



(51) International Patent Classification:

B25J 9/06 (2006.01)

B63G 8/14 (2006.01)

Institute of Technology Madras, IIT P.O., Chennai 600036 (IN).

(21) International Application Number:

PCT/IN2018/050655

(72) Inventors: THONDIYATH, Asokan; Robotics Laboratory,

Dept. of Engineering Design, Indian Institute of Technology Madras, Chennai 600036 (IN). RANGANATHAN, Thiagarajan; Robotics Laboratory, Dept. of Engineering Design, Indian Institute of Technology Madras, Chennai 600036 (IN).

(22) International Filing Date:

12 October 2018 (12.10.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(74) Agent: VENKATARAMAN, Shankar; Maxval-IP Ventures India (P) LTD., 3 Floor, G 3/6 Phase II, IITM Research Park, Kaanagam Road, Taramani, Chennai 600 113 (IN).

(30) Priority Data:

201741036333 12 October 2017 (12.10.2017) IN

201741036720 16 October 2017 (16.10.2017) IN

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,

(71) Applicant: INDIAN INSTITUTE OF TECHNOLOGY MADRAS (IIT MADRAS) [IN/IN]; Dean, ICSR, Indian

(54) Title: VARIABLE BUOYANCY ELEMENTS AND UNDERWATER DEVICES INCORPORATED THEREWITH

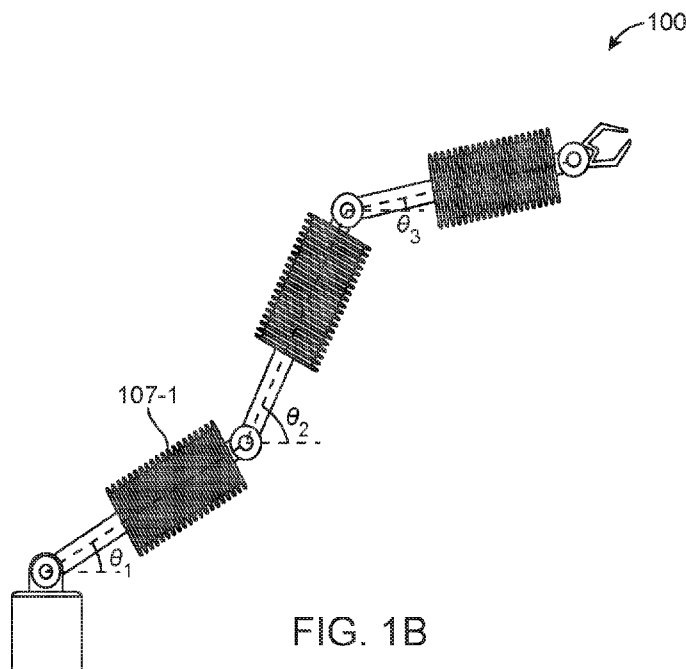


FIG. 1B

(57) Abstract: The invention relates to variable buoyancy (VB) element and underwater manipulators and glider devices based thereon. The VB element includes an axially elongatable cylinder, which when actuated by a linear actuator, causes motion of the cylinder in an upward or downward direction. The cylinder may include a sealed airtight bellows that acts as hull. The underwater manipulator is a flexible elongated structure which is anchored at one end and having an end effector at the other. The flexible structure includes a plurality of arms connected by pin joints, each arm including a rigid link and a VB element. A glider incorporating a winged VB element with one or more linear actuators is disclosed. The glider is configured to provide, surge, heave or pitch motions by changing volume and orientation of the VB element. Methods of operating the manipulator or glider are further disclosed.

HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*
 — *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

**VARIABLE BUOYANCY ELEMENTS AND UNDERWATER DEVICES
INCORPORATED THEREWITH**

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application takes priority to Indian patent application nos. 201741036333 entitled UNDERWATER GLIDER WITH FLEXIBLE CHAMBER FOR VARIABLE BUOYANCY filed on October 12, 2017 and 201741036720 entitled UNDERWATER MANIPULATOR USING VARIABLE BUOYANCY ACTUATORS filed on October 16, 2017.

FIELD OF THE INVENTION

[0002] The present invention generally relates to underwater robots. Specifically, the invention relates to manipulators or underwater vehicles based on variable buoyancy mechanism.

DESCRIPTION OF THE RELATED ART

[0003] In the recent past, underwater robots are being employed for various operations at higher depths, where human reach is impossible. The applications range from search and rescue, inspection and deployment of pipes and underwater structures, sampling of the ocean and its resources, etc. Some of these applications require manipulation and the present day underwater remotely operated vehicles are equipped with manipulators. Such manipulators have to be designed with specific considerations like the depth of operation, water sealing etc. The manipulators attached to the robots will have multiple rigid arms with a specific configuration based on the application. For some applications, planar manipulators (with respect to the robot) are sufficient to accomplish a task. Manipulators usually have serially linked rigid arms with each arm individually actuated using electric or hydraulic motors. Sealing of motors to operate at higher depths is a challenging task and the system becomes bulkier.

[0004] Variable buoyancy systems are common subsystems in underwater vehicles which are proven to be power efficient for their motion along heave (up and down) direction.

Variable buoyancy is achieved either by changing the overall volume of the system without change in mass or by change of mass without any change in volume. When the system is heavier compared to the buoyancy contributed from its volume, it sinks and if the buoyancy force is more than the weight, the system starts to move upwards. By controlling either mass or volume of the system, motion of the system along heave can be controlled and thereby any depth can be achieved. Different methods of variable buoyancy are available in literature and are commonly used in underwater robots.

[0005] The US patent US8317555B2 discloses an amphibious robotic crawler having two frame units coupled end-to-end or in tandem by an actuated linkage arm, a control module and a buoyancy control element, however, the unit requires high power to operate as the structure is not neutrally buoyant. The US patent US3165899A relates to an underwater manipulator attached to a storage tank or similar vessel positioned on the ocean floor at enormous depths below the surface of the ocean. The interior of the manipulator device in '899 patent acts as an air chamber tending to float the device, and the buoyancy of the chamber is altered as desired by admitting water into it. The US application US20180021945A1 proposes a "snake-like" underwater robot with a plurality of links that can be filled with pressurized air or alternatively any "bladder" or fluid that can be compressed or expanded. The '945 patent also includes thrust devices.

[0006] A submarine boat incorporating bellows for variable buoyancy is disclosed in US3943869. However, the device requires a separate hull and power source external to the bellows structure.

[0007] While in most of the existing underwater vehicles, variable buoyancy system/engine is an integral part designed along with other subsystems, they can also be designed as standalone modules which can be used to have motion along heave (up and down) direction. Any method of variable buoyancy can be used to design a standalone variable buoyancy module.

SUMMARY OF THE INVENTION

[0008] The invention in its various embodiments discloses an underwater manipulator having a flexible structure anchored at one end and rotatable 360° about the anchor point with an end effector at the other end. The flexible structure includes a plurality of arms connected at pin joints, with each arm configured to rotate within a plane to a predetermined angle. Each arm of the manipulator has a rigid link and an axially flexible, elongatable cylindrical unit which forms at least a portion of the length of the arm, where the cylindrical units are configured to vary buoyancy of the arm to cause a moment that results in motion of the arm in upward or downward direction. The manipulator is configured to place the end effector at a 3-dimensional location within a predetermined radius of the elongated flexible structure.

[0009] In some embodiments the pin joint is configured to restrict rotation of the arm to an angle of rotation Θ which ranges between 0° to 90°. The elongatable cylindrical unit encloses a linear actuator assembly configured to expand and compress the flexible unit and includes a linear actuator with a linear actuator piston operated using hydraulic or electric means. The manipulator may operate as a standalone, anchored at one end to the sea floor by a base unit, or as an add-on to any autonomous underwater vehicle (AUV). In one embodiment the manipulator arms are of varying sizes with elongatable cylindrical units of capacity based on size of arm and with the biggest link placed closest to the anchor point. Also each arm is configured to be neutrally buoyant to reduce the load on the preceding arms. The actuator assembly is driven by a power source which is placed within the cylindrical unit or it may be placed externally.

[0010] In certain embodiments the moment caused due to the actuation of the elongatable cylindrical unit is either positive or negative based on the position of the center of buoyancy (CoB) with respect to the center of gravity (CoG) along the axis of the manipulator. In one embodiment an encoder is used, to provide feedback including angle of orientation of each link and the depth at which the cylindrical unit is placed.

[0011] In various embodiments, the invention discloses a method of manipulating the underwater manipulator which includes changing the position of the arm from the current angle of orientation to desired effector position by traversing azimuthally through an angle of

rotation Θ defined between the base and the axis of the manipulator arm. The method achieves the change in position of the arm by elongating the cylindrical unit axially to create a moment when buoyancy (B) of the rigid arm acting through the CoB is greater than the weight (W) acting through CoG, causing an upward motion of rigid arm or by compressing the cylindrical unit to create a moment when the weight (W) of the rigid arm acting through the CoG is greater than the buoyancy (B) acting through CoB, causing a downward motion of rigid arm. Once the arm becomes perpendicular to the base i.e., Θ is 90° , the CoG is offset around the axis of link by rotating the actuator for the arm to traverse from 90° to 180° , since the maximum range of Θ is restricted to 90° .

[0012] The invention disclosed here in its various embodiments discloses a novel underwater glider device and methods of operation and control for efficient gliding underwater using variable buoyancy mechanism based on change of volume of the device. In some embodiments the underwater glider includes a flexible, elongatable cylindrical structure with a pair of wing structures affixed to its body to enable gliding underwater and an electric linear actuator assembly configured to elongate or contract the cylindrical structure enclosed in the bellows assembly, where the actuator assembly is configured to cause separation of a center of gravity (CoG) with reference to a center of buoyancy (CoB) of the structure, thereby providing, surge, heave or pitch motions to the structure. The elongatable cylindrical structure has a bellows assembly, which further includes a flexible hollow cylindrical metallic bellows for at least a portion of the structure, and bellows sealing arrangements at the bellows terminal ends, wherein the bellows sealing arrangement comprises a flange with lock heads and a bellows sealing plate.

[0013] In one embodiment the elongatable cylindrical structure contains a bellows assembly of predetermined lengths near the ends thereof with a middle portion having a hollow cylindrical profile. In another embodiment the bellows assembly is of a predetermined length near a middle portion thereof, the end portions having a hollow cylindrical profile. In yet another embodiment bellows assembly of a predetermined length covering a portion of the length from one end thereof. In some embodiments the electric linear actuator assembly enclosed in the bellows assembly, includes at least two linear actuators coupled with a

connector placed at a middle portion of the structure, wherein each linear actuator has an actuator motor and a piston and wherein the linear actuators are operable independently to position the CoB with reference to the CoG to cause surge, heave or pitch motion to the structure. The bellows assembly further includes, a power source, electrical and electronic components and payload sensors. The wing assembly affixed to the structure includes a pair of rigid wing plates attached to the bellows. The glider device further includes a nose portion and a tail portion configured to minimize hydrodynamic drag on the structure. In a certain embodiment the tail portion is provided with thrusters and a rudder for improved speed and range.

[0014] In some embodiments the method of controlling the underwater glider having a flexible, elongatable cylindrical structure, an electric linear actuator assembly configured to elongate or contract the cylindrical structure to vary its centre of buoyancy (CoB) with reference to its center of gravity (CoG), a wing assembly, nose and tail structures, the tail comprising a thruster along with rudder is provided. The method in one embodiment includes contracting one or more of the linear actuators to cause the CoB to rise above the CoG, thereby causing downward motion in the (z) direction. In another embodiment The method expands one or more of the linear actuators to cause the CoB to fall below the CoG to cause an upward motion in the (z) direction. The differentially expanding or contracting of the linear actuators in tandem to cause either forward or backward tilt of the structure about a y directional axis; and operating the thruster with rudder to cause a lateral yawing motion of the glider wherein the method causes the glider to follow a predetermined trajectory in the x (longitudinal), y (lateral) or z (depth) directions.

[0015] In various embodiments the method of operating the glider underwater involves changing the pitch motion or by adjusting the position of wing structures or both. In one embodiment the method changes the pitch by causing a shift in the CoB to rise above or fall below the CoG along the (z) direction thereby creating a moment along (y) direction, which is used along with the drag of the wing structures to vector the residual buoyancy (b) to achieve surge (horizontal motion). In another embodiment the method adjusts the position of wing structures to create a moment, which in combination with the contraction of the

bellows, vectors the residual buoyancy (b) to achieve surge (horizontal motion). Both the methods of operating the underwater glider cause the glider to follow a predetermined trajectory in the x (longitudinal), y (lateral) or z (depth) directions.

[0016] This and other aspects are disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawings, in which:

[0019] FIG. 1A shows underwater manipulator configuration.

[0020] FIG. 1B shows a three link manipulator actuated by variable buoyancy modules based on axially flexible metallic bellows.

[0021] FIG. 1C shows an axially flexible metallic bellows with details of linear actuator assembly.

[0022] FIG. 2A shows a single link manipulator at an intermediate joint angle.

[0023] FIG. 2B shows a single link manipulator at singular position.

[0024] FIG. 3 illustrates the stages involved in manipulation of a single link manipulator.

[0025] FIG. 3A shows the initial position of link where $\Theta = 0^\circ$.

[0026] FIG. 3B shows the singular position of link where $\Theta = 90^\circ$.

[0027] FIG. 3C depicts the changed location of CoG around the axis of link.

[0028] FIG. 3D shows the final position of link where $\Theta = 180^\circ$.

[0029] FIG. 4 flowchart showing methodology of manipulation of underwater manipulator.

[0030] FIG. 5A shows the neutrally buoyant underwater glider.

[0031] FIG. 5B shows exploded view of neutrally buoyant underwater glider.

[0032] FIG. 5C illustrates the electric linear actuator assembly.

[0033] FIG. 5D illustrates the bellows assembly.

[0034] FIG. 5E shows the bellows sealing arrangement.

[0035] FIG. 5F illustrates the wing assembly.

[0036] FIG. 6A-6C depict alternative embodiments of bellows assembly.

[0037] FIG. 7 represents a hybrid glider with tail thruster.

- [0038] FIG. 8 delineates the methodology of controlling a neutrally buoyant underwater glider using change of volume based variable buoyancy mechanism.
- [0039] FIG. 9A depicts glider body co-ordinate frame.
- [0040] FIG. 9B shows the location of CoG and CoB in the glider body.
- [0041] FIG. 10A-10F illustrates the shift in CoG and CoB based on expansion and compression of bellows and the resulting dive action.
- [0042] FIG. 11: Schematic of dive path of glider.
- [0043] FIG. 12A shows the joint angle control architecture.
- [0044] FIG. 12B shows the response time results of joint angle control manipulation.
- [0045] FIG. 13 illustrates an AUV with the proposed manipulator.
- [0046] FIG. 14A-14F: Simulation results of prototype glider.
- [0047] FIG. 15: Mechatronic architecture of prototype.
- [0048] Referring to the figures, like numbers refer to like parts throughout this specification.

DETAILED DESCRIPTION

[0049] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material to the teachings of the invention without departing from its scope.

[0050] Throughout the specification and claims, the following terms take the meanings explicitly associated herein unless the context clearly dictates otherwise. The meaning of "a", "an", and "the" include plural references. The meaning of "in" includes "in" and "on." Referring to the drawings, like numbers indicate like parts throughout the views. Additionally, a reference to the singular includes a reference to the plural unless otherwise stated or inconsistent with the disclosure herein.

[0051] The invention in its various embodiments relates to an underwater manipulator configuration and a method of manipulation based on variable buoyancy (VB) technique. The underwater manipulator is equipped with serially linked multiple rigid arms of different sizes with each arm individually controlled using a variable buoyancy element of respective capacity, actuated using a linear actuator assembly and operated by hydraulic or electric means. The moment caused due to the actuation of the variable buoyancy element is either positive or negative based on the offset of the center of buoyancy (CoB) with respect to the center of gravity (CoG) along the axis of the manipulator and results in motion of the arm in heave direction (upward or downward).

[0052] The invention in its various embodiments further relates to an underwater glider device and control method that uses change of volume based variable buoyancy using a flexible chamber actuated by a linear actuator. The actuation causes separation of the center of gravity (CoG) with reference to a center of buoyancy (CoB) of the glider structure, thereby providing, surge, heave or pitch motions to the structure. The glider disclosed is neutrally buoyant by design.

[0053] In several embodiments the invention proposes an underwater manipulator **100**, which is an elongated structure having multiple arms **101-1,2..n**, that are serially linked, with each arm individually controlled by a variable buoyancy element **103-1..n** and a rigid link **102-1...n** forming the remaining part of the arm, as shown in FIGs. 1A and 1B. The manipulator **100** may have a suitable end effector **105** at the end thereof. In some embodiments the arms **101-1,2..n** may be of varying sizes with variable buoyancy elements **103-1..n** having capacity corresponding to the size of the arm. In various embodiments variable buoyancy elements **103-1..n** are configured with flexible bellows **107-1...n** that are actuated using a linear actuator assembly **110-1...n** enclosed within it, as shown in FIG. 1C, to achieve a particular end effector position. The actuator assembly further comprises a linear actuator **112** with a linear actuator piston **114** operated using hydraulic or electric means. A gripper **105** is attached to the end of the last rigid arm link. Two adjacent links are coupled using a passive joint (J) **104-1...n** configured to enable rotation of arm at an angle of rotation Θ which ranges between 0° to 90° .

[0054] In various embodiments the manipulator **100** either operates as a standalone unit to perform a particular task or as an add-on to any autonomous underwater vehicle (AUV), platform or other structure. In one embodiment where manipulator **100** is used in a standalone configuration as shown in FIG.1A, the first arm from the bottom is hinged to a base unit **106** which may be anchored to the bed. The number of links in various embodiments is based on the type of application. In one embodiment the variable buoyancy elements **103-1..n** are attached to the top end of each of the arms **101-1,2..n**. In some embodiments the arms **101-1,2..n** along with the elements **103-1..n** are configured to be neutrally buoyant in order to reduce the load on the lower links. In various embodiments the length and size of the arms **101-1,2..n** may vary and capacity of the buoyancy element **103-1..n** may be configured to match the size of the arms. In some embodiments the arms **101-1,2..n** near the base may be configured to be of a bigger diameter or have larger sized bellows **107-1...n**. The power source to operate the linear actuator assembly **110-1...n** may in various embodiments be placed inside the element itself or may be provided externally.

[0055] In some embodiments each module of the linear actuator assembly **110-1...n** may have at least one linear actuator piston **114**, to expand or compress the metallic bellows **107-1**, as shown in FIG. 1C, which provides the internal view of the variable buoyancy element **103** in section through the bellows **107**. Actuating the bellows i.e. expanding or compressing the bellows is accomplished using the piston **114** to attain the required residual buoyancy. Based on the direction of residual buoyancy, the arm **101** is configured to move either upwards or downwards. The flexible metallic bellows **107-1** is sealed water-tight on both ends using sealing plates **118**. The linear actuator piston **114** is operated using an electric motor **116** or by hydraulic means. The arm may further include an axially mounted motor **117** to rotate the variable buoyancy element **103** by up to 180° in order to adjust directionality of movement of the element.

[0056] FIGs. 2A and 2B show two different positions of a single link manipulator after actuation of the VB element. The right handed co-ordinate frames are appropriately associated at the base and the joint to derive the kinematics and dynamics. The forces on the arm module and their point of action are also shown. Weight (W) and the buoyancy (B) are acting through CoG and CoB respectively. The CoG and CoB always act opposite to each other and the magnitude of B is a function of the length of expansion of bellows.

[0057] In one embodiment the CoB is the volumetric center of the rigid arm module **101** and it is aligned to the axis of rigid link **102**. In some embodiments the CoG of the arm **101** is offset from the axis thereof, because of the mechanical construction of the module. In some embodiments the CoB or CoG are configured to be offset from the axis of the arm **101**. When the module is neutrally buoyant, the link is configured to stay still. When the element **103** is positively buoyant, it creates a moment at joint J_1 , resulting in upward movement of the link. Whenever the module is brought back to neutrally buoyant condition, the motion gradually subsides. In the singular position of the manipulator where θ_1 is 90° the buoyancy force is configured to align with the axis of the manipulator. When the module is actuated to become negatively buoyant, weight acting through the CoG will be more than B and hence there will be a moment along the line connecting CoG and joint J_1 which will result in a

downwards movement of the link. Hence the maximum range of θ_1 in this configuration is between 0° and 90° as shown in FIG. 2B. The CoG is configured to be offset from the axis of the link to ensure that once the module reaches singularity at the topmost position, the residual buoyancy creates a moment to exit the singular position. In some embodiments of the method the location of CoG is modified in order to increase the range of motion up to 180° . In some embodiments the location of CoG is modified using axial rotation of the linear actuator **112** using motor **117** by up to 180° to shift this location from one side of the axis of the link to another.

[0058] The methodology of manipulation of the single link manipulator, is shown in FIG. 4 corresponding to positions as illustrated in FIG. 3A-3D, from $\theta_1 = 0^\circ$ to 180° and back to 0° is as follows:

1. In step **421**, initial link position is at horizontal with $\theta_1=0^\circ$, shown in FIG. 3A
2. In step **422**, the cylindrical module is elongated axially to become positively buoyant ($B>W$) resulting in upward motion of the rigid arm
3. Upward motion continues until the arm reaches singular position in step **423**, and $\theta_1=90^\circ$, as shown in FIG. 3B
4. In step **424**, location of CoG of the link is brought to the other side by turning the link by 180° using motor **117**, as shown in FIG. 3C
5. In the next step **425**, the module is compressed to become negatively buoyant ($B<W$) resulting in downward motion and reach 180° position, as shown in FIG. 3C and attain 180° position (step **426**)

In some embodiments the steps involved in the method of manipulation **400** of the underwater manipulator discussed above, may be repeated as required. In other embodiments, the method **400** may be followed with other variable buoyancy methods with appropriate mechanisms of shifting the CoG.

[0059] In some embodiments, the invention includes a control strategy to position the manipulator at the required joint angle. The control method allows the link to reach

intermediate joint angle between 0° and 180° . This may be achieved by precisely controlling the buoyancy force based on the feedback either from the joint encoder or from the depth at which the module is placed.

[0060] The architecture of the proposed underwater manipulator is suited for implementing various other techniques of variable buoyancy. Especially at higher depths, hydraulic variable buoyancy modules are used to handle high pressure. If the manipulator is attached to any existing underwater vehicle, the hydraulics in the vehicle itself can be extended to be used for this application with fewer modifications. In conventional manipulators the operation at higher depths is limited by the rotary actuators. Waterproofing and sealing the motors to withstand the hydrodynamic pressure at greater depths is challenging. The actuators with pressure casings are exposed to the environment and it requires frequent maintenance and servicing. The actuator proposed in this invention is completely concealed and the essential components for VB are packed inside a water sealed module. This allows the manipulators to be used at higher depths.

[0061] In several embodiments an underwater glider device **1500** as illustrated in FIG. 5A-5F, is disclosed. The device (FIG. 5A) includes a cylindrical hull structure **1530** incorporating a bellows assembly **1531** (FIG. 5D), electric linear actuator assembly **1510** (FIG. 5C) and wing assembly **1540** (FIG. 5F). The exploded view of the novel glider in FIG. 5B depicts its major parts. The bellows assembly **1531**, as shown in FIGs. 5C, 5D, includes a flexible hollow cylindrical metallic bellows **1507** for at least a portion of the structure, and bellows sealing arrangements **1533** at the bellows terminal ends, wherein the bellows sealing arrangement includes a flange **1534** with lock heads **1535-1,2...n** and a bellows sealing plate **1518**. The bellows is configured with crests and troughs for enabling flexibility as shown FIG. 5D.

[0062] The bellows could be of any corrosion resistant material with suitable mechanical properties for providing a controllable volume capable of withstanding pressure of the surrounding fluid. Such materials may include various grades of stainless steel, nickel

or cobalt-containing alloys. Metallic bellows may be made of sheet metal of suitable thickness and may either be welded or hydroformed to provide pressure-resistance and flexibility. The sheet metal thickness and configuration of bellows may be decided based on maximum expansion/compression required and the elastic properties of the material.

[0063] In some embodiments the wing assembly **1540** is attached to the bellows, with the wings **1541-1,2** on either sides of the bellows structure. In various embodiments the wing may be flat or of airfoil shape. The wings in some embodiments are attached to the bellows by means of a detachable attachment hoop **1542** coupled to the wings using a connector plate **1543**. The wing assembly is shown in FIG.5F. Alternative embodiments of the wing assembly may use hinged semicircular hoops. Wings are attached at a fixed angle. The hoop in some embodiments is configured to fit into the undulations of the bellows. The position of the wing assembly in various embodiments is configured to be adjustable with respect to the body frame based on performance optimization. In some embodiments the wing assembly is easily detachable. Based on the application, the wing position may be easily changed. Since the wing assembly is attached with the flexible hull directly, the position of the wings with respect to the body frame may change as a function of overall length of the chamber.

[0064] A partially rigid hull may in some embodiments be used if the continuous shift in the position of wing is undesirable. In some embodiments, the position of the wing is not symmetric and is placed towards the rear/tail end of the glider. This results in a shift in the location of CoG which may be compensated in some embodiments by adding a dead mass or by increasing thickness of front bellows sealing plate.

[0065] In certain embodiments the electric linear actuator (LA) assembly **1510**, includes two linear actuators **1512-1,2** connected back to back using a rigid LA coupling **1546**, LA motors **1516-1,2** and LA pistons **1514-1,2** as shown in FIG. 5C. The LA assembly expands or compresses the cylindrical hull structure axially. This actuation causes separation of a center of gravity (CoG) with reference to a center of buoyancy (CoB) of the structure, thereby providing, surge, heave or pitch motions to the structure. The piston end of the linear

actuator is connected to the LA piston coupling **1548** which in turn is connected to the flange **1534** using flange outfit **1549**, flange connector plate **1550**. The hull is completely water sealed on both sides using bellows sealing arrangements as shown in the exploded view in FIG. 5E. The bellows sealing plate and the flange have appropriate grooves **1551** to accommodate an O-ring **1552** to make the bellows assembly water tight. The bellows sealing plate is a circular plate with lock heads and provisions for payload sensors. The provisions for mounting the payloads may be a simple hole or special couplings based on the mounting requirements of the sensor. Lock heads **1535-1,2..n** are welded equispaced along the circumference of the flange and bellows sealing plate through which, fasteners will be used to lock the hull water tight. While locking the hull at atmospheric pressure, the LAs should be expanded to half the maximum stroke, which will make the glider neutrally buoyant. The bellows assembly further encloses a power source, and electrical and electronic components required for operation of glider device.

[0066] The linear actuator in various embodiments may be electric, pneumatic or hydraulically actuated. The choice of linear actuator may in some embodiments depend upon the maximum depth of operation, stroke required and the scale of the glider. Electric linear actuators may include a motor, gear and screw mechanism and a piston in some embodiments. Embodiments of the electric linear actuators are optimal for shallow water applications. Ideally, single linear actuator is sufficient for the glider to work but some embodiments may involve proper weight balancing in order to maintain the alignment of CoG and CoB. In order to maintain symmetry and to maximize the limits of expansion and compression, two similar linear actuators may be used in some embodiments.

[0067] Nose **1560** and tail **1570** structures are attached to the hull to reduce the drag effects in some embodiments. The nose and tail are also concealed structures along with the hull. They can house payload sensors or cameras. The connector end of nose and tail has equispaced lock heads using which they can be fastened to the hull.

[0068] Some embodiments of hulls of the inventive device are shown in FIG. 6A-6C. The hull may be partially rigid and partially flexible depending upon the number of linear actuators used or the level of expansion/compression required, as illustrated in the embodiments of FIG. 6A-6C. The embodiments having a partially rigid hull may provide an advantage of firmly connecting the linear actuator at the middle of the hull to a rigid portion. In such embodiments, the rigid part of the hull may have suitable provisions to hold the linear actuator and the other subsystems. In embodiments of the device where the hull is completely flexible, the linear actuators are connected to the ends of the bellows which may result in sagging of bellows, even for a very small imperfection in the connection. Also, the electronics and payloads may be supported entirely on the linear actuator. In some embodiments, a guiding mechanism using telescopic rods/cylinders may be used in order to avoid sagging effect. In some embodiments an external telescopic enclosure may be provided around the bellows in other embodiments, to smoothen the hydrodynamic profile around the hull.

[0069] In some embodiments of the device, a hybrid glider **1600** based on the concept illustrated in FIG. 5A is proposed in FIG. 7. In addition to the major parts of the glider, thrusters **1653** may be included at the rear end of the glider as shown in FIG. 7. Proper ducting for the flow of water through the inlet and outlet of the thruster is provided. Multiple thrusters along the sides of the hull may also be provided in alternative embodiments. The advantage of the hybrid device embodiments is the improved speed and range of the device. The size of the wings may be comparatively smaller than the ones discussed earlier. In some embodiments, an actuated wing may be incorporated with a suitable mechanism to improve the gliding performance.

[0070] In various embodiments the method of controlling the underwater glider device includes achieving the three degrees of freedom i.e., surge, heave, and pitch. The flowchart in FIG. 8 represents the methodology of control **1700**. By design, CoG is below the CoB which ensures roll stability. The right handed co-ordinate frame assumed on the glider and the location of CoG and CoB with respect to the body centered co-ordinate frame is shown in

FIGs. 9A and 9B respectively. The glider is initially designed to be neutrally buoyant. When the bellows is compressed by retracting the linear actuators, the glider becomes negatively buoyant and starts to sink (heave). Similarly when the bellows is expanded, the glider becomes positively buoyant and starts to surface. The shift in CoG and CoB based on expansion and compression of bellows and the resulting dive action are illustrated in FIG. 10A-10F, where FIGs. 10A-10C depict sinking during bellows compression and FIGs. 10D-10F depict rising during bellows expansion. In both the cases the weight remains same. Now, the pitch degree of freedom, which is rotation about Y axis, is to be achieved in order to vector the residual buoyancy.

[0071] In one embodiment the method achieves the pitch using the restoring moment created due to the misalignment of CoG and CoB along Z axis. CoB in the glider device is approximately the volumetric center of the hull along the X axis of the body frame, based on the length of bellows as shown in FIG. 9B. There is a shift in the location of CoG also, but insignificant compared to the change in location of CoB. In some embodiments shifting of CoG and CoB along Z axis of body frame creates a moment along Y axis is configured to result in pitch. The wing structure, along with the pitch, in various embodiments is configured to vector the residual buoyancy, resulting in surge motion. In one embodiment only one linear actuator is sufficient to provide glide motion. In some embodiments the position of the wing assembly is at the center of the hull.

[0072] In another embodiment the method may rely on the position of wing to provide gliding motion. In one embodiment the wings are placed at the rear end of the glider. In this embodiment two linear actuators **1512-1,2** are used, and when the actuation is configured to be symmetric, there will not be any shift in the location of CoB. In this embodiment, since the wings are towards the rear end of the glider, the drag on the wings is configured to create a pitch and thus the residual buoyancy force caused due to compression of bellows is vectored along X axis, resulting in surge motion. Similarly, by expanding the linear actuators, the glider may be made positively buoyant, thereby diving up. In some embodiments, dissimilar motion of the linear actuator is configured to result in additional pitch. In some embodiments

the additional pitch may be constructively used to improve the gliding performance. In various embodiments, by controlling the level of expansion or compression of the LAs, an effective gliding performance of the glider may be achieved. A schematic of the path traced by the glider is shown in FIG. 11. It is to be noted that the residual buoyant force exists even after the termination of actuation (after maximum expansion/compression) of the metallic bellows. Hence the glider does not consume power to continue its current dive action. Only to change the direction of dive, the bellows needs to be actuated again in the reverse direction.

[0073] In the proposed invention the glider device uses linear actuators to actuate the flexible chamber and the bellows is locked at atmospheric pressure, filled with air. Hence the motion dynamics is purely dependent on the expansion/compression of the bellows. Also, the chamber by itself acts as a hull. Hence the glider device is simple in construction and uses fewer components compared to the conventional gliders.

[0074] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material the teachings of the invention without departing from its scope. Further, the examples to follow are not to be construed as limiting the scope of the invention which will be as delineated in the claims appended hereto.

[0075] EXAMPLES

[0076] Example 1: One embodiment architecture of implementation of control for such manipulators is shown in FIG. 12A. A PID control strategy has been implemented to the single link manipulator with feedback from both joint encoder and depth. The comparison of the control performances is shown in FIG. 12B. The results presented in FIG. 12B shows that the joint angle control may be implemented by controlling each joint angle precisely using the VB element of each rigid arm.

[0077] **Example 2:** The manipulator may also in some embodiments be used with other underwater vehicles. One such possible schematic of an AUV with the proposed manipulator is shown in FIG. 13. The necessary power and communications for the manipulator may be provided from AUV through appropriate cables and connectors. In some embodiments, out of the plane motion of the manipulator is also possible using suitable mechanism in the AUV.

[0078] **Example 3:** Simulation results of underwater glider: Numerical simulations were carried out in MATLAB Simulink at different input conditions. The dimensions of the fuselage of the glider which is the hull along with the nose and the tail, are optimally chosen to make the system neutrally buoyant. The dimensions of wings are decided in a way to maximize the lift to drag ratio. The design variables used in this maximization problem are σ_s and d . CFD based simulations are carried out with the optimized dimensions to estimate the added mass and drag parameters of the fuselage. Initially, few simulations were conducted to test the motion of the fuselage alone without the wings, to understand the behavior of the system in heave direction. The shift in the location of CoG and CoB helps in roll stability. Later the wing dynamics were also included in the model for simulation studies.

[0079] The results of one of the cases of simulation for the whole system is presented in Figure 14A-14F. A pulsed input voltage is given to the system and the corresponding change in the residual buoyancy is shown. The maximum residual buoyancy of the system is +/-19 N. The path traced by the glider in XZ plane is shown in Figure 14B and the corresponding variation in the angle of attack, pitch, and the velocities in body frame is also shown. Multiple such simulations were carried out at different gliding conditions and the results proved the ability of the system to be able to glide underwater.

[0080] **Example 4:** Experimental prototype underwater glider: The overall mechatronic architecture of the system is shown in Figure 15. The electronic subsystem comprises user console and the glider console. Commands to the linear actuator and the parameter adjustments can be made from the GUI in the PC. The data and power communications between the user and glider consoles happen through a tether. The glider is equipped with an

accelerometer to measure accelerations along surge and heave axis along with pitch measurement. The depth is measured using a pressure sensor and another pressure sensor is used inside the chamber to estimate the overall level of expansion/compression. The information from all these sensors is gathered using a microcontroller and sent to the user console. The linear actuators are controlled using individual motor drivers and the rate of buoyancy change can be controlled using pulse width modulated signals from the microcontroller. The experimental prototype was successfully tested for diving with open loop commands from the user. The performance of the glider was found to be suitable for shallow water applications.

WE CLAIM:

1. An underwater manipulator (100) comprising:

at least one elongated flexible structure anchored at one end and rotatable 360° about the anchor point and having an end effector (105) at the other end, the flexible structure comprising a plurality of arms (101-1,2...n) connected at pin joints (104-1,2...n), each arm configured to rotate within a plane to a predetermined angle, wherein each arm comprises:

a rigid link (102-1); and

an axially flexible, elongatable cylindrical unit (107-1) forming at least a portion of the length of the arm, the cylindrical units configured to vary buoyancy of the arm to cause a moment that results in motion of the arm in upward or downward direction, and, wherein the manipulator is configured to place the end effector at a 3-dimensional location within a predetermined radius of the elongated flexible structure.

2. The underwater manipulator of claim 1, wherein the pin joint is configured to restrict axial rotation of the arm to an angle of rotation Θ which ranges between 0° to 90°.

3. The underwater manipulator of claim 1, wherein the elongatable cylindrical unit is actuated using a linear actuator assembly (110) which comprises a linear actuator (112), linear actuator piston (114) operated using hydraulic or electric means.

4. The underwater manipulator of claim 1, wherein the manipulator is configured to be a standalone and anchored to a base unit (106) on the sea or ocean floor.

5. The underwater manipulator of claim 1, wherein the arms of the manipulator are of varying sizes with elongatable cylindrical units of capacity based on size of arm and with the biggest link placed closest to the anchor point.

6. The underwater manipulator of claim 1, wherein the manipulator is configured to be an add-on to any autonomous underwater vehicle (AUV).

7. The underwater manipulator of claim 1, wherein each arm is configured to be neutrally buoyant to reduce the load on the preceding arms.
8. The underwater manipulator of claim 1, wherein the actuator assembly is driven by a power source placed within the cylindrical unit or externally.
9. The underwater manipulator of claim 1, wherein the moment caused due to the actuation of the elongatable cylindrical unit is either positive or negative based on the position of the center of buoyancy (CoB) with respect to the center of gravity (CoG) along the axis of the manipulator.
10. The underwater manipulator of claim 1, wherein the manipulator is configured with an encoder to provide feedback including angle of orientation of each link and the depth at which the cylindrical unit is placed.
11. A method of manipulating (400) an underwater manipulator (100), wherein the manipulator comprises at least one elongated flexible structure anchored at one end and having an end effector (105) at the other end, the flexible structure having a plurality of arms (101-1,2...n) connected at pin joints (104-1,2...n), wherein each arm comprises a rigid link (102-1,) and an axially flexible, elongatable cylindrical unit (107-1) configured to vary buoyancy of the arm, the method comprising:
 - changing the position of the arm from current angle of orientation to desired effector position by traversing azimuthally through an angle of rotation Θ defined between the base and the axis of the arm, comprising;
 - elongating the cylindrical unit axially to create a moment when buoyancy (B) of the rigid arm acting through the CoB is greater than the weight (W) acting through CoG, causing upward motion of rigid arm; or

compressing the cylindrical unit to create a moment when the weight (W) of the rigid arm acting through the CoG is greater than the buoyancy (B) acting through CoB, causing downward motion of rigid arm; and

counterpoising the CoG around the axis of link by rotating the actuator when the arm becomes perpendicular to the base or Θ is 90° , for the arm to traverse from 90° to 180° .

12. An underwater glider (1500) comprising:

a flexible, elongatable sealed cylindrical structure (1530);

a pair of wing structures (1541-1,2) affixed to the cylindrical structure to enable gliding underwater; and

an electric linear actuator assembly (1510) configured to elongate or contract the cylindrical structure (1530) and placed therewithin, wherein the actuator assembly (1510) is configured to cause separation of a center of gravity (CoG) with reference to a center of buoyancy (CoB) of the structure, thereby providing, surge, heave or pitch motions to the structure.

13. The underwater glider of claim 12, wherein the elongatable cylindrical structure comprises a bellows assembly (1531), comprising a flexible hollow cylindrical metallic bellows (1507) for at least a portion of the structure, and bellows sealing arrangements (1533) at the bellows's terminal ends, wherein the bellows sealing arrangement comprises a flange (1534) with lock heads (1535-1,2...n) and a bellows sealing plate (1518).

14. The underwater glider of claim 13, wherein the elongatable cylindrical structure comprises one of:

a) bellows assembly (1537) for predetermined lengths near the ends thereof, a middle portion having a hollow cylindrical profile;

b) bellows assembly (1539) for a predetermined length near a middle portion thereof, the end portions having a hollow cylindrical profile; or

c) bellows assembly (1538) for a predetermined length covering a portion of the length from one end thereof.

15. The underwater glider of claim 12, wherein the electric linear actuator assembly (1510) enclosed in the bellows assembly, comprises at least two linear actuators (1512-1,2) coupled with a connector (1546) placed at a middle portion of the structure, wherein each linear actuator comprises an actuator motor (1516-1,2) and a piston (1514-1,2) and wherein the linear actuators are operable independently to position the CoB with reference to the CoG to cause surge, heave or pitch motion to the structure (1530).

16. The underwater glider of claim 12, wherein the wing assembly (1540) comprises a pair of rigid wing plates (1541-1,2) attached to the bellows (1507).

17. The glider of claim 15, wherein the bellows assembly further comprises, a power source, electrical and electronic components and payload sensors.

