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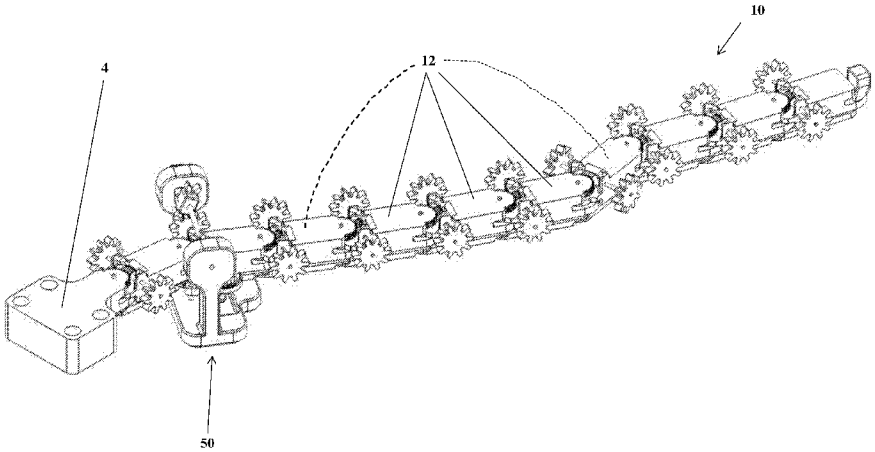
Fig 1A



(57) Abstract: The present invention relates to a robot device comprising a chain comprising a plurality of fixedly connected links and a mobile actuator movable thereon configured to change a position of a link relative to a position of an adjacent link; wherein said mobile actuator comprises at least a first motor to drive it along said chain of connected links; and wherein said mobile actuator is engageable with a position-determining element in said link.

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Minimally Actuated Serial Robot

FIELD OF THE INVENTION:

The present invention relates to the field mechanics. More particularly, the present invention relates to a mechanical robot capable of being maneuvered by a single actuator.

BACKGROUND OF THE INVENTION:

Hyper redundant robots are robots with serially connected links that possess a large kinematic redundancy. Alternatively known as snake robots, they are the subject of extensive research over the past several decades with many different configurations, mechanisms, control strategies, and motion planning algorithms being proposed over the years. The principle motivation for developing hyper redundant robots is their ability to navigate around obstacles and in highly confined spaces.

Algorithms for planning the motion of hyper redundant robots present a formidable challenge. Early motion planners for hyper-redundant robot motion planning were developed by Gregory Chirkjian in:

- *G.S. Chirikjian, "Theory and Applications of Hyper-Redundant Robotic Manipulators," California Institute Of Technology, Ph.D. dissertation 1992.*
- *G.S. Chirikjian and J.W. Burdick, "An obstacle avoidance algorithm for hyper-redundant manipulators," , Cincinnatti, OH, May 1990.*
- *G.S. Chirikjian and J.W. Burdick, "Design and experiments with a 30 DOF robot," , Atlanta, GA, May*

1993.

- *G.S. Chirikjian, "Hyper-Redundant Robot Mechanisms and Their Applications," , Osaka, Japan, November 1991.*

In those works, the curvature of the robotic snake was approximated as a continuous modal function with the obstacles expressed as boundary constraints on the robot's shape. Many recent works have addressed obstacle avoidance schemes for hyper redundant robots. State-of-the-art approaches including genetic algorithms, variational methods, and probabilistic roadmaps are used to plan the motions of the robots.

Flexible robots have been developed as an alternative. Also known as soft robots or continuum robots, they consist of a flexible continuous structure that possess, at least in theory, an infinite number of degrees of freedom. The advantage of flexible robots over hyper-redundant robots is their lightweight and speed. However, they are inaccurate, difficult to control, and have low position sensing capabilities.

It is therefore an object of the present invention to provide means for an energy efficient robot to carry out various tasks.

It is a further object of the present invention to provide means for an accurate compact robot.

Other objects and advantages of the present invention will become apparent as the description proceeds.

SUMMARY OF THE INVENTION:

The present invention relates to a robotic device comprised of connected links. The device can execute complex motions with a small number of actuators. The present invention comprises a mobile actuator that shifts the position of the links along the joints of the robot. This enables the shaping of the robot to any desired position by incrementally adjusting its joints. The robot is suitable for applications in a complex and confined environment with low payload and that do not require rapid deployment. The robot is also very modular, the number of links and mobile actuators can be changed easily.

The present invention mobile actuator is travelable on the connected links and is engageable with a position determining element at the joints of the links. The mobile actuator may activate a motor that powers the position shifting of one of the links in relation to its adjacent link. The links positioning one in relation to its adjacent other may be in in the same plane or in various 3D directions.

The present invention relates to a robot device comprising a chain of a plurality of fixedly connected links and a mobile actuator movable thereon configured to change a fixed orientation between two adjacent connected links of said plurality of fixedly connected links;
wherein said mobile actuator comprises a first motor to travel along the connected links, and a second motor to change the fixed orientation between two connected links.

The present invention relates to a robot device comprising a chain comprising a plurality of fixedly connected links and a mobile actuator movable thereon configured to change a position of a link relative to a position of an adjacent link;
wherein said mobile actuator comprises at least a first motor to drive it along said chain of connected links; and
wherein said mobile actuator is engageable with a position-determining element in said link.

Preferably, each of said links is responsive to a rotational movement generated in said actuator by a second motor coupled to said actuator such that said rotational movement affects the position of the link in relation to its adjacent link.

Preferably, the changing of a position of a link relative to a position of an adjacent link is carried out by a worm gear mechanism.

Preferably, the connection between two adjacent links comprises a shaft inserted in an aperture on a surface extending proximally from the distal adjacent link and in an aperture on a surface extending distally from the proximal adjacent link.

Preferably, the changing of a position of a distal link of two adjacent links of the chain of links relative to a position of the proximal link of said two adjacent links is carried out by a worm gear mechanism;
wherein the proximal link of the two adjacent links comprises a worm wheel surface extending distally therefrom

that engages with a worm screw attached on the proximal side of the distal link.

Preferably, the worm screw is mounted on a rotatable horizontal shaft fixed on the proximal side of the distal link.

Preferably, the robot device further comprises at least one wheel gear fixedly mounted on the shaft such that when the wheel gear rotates the shaft rotates respectively.

Preferably, the mobile actuator comprises a horizontal rotatable axle mounted thereon and at least one spinning gear element fixedly mounted on said horizontal rotatable axle such that the spinning gear element is engageable with the wheel gear.

Preferably, the robot device further comprises a second motor coupled to the mobile actuator configured to generate a rotational movement that rotates the horizontal rotatable axle.

Preferably, the links further comprise two side channels along their length wherein each side channel is substantially continuous with its corresponding side channel of its adjacent link thus forming a track;
wherein the mobile actuator comprises two wheels mounted thereon configured to drive along said track (e.g. each wheel along and within one side channel).

Preferably, the links are disposed on an imaginary plane; and the change of a position of a link relative to a

position of its adjacent link is such that one of said adjacent links is rotationally displaceable, with respect to an axis substantially perpendicular to said imaginary plane, in relation the other adjacent link.

Preferably, the changing of a position of a link relative to a position of an adjacent link is carried out by a rack and pinion mechanism.

Preferably, the changing of a position of a distal link of two adjacent links of the chain of links relative to a position of the proximal link of said two adjacent links is carried out by a rack and pinion mechanism;
wherein the distal link of the two adjacent links comprises a fixation element extending proximally therefrom;
wherein said fixation element comprises a clamp extending downwards from said fixation element proximal end;
wherein said clamp is engageable with a top portion of the distal link, pushing down on it maintaining fixation therebetween.

Preferably, the robot device further comprises a torsion spring fixed at one of its ends to a portion of the distal link and fixed at its other end on top of the fixation element such that the torsion force of the torsion spring applies a downward force causing the clamp to push down on the top portion of the distal link.

Preferably, the robot device further comprises a rotatable horizontal shaft fixed to the distal link;
wherein the torsion spring is mounted on said shaft; and

wherein the fixation element comprises at least one distal arm fixedly mounted on said shaft such that said fixation element is rotationally displaceable with respect to said shaft axis.

Preferably, the mobile actuator comprises a circular pinion element and a linear rack element engageable therewith such that a rotational movement that rotates said pinion element around its central axis causes said rack element to move linearly;
said device further comprising a second motor coupled to the mobile actuator configured to generate a rotational movement that rotates said pinion element around its central axis;
wherein said linear rack element comprises two spaced apart protrusion elements extending downwards therefrom engageable with the clamp.

Preferably, the protrusion elements are configured to push the clamp sideways when engaged therewith, upon a linear movement of the rack element causing said changing of a position.

Preferably, the robot device further comprises a second motor coupled to the mobile actuator and a controller coupled to the first and second motor configured to activate them.

Preferably, the robot device further comprises an encoder;
said encoder comprising a sensor attached to the mobile actuator and coupled to the controller and scales that

encode location placed on or near the joints between two adjacent links.

Preferably, the robot device further comprises a rotary encoder;
said rotary encoder comprising a sensor attached to the mobile actuator and coupled to the controller, and pairs of two identifiable elements placed on or near the joints between two adjacent links;
wherein one of the identifiable elements of each pair is placed on the distal link of the adjacent links and the other identifiable elements of each pair is placed on the proximal link of the adjacent links.

BRIEF DESCRIPTION OF THE DRAWINGS:

The present invention is illustrated by way of example in the accompanying drawings, in which similar references consistently indicate similar elements and in which:

- Fig. 1A illustrates a worm gear embodiment of the present invention.
- Figs. 1B-1C illustrate top and bottom views respectively of the embodiment of Fig. 1A.
- Figs. 2A-2C illustrate different angles of the link of the worm gear embodiment of the present invention.
- Figs. 2D-2E illustrate different angles of two adjacent links of the worm gear embodiment of the present invention.
- Figs. 3A-3B illustrate different angles of an embodiment of the mobile actuator of the present invention.

- Figs. 4A-4B illustrate different angles of a wheel assembly according to an embodiment of the present invention.
- Fig. 4C illustrates an embodiment of a motor according to an embodiment of the present invention.
- Fig. 5A illustrates a rack and pinion embodiment of the present invention.
- Fig. 5B illustrates a side view of Fig. 5A.
- Figs. 6A-6C illustrate a diagonal, top and bottom view (respectively) of a rack and pinion embodiment of the present invention.
- Figs. 7A-7B illustrate different angles of the link with the torsion spring embodiment of the present invention.
- Figure 7C illustrates a protruding section of a link according to an embodiment of the present invention.
- Figure 7D illustrates a side view of the torsion spring link according to an embodiment of the present invention.
- Figs. 7E-7F illustrate different angles of two adjacent links of the torsion spring embodiment of the present invention.
- Figs. 8A-8C illustrate different angles of an embodiment of the mobile actuator of the present invention.
- Figs. 8D-8H illustrate elements relating to the rack and pinion embodiment of the present invention.
- Figs. 9A-9C illustrate different angles of an embodiment of the mobile actuator of the present invention.
- Figure 10 illustrates an example of use according to an embodiment of the present invention.

- Figure 11a illustrates two views of two adjacent links according to an embodiment of the present invention.
- Figure 11b illustrates an actuator according to an embodiment of the present invention.
- Figure 12A illustrates an example of use according to an embodiment of the present invention.
- Figure 12B illustrates an example of use according to an embodiment of the present invention.
- Figure 13 illustrates an example of use according to an embodiment of the present invention.
- Figure 14 illustrates an example of use according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION:

The present invention relates to a serial robot with minimal actuation. The robot is a serial (preferably rigid) structure comprising a plurality of links connected by passive joints and one or more mobile actuators movable thereon. The mobile actuators travel over the links to a given joint and adjust the relative angle between two adjacent links. The joints passively preserve their angles until the actuator adjusts them again. This actuation can be applied on a robot with two or more links. As the prior art hyper-redundant robots typically comprise actuators/motors at the joints between each pair of two adjacent links in order to change the angle, the present invention configuration enables the robot to undergo the same wide range of motions typically associated with prior art hyper-redundant robots, but with much fewer actuators. This contributes to the power efficiency of the robot.

The present invention robot is advantageous as it does not need to have any motors or encoders that are fixed on the joints of the links which will substantially lower the weight of moment of inertia of the robot. The present invention does not have a large number of fixed actuators at each joint which can cause slow-acting, consume power even when static and being energy inefficient. Furthermore, the present invention does not have a large number of fixed actuators at each joint that produces a bulky design which can result in a low operating payload and large deflections. The present invention robot that obviates these elements also obviates the need to have wirings along the links. As a result the present invention robot has a lightweight and is cheap to manufacture. Another advantage is that in many cases, the robot will be more efficient energy wise because of its lower weight.

The passivity of the joints is defined by there being no motors in between them, while the angle between adjacent links is preserved. The position of a link is fixed in relation to its adjacent link. The number of links and mobile actuators can be easily varied depending on the proposed task. When a mobile actuator travels over the links, it can rotate the desired joint thereby changing the relative angle between the links by a desired angle. The base is where the robot is connected to a constant support or a mobile platform.

The present invention robot may be modular and its size and geometry can be adapted for various applications. The present invention has various maneuvering capabilities

including obstacle avoidance and maneuvering through a confined space to reach its target.

The present invention robot (herein referred to as MASR - Minimally Actuated Serial Robot – interchangeably) combines some characteristics and advantages from both hyper redundant robots and compliant robots. The actuators translate over the links to any given joint and adjust it to the desired angular displacement. The joint passively preserves its angle until it is actuated again. The number of degrees of reconfigurability (DOR) is equal to the number of joints. This enables the MASR to achieve similar mobility to regular hyper redundant robots. The advantages of MASR are its simplicity, smaller weight, higher energy density (power/mass), low cost and modularity, as the number of links and actuators can be easily and quickly changed.

The minimal actuation is in that the entire mobility of the robot may be maneuvered by just one mobile actuator that may comprise just two motors. One of the two motors is for the mobility of the mobile actuator itself traveling on the links (to drive the mobile actuator along the chain of links) and the other motor is for changing the angle of the joints. This advantage contributes to an energy efficient consumption of power in relation to prior art robots comprising actuators at each joint. Other embodiments may include the length distancing between two adjacent links by the mobile actuator. The angle changing may be in the 3D dimension.

The present invention may have various uses such as in machinery, piping applications, manufacturing applications, medical applications, agricultural applications, rescue appliances, space applications etc.

Figs. 1A-1C show a preferred embodiment of the present invention. Fig. 1A shows a serial robot **10** comprising a chain comprising a plurality of links **12** and a mobile actuator **50** movable thereon. Each pair of adjacent links form a passive joint therebetween. The mobile actuator **50** is configured to travel over the links to a given joint and adjust the position of a link relative to a position of an adjacent link, e.g. adjust the relative angle between two adjacent links. The joints passively preserve their angles until the actuators adjusts them again. This embodiment is explained in relation to the links and adjusted angles being on a common plane, however, the present invention also relates to angle adjusting between links in the three dimensions in space.

The robot **10** comprises a base **4** at its proximal end configured to be fixed to a surface or platform. According to one embodiment the base is at a location high enough such that all the links will be horizontally in the air such that the mobile actuator can fully travel while being around the links. Other embodiments may comprise the links resting on a surface and the mobile actuator engaging the links from above and on the side (without portions driving under).

Optionally the present invention robot may comprise an end effector (not shown) at its distal end connected to the

most distal link. Within this disclosure the terms "distal direction" as used in connection with the robot is the direction towards the front of the robot away from the base **4** and the "proximal direction" is opposite to the distal (e.g. the direction towards the base **4**).

In general the term horizontal herein refers to the direction parallel to an imaginary plane whereon the links are initially disposed on. In general the term vertical herein relates to the direction perpendicular to the imaginary plane whereon the links are initially disposed on.

The end effector may comprise one or more of the following: a gripper, a magnet, a welding power supply (welding unit), a scissors, an illumination unit, etc. The present invention robot may use the end effector for carrying out various tasks.

According to this preferred embodiment, the angle adjusting between the links at the joints is according to a worm drive (worm gear) mechanism. The distal portion of link **12** comprises a round portion being the worm wheel that meshes with a worm screw located at the proximal portion of the link's adjacent distal link. Figs. 1B-1C show a top view and a bottom view of robot **10** respectively. Figs. 2A-2D show an embodiment of the worm drive links.

Fig. 2A shows an embodiment of a single link **12** of the robot **10**. Link **12** comprises a rectangular cuboid body comprising distal and proximal surfaces extending therefrom that assist in connecting with adjacent links in a

supportive and stable manner. The top portion of the link **12** comprises a flat distal surface **13** having a thickness, extending distally therefrom. The top portion distal surface **13** comprises a distal round surface extending distally therefrom being the worm wheel **14**. The worm wheel **14** preferably comprises a round half circular shape having peripheral teeth at its half circular edge and having a thickness configured to mesh with the worm screw of its adjacent distal link. The teeth are curved inwards such that they adequately mesh with the worm screw of the adjacent distal link. The link **12** comprises a flat surface **15** having a thickness, parallel to worm wheel **14** and extends distally from the body of the link **12**. Flat surface **15** is lower than worm wheel **14**. The link **12** comprises a flat surface **16** having a thickness, and is parallel to worm wheel **14** and to flat surface **15**. Flat surface **16** extends distally from a low portion of link **12** and is lower than flat surface **15**. The flat surfaces **15** and **16** preferably comprise a round half circular shape. According to a specific embodiment, the radius of the round half circular shape of worm wheel **14** is larger than that of flat surface **16** and smaller than that of flat surface **15**. Worm wheel **14** and flat surfaces **15** and **16** each comprise an aperture **14a**, **15a** and **16a** respectively (having the same diameter length), all being aligned with each other such that a shaft can be inserted therethrough.

Fig. 2B shows another angle of the embodiment of Fig. 2A. The link **12** comprises a flat surface **17** having a thickness, extending proximally from the body of the link **12**. Flat surface **17** is on a plane that is parallel to the planes that surfaces **15**, **16** and worm wheel **14** are on. Flat surface

17 is paced beneath the plane worm wheel **14** is on and above the plane surface **15** is on. The link **12** comprises a flat surface **18** having a thickness, extending proximally from a low portion of link **12**. Flat surface **18** is on a plane that is parallel to the planes that surfaces **17**, **15**, **16** and worm wheel **14** are on, and is placed beneath the plane surface **16** is on. Flat surfaces **17** and **18** (which are parallel) each comprise an aperture **17a** and **18a** respectively, being aligned with each other such that a shaft can be inserted therethrough.

The link **12** comprises two side channels **25** along the link **12** bottom portion sides, thus forming a track/rail to enable the traveling of the wheels of the mobile actuator thereon. Link **12** is preferably symmetric and one channel will be explained here and it is correct for the other channel. The bottom of channel **25** is a surface **26** aligned and in continuation with the top of surface **16**. The top of channel **25** is a surface (not shown) aligned and in continuation with the bottom of surface **15** (wherein the connection between the links form a small gap between adjacent (distal-proximal) channels (one side channel adjacent to its corresponding side channel in the adjacent link) that do not affect the wheels traveling therein even in cases with a large angle between the links, thus substantial continuous channels are formed being a track/rail where the wheels travel along). Channels **25** further comprise an inward side wall surface **20** having a thickness, common to both side channels (and separates them from one another) extending along the length of link **12**. The height of side wall **20** is the height between the top of surface **16** and the bottom of surface **15**. Side wall **20**

distal end is placed between the line connecting the most proximal edge portions of apertures **15a** and **16a**. Side wall **20** proximal end is placed between the imaginary line connecting the most distal edge portions of apertures **17a** and **18a**. The distal end of side wall **20** is round and curved inward (proximally) such as to be configured to mesh with a shaft inserted through apertures **15a** and **16a**. The proximal end of side wall **20** is round and curved inward (distally) such as to be configured to mesh with a shaft inserted through apertures **17a** and **18a**. Optionally, the channels **25** comprise two curved surfaces, one at the attachment line between side wall **20** and surface **26** and one between the attachment line between top surface of channel **25** and side wall **20**.

The link **12** further comprises two proximal side ears **30** that extend proximally from an upper portion of link **12** and elevate from the sides of surface **17**. Each side ear **30** comprises an aperture (not shown). The apertures are aligned with one another. A shaft **32** is inserted within both apertures such that it extends outwards beyond both apertures (wherein the shaft **32** is placed horizontally, i.e. parallel to an imaginary plane whereon the links are disposed thereon). The mobile actuator is engageable with position-determining elements - two wheel gears **35**, that when rotated change the position of the link in relation to its proximal adjacent link. The two wheel gears **35** comprise apertures at their centers and peripheral teeth **35t** extending outwards and are mounted (by their center apertures) and fixed to the edges of shaft **32** such that when the wheel gears **35** rotate the shaft **32** spins/rotates respectively. A worm screw **40** is mounted on the shaft **32** at

the portions between side ears **30**. The height of the worm screw **40** is such that when link **12** is aligned and connected to an adjacent proximal link the worm screw **40** meshes with the worm wheel **14** of the proximal adjacent link.

Fig. 2C shows a side view of link **12**. Figs. 2D and 2E show a side view and a diagonal view of two adjacent links **12** respectively where the respective heights of the parallel surfaces can be seen. For simplicity, only the connection portion including the distal portions of the proximal link and the proximal portions of the distal link are numbered. The adjacent links are connected such that the following apertures are aligned from top to bottom - **14a** (of proximal link), **17a** (of distal link), **15a** (of proximal link), **16a** (of proximal link) and **18a** (of distal link). A connecting shaft **39** is inserted through all five apertures connecting the links together allowing the joint angle between the links to vary, thus being a rotational joint wherein the distal link is rotationally displaceable (with respect to the axis being the shaft) in relation the proximal link.

With respect to two connected adjacent links, preferably, the thickness of surface **17** (of the distal link) is such that it is tightly fitted between surface **13** (of proximal link) and surface **15** (of proximal link). Preferably the thickness of surface **15** (of proximal link) is tightly fitted within the space between surface **17** (of the distal link) and the top of wall **20** (of the distal link). Preferably, the height of wall **20** (of the distal link) is such that the proximal end of the wall **20** (of the distal link) is tightly fitted within the space between surface **15** (of the proximal link) and surface **16** (of the proximal

link). Optionally, the thickness of surface **16** (of proximal link) is tightly fitted within the space between surface **18** (of the distal link) and bottom of wall **20** (of the distal link). These tight fittings contribute to the stability of the connection of the links and to the joint angle change while maintaining a position on the same aligned plane.

Preferably, at the connection area between two adjacent links, the space between surfaces **13** and **15** is curved and complementary to surface **17**. Preferably, the space between surface **17** and top of wall **20** is curved and complementary to surface **15**. Preferably, the space between surface **18** and bottom of wall **20** is curved and complementary to surface **16**.

Worm screw **40** of a distal link meshes with the worm wheel **14** of a proximal link. When the wheel gears **35** are rotated the worm drive mechanism changes the angle between the links (typically changing the distal link position due to the fixation of base **4**) around the axis of shaft **39**. The worm screw **40** contacts a peripheral portion of the half circular surface **14**. The spinning of the worm screw **40** causes a shifting of the angle of the link (comprising the worm screw) caused by the change in the contact location of worm screw **40** on the peripheral portion of circular surface **14**. When the wheel gears **35** are not rotated the drive mechanism firmly maintains the links position and angle therebetween (e.g. the worm gear comprises a self-locking mechanism). The rotation of wheel gears **35** in one direction causes a change in the angle in a corresponding direction, wherein the rotation of wheel gears **35** in the opposite

direction causes a change in the angle in the opposite direction.

In other embodiments, the distal/proximal portions of adjacent links may be constructed in a reversed manner, e.g. the worm wheel (and other distal extending surfaces) may extend proximally from the distal link, and the worm screw, shaft, wheel gears and proximal extending surfaces may be located at the distal portion of the link (with the respective surfaces extending distally from the proximal link), mutatis mutandis.

Figures 3A-3B show an embodiment of the mobile actuator **50** movable on the connected links. The mobile actuator **50** is hollow and when in motion the connected links pass through the hollow portion. The connected links are surrounded by the mobile actuator **50** elements. Mobile actuator **50** comprises a bottom surface **51** having a thickness and two side arm surfaces **52** having a thickness, extending upwards from the sides of surface **51**. A rotatable axle **54** is connected between the inner sides of upper portions of both arms **52** (typically horizontally). One of the side arms **52** comprises a first motor **55** configured to generating rotational movement. The motor **55** is connected to the upper portion of the side arm **52** and is fixed thereto (typically passing through the arm and protruding outwards). The motor **55** is configured to rotate the rotatable axle **54** in both directions. Two spinning gear elements **57** are mounted and fixed on axle **54**. Each spinning gear element **57** comprises teeth **57t** extending outwards therefrom. The two spinning gear elements **57** are spaced apart from each other at a distance corresponding to the distance between wheel gears

35 such that when mobile actuator **50** is placed at a joint between two adjacent links, each of them meshes with a corresponding wheel gear **35**. When the motor **55** spins the axle **54** the spinning gear elements **57** rotate, and rotate the corresponding wheel gear **35**. The motor **55** can cause rotation in both directions thus configured to cause the wheel gears **35** to rotate in both directions, thus configured to change the angle between two adjacent links at the joint in both directions.

The mobile actuator **50** further comprises a second motor **60** configured to generate rotational movement for causing spinning motion of wheels that cause the traveling of the mobile actuator **50** distally and proximally along the connected plurality of links **12**. The motor **60** is connected to the bottom surface **51** and is fixed thereto (typically passing through the surface **51** and protruding downwards). The motor **60** is configured to rotate a rotatable shaft **60s** extending upwards therefrom (shown in Fig. 4C). The motor can cause rotation of shaft **60s** in both directions thus configured to cause the wheels to move the mobile actuator distally or proximally.

The mobile actuator **50** comprises a wheel assembly **62** (Figs. 4A-4B) comprising an upper wheel **63** attached to (and parallel to) a lower wheel gear **64** (wherein their circle centers are aligned). The upper wheel **63** has a circular shape and is configured to enter channel **25** of the links **12** and travel along it within it (when spinning). Lower wheel gear **64** has a circular shape and comprises peripheral teeth **64t** at its edge. A hollow bore **66** passes from top to bottom

of wheel assembly **62** along the aligned centers of upper wheel **63** and lower wheel gear **64**.

The wheel assembly **62** is placed above motor **60** and mounted on shaft **60s**. The hollow bore **66** comprises a cross sectional shape complementary to the shape of shaft **60s** such that hollow bore **66** is tightly fitted thereon. The rotation of shaft **60s** causes a corresponding rotation of wheel assembly **62**.

The mobile actuator **50** comprises a second wheel assembly **72** comprising an upper wheel **73** attached to (and parallel to) a lower wheel gear **74** (wherein their circle centers are aligned). