated in FIG. **4**, a block K.sub.s represents a position control system for settling to a target drive displacement l.sub.pref of the wire.

[0080] Also, in the continuum robot control system **300-1** illustrated in FIG. **4**, a block P.sub.1 represents an operating system (following operating means), including a motor, for operating a following bending section. In the example illustrated in FIG. **3**, the block P.sub.1 is, for example, an operating system corresponding to the second operating unit **220** and the first operating unit **210** for operating the second bending section **172** and the first bending section **171** (following bending sections). Also, in FIG. **4**, d.sub.θ1f denotes an operating torque the operator applies to the operating lever for the bending angle of the following bending section and d.sub.ζ1f denotes an operating torque the operator applies to the operating lever for the rotational angle of the following bending section. In FIG. **4**, a target bending angle θ.sub.1f and a target rotational angle ζ.sub.1f of the following bending section, which are outputs of the block P.sub.1, are angles of the operating levers in the second operating unit **220** and the first operating unit **210** for controlling the bending angle and the rotational angle of the following bending sections. Also, in FIG. **4**, a block K.sub.1 is a position control system for settling these angles to target values. Blocks G.sub.in and G.sub.out connected to an input end and an output end, respectively, of the block K.sub.1 are gains that take values from 0 to 1.

[0081] In the continuum robot control system **300-1** illustrated in FIG. **4**, an input device **310** is a device that provides a block FTL and a kinematic computing unit **340** with a target bending angle θ.sub.1t and a target rotational angle Sit of the distal-most bending section (or third bending section **173** in the example illustrated in FIG. **1**). The target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section, which are outputs of the input device **310**, are angles of the operating levers **231** and **234** in the third operating unit **230** for controlling the bending angle and the rotational angle of the distal-most bending section. In the present embodiment, the operating levers **231** and **234** included in the third operating unit **230**, illustrated in FIG. **3**, for operating the third bending section **173** (distal-most bending section) are not motor-driven.

[0082] In the continuum robot control system **300-1** illustrated in FIG. **4**, an input device **320** is a device that provides the block FTL with the displacement z.sub.b of the base **140** in the direction of movement (e.g., forward movement) of the continuum robot **100**.

[0083] In the continuum robot control system **300-1** illustrated in FIG. **4**, the block FTL represents an exemplary configuration of a follow-the-leader control algorithm. The block FTL is following calculating means that calculates the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section on the basis of the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section received from the input device **310** and the displacement z.sub.b of the base **140** received from the input device **320**. Specifically, the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL are vectors of target values of a follow-the-leader control system for the following bending section.

[0084] In the continuum robot control system **300-1** illustrated in FIG. **4**, a switch unit **330** includes a first switch **331** and a second switch **332**. The first switch **331** is a switch (following switching means) that performs a switching operation for selecting the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section obtained from the block FTL, or the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section obtained from the block P.sub.1. The second switch **332** is a switch that receives a “0” or “1” signal and performs switching in accordance with the input signal. During follow-the-leader control (specifically, while the “1” signal is being received by the second switch **332**), the switch unit **330** is in the state of a double-pole double-throw switch illustrated in FIG. **4**. That is, during the follow-the-leader control described above, the first switch **331** performs a switching operation for selecting the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section obtained from the block FTL. When operator's contact with the operating lever for the following bending section is detected (specifically, when the second switch **332** receives the “0” signal), the control system of the present embodiment causes the switch unit **330** to reverse the position of the double-pole double-throw switch illustrated in FIG. **4**. That is, when operator's contact with the operating lever for the following bending section is detected as described above, the first switch **331** performs a switching operation for selecting the target bending angle θ.sub.1f and the target rotational angle δ.sub.1f of the following bending section obtained from the block P.sub.i. This allows seamless transition from the follow-the-leader control to addition of an operator's operation onto the attitude (bending shape) of the continuum robot **100**.

[0085] In the continuum robot control system **300-1** illustrated in FIG. **4**, the kinematic computing unit (kinematics) **340** is computing means that computes, on the basis of the target bending angle θ and the target rotational angle ζ of the following bending section selected by the first switch **331**, the target drive displacement l.sub.pref by which the driving unit of the continuum robot **100** drives the wire in the following bending section. Additionally, in the present embodiment, the kinematic computing unit **340** also computes, on the basis of the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section received from the input device **310**, the target drive displacement l.sub.pref by which the driving unit of the continuum robot **100** drives the wire in the distal-most bending section.

1) Modeling

[0086] In the present chapter, kinematics is derived to determine the target drive displacement by which the actuator drives the wire to control the bending angle θ and the rotational angle ζ of the continuum robot **100**. Definitions of symbols used in the present chapter are as follows: [0087] l.sub.d: length of central axis of bending section [0088] θ.sub.n: bending angle of distal end [0089] ζ.sub.n: rotational angle of distal end [0090] ρ.sub.n: radius of curvature of bending section

[0091] In the present embodiment, as described above, three wires for the bending sections, corresponding to the three wires **111**, **112**, and **113** illustrated in FIG. **2**, are referred to as Wire a, Wire b, and Wire c, respectively, counterclockwise in the xy plane. The drive displacements of Wires a to c that drive the n-th bending section are referred to as l.sub.pna, l.sub.pnb, and l.sub.pnc.

[0092] FIG. **5** is a diagram illustrating an example of how the three wires (Wires a to c) for the n-th bending section, corresponding to the three wires **111** to **113** illustrated in FIG. **2**, are arranged in

the xy plane. As illustrated in FIG. **5**, Wires a to c are arranged at the vertices of a regular triangle with a length of r.sub.s on each side. A phase angle ξ.sub.n in FIG. **5** is an angle that determines the position of the wire that drives the n-th bending section. The phase angle μ.sub.1 is zero (ξ.sub.1=0) in the present embodiment.
[0093] The kinematics of the continuum robot **100** is derived on the following assumptions: [0094] 1. In each bending section, the wires deform with a constant curvature; [0095] 2. Torsional deformation of the wires is not taken into account; [0096] 3. The wires do not deform in the longitudinal direction; and [0097] 4. Friction between the wire guides and the wires is not taken into account.
[0098] First, a relation between each of the drive displacements l.sub.p1a, l.sub.p1b, and l.sub.p1c of Wires a to c in the first bending section (corresponding to the bending section **171** in FIG. **1** and FIG. **2**) and the bending angle θ.sub.1 and the rotational angle ζ.sub.1 of the distal end of the first bending section is represented by Equation (1):

[00001]
$$\begin{aligned} l_{p1c} &= \tfrac{r_s}{\sqrt{3}}\cos \;{}_1\; {}_1 \\ l_{p1b} &= \tfrac{r_s}{\sqrt{3}}\cos(\tfrac{}{6} + \;{}_1)\; {}_1 \\ l_{p1c} &= \tfrac{r_s}{\sqrt{3}}\cos(\tfrac{}{6} - \;{}_1)\; {}_1 \end{aligned} \quad (1)$$

[0099] Next, a relation between each of the drive displacements l.sub.pna, l.sub.pnb, and l.sub.pnc of Wires a to c in the n-th bending section of the plurality of bending sections of the continuum robot **100** and the bending angle θ.sub.n and the rotational angle ζ.sub.n of the distal end of the n-th bending section is determined. The phase angle ζ.sub.n of the wire that drives the n-th bending section is represented by Equation (2):

[00002] $${}_n = \tfrac{120}{e} n \quad (2)$$ [0100] where e is the number of bending sections.

[0101] The drive displacements l.sub.pna, l.sub.pnb, and l.sub.pnc of Wires a to c in the n-th bending section are thus represented by Equation (3):

[00003]
$$\begin{aligned} l_{\mathrm{pna}} &= \tfrac{r_s}{\sqrt{3}}\cos(\;{}_n - \;{}_n)\; {}_n \\ l_{\mathrm{pnb}} &= \tfrac{r_s}{\sqrt{3}}\cos(\tfrac{}{6} + \;{}_n - \;{}_n)\; {}_n \\ l_{\mathrm{pnc}} &= \tfrac{r_s}{\sqrt{3}}\cos(\tfrac{}{6} - \;{}_n + \;{}_n)\; {}_n \end{aligned} \quad (3)$$

[0102] Next, modeling of the operating device **200-1** illustrated in FIG. **3** is performed.
[0103] The equation of motion is expressed as Equation (4):

[00004]
$$\begin{bmatrix} J_{\theta 1} & & & & & 0 \\ & \ddots & & & & \\ & & J_{n} & & & \\ & & & J_{\zeta 1} & & \\ & & & & \ddots & \\ 0 & & & & & J_{n} \end{bmatrix} \begin{bmatrix} \text{.Math.} \\ l1 \\ \text{.Math.} \\ \text{.Math.} \\ \text{.Math.} \\ ln \\ \text{.Math.} \\ l1 \\ \text{.Math.} \\ \text{.Math.} \\ \text{.Math.} \\ ln \end{bmatrix} = \begin{bmatrix} d_1 \\ \text{.Math.} \\ d_n \\ d_1 \\ \text{.Math.} \\ d_n \end{bmatrix} + \begin{bmatrix} u_1 \\ \text{.Math.} \\ u_n \\ u_1 \\ \text{.Math.} \\ u_n \end{bmatrix} \quad (4)$$

[0104] where Jθ.sub.n is the moment of inertia of the operating lever for setting the bending angle θ.sub.n of the n-th bending section and the motor for the operating lever, J.sub.vn is the moment of inertia of the operating lever for setting the rotational angle ζ.sub.n of the n-th bending section and the motor for the operating lever, den is an operating torque applied by the operator to the operating lever for setting the bending angle θ.sub.n of the n-th bending section, d.sub.vn is an operating torque

applied by the operator to the operating lever for setting the rotational angle ζ.sub.n of the n-th bending section, uθ.sub.n is a control torque applied to the operating lever for setting the bending angle θ.sub.n of the n-th bending section, and u.sub.vn is a control torque applied to the operating lever for setting the rotational angle ζ.sub.n of the n-th bending section.
[0105] When Equation (4) is expressed as Equation (5) below,
[00005] $J_l \ddot{q} = d_v + u_v$ (5) [0106] the equation of state is expressed as Equation (6) below:
[00006] $\dot{x}_l = A_l x_l + H_l d_v + B_l u_v, x_l = [q, \dot{q}]^T$ (6)
[0107] The amount of observation y.sub.1 is represented by an output equation, Equation (7) below:
[00007] $y_l = [\, I_{1 \times 2n} \quad 0_{1 \times 2n} \,]\, x_l = C_g x_l$ (7)
2) Design of Control System
[0108] The present chapter deals with design of a follow-the-leader control system and a control system for observation motion control performed in the process of follow-the-leader control.
[0109] FIG. **6** is a diagram illustrating an example of follow-the-leader control of the continuum robot **100** according to the first embodiment of the present disclosure. In FIG. **6**, the same elements as those in FIG. **1** are denoted by the same reference numerals. Also, the z direction in FIG. **1** is the upward direction from the lower side of the drawing of FIG. **6**. Dotted lines in FIG. **6** each indicate a target path **610** along which the continuum robot **100** including the base **140** and the bendable portion **170** moves.
[0110] As illustrated in FIG. **6**, the follow-the-leader control is a method that performs control in such a way that the following bending section of the bendable portion **170** passes along the path (target path **610**) along which the distal-most bending section of the bendable portion **170** passes.
[0111] Examples of the follow-the-leader control include control that is performed in such a way that the bending angle of a following bending section corresponding to forward movement of the continuum robot **100** reaches a first target bending angle of a distal-most bending section received, in accordance with a profile of a first bending angle related to the bending angle of the following bending section and determined in accordance with the first target bending angle.
[0112] In FIG. **6**, a time point **601** corresponds to an initial state where the bendable portion **170** extending from the upper surface **141** of the base **140** in the z direction does not bend. Then, as time passes from a time point **602**, a time point **603**, a time point **604**, and a time point **605** in FIG. **6**, the bendable portion **170** bends as the base **140** moves in the z direction.
[0113] The follow-the-leader control thus allows the continuum robot **100** to move in such a way as to pass through a space. It is not essential for the follow-the-leader control to determine the target path **610** in advance. For example, the bending angle of the distal-most bending section may be continuously transmitted to the bending angle of the following bending section along the length of the bending section. With this method, for example, by giving a command with a joystick to the bending angle of the distal-most bending section and the displacement (or the amount of movement (forward movement)) of the base **140**, the operator can perform the follow-the-leader control of the continuum robot **100** in real time.
2.1) Follow-the-Leader Control
[0114] FIG. **7**A and FIG. **7**B are diagrams illustrating an example of how the block FTL illustrated in FIG. **4** calculates the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section, according to the first embodiment of the present disclosure. The example illustrated in FIG. **7**A and FIG. **7**B assumes that the distal-most bending section is the bending section **173** illustrated in FIG. **1** and the following bending section is the bending section **172** illustrated in FIG. **1**.
[0115] Coordinates in the graphs of FIG. **7**A and FIG. **7**B represent a pair of the position of the base **140** and the angle of the bending section. For the purposes of explanation, an angle

corresponding to coordinates “a” may be referred to as an angle “a”, and the position (displacement) of the base **140** corresponding to coordinates “a” may be referred to as a position “a” (displacement “a”).

[0116] In FIG. **7**A, the horizontal axis represents the displacement Z.sub.b of the base **140** and the vertical axis represents the bending angle θ of the distal-most bending section and the following bending section. In FIG. **7**A, “Leader” indicated by a broken line represents a profile of the bending angle of the distal-most bending section corresponding to the target bending angle θ.sub.1t of the distal-most bending section, for example, the operator has entered through the input device **310**. Also, in FIG. **7**A, “Follower” indicated by a thick broken line represents a profile of the bending angle of the following bending section corresponding to, for example, the target bending angle θ.sub.1f of the following bending section.

[0117] In FIG. **7**B, the horizontal axis represents the displacement Z.sub.b of the base **140** and the vertical axis represents the target rotational angle ζ of the distal-most bending section and the following bending section. In FIG. **7**B, “Leader” indicated by a broken line represents a profile of the rotational angle related to the target rotational angle ζ.sub.1t of the distal-most bending section, for example, the operator has entered through the input device **310**. Also, in FIG. **7**B, “Follower” indicated by a thick broken line represents a profile of the rotational angle related to, for example, the target rotational angle ζ.sub.1f of the following bending section.

[0118] Referring to FIG. **7**A, when the displacement z.sub.b of the base **140** is a displacement “a”, if the target bending angle θ.sub.1t of the distal-most bending section is changed from a distal-most bending angle “a” to a distal-most bending angle “B”, for example, the target bending angle θ.sub.1f of the following bending section represented by “Follower”, indicated by a thick broken line, is automatically updated to change from a following bending angle “c” to a following bending angle “D” when the displacement z.sub.b of the base **140** is a displacement “c”. Referring to FIG. **7**B, when the displacement z.sub.b of the base **140** is a displacement “a”, if the target rotational angle ζ.sub.1t of the distal-most bending section is changed from a distal-most rotational angle “a” to a distal-most rotational angle “b”, for example, the target rotational angle ζ.sub.1f of the following bending section represented by “Follower”, indicated by a thick broken line, is automatically updated to change from a following rotational angle “c” to a following rotational angle “d” when the displacement z.sub.b of the base **140** is a displacement “c”. The displacement “c” is determined in such a way that the length between the displacement “a” and the displacement “c” is equal to the length l.sub.d of the following bending section.

[0119] When the displacement z.sub.b of the base **140** is between the displacement “a” and the displacement “c” in FIG. **7**A and FIG. **7**B, however, the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section represented by “Follower”, indicated by a thick broken line, do not change. The target bending angle θ.sub.1f of the following bending section represented by “Follower”, indicated by a thick broken line in FIG. **7**A, changes from the following bending angle “c” to the following bending angle “D” at the displacement “c”, and the target rotational angle ζ.sub.1f of the following bending section, indicated by a thick broken line in FIG. **7**B, changes from the following rotational angle “c” to the following rotational angle “d” at the displacement “c”. The continuum robot **100** thus behaves abruptly and the operability of the continuum robot **100** is lost.

[0120] Accordingly, in the present embodiment, the block FTL illustrated in in FIG. **4** calculates the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section in the manner described below.

[0121] In FIG. **7**A, the target bending angle θ between the displacement “a” and the displacement “c” is interpolated by a line that connects the target bending angle “a” at the displacement “a” and the target bending angle “D” at the displacement “c”, so that the block FTL in FIG. **4** calculates the resulting angle as the target bending angle θ.sub.fFTL of the following bending section. In FIG. **7**A, the interpolated portion is indicated by a solid line. Similarly, in FIG. **7**B, the target rotational

angle ζ between the displacement “a” and the displacement “c” is interpolated by a line that connects the target rotational angle “a” at the displacement “a” and the target rotational angle “d” at the displacement “c”, so that the block FTL in FIG. **4** calculates the resulting angle as the target rotational angle ζ.sub.fFTL of the following bending section. In FIG. **7**B, the interpolated portion is indicated by a solid line. Then, the block FTL in FIG. **4** stores the profile of the bending angle related to the calculated target bending angle θ.sub.fFTL of the following bending section and the profile of the rotational angle related to the calculated target rotational angle θ.sub.fFTL of the following bending section, for example, in an internal storage unit.
[0122] The explanation of FIG. **7** assumes that the distal-most bending section is the bending section **173** illustrated in FIG. **1** and the following bending section is the bending section **172** illustrated in FIG. **1**. When the bendable portion **170** of the continuum robot **100** includes three or more bending sections, that is, when, for example, the bendable portion **170** illustrated in FIG. **1** includes three bending sections, and the bending section **171** illustrated in FIG. **1** is used as the following bending section, the immediately preceding bending section **172** illustrated in FIG. **1** can be used as the distal-most bending section.
2.2) Control for Switching to Observation Motion Control
[0123] The follow-the-leader control system described in the previous chapter “2.1) Follow-the-leader control” allows the operator to control the attitudes of all the following bending sections simply by giving an angle command to the distal-most bending section. Depending on the condition of the target path **610**, however, the operator may be required to perform observation motion control in the middle. This can be performed by giving an additional command to the attitude of the following bending section. For example, the attitude of the third bending section **173** does not change when the actuator for the second bending section **172** alone is driven. This motion can change the position of the distal-most end of the bendable portion **170** while keeping constant the direction of the leading end of the third bending section **173**, and is suitable for observation along walls, such as stomach and intestinal walls, that extend obliquely from the direction of movement of the continuum robot **100** (hereinafter referred to as “oblique motion”). Here, the operator adds a command value to the bending attitude set by the follow-the-leader control system. For example, if the operating system for giving an additional command is a midpoint return lever, it is difficult to keep track of the bending shape set by the follow-the-leader control, and incorrect operation may damage the continuum robot **100** or the object therearound. Also, the amount of additional operation is reset when the operator's hand is off the operating lever. If, for example, the operating system that gives an additional command is a system that gives a bending angular velocity, keeping track of the resulting bending angle is indirect and thus is difficult, although the amount of additional operation is not reset. To solve this, it is desirable that during the follow-the-leader control, the angle of the operating lever be synchronized with the bending angle or the rotational angle. Accordingly, in the present embodiment, an operating system including a motor and an angular sensor, such as an encoder, is used as the operating device **200-1**. This allows the operator to keep track of the attitude of the continuum robot **100** set by the follow-the-leader control, so that the operator can add a command value simply by giving an operating torque to the operating lever.
[0124] Further description of FIG. **4** will now be provided.
[0125] Hereinafter, a relation between the continuum robot control system **300-1** illustrated in FIG. **4**, and the model described in “1) Modeling” and the follow-the-leader control system described in “2.1) Follow-the-leader control”, will be described.
[0126] As described with reference to FIG. **4**, the block P.sub.s is the continuum robot **100** to be controlled, the output l.sub.p from the block P.sub.s is a vector representing the drive displacement of a wire, and the block K.sub.s is a position control system for settling to the target drive displacement l.sub.pref of the wire. The block P.sub.1 is an operating system including a motor represented by Equation (4), the block K.sub.l is a position control system for settling to target

values, and the blocks G.sub.in and G.sub.out connected to the input end and the output end of the position control system are gains that take values from 0 to 1. In the present embodiment, as described above, the operating levers included in the operating unit for operating the distal-most bending section are not motor-driven.

[0127] The target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section are, for example, the angles of the operating levers for the bending angle and the rotational angle of the distal-most bending section and are equal to θ.sub.in and ζ.sub.1n in Equation (4). Also, the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section are, for example, the angles of the operating levers for the bending angle and the rotational angle of the following bending section, and are vectors constituted by [θ.sub.11, . . . , θ.sub.ln−1, ζ.sub.11, . . . ζ.sub.1n−1] in Equation (4). Also, as described above, the operating torques d.sub.θ1f and d.sub.ζ1f are operating torques the operator applies to the operating levers for the bending angle and the rotational angle of the following bending section, and are vectors constituted by [d.sub.θ1, . . . , d.sub.θn−1, d.sub.ζ1, . . . , d.sub.ζn−1] in Equation (4).

[0128] As described above, during follow-the-leader control (specifically, while the “1” signal is being received by the second switch **332**), the switch unit **330** is in the state of the double-pole double-throw switch illustrated in FIG. **4**. In this case, the kinematic computing unit **340** receives the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section for the follow-the-leader control system, output from the block FTL. At the same time, since the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section for the follow-the-leader control system are target angles of the operating levers and the block G.sub.in and the block G.sub.out receive a value of 1, the angles of the operating levers are feedback-controlled by the block k.sub.1 to follow the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section. In this case, the operating torques d.sub.θ1f and d.sub.ζ1f applied to the operating levers are suppressed as disturbance, and thus have little impact on the angles θ.sub.1f and ζ.sub.1f of the operating levers.

[0129] When operator's contact with the operating lever for the following bending section is detected (specifically, when the second switch **332** receives the “0” signal), the switch unit **330** reverses the position of the double-pole double-throw switch illustrated in FIG. **4**. Since the block G.sub.in and the block G.sub.out receive a value of 0 in this case, the control system for the operating levers is shut off, and the operating torques d.sub.θ1f and d.sub.ζ1f can vary the angles θ.sub.1f and ζ.sub.1f of the operating levers. At the same time, the kinematic computing unit **340** receives the angles θ.sub.1f and ζ.sub.1f of the operating levers. This allows seamless transition from the follow-the-leader control to addition of an operator's operation onto the attitude of the continuum robot **100**. Then, when operator's contact with the operating lever for the following bending section becomes undetected again (specifically, when the second switch **332** receives the “1” signal), the switch unit **330** switches to the position of the double-pole double-throw switch illustrated in FIG. **4**. The angles of the continuum robot **100** and the operating levers are thus returned to the attitude set by the follow-the-leader control. Although the attitude angle of the continuum robot **100** is equal to the angles of the operating levers in the present embodiment, the configuration is not limited to this and, for example, one angle may be a multiple of the other.

3) Simulation

[0130] In the present chapter, simulations are performed using the follow-the-leader control system described in the previous chapter “2) Design of control system”. The continuum robot **100** illustrated in FIG. **1** is simulated, which includes the bendable portion **170** having three bending sections with a length of 0.01 m.

[0131] FIG. **8**A to FIG. **8**F are diagrams illustrating a first example of a result of simulation of a method of controlling the continuum robot **100** by the continuum robot control system **300-1** according to the first embodiment of the present disclosure. In FIG. **8**A to FIG. **8**F, the horizontal direction corresponds to the x direction in FIG. **1**, and the vertical direction corresponds to the z direction in FIG. **1**. FIG. **8**A to FIG. **8**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, FIG. **8**A to FIG. **8**F are stick diagrams that illustrate, in a stepwise manner, how the attitude of the bendable portion **170** is controlled by the follow-the-leader control and the additional operation until the base **140** advances 0.02 m. In FIG. **8**A to FIG. **8**F, a solid line represents the shape of the bendable portion **170** of the continuum robot **100**, an open circle represents the leading end of each bending section, and a thin line represents the locus of the leading end of each bending section.

[0132] First, FIG. **8**A illustrates an attitude where the third bending section **173** (distal-most bending section) is bent and the base **140** is started to move by an operator's bending operation. FIG. **8**B shows that when the base **140** is moved further by the operator, the follow-the-leader control system allows the second bending section **172** to follow the third bending section **173**.

[0133] FIG. **8**C illustrates motion control based on an operator's operation of the operating lever at the bending angle θ of the second bending section **172**. This causes the switch unit **330** to reverse the position of the double-pole double-throw switch illustrated in FIG. **4**, so that the attitude illustrated in FIG. **8**C is reached by adding an operation to the attitude set by the follow-the-leader control. FIG. **8**D illustrates an attitude reached by an additional operation in the direction of shallowing the bending angle θ of the second bending section **172**. This shows that an oblique motion can be performed which changes the position of the distal-most end of the bendable portion **170** while keeping constant the direction of the leading end of the third bending section **173**.

[0134] In FIG. **8**E, the operator's operation of the operating lever at the bending angle θ of the second bending section **172** ends and the attitude before the additional operation is resumed. FIG. **8**F then shows that as the base **140** moves further, the follow-the-leader control can continue, which allows the second bending section **172** and the first bending section **171** to follow the third bending section **173** and the second bending section **172**, respectively.

[0135] FIG. **9**A to FIG. **9**F are diagrams illustrating a second example of the result of simulation of the method of controlling the continuum robot **100** by the continuum robot control system **300-1** according to the first embodiment of the present disclosure. In FIG. **9**A to FIG. **9**F, the horizontal direction corresponds to the y direction in FIG. **1**, the vertical direction corresponds to the z direction in FIG. **1**, and the depth direction corresponds to the x direction in FIG. **1**. FIG. **9**A to FIG. **9**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, FIG. **9**A to FIG. **9**F illustrate a simulation response of giving an additional operation to the rotational angle ζ.

[0136] In FIG. **9**A and FIG. **9**B, follow-the-leader control is performed in the same manner as that illustrated in FIG. **8**A and FIG. **8**B.

[0137] FIG. **9**C illustrates an operator's operation of the operating lever in the direction of deepening the rotational angle ζ of the second bending section **172**. This causes the switch unit **330** to reverse the position of the double-pole double-throw switch illustrated in FIG. **4**, so that the attitude illustrated in FIG. **9**C is reached by adding an operation to the attitude set by the follow-the-leader control. FIG. **9**D illustrates an attitude reached by an additional operation in the direction of shallowing the rotational angle ζ of the second bending section **172**. This shows that it is possible to change the position of the distal-most end of the bendable portion **170** in an out-of-plane direction of the bending shape while keeping constant the direction of the leading end of the third bending section **173**.

[0138] FIG. **9**E and FIG. **9**F show that as the base **140** moves further, the follow-the-leader control can continue, which allows the second bending section **172** and the first bending section **171** to follow the third bending section **173** and the second bending section **172**, respectively.

[0139] FIG. **10**A to FIG. **10**F are diagrams illustrating a third example of the result of simulation of the method of controlling the continuum robot **100** by the continuum robot control system **300-1** according to the first embodiment of the present disclosure. In FIG. **10**A to FIG. **10**F, the horizontal direction corresponds to the y direction in FIG. **1**, the vertical direction corresponds to the z direction in FIG. **1**, and the depth direction corresponds to the x direction in FIG. **1**. FIG. **10**A to FIG. **10**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, in FIG. **10**A to FIG. **10**F, the operation in FIG. **8**A to FIG. **8**F and the operation in FIG. **9**A to FIG. **9**F are combined, so as to control the position of the distal-most end of the bendable portion **170** while keeping constant the direction of the leading end of the third bending section **173** in a three-dimensional space.

[0140] In the continuum robot control system **300-1** according to the first embodiment, the block FTL calculates the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section on the basis of the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section and the displacement of the base **140**. The switch unit **330** performs a switching operation for selecting the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section obtained from the block FTL, or the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section obtained from the block P.sub.1 corresponding to the following operating means. The kinematic computing unit **340** computes, on the basis of the target bending angle and the target rotational angle of the following bending section selected by the switch unit **330**, the drive displacement by which the driving unit of the continuum robot **100** drives the wire in the following bending section.

[0141] This configuration enables switching between the motion control of the following bending section based on the follow-the-leader control and the motion control of the following bending section based on the operation by the following operating means, and thus can prevent the continuum robot **100** from accidentally coming into contact with an object. Therefore, it is possible to prevent the object or the continuum robot **100** from being damaged, and ensure safe operation of the continuum robot **100**. Specifically, in the present embodiment, follow-the-leader control can seamlessly transition to observation motion control, an oblique motion can be performed by an additional operation, and the follow-the-leader control can be performed again after completion of the additional operation.

Second Embodiment

[0142] A second embodiment of the present disclosure will now be described. In the description of the second embodiment, things in common with the first embodiment will be omitted, and things different from the first embodiment will be described.

[0143] A general configuration of a continuum robot according to the second embodiment is the same as the general configuration of the continuum robot **100** according to the first embodiment illustrated in FIG. **1** and FIG. **2**. A general configuration of an operating device according to the second embodiment is the same as the general configuration of the operating device **200-1** according to the first embodiment illustrated in FIG. **3**.

[0144] The control system described in the first embodiment simply gives an operator's operation command to the distal-most bending section. In the second embodiment, however, the distal-most bending section is operated in conjunction with an additional operation of the following bending section to provide more types of observation motions. For example, when the bendable portion **170** of the continuum robot **100** includes three bending sections as in the case of FIG. **1**, the position of the leading end of the bendable portion **170** of the continuum robot **100** can be significantly changed by driving the second bending section **172** and the third bending section **173** in the same direction. This motion is suitable for significantly moving the distal-most end of the continuum robot **100**, for example, to observe across a wide area inside the body, or to avoid contact with organs (hereinafter referred to as “large bending motion”).

[0145] FIG. **11** is a diagram illustrating an example of a general configuration of the continuum robot control system **300** according to the second embodiment of the present disclosure. In the following description, the continuum robot control system **300** according to the second embodiment illustrated in FIG. **11** is referred to as a “continuum robot control system **300-2**”. In FIG. **11**, the same elements as those in FIG. **4** are denoted by the same reference numerals and their detailed description will be omitted. Specifically, FIG. **11** is a block diagram illustrating a control system that operates the distal-most bending section in conjunction with addition of an operation to the following bending section.

[0146] The continuum robot control system **300-2** according to the second embodiment, illustrated in FIG. **11**, is obtained by adding some components (described below) to, and changing some components (described below) of, the continuum robot control system **300-1** according to the first embodiment illustrated in FIG. **4**.

[0147] Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-2** includes a block K.sub.1t, blocks G.sub.in and G.sub.out connected to an input end and an output end, respectively, of the block K.sub.1t, a block P.sub.1t, and a block K.sub.r. The continuum robot control system **300-2** does not include the input device **310** of the continuum robot control system **300-1** illustrated in FIG. **4**. The block FTL, the block K.sub.1, and the block P.sub.1 of the continuum robot control system **300-1** illustrated in FIG. **4** are changed to a block FTL+Memory (storage unit), a block K.sub.1f, and a block P.sub.1f, respectively, in the continuum robot control system **300-2**. The switch unit **330** of the continuum robot control system **300-2** includes a third switch **333**, as well as the first switch **331** and the second switch **332** of the continuum robot control system **300-1** illustrated in FIG. **4**. Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-2** includes a NOT gate downstream of the second switch **332**.

[0148] The block P.sub.1t in FIG. **11** is an operating system including a motor for the distal-most bending section (distal-most operating means), the block P.sub.1f in FIG. **11** is an operating system including a motor for the following bending section (following operating means). Also, the block K.sub.1t in FIG. **11** is an operating-system position control system for the distal-most bending section, and the block K.sub.1f in FIG. **11** is an operating-system position control system for the following bending section. Also, the target bending angle θ.sub.1t of the distal-most bending section in FIG. **11** is the angle of the operating lever for the bending angle of the distal-most section, and the target rotational angle ζ.sub.1t of the distal-most bending section in FIG. **11** is the angle of the operating lever for the rotational angle of the distal-most section. The target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t correspond to θ.sub.1n and ζ.sub.1n, respectively, in Equation (4). Operating torques d.sub.θ1t and d.sub.ζ1t are operating torques the operator applies to the operating levers for the bending angle and the rotational angle, respectively, of the distal-most bending section, and correspond to d.sub.θn and d.sub.ζn, respectively, in Equation (4). The block FTL+Memory (storage unit) includes a storage unit that stores the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section, as well as the target bending angle θ.sup.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section for the follow-the-leader control of the first embodiment.

[0149] The block K.sub.r is an algorithm that makes the attitudes of the following bending section the distal-most bending section in conjunction with each other. Switching the block K.sub.r can change the type of motion. Specifically, the block K.sub.r is distal-most calculating means that calculates the target bending angle and the target rotational angle of the distal-most bending section on the basis of the target bending angle θ.sub.1t and the target rotational angle Sit of the distal-most bending section stored in the block FTL+Memory (storage unit), and also on the basis of the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section received from the block P.sub.1f corresponding to the following operating means.

[0150] The third switch **333** of the switch unit **330** is a switch (distal-most switching means) that performs a switching operation for selecting the target bending angle and the target rotational angle of the distal-most bending section obtained from the block K.sub.r, or the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section obtained from the block Pit (distal-most operating means).

[0151] In the present embodiment, the kinematic computing unit **340** computes, on the basis of the target bending angle and the target rotational angle of the distal-most bending section selected by the third switch **333**, the drive displacement by which the driving unit of the continuum robot **100** drives the wire in the distal-most bending section.

[0152] In the present embodiment, during follow-the-leader control (specifically, while the "1" signal is being received by the second switch **332**), the switch unit **330** is in the state of a triple-pole double-throw switch illustrated in FIG. **11**. In this case, the NOT gate downstream of the second switch **332** provides a value of 0 to the blocks G.sub.in and G.sub.out in a feedback loop of the operating system for the distal-most bending section, illustrated in the upper part of FIG. **11**. This shuts off the operating system for the distal-most bending section and allows the operating torques d.sub.θ1t and d.sub.θ1t to change the angles θ.sub.1t and ζ.sub.1t of the operating levers. That is, during the follow-the-leader control described above, the third switch **333** performs a switching operation for selecting the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section obtained from the block P.sub.1t. In this case, the kinematic computing unit **340** receives the target bending angle θ.sub.1t and the target rotational angle ζ.sub.1t of the distal-most bending section, obtained from the block P.sub.1t, and the target bending angle θ.sub.fFTL and the target rotational angle ζ.sub.fFTL of the following bending section, obtained from the block FTL+Memory.

[0153] At this point, when operator's contact with the operating lever for the following bending section is detected (specifically, when the second switch **332** receives the "0" signal), the switch unit **330** reverses the position of the triple-pole double-throw switch illustrated in FIG. **11**. In this case, the blocks G.sub.in and G.sub.out in a feedback loop of the operating system for the following bending section, illustrated in the lower part of FIG. **11**, receive a value of 0. This shuts off the operating system for the following bending section and allows the operating torques d.sub.θ1f and d.sub.θ1f to change the angles θ.sub.1f and θ.sub.1f of the operating levers. At the same time, the kinematic computing unit **340** receives the target bending angle θ.sub.1f and the target rotational angle ζ.sub.1f of the following bending section through the first switch **331**. This allows seamless transition from the follow-the-leader control to addition of an operator's operation onto the attitude of the continuum robot **100**. On the other hand, the NOT gate downstream of the second switch **332** provides a value of 1 to the blocks G.sub.in and G.sub.out in the feedback loop of the operating system for the distal-most bending section, illustrated in in the upper part of FIG. **11**. This enables positioning control by the block K.sub.1t and suppresses the operating torques d.sub.θ1t and d.sub.ζ1t from the operator as disturbance. In this case, the third switch **333** performs a switching operation for selecting the target bending angle and the target rotational angle of the distal-most bending section obtained from the block K.sub.r. This allows the continuum robot **100** and the operating levers to operate in conjunction with the amount of additional operation and allows angles related to the distal-most bending section to change in conjunction with the amount of additional operation on the following bending section.

[0154] FIG. **12**A to FIG. **12**F are diagrams illustrating a first example of a result of simulation of a method of controlling the continuum robot **100** by the continuum robot control system **300-2** according to the second embodiment of the present disclosure. In FIG. **12**A to FIG. **12**F, the horizontal direction corresponds to the x direction in FIG. **1**, and the vertical direction corresponds to the z direction in FIG. **1**. FIG. **12**A to FIG. **12**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, FIG. **12**A to FIG. **12**F illustrate a simulation response of giving an additional operation. In FIG. **12**A to FIG. **12**F, a solid line represents the shape of the bendable portion **170** of the continuum robot **100**, an open circle represents the leading end of each bending section, and a thin line represents the locus of the leading end of each bending section.

[0155] In FIG. **12**A and FIG. **12**B, the same follow-the-leader control as that illustrated in FIG. **9**A

and FIG. **9**B is performed.
[0156] FIG. **12**C illustrates motion control based on an operator's operation of the operating lever at the bending angle θ of the second bending section **172**. This causes the switch unit **330** to reverse the position of the triple-pole double-throw switch illustrated in FIG. **11**, so that the attitude illustrated in FIG. **12**C is reached by adding an operation to the attitude set by the follow-the-leader control. In this simulation, a bending angle θ.sub.3ref of the distal-most bending section is changed in conjunction with the difference between the command angle of the follow-the-leader control on the second bending section **172** and the angle of the additional operation (θ.sub.12-θ.sub.2FTL) in such a way as to satisfy Equation (8) below:
[00008] ${}_{3ref} = {}_{3Mem} - 0.5({}_{l2} - {}_{2FTL})$ (8) [0157] where θ.sub.3Mem is the bending angle of the distal-most bending section immediately before switching of the triple-pole double-throw switch of the switch unit **330**, stored in the block FTL+Memory (storage unit).
[0158] FIG. **12**D illustrates an attitude reached by an additional operation in the direction of shallowing the bending angle θ of the second bending section **172**. This shows that the direction of observation is changed by an additional operation while the third bending section **173** is always directed toward a small region around [x, y]= [0.015, 0.4] in front.
[0159] FIG. **12**E and FIG. **12**F show that as the base **140** moves further, the follow-the-leader control can continue, which allows the second bending section **172** and the first bending section **171** to follow the third bending section **173** and the second bending section **172**, respectively.
[0160] FIG. **13**A to FIG. **13**F are diagrams illustrating a second example of the result of simulation of the method of controlling the continuum robot **100** by the continuum robot control system **300-2** according to the second embodiment of the present disclosure. In FIG. **13**A to FIG. **13**F, the horizontal direction corresponds to the x direction in FIG. **1**, and the vertical direction corresponds to the z direction in FIG. **1**. FIG. **13**A to FIG. **13**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, FIG. **13**A to FIG. **13**F illustrate a large bending motion provided by an additional operation.
[0161] In the simulation illustrated in FIG. **13**A to FIG. **13**F, the bending angle θ.sub.3ref of the distal-most end is changed in conjunction with the difference between the command angle of the follow-the-leader control on the second bending section **172** and the angle of the additional operation in such a way as to satisfy Equation (9) below:
[00009] ${}_{3ref} = {}_{3Mem} + 3({}_{l2} - {}_{2FTL})$ (9)
[0162] The second bending section **172** and the third bending section **173** are thus moved in conjunction with each other to provide a large bending motion. FIG. **13**E and FIG. **13**F show that as the base **140** moves further, the follow-the-leader control can continue, which allows the second bending section **172** and the first bending section **171** to follow the third bending section **173** and the second bending section **172**, respectively.
[0163] The simulations illustrated in FIG. **12**A to FIGS. **12**F and **13**A to FIG. **13**F have been described by taking the bending angle θ into account, because the motion control of the bendable portion **170** is assumed to take place in the xz plane. If the motion control takes place in the xyz three-dimensional space, the rotational angle ζ may also be taken into account.
[0164] Like the first embodiment, the second embodiment can prevent the continuum robot **100** from accidentally coming into contact with an object. Therefore, it is possible to prevent the object or the continuum robot **100** from being damaged, and ensure safe operation of the continuum robot **100**.
Third Embodiment
[0165] A third embodiment of the present disclosure will now be described. In the description of the third embodiment, things in common with the first and second embodiments will be omitted, and things different from the first and second embodiments will be described.

[0166] A general configuration of a continuum robot according to the third embodiment is the same as the general configuration of the continuum robot **100** according to the first embodiment illustrated in FIG. **1** and FIG. **2**. A general configuration of an operating device according to the third embodiment is the same as the general configuration of the operating device **200-1** according to the first embodiment illustrated in FIG. **3**.

[0167] The control system of the second embodiment operates the distal-most bending section in conjunction with an additional operation of the following bending section. In the third embodiment, however, the following bending sections are operated in conjunction with each other to provide more types of observation motions.

[0168] FIG. **14** is a diagram illustrating an example of a general configuration of the continuum robot control system **300** according to the third embodiment of the present disclosure. In the following description, the continuum robot control system **300** according to the third embodiment illustrated in FIG. **14** is referred to as a “continuum robot control system **300-3**”. In FIG. **14**, the same elements as those in FIG. **4** are denoted by the same reference numerals and their detailed description will be omitted. Specifically, FIG. **14** is a block diagram illustrating a control system that allows the following bending sections to be operated in conjunction with each other by an additional operation.

[0169] The continuum robot control system **300-3** according to the third embodiment, illustrated in FIG. **14**, is obtained by adding some components (described below) to, and changing some components (described below) of, the continuum robot control system **300-1** according to the first embodiment illustrated in FIG. **4**.

[0170] Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-3** includes two control systems for following bending sections. Specifically, the control system for the following bending section including the block K.sub.1, the blocks G.sub.in and G.sub.out connected to the input end and the output end of the block K.sub.1, and the block P.sub.1, illustrated in FIG. **4**, is changed to a control system for the second bending section **172** (second following bending section) in the continuum robot control system **300-3**. More specifically, the control system for the second bending section **172** is a control system for the following bending section including a block K.sub.12, the blocks G.sub.in and G.sub.out connected to the input end and the output end of the block K.sub.12, and a block P.sub.12 illustrated in FIG. **14**. Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-3** further includes a control system for the first bending section **171** (first following bending section). More specifically, the control system for the first bending section **171** is a control system for the following bending section including a block K.sub.11 and a block P.sub.11 illustrated in FIG. **14**. Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-3** further includes a control gain block G.sub.w. Also, the switch unit **330** of the continuum robot control system **300-3** includes a fourth switch **334** and a fifth switch **335**, instead of the first switch **331** of the continuum robot control system **300-1** illustrated in FIG. **4**.

[0171] The block Pu is an operating system (first following operating means), including a motor, for receiving a target bending angle θ.sub.1f1 and a target rotational angle ζ.sub.1f1 of the first bending section **171** (first following bending section). In the example illustrated in FIG. **3**, for example, the block Pu is an operating system corresponding to the first operating unit **210** for operating the first bending section **171** (following bending section). Specifically, the target bending angle θ.sub.1f1 and the target rotational angle θ.sub.1f1 of the first bending section **171** are angles of the operating levers for the first bending section **171**. Operating torques d.sub.θ1f1 and d.sub.ζ1f1 are operating torques the operator applies to the operating lever at the bending angle of the first bending section **171** and to the operating lever at the rotational angle of the first bending section **171**.

[0172] The block P.sub.12 is an operating system (second following operating means), including a motor, for receiving a target bending angle θ.sub.1f2 and a target rotational angle ζ.sub.1f2 of the second bending section **172** (second following bending section). In the example illustrated in FIG. **3**, for example, the block P.sub.12 is an operating system corresponding to the second operating unit **220** for operating the second bending section **172** (following bending section). Specifically, the target bending angle θ.sub.1f2 and the target rotational angle ζ.sub.1f2 of the second bending section **172** are angles of the operating levers for the second bending section **172**. Operating torques d.sub.θ1f2 and d.sub.ζ1f2 are operating torques the operator applies to the operating lever at the bending angle of the second bending section **172** and to the operating lever at the rotational angle of the second bending section **172**.

[0173] The block K.sub.11 is an operating-system position control system for the first bending section **171** (first following bending section), and the block K.sub.12 is an operating-system position control system for the second bending section **172** (second following bending section).

[0174] In the present embodiment, the block FTL calculates a target bending angle θ.sub.f2FTL and a target rotational angle ζ.sub.f2FTL of the second bending section **172**, and also calculates a target bending angle θ.sub.f1FTL and a target rotational angle ζ.sub.f1FTL of the first bending section **171**.

[0175] In the continuum robot control system **300-3** illustrated in FIG. **14**, the control gain block G.sub.w is a matrix that specifies the ratio of the attitudes of the following bending section and the distal-most bending section, and switching the control gain block G.sub.w can change the type of motion. Specifically, in the example illustrated in FIG. **14**, the control gain block G.sub.w is control gain means that multiplies, by a control gain, the target bending angle θ.sub.1f2 and the target rotational angle ζ.sub.1f2 of the second bending section **172** obtained from the block P.sub.12 (second following operating means).

[0176] In the present embodiment, for example, when operator's contact with the operating lever for the second bending section **172** is detected (specifically, when the second switch **332** receives the “0” signal), the switch unit **330** reverses the position of the triple-pole double-throw switch illustrated in FIG. **14**. The switch unit **330** thus causes the fourth switch **334** to perform a switching operation for selecting, as the target bending angle and the target rotational angle of the second bending section **172**, the target bending angle θ.sub.1f2 and the target rotational angle ζ.sub.1f2 of the second bending section **172** obtained from the block P.sub.12 (second following operating means), and also causes the fifth switch **335** to perform a switching operation for selecting, as the target bending angle and the target rotational angle of the first bending section **171**, the target bending angle θ.sub.1f2 and the target rotational angle ζ.sub.1f2 of the second bending section **172** multiplied by the control gain by the control gain block G.sub.w.

[0177] FIG. **15**A to FIG. **15**F are diagrams illustrating an example of the result of simulation of the method of controlling the continuum robot **100** by the continuum robot control system **300-3** according to the third embodiment of the present disclosure. In FIG. **15**A to FIG. **15**F, the horizontal direction corresponds to the x direction in FIG. **1**, and the vertical direction corresponds to the z direction in FIG. **1**. FIG. **15**A to FIG. **15**F illustrate how the motion control of the bending sections **171** to **173** in the bendable portion **170** of the continuum robot **100** proceeds with time. Specifically, FIG. **15**A to FIG. **15**F illustrate a simulation response of giving an additional operation. In FIG. **15**A to FIG. **15**F, a solid line represents the shape of the bendable portion **170** of the continuum robot **100**, an open circle represents the leading end of each bending section, and a thin line represents the locus of the leading end of each bending section.

[0178] In FIG. **15**A and FIG. **15**B, the same follow-the-leader control as that illustrated in FIG. **9**A and FIG. **9**B is performed.

[0179] FIG. **15**C and FIG. **15**D illustrate an operator's operation of the operating lever for the bending angle of the second bending section **172**. This causes the switch unit **330** to reverse the position of the triple-pole double-throw switch illustrated in FIG. **14**, so that the attitudes illustrated in FIG. **15**C and FIG. **15**D are reached by adding an operation to the attitude set by the follow-the-leader control. In this simulation, the bending angle of the first bending section **171** θ.sub.1ref is changed in conjunction with the difference between the command angle of the follow-the-leader control on the second bending section **172** and the angle of the additional operation (θ.sub.12-θ.sub.2FTL) in such a way as to satisfy Equation (10) below:

[00010] ${}_{1\mathrm{ref}} = {}_{1\mathrm{FTL}} - ({}_{l2} - {}_{2\mathrm{FTL}})$ (10)

[0180] The operator can thus change the displacement of the distal-most end in the forward and backward direction of movement while keeping constant the direction of the leading end of the third bending section **173**.

[0181] FIG. **15**E and FIG. **15**F show that as the base **140** moves further, the follow-the-leader control can continue, which allows the second bending section **172** and the first bending section **171** to follow the third bending section **173** and the second bending section **172**, respectively.

[0182] The simulations illustrated in FIG. **15**A to FIG. **15**F have been described by taking the bending angle θ into account, because motion control of the bendable portion **170** is assumed to take place in the xz plane. If the motion control takes place in the xyz three-dimensional space, the rotational angle ζ may also be taken into account.

[0183] Like the first embodiment, the third embodiment can prevent the continuum robot **100** from accidentally coming into contact with an object. Therefore, it is possible to prevent the object or the continuum robot **100** from being damaged, and ensure safe operation of the continuum robot **100**.

Fourth Embodiment

[0184] A fourth embodiment of the present disclosure will now be described. In the description of the fourth embodiment, things in common with the first to third embodiments will be omitted, and things different from the first to third embodiments will be described.

[0185] A general configuration of a continuum robot according to the fourth embodiment is the same as the general configuration of the continuum robot **100** according to the first embodiment illustrated in FIG. **1** and FIG. **2**. A general configuration of an operating device according to the fourth embodiment is the same as the general configuration of the operating device **200-1** according to the first embodiment illustrated in FIG. **3**.

[0186] The first to third embodiments described above assume that an additional bending operation takes place during forward movement which involves follow-the-leader control. In the fourth embodiment, an additional bending operation that takes place during backward movement will be described. During backward movement, the bending angle θ and the rotational angle ζ of the distal-most bending section may be controlled by the operator as in the case of during forward movement. Alternatively, an operation during forward movement may be recorded and reproduced in accordance with the displacement z.sub.b of the base **140**.

[0187] FIG. **16** is a diagram illustrating an example of a general configuration of the continuum robot control system **300** according to the fourth embodiment of the present disclosure. In the following description, the continuum robot control system **300** according to the fourth embodiment illustrated in FIG. **16** is referred to as a “continuum robot control system **300-4**”. In FIG. **16**, the same elements as those in FIG. **11** are denoted by the same reference numerals and their detailed description will be omitted.

[0188] The continuum robot control system **300-4** according to the fourth embodiment, illustrated in FIG. **16**, is obtained by adding some components (described below) to, and changing some components (described below) of, the continuum robot control system **300-2** according to the second embodiment illustrated in FIG. **11**.

[0189] Unlike the continuum robot control system **300-2** illustrated in FIG. **11**, the continuum robot control system **300-4** includes a “Bk=1 Fw=0” block **350** and a switch unit **360**. The continuum robot control system **300-4** does not include the block K.sub.r of the continuum robot control system **300-2** illustrated in FIG. **11**. The switch unit **330** of the continuum robot control system **300-4** includes a sixth switch **336**, instead of the third switch **333** of the continuum robot control system **300-2** illustrated in FIG. **11**. The continuum robot control system **300-4** includes a multiplication block **370**, instead of the NOT gate downstream of the second switch **332** in the continuum robot control system **300-2** illustrated in FIG. **11**.

[0190] The “Bk=1 Fw=0” block **350** is base determining means that determines whether the base **140** is moving forward or backward, on the basis of the displacement z.sub.b of the base **140**. The “Bk=1 Fw=0” block **350** outputs a “0” signal if determining that the base **140** is moving forward, and outputs a “1” signal if determining that the base **140** is moving backward.

[0191] The switch unit **360** is distal-most switching means that performs a switching operation for selecting, on the basis of the determination made by the “Bk=1 Fw=0” block **350**, the target bending angle and the target rotational angle of the distal-most bending section stored in the block FTL+Memory (storage unit), or the target bending angle θ.sub.1t and the target rotational angle Sit of the distal-most bending section obtained from the block Pit (distal-most operating means). Specifically, the switch unit **360** operates in conjunction with an output signal of the “Bk=1 Fw=0” block **350**. For example, if the “Bk=1 Fw=0” block **350** determines that the base **140** is moving backward (if a “1” signal is output), the switch unit **360** performs a switching operation for selecting the target bending angle and the target rotational angle of the distal-most bending section stored in the block FTL+Memory (storage unit). On the basis of the target bending angle and the target rotational angle of the distal-most bending section selected by the switch unit **360**, the kinematic computing unit **340** computes the drive displacement by which the driving unit of the continuum robot **100** drives the wire in the distal-most bending section.

[0192] Specifically, in the state of the triple-pole double-throw switch of the switch unit **330** and the state of a single-pole double-throw switch of the switch unit **360** illustrated in FIG. **16**, the positioning control of the operating lever for the distal-most bending section is disabled. In this case, the operating angle of the operating lever operated by the operator is received through the single-pole double-throw switch of the switch unit **360** by the kinematic computing unit **340**, so that follow-the-leader control is performed. If the base **140** is moved backward at this point, the switch unit **360** reverses the position of the single-pole double-throw switch illustrated in FIG. **16**. In this case, the positioning control of the operating lever for the distal-most bending section is enabled. As the target values of the positioning control, the target bending angle and the target rotational angle of the distal-most bending section recorded during forward movement and corresponding to the displacement z.sub.b of the base **140** are output from the FTL+Memory (storage unit). At the same time, the target bending angle and the target rotational angle of the distal-most bending section are received by the kinematic computing unit **340**, so that the continuum robot **100** reproduces the shape recoded during forward movement while moving backward.

[0193] When operator's contact with the operating lever for the following bending section is detected, the control system of the present embodiment causes the switch unit **330** to reverse the position of the triple-pole double-throw switch illustrated in FIG. **16**. The motion of the following bending section at this point is the same as that in the first embodiment. As for control of the distal-most bending section, the positioning control of the operating lever for the distal-most bending section is disabled regardless of whether the displacement z.sub.b of the base **140** is forward or backward, and the operating angle of the operating lever operated by the operator is received through the switch unit **330** by the kinematic computing unit **340** without passing through the switch unit **360**.

[0194] The third embodiment allows seamless transition to an operator's additional operation as in the first embodiment while controlling the distal-most bending section during backward movement in such a way as to reproduce the operation recorded during forward movement.

Fifth Embodiment

[0195] A fifth embodiment of the present disclosure will now be described. In the description of the fifth embodiment, things in common with the first to fourth embodiments will be omitted, and things different from the first to fourth embodiments will be described.

[0196] A general configuration of a continuum robot according to the fifth embodiment is the same as the general configuration of the continuum robot **100** according to the first embodiment illustrated in FIG. **1** and FIG. **2**. A general configuration of a continuum robot control system according to the fifth embodiment of the present disclosure may be any of the general configurations of the continuum robot control systems **300-1** to **300-4** according to the first to fourth embodiments.
[0197] The first to fourth embodiments assume that the operating device **200-1**, illustrated in FIG. **3**, is used which includes operating levers that correspond one-to-one to the bending angle and the rotational angle of each bending section. In the fifth embodiment, a joystick with a dual-axis motor is used as the operating device **200**.
[0198] FIG. **17** is a diagram illustrating an example of a general configuration of the operating device **200** for operating the three bending sections **171** to **173** of the continuum robot **100** illustrated in FIG. **1**, according to the fifth embodiment of the present disclosure. In the following description, the operating device **200** according to the fifth embodiment illustrated in FIG. **17** is referred to as an "operating device **200-5**".
[0199] As illustrated in FIG. **17**, the operating device **200-5** includes a first operating unit **240** for operating the first bending section **171**, a second operating unit **250** for operating the second bending section **172**, and a third operating unit **260** for operating the third bending section **173**.
[0200] The first operating unit **240** includes an operating lever **241**, motors **242** and **244**, and angular sensors **243** and **245**. The operating lever **241** is an operating lever for the first bending section **171**. The angular sensors **243** and **245** detect operating angles φ.sub.x1 and φ.sub.y1, respectively, with respect to the first bending section **171**. The motors **242** and **244** are motors for applying control torques to the operating angles φ.sub.x1 and φ.sub.y1, respectively.
[0201] The second operating unit **250** includes an operating lever **251**, motors **252** and **254**, and angular sensors **253** and **255**. The operating lever **251** is an operating lever for the second bending section **172**. The angular sensors **253** and **255** detect operating angles φ.sub.x2 and φ.sub.y2, respectively, with respect to the second bending section **172**. The motors **252** and **254** are motors for applying control torques to the operating angles φ.sub.x2 and φ.sub.y2, respectively.
[0202] The third operating unit **260** includes an operating lever **261**, motors **262** and **264**, and angular sensors **263** and **265**. The operating lever **261** is an operating lever for the third bending section **173**. The angular sensors **263** and **265** detect operating angles φ.sub.x3 and φ.sub.y3, respectively, with respect to the third bending section **173**. The motors **262** and **264** are motors for applying control torques to the operating angles φ.sub.x3 and φ.sub.y3, respectively.
[0203] For use in the control systems described in the first to fourth embodiments, a coordinate transformation may be performed as in Equation (11) below:

[00011] $$_{ln} = \sqrt{{}_{xn}^{2} + {}_{yn}^{2}}, \quad _{ln} = \tan^{-1}\frac{_{yn}}{_{rn}} \quad (11)$$ [0204] where φ.sub.xn and φ.sub.yn are operating angles with respect to the n-th bending section.

Sixth Embodiment
[0205] A sixth embodiment of the present disclosure will now be described. In the description of the sixth embodiment, things in common with the first to fifth embodiments will be omitted, and things different from the first to fifth embodiments will be described.
[0206] A general configuration of a continuum robot according to the sixth embodiment is the same as the general configuration of the continuum robot **100** according to the first embodiment illustrated in FIG. **1** and FIG. **2**. A general configuration of an operating device according to the sixth embodiment is the same as the general configuration of the operating device **200-1** according to the first embodiment illustrated in FIG. **3**.
[0207] For switching between the follow-the-leader control and the additional operation, the control systems described in the first to fifth embodiments use a value of 0 or 1 for the blocks G.sub.in and G.sub.out. However, since such switching between two values may lead to abrupt

behavior caused by operation of an operating lever, a control system illustrated in FIG. **18** may be used.
[0208] FIG. **18** is a diagram illustrating an example of a general configuration of the continuum robot control system **300** according to the sixth embodiment of the present disclosure. In the following description, the continuum robot control system **300** according to the sixth embodiment illustrated in FIG. **18** is referred to as a "continuum robot control system **300-6**". In FIG. **18**, the same elements as those in FIG. **4** are denoted by the same reference numerals and their detailed description will be omitted.
[0209] The continuum robot control system **300-6** according to the sixth embodiment, illustrated in FIG. **18**, is obtained by adding some components (described below) to, and changing some components (described below) of, the continuum robot control system **300-1** according to the first embodiment illustrated in FIG. **4**.
[0210] Unlike the continuum robot control system **300-1** illustrated in FIG. **4**, the continuum robot control system **300-6** includes a low-pass filter F.sub.1pf downstream of the second switch **332** of the switch unit **330**. In the continuum robot control system **300-6** according to the sixth embodiment illustrated in FIG. **18**, a signal passing through the low-pass filter F.sub.1pf is received by the blocks G.sub.in and G.sub.out. In this case, the break frequency of the low-pass filter F.sub.1pf may be about 1 Hz. FIG. **18** illustrates the changes made to the control system of the first embodiment. The same changes as those described may be made to the control systems of the second to fourth embodiments.
OTHER EMBODIMENTS
[0211] One or more features of the present disclosure can also be implemented by processing where a program that performs one or more functions of the embodiments described above is supplied through a network or storage medium to a system or apparatus, and one or more processors in a computer of the system or apparatus read and execute the program. One or more features of the present disclosure can also be implemented by a circuit (e.g., application-specific integrated circuit or ASIC) that performs one or more functions.
[0212] A program and a computer-readable storage medium that stores the program are included in the present disclosure.
[0213] One or more features of the present disclosure can ensure safe operation of the continuum robot.
[0214] While one or more features of the present disclosure have been described with reference to exemplary embodiments, it is to be understood that the disclosure is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

Claims

1. A continuum robot control system, comprising: a driving unit configured to drive a wire; a bendable portion having a plurality of bending sections bent by being driven by the wire; a base configured to support the bendable portion, wherein the plurality of bending sections includes a distal-most bending section located farthest from the base, and a following bending section located between the distal-most bending section and the base; a computing unit configured to compute a drive displacement by which the driving unit drives the wire in the following bending section, a following computing unit configured to compute a target bending angle of the following bending section on a basis of a target bending angle of the distal-most bending section and on a basis of a displacement of the base in a direction of movement of the continuum robot, and inputs a computation result into the computing unit; a following operating unit configured to input the target bending angle of the following bending section into the computing unit on a basis of an input by an operator into a following operation input unit; and a following switching unit configured to switch a means for inputting the target bending angle of the following bending section into the computing unit, wherein the following switching unit executes switching processing to switch the means for inputting the target bending angle of the following bending section into the computing unit to the following computing unit and to the following operating unit.

2. The continuum robot control system according to claim 1, wherein the switching processing is processing that the following switching unit performs switching such that the target bending angle of the following bending section is inputted into the computing unit from the following computing unit in a case where the input into the following operation input unit does not exist, and such that the target bending angle of the following bending section is inputted into the computing unit from the following operating unit in a case where the input into the following operation input unit exists.

3. The continuum robot control system according to claim 1, further comprising: a storage unit configured to store the target bending angle of the distal-most bending section; a distal-most computing unit configured to compute the target bending angle of the distal-most bending section on a basis of the target bending angle of the distal-most bending section stored in the storage unit and on a basis of the target bending angle of the following bending section inputted from the following operating unit; a distal-most operating unit configured to input the target bending angle of the distal-most bending section into the computing unit on a basis of an input by an operator into a distal-most operation input unit; and a distal-most switching unit configured to switch a means for inputting the target bending angle of the distal-most bending section into the computing unit, wherein the computing unit computes a drive displacement by which the driving unit drives the wire in the distal-most bending section on a basis of the target bending angle of the distal-most bending section selected by the distal-most switching unit, wherein the distal-most switching unit executes switching processing to switch between inputting the target bending angle of the distal-most bending section into the computing unit from the distal-most operating unit and inputting the target bending angle of the distal-most bending section into the computing unit from the distal-most computing unit, and wherein the distal-most switching unit executes the switching processing to input the target bending angle of the distal-most bending section into the computing unit from the distal-most operating unit in a case where the input into the following operation input unit does not exist, and to input the target bending angle of the distal-most bending section into the computing unit from the distal-most computing unit in a case where the input into the following operation input unit exists.

4. The continuum robot control system according to claim 1, wherein the following bending section includes a first following bending section and a second following bending section located between the first following bending section and the distal-most bending section, the following operating unit includes a first following operating unit and a second following operating unit, the first following operating unit being configured to input a target bending angle of the first following bending section into the computing unit on a basis of an input by the operator into the first following operation input unit, the second following operating unit being configured to input a target bending angle of the second following bending section into the computing unit on a basis of an input by the operator into the second following operation input unit; and a gain control unit configured to multiply, with a control gain, the target bending angle of the second following bending section inputted by the second following operating unit into the computing unit, wherein the switching processing is processing that the following switching unit performs switching such that the target bending angle of the second following bending section is inputted into the computing unit from the following computing unit in a case where the input into the second following operation input unit does not exist, and such that the target bending angle of the second following bending section is inputted into the computing unit from the second following operating unit in a case where the input into the second following operation input unit exists, and wherein, in the switching processing, when performing switching to input the target bending angle of the second following bending section into the computing unit from the second following operating unit, the following switching unit performs switching to select, as the target bending angle of the first following bending section, the target bending angle of the second following bending section multiplied with the control gain by the gain control unit.

5. The continuum robot control system according to claim 1, further comprising: a storage unit configured to store the target bending angle of the distal-most bending section; a base determining unit configured to determine whether the base is moving forward or backward on a basis of the displacement of the base; a distal-most operating unit configured to input the target bending angle of the distal-most bending section into the computing unit on a basis of an input by the operator into the distal-most operation input unit; and a distal-most switching unit configured to switch a means for inputting the target bending angle of the distal-most bending section into the computing unit, wherein the distal-most switching unit inputs the target bending angle of the distal-most bending section into the computing unit from the distal-most operating unit in a case where the base determining unit determines that the base is moving forward, and inputs the target bending angle of the distal-most bending section stored in the storage unit into the computing unit in a case where the base determining unit determines that the base is moving backward, and wherein the computing unit computes a drive displacement by which the driving unit drives the wire in the distal-most bending section on a basis of the inputted target bending angle of the distal-most bending section.

6. The continuum robot control system according to claim 1, further comprising: a distal-most operating unit configured to input the target bending angle of the distal-most bending section into the computing unit on a basis of an input by the operator into the distal-most operation input unit; the following computing unit computes the target bending angle of the following bending section by using the target bending angle of the distal-most bending section obtained from the distal-most operating unit.

7. A control method for controlling a continuum robot, the continuum robot comprising: a driving unit configured to drive a wire, a bendable portion having a plurality of bending sections bent by being driven by the wire, a base configured to support the bendable portion, wherein the plurality of bending sections includes a distal-most bending section located farthest from the base, and a following bending section located between the distal-most bending section and the base, a following computing unit configured to compute a target bending angle of the following bending section on a basis of a target bending angle of the distal-most bending section and on a basis of a displacement of the base in a direction of movement of the continuum robot, and inputs a computation result into a computing unit configured to compute a drive displacement by which the driving unit drives the wire in the following bending section, and a following operating unit configured to input the target bending angle of the following bending section into the computing unit on a basis of an input by an operator into a following operation input unit, the control method comprising: switching a means for inputting the target bending angle of the following bending section into the computing unit to the following computing unit and to the following operating unit; and computing a drive displacement by which the driving unit drives the wire in the following bending section on a basis of the target bending angle of the following bending section inputted by the means to which the switching is performed.

8. A non-transitory computer-readable storage medium storing a program, the program causing a computer to execute controlling of a continuum robot, the continuum robot comprising: a driving unit configured to drive a wire, a bendable portion having a plurality of bending sections bent by being driven by the wire, a base configured to support the bendable portion, wherein the plurality of bending sections includes a distal-most bending section located farthest from the base, and a following bending section located between the distal-most bending section and the base; a following computing unit configured to compute a target bending angle of the following bending section on a basis of a target bending angle of the distal-most bending section and on a basis of a displacement of the base in a direction of movement of the continuum robot, and inputs a computation result into a computing unit configured to compute a drive displacement by which the driving unit drives the wire in the following bending section, and a following operating unit configured to input the target bending angle of the following bending section into the computing unit on a basis of an input by an operator into a following operation input unit, wherein the program causes the computer to execute: switching a means for inputting the target bending angle of the following bending section into the computing unit to the following computing unit and to the following operating unit; and computing a drive displacement by which the driving unit drives the wire in the following bending section on a basis of the target bending angle of the following bending section inputted in the switching.