18. The glider of claim 12, further comprising a nose portion (1560) and a tail portion (1570) configured to minimize hydrodynamic drag on the structure (1530).

19. The glider of claim 18, wherein the tail portion is provided with thrusters (1653) and a rudder.

20. A method of operating an underwater glider (1500) having a flexible, elongatable cylindrical structure (1530), an electric linear actuator assembly (1510) configured to elongate or contract the cylindrical structure to vary its centre of buoyancy (CoB) with reference to its center of gravity (CoG), a wing assembly (1540), nose (1560) and tail (1570)

structures, the tail (1570) comprising a thruster (1563) along with rudder to achieve efficient gliding underwater, the method comprising carrying out one or more of:

a. changing the pitch by causing a shift in the CoB to rise above or fall below the CoG along the (z) direction thereby creating a moment along (y) direction, wherein the moment created is used along with the drag of the wing structures to vector the residual buoyancy (b) to achieve surge (horizontal motion); and

b. adjusting the position of wing structures to create a moment, wherein the moment created along with the contraction of the cylindrical structure, vectors the residual buoyancy (b) to achieve surge (horizontal motion),

wherein the method comprises causing the glider to follow a predetermined trajectory in the x (longitudinal), y (lateral) or z (depth) directions.

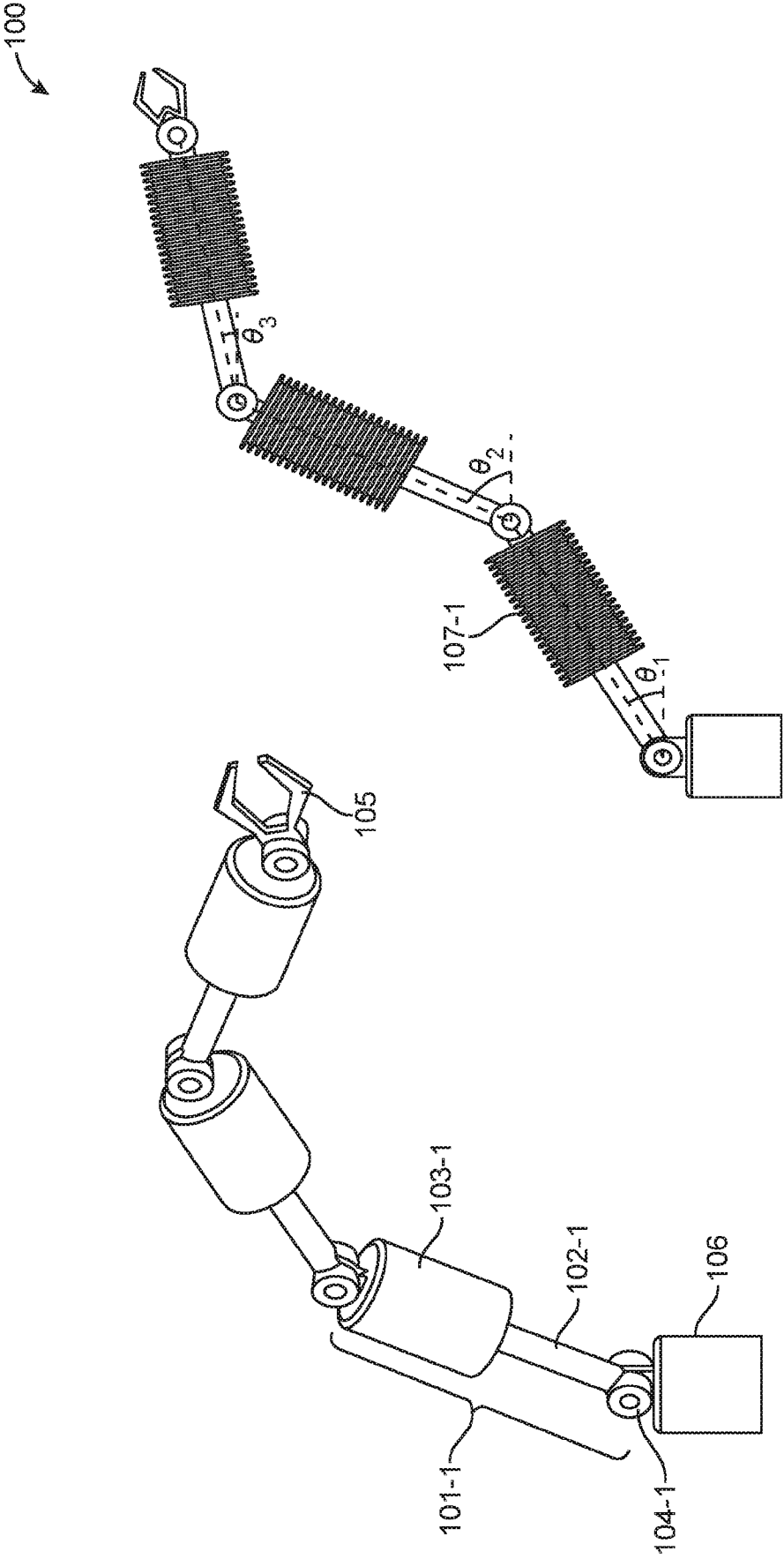


FIG. 1A

FIG. 1B

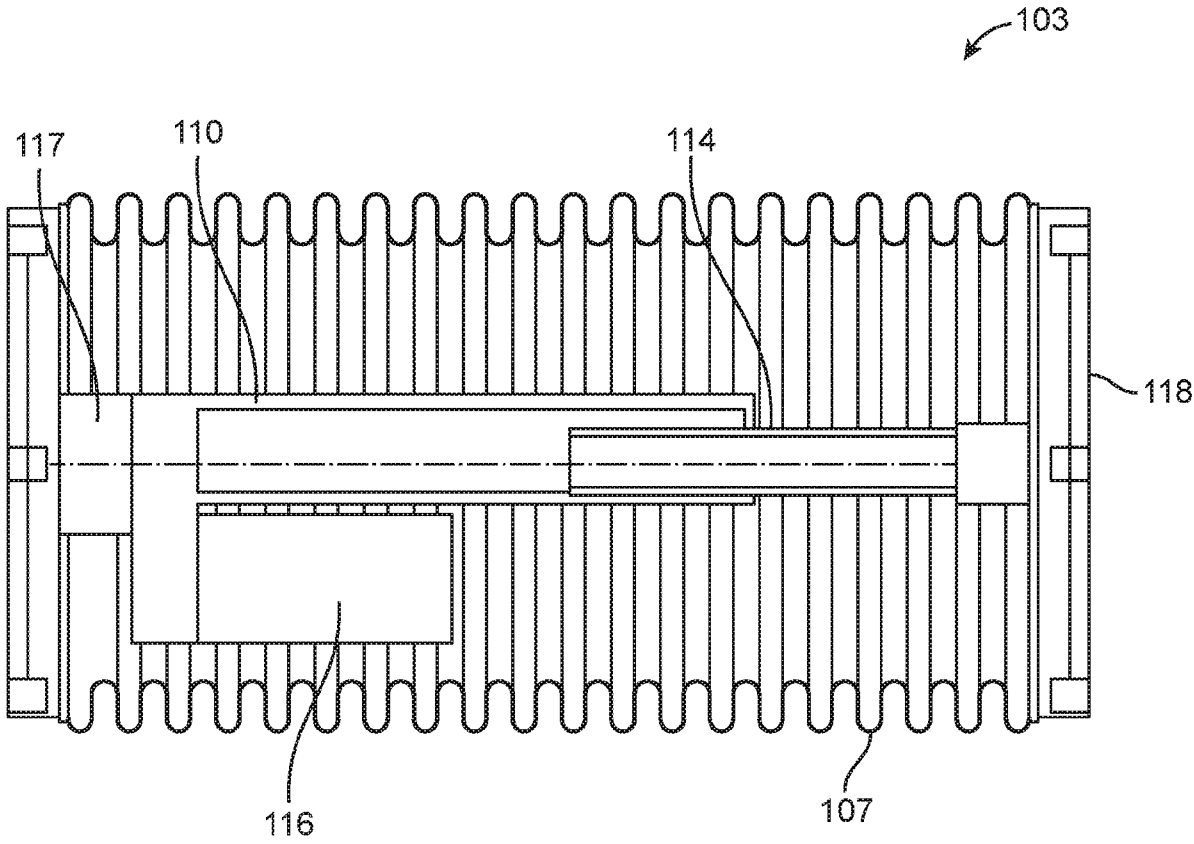


FIG. 1C

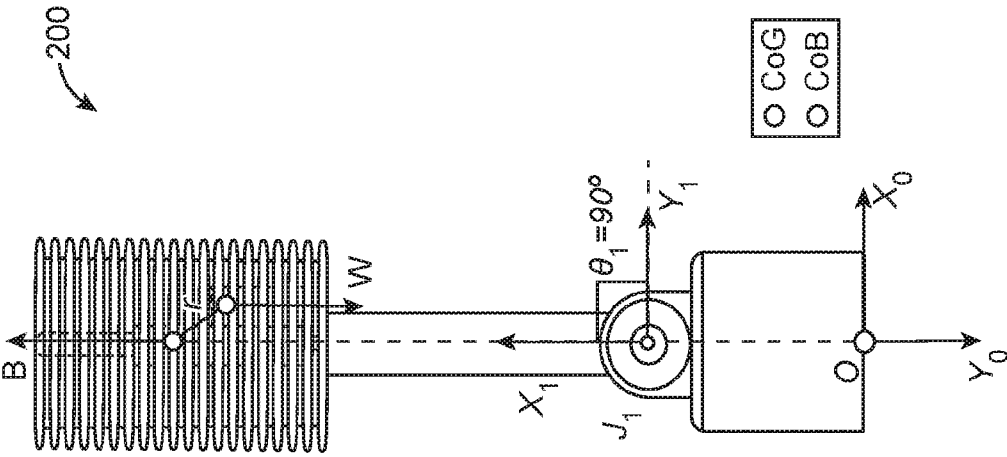


FIG. 2B

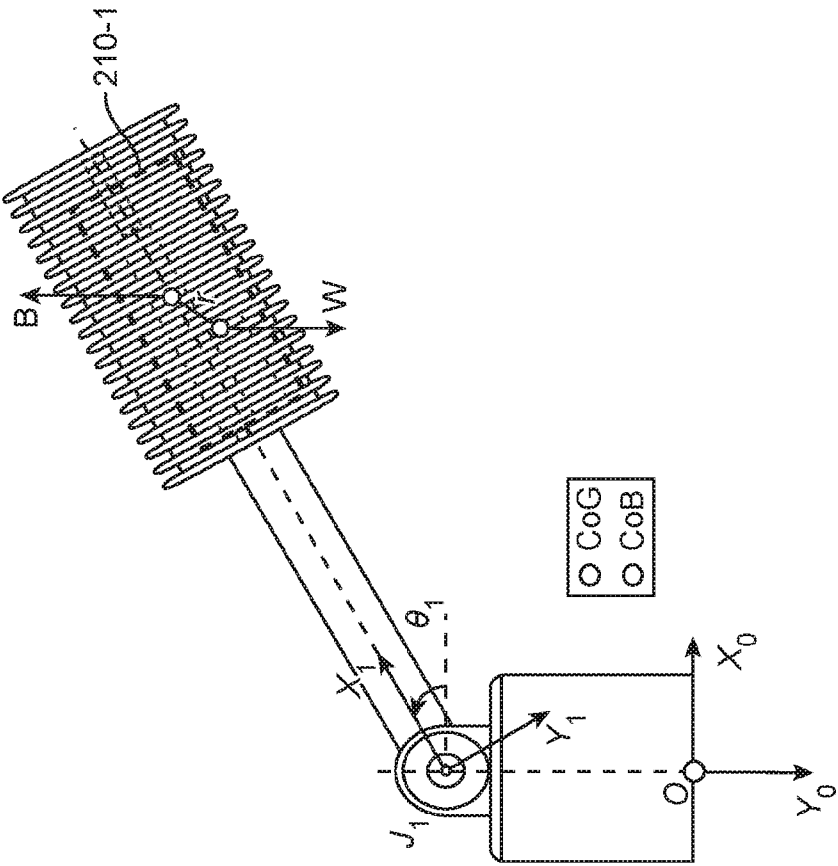


FIG. 2A

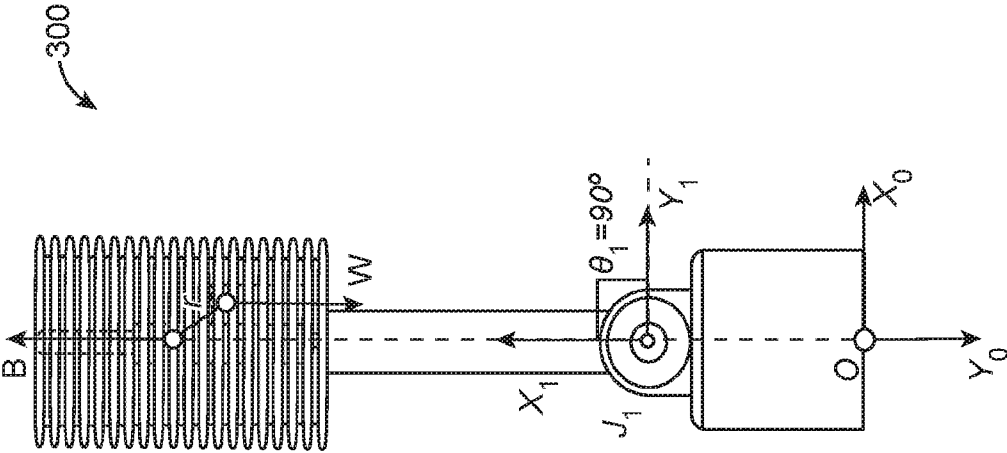


FIG. 3B

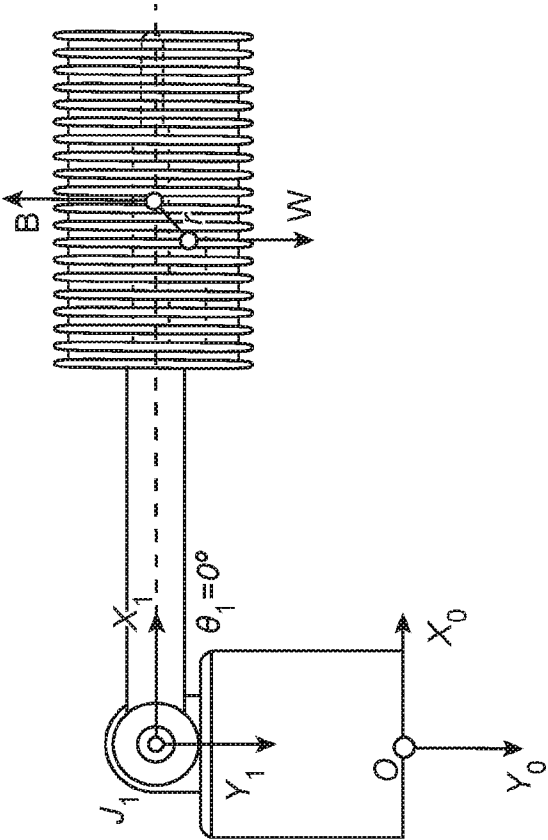


FIG. 3A

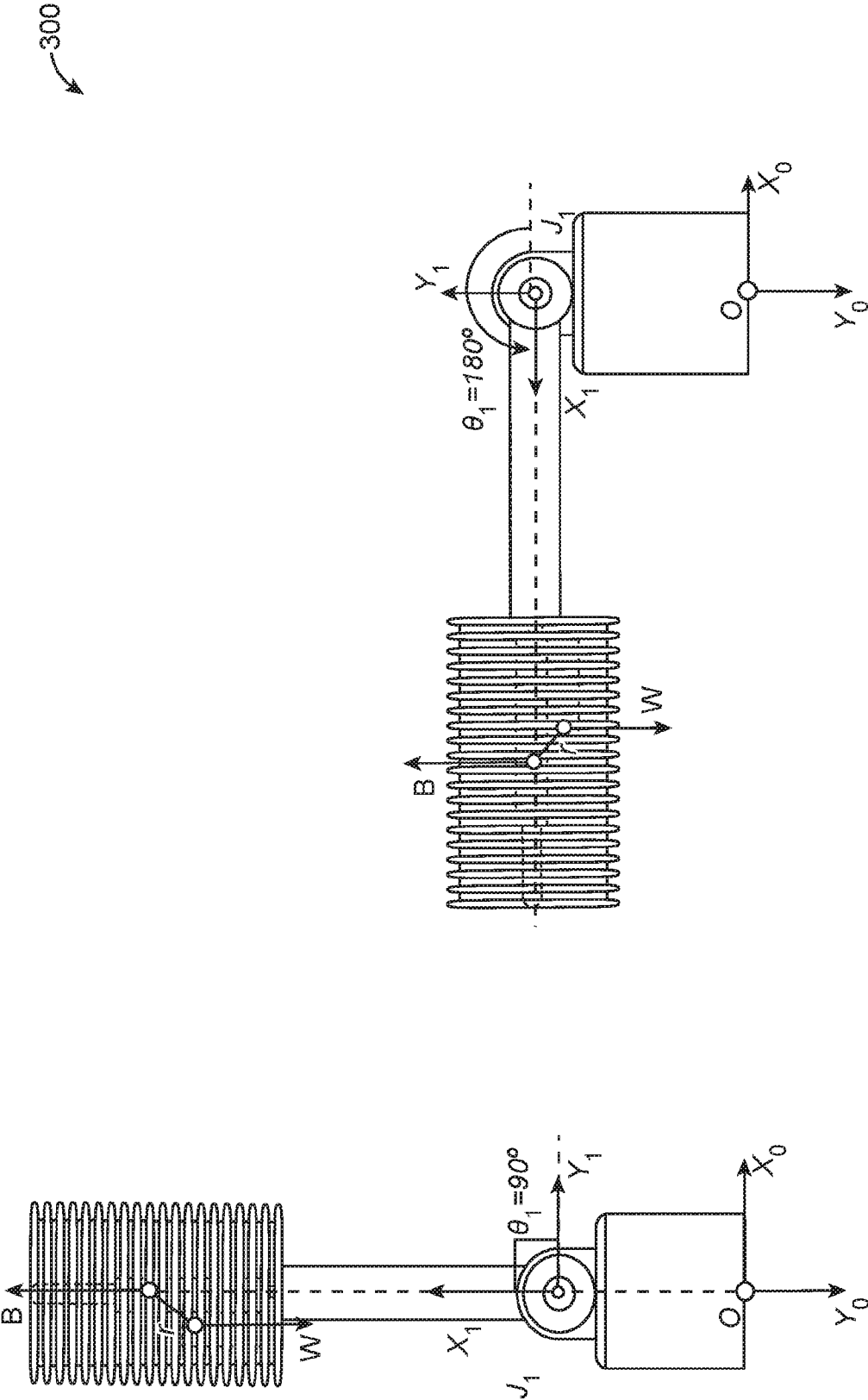


FIG. 3D

FIG. 3C

6 / 17

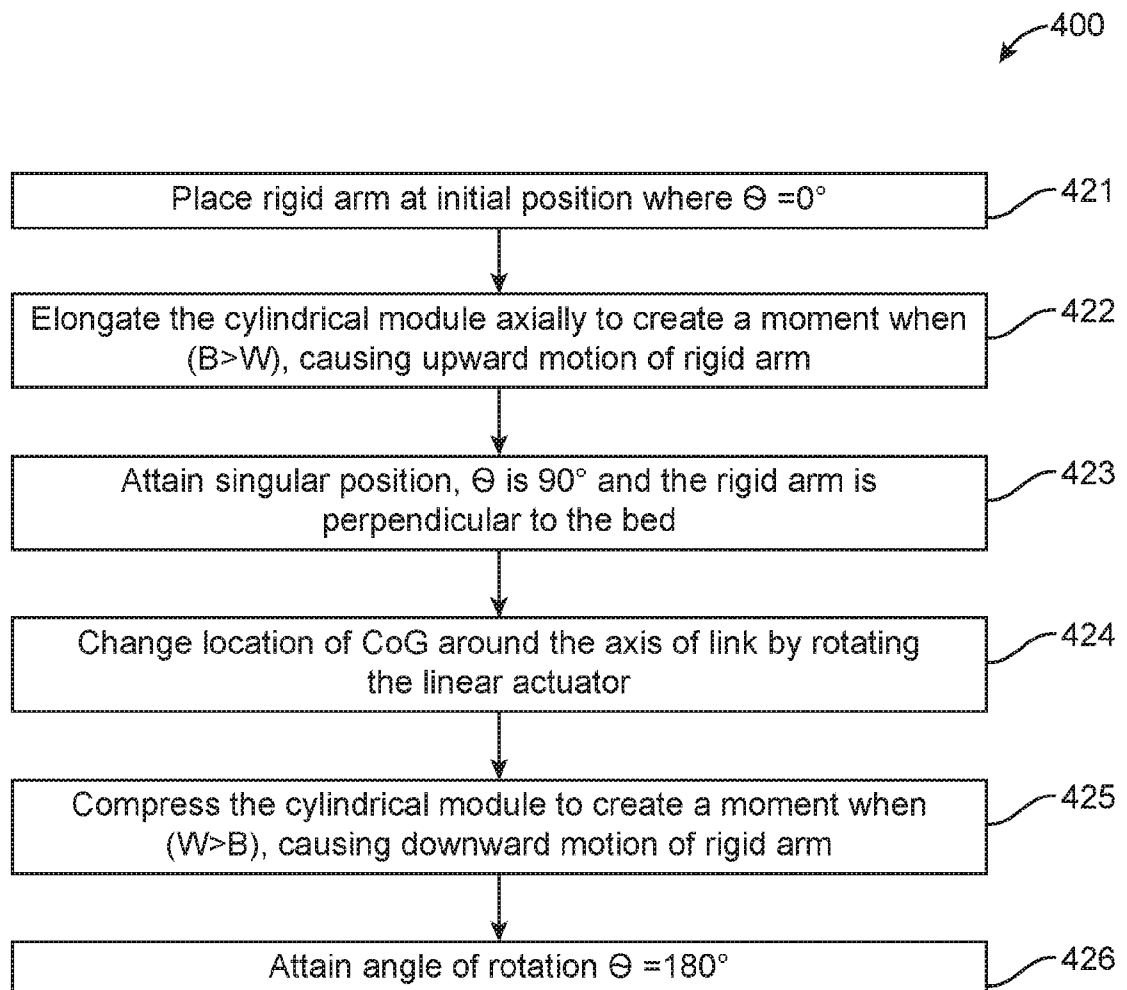


FIG. 4

7 / 17

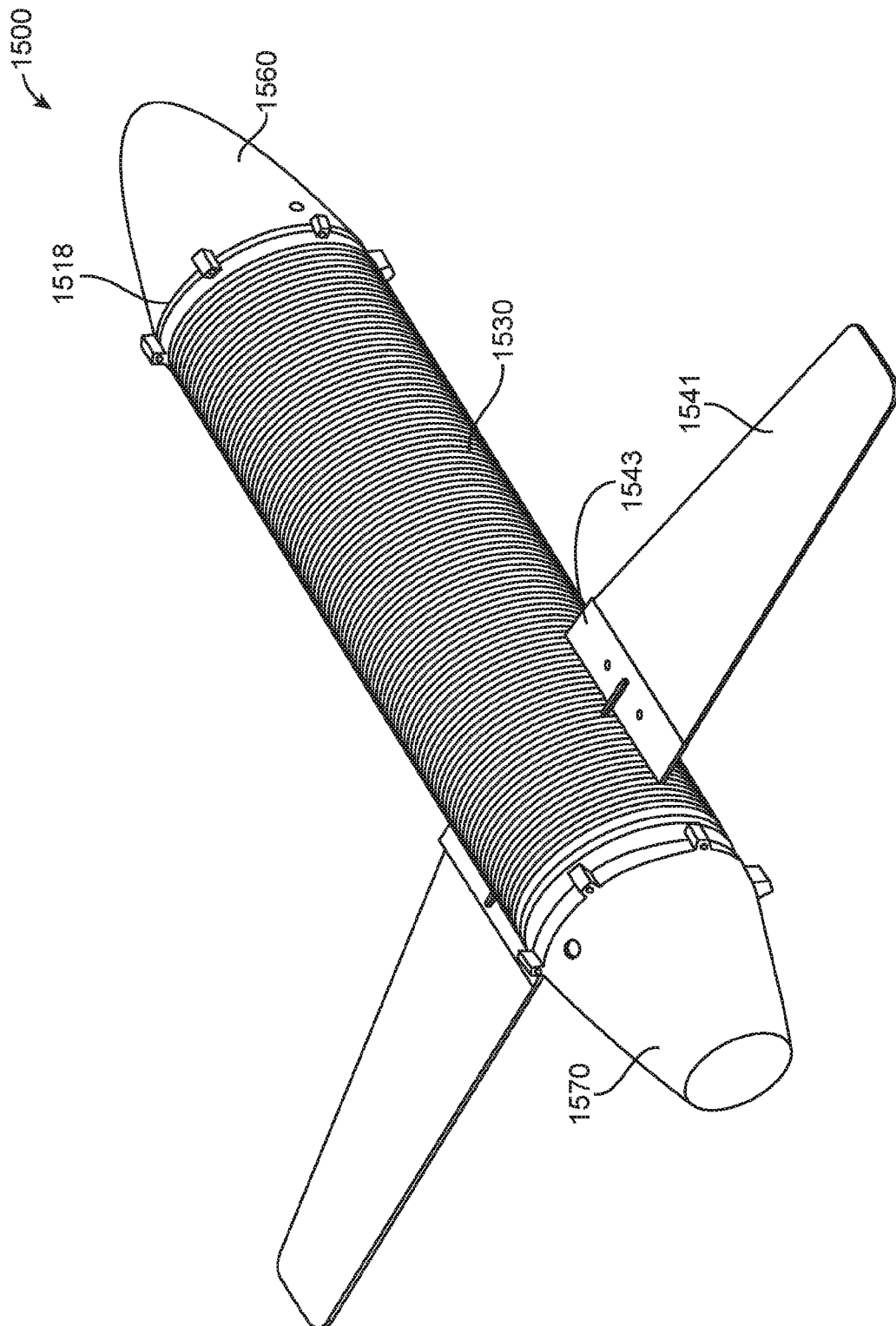
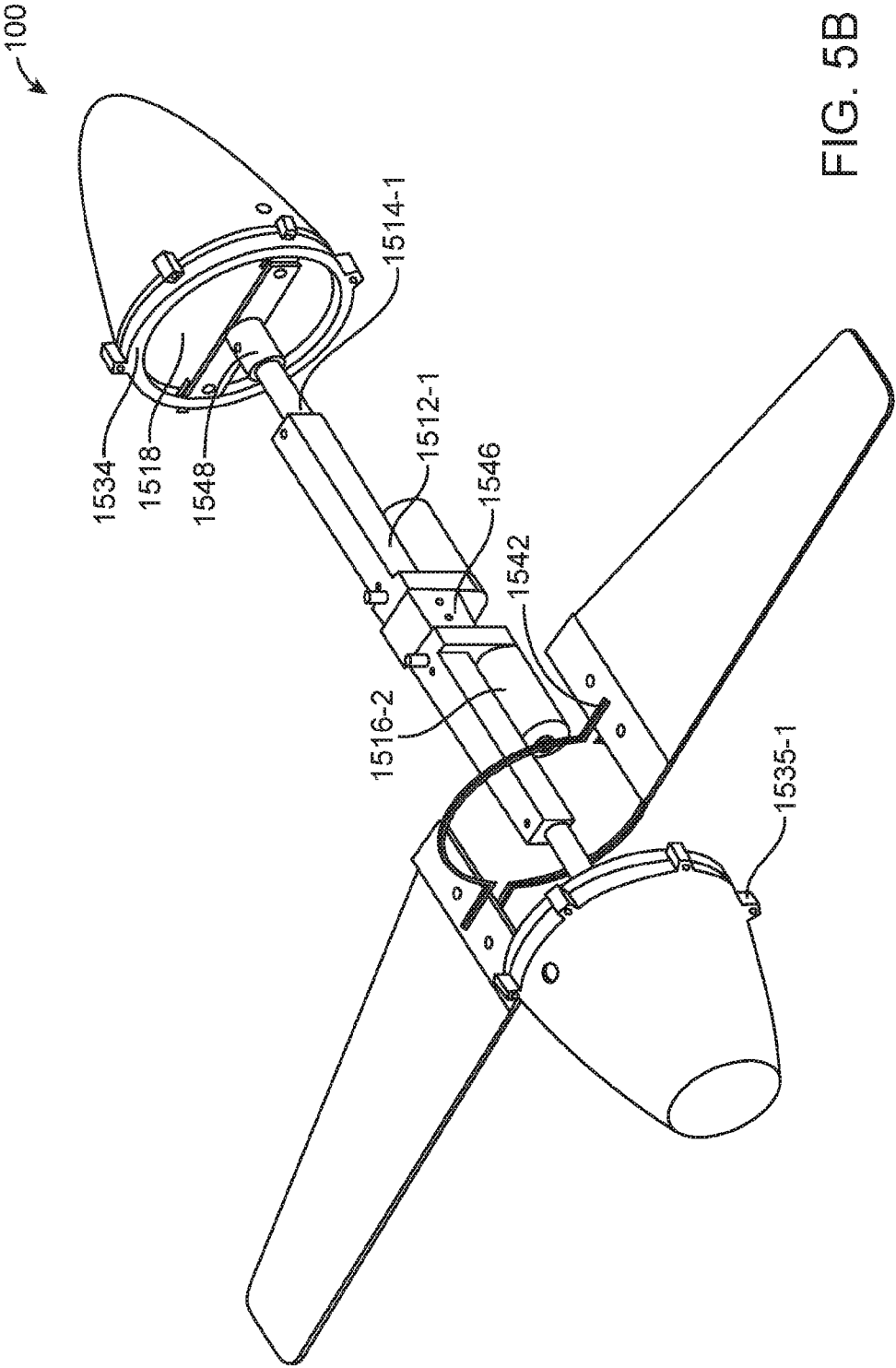


FIG. 5A



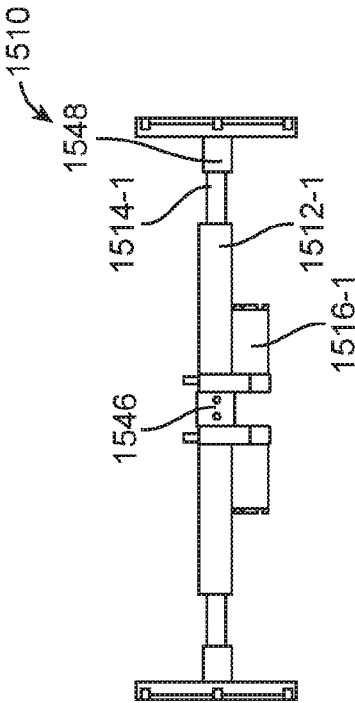


FIG. 5C

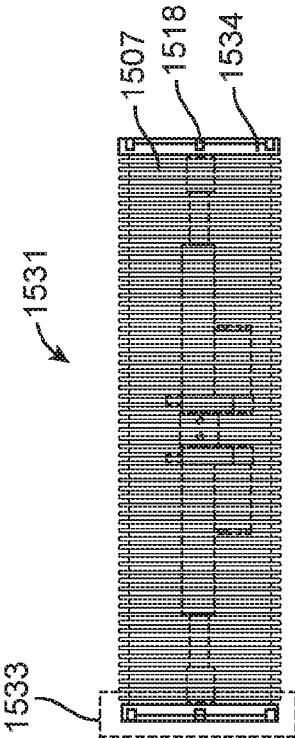


FIG. 5D

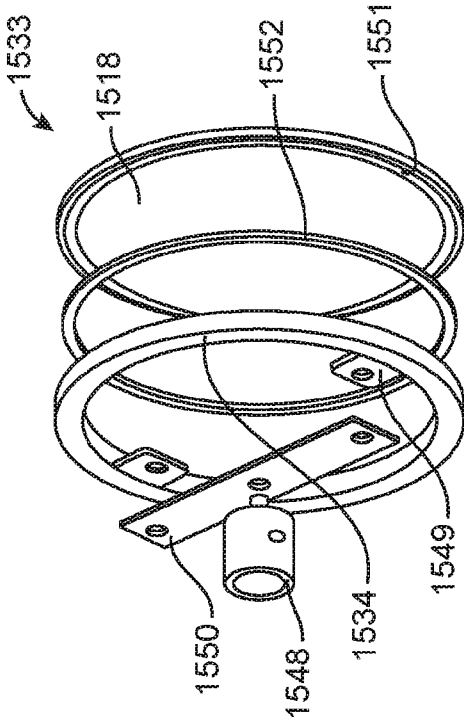


FIG. 5E

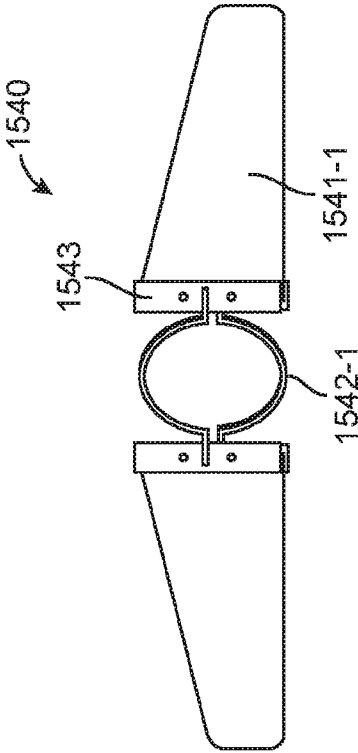


FIG. 5F

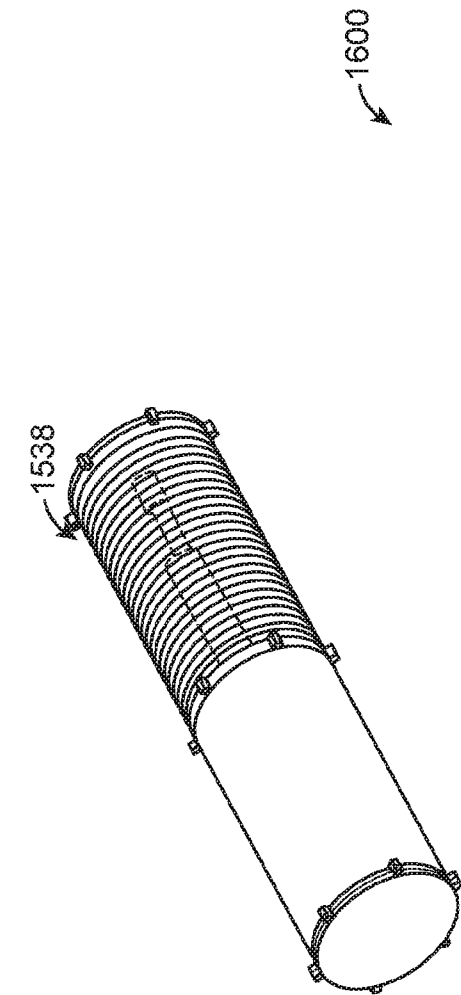


FIG. 6B

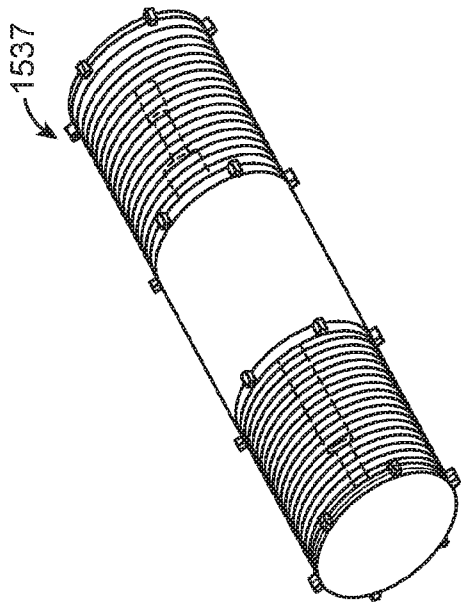


FIG. 6A

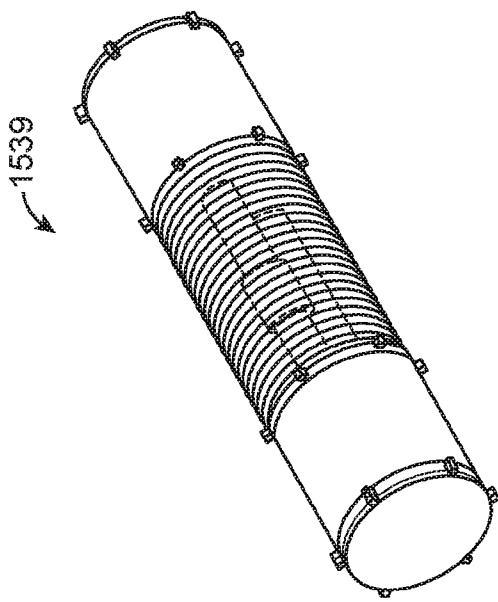


FIG. 6C

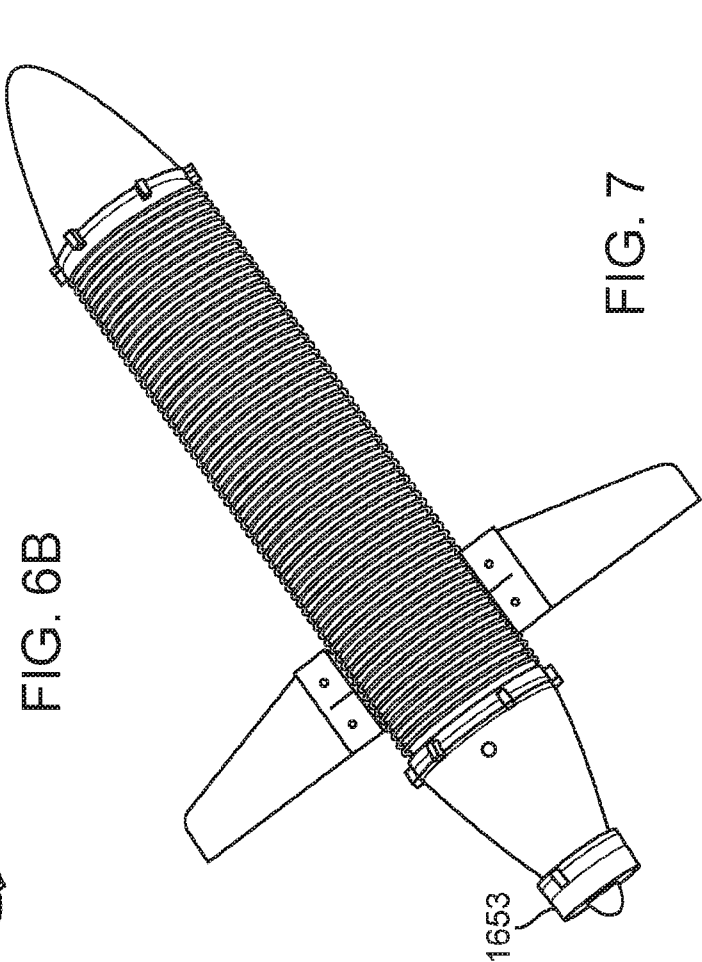


FIG. 7

11 / 17

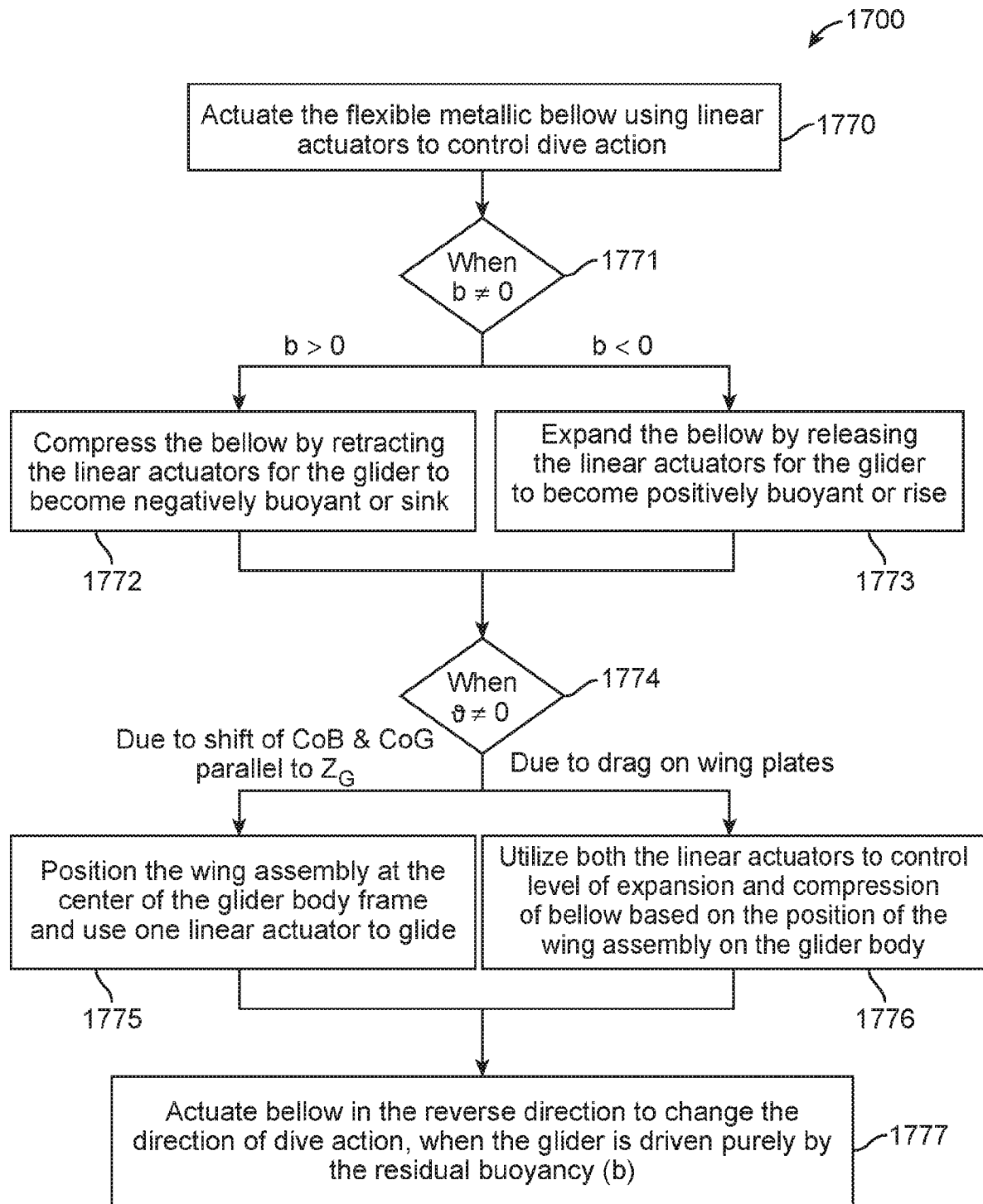


FIG. 8

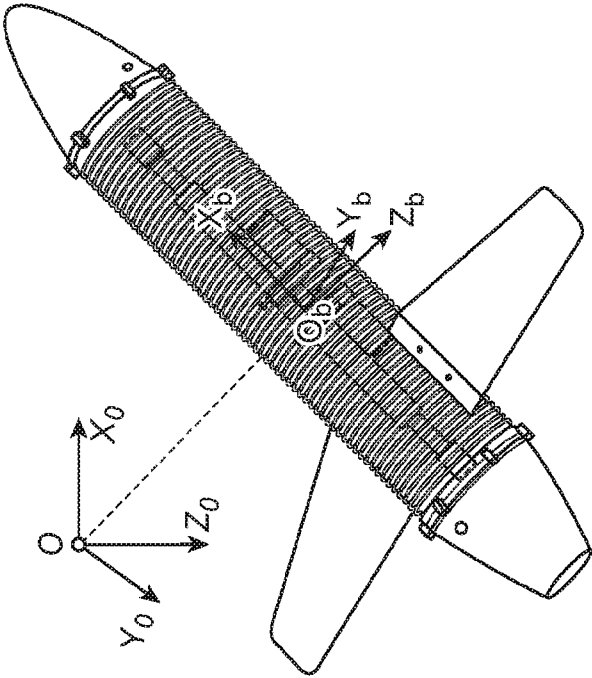


FIG. 9A

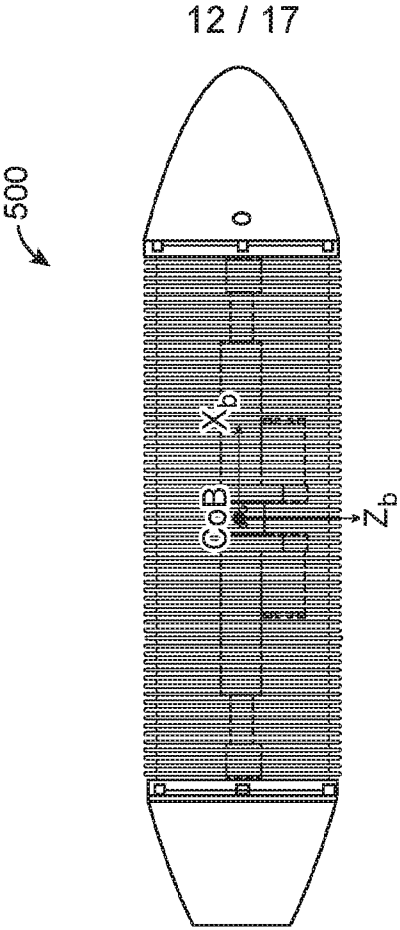


FIG. 9B

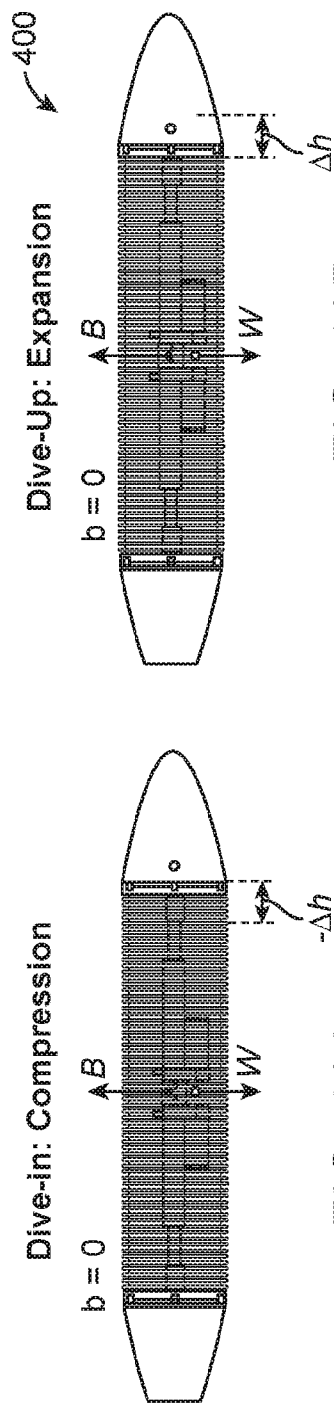


FIG. 10D

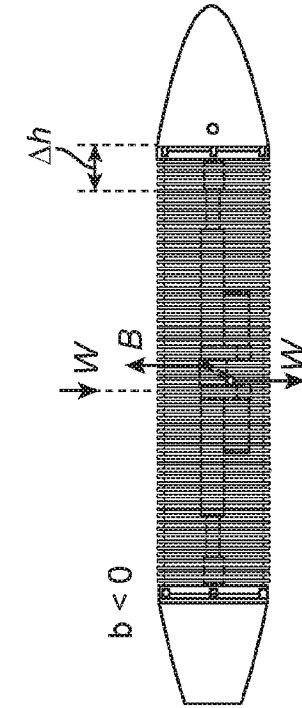


FIG. 10E

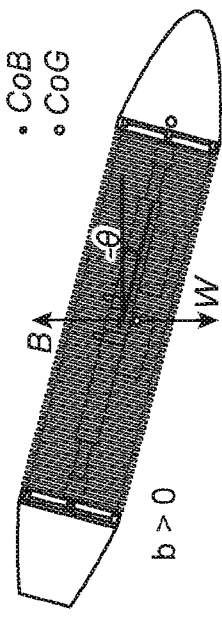


FIG. 10B

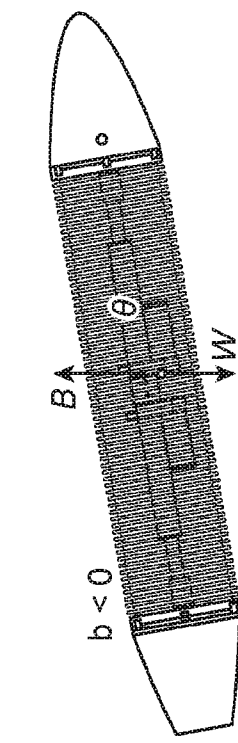


FIG. 10F

FIG. 10C

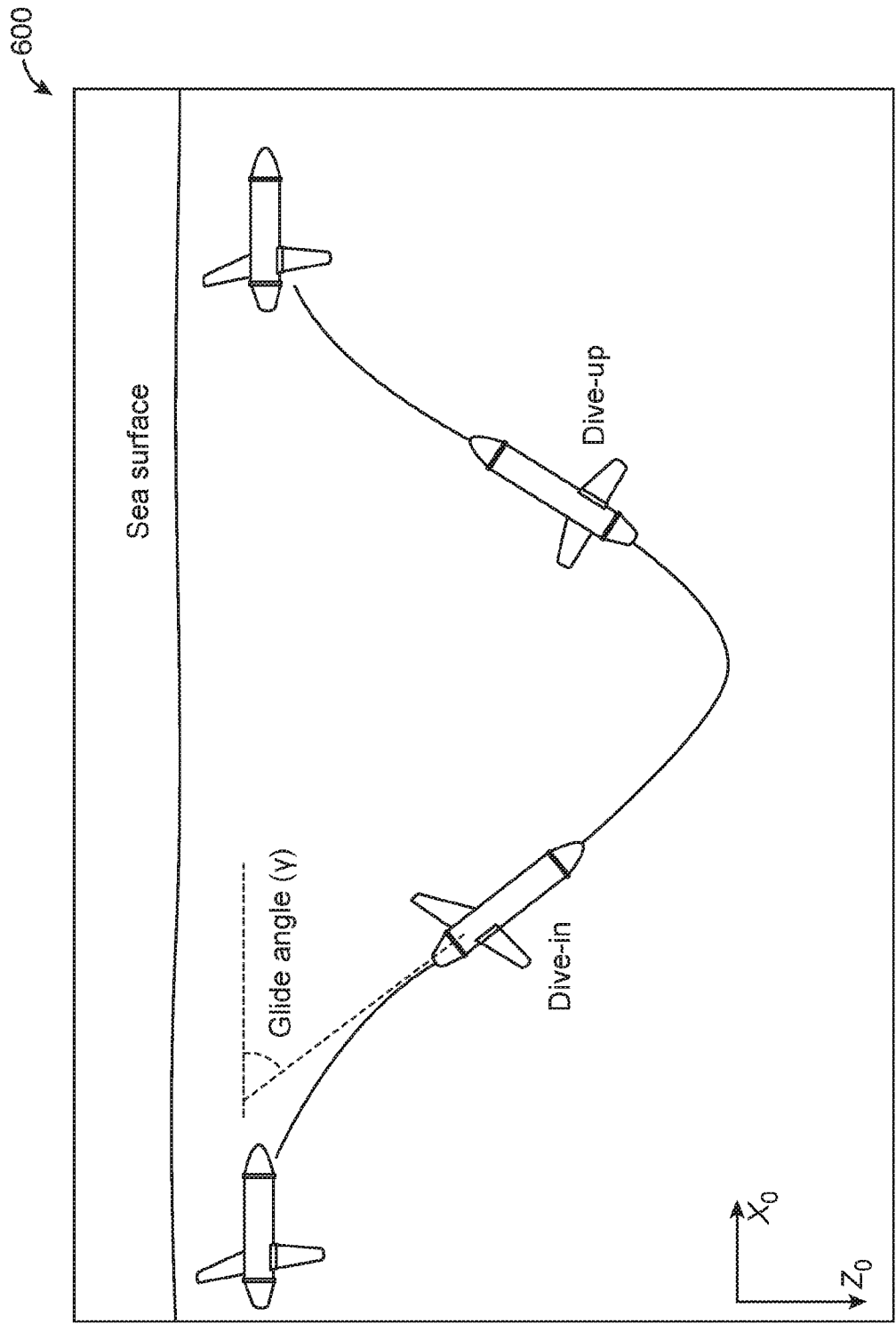


FIG. 11

15 / 17

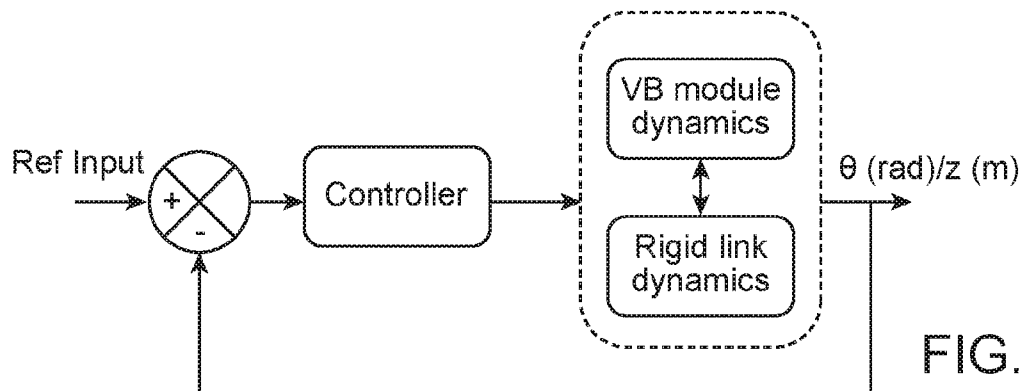


FIG. 12A

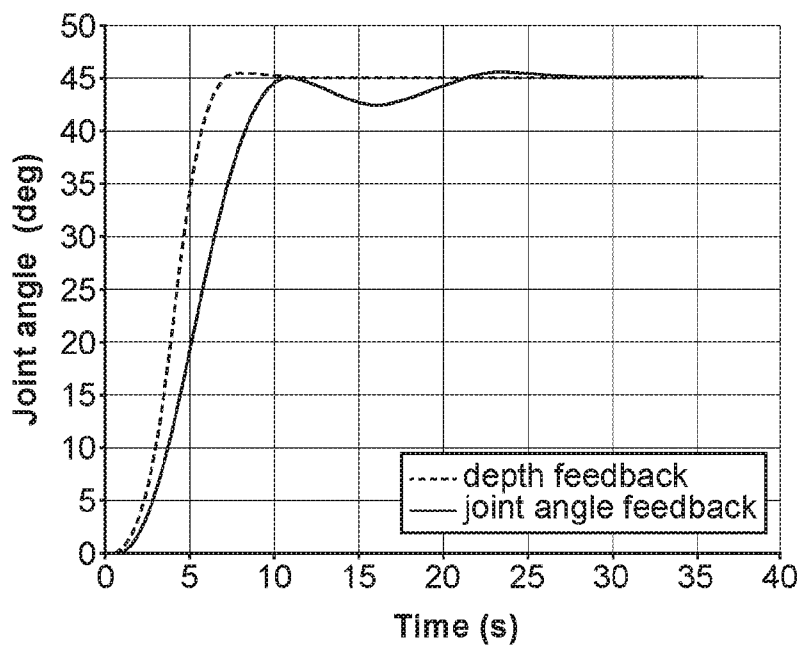


FIG. 12B

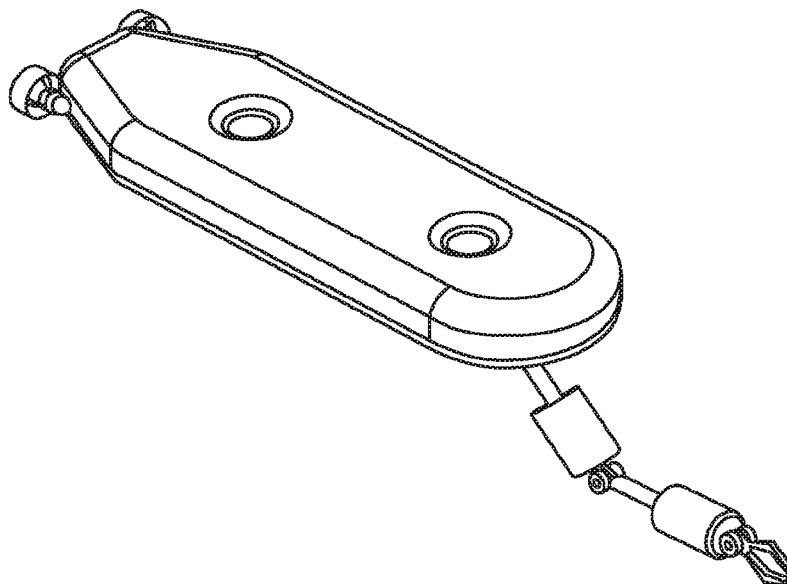
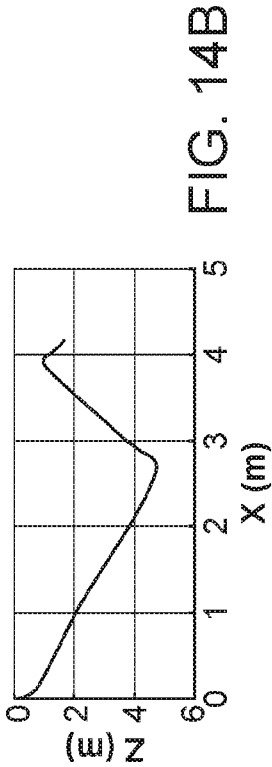
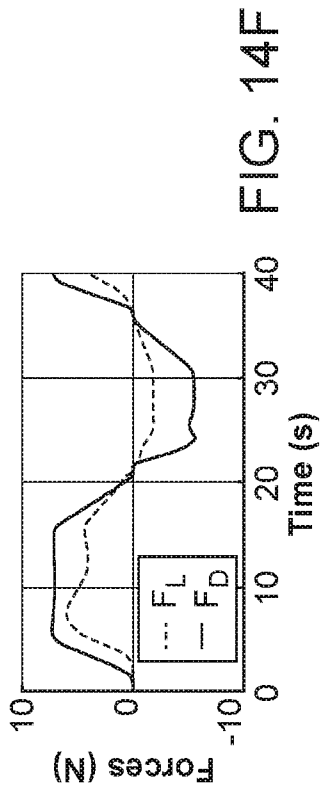
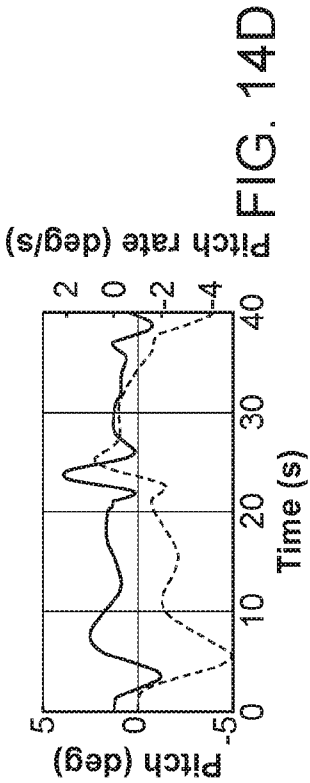
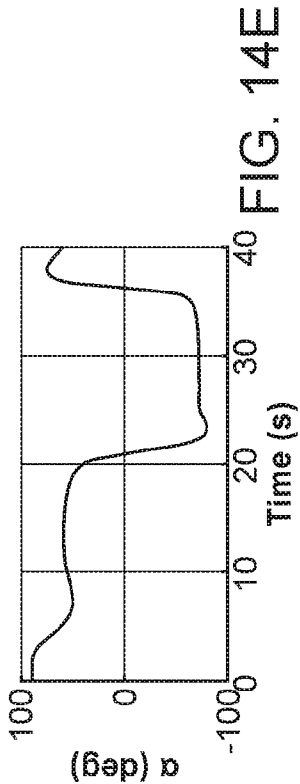
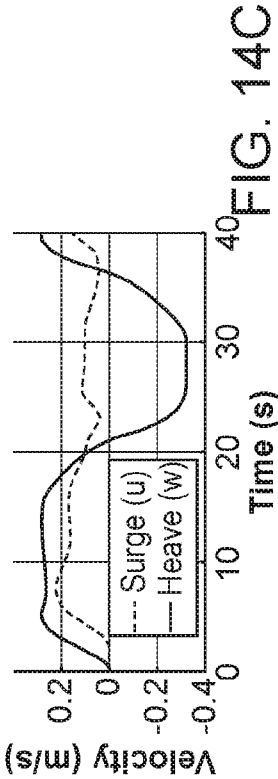
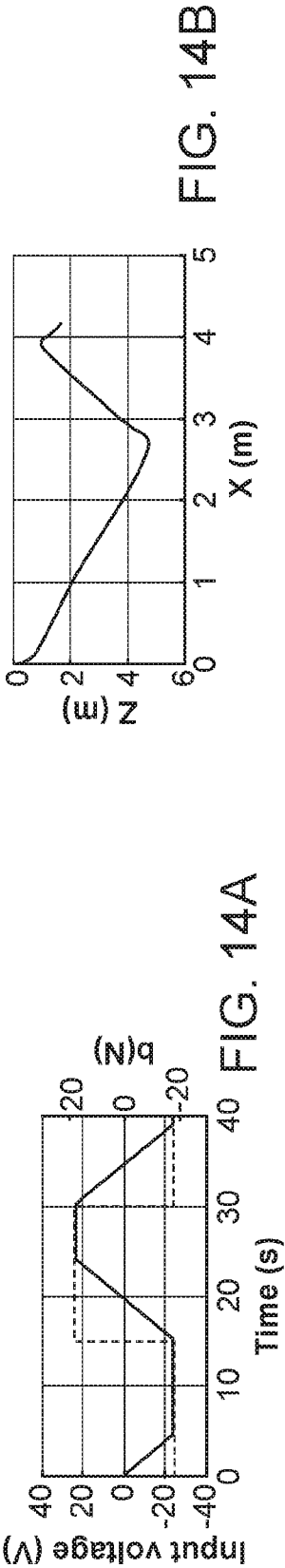


FIG. 13



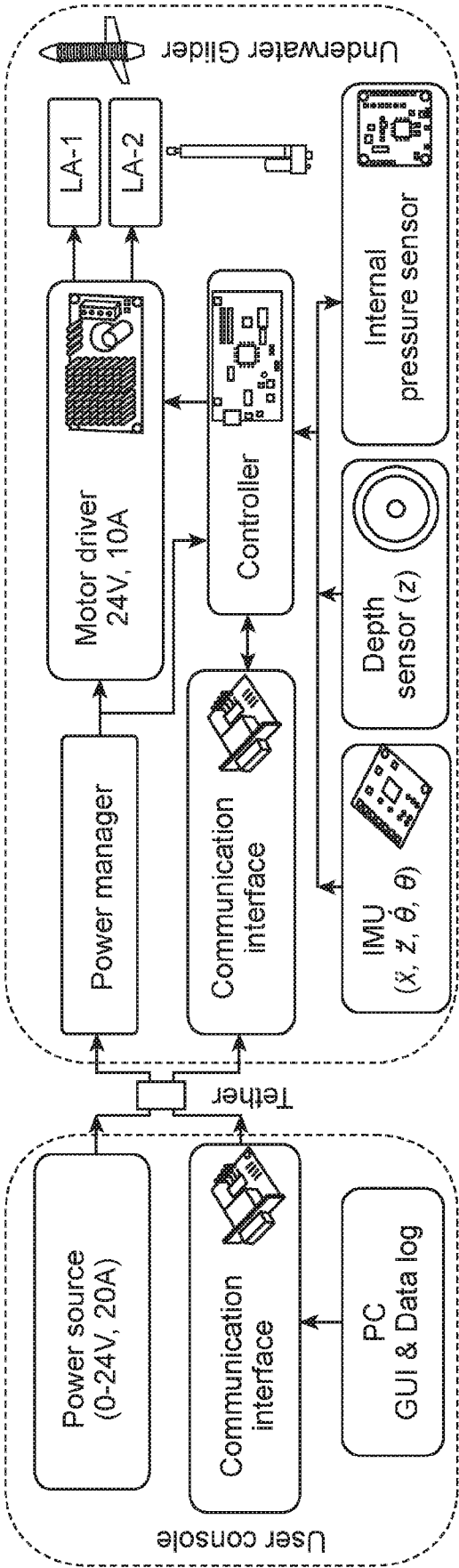


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2018/050655

A. CLASSIFICATION OF SUBJECT MATTER
B25J9/06, B63G8/14 Version=2019.01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B25J, B63G

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

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

TotalPatent One, IPO Internal Database, Google Scholar, Google Patents

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP2014046421 A (TOKYO INSTITUTE OF TECHNOLOGY) 17 March 2014 (17.03.2014) Para [0033], [0045], [0079]-[0082], Figure 1, 9	1-10
A	Para [0033], [0045], [0079]-[0082], Figure 1, 9 -----	11
Y	IN 4683/CHE/2015 A (INDIAN INSTITUTE OF TECHNOLOGY MADRAS (IIT Madras)) 10 March 2017 (10.03.2017) Page 5; line 12-26, Page 6; line 10-13, Figure 1-4	1-10
A	Page 5; line 12-26, Page 6; line 10-13, Figure 1-4 -----	11
Y	RANGANATHAN, T., et al. "Design of a controllable variable buoyancy module and its performance analysis as a cascaded system for selective underwater deployment" Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Volume 231, Issue 4, Page 888-901, SAGE JOURNALS	9-10



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

18-01-2019

Date of mailing of the international search report

18-01-2019

Name and mailing address of the ISA/

Indian Patent Office
Plot No.32, Sector 14, Dwarka, New Delhi-110075
Facsimile No.

Authorized officer

Seetha Raman A

Telephone No. +91-1125300200

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2018/050655

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	https://doi.org/10.1177/1475090216688819 30 January 2017 (30.01.2017) Simulation studies para on Page 895, Conclusion on Page 901	
A	US3157145 A (OCEANIC SYSTEMS CORPORATION) 17 November 1964 (17.11.1964) Column 3; lines 1-10, 46-60, Figure 3, 5	12-20
A	US20140109821 A1 (BOSTON ENGINEERING CORPORATION) 24 April 2014 (24.04.2014) Para [0058]	12-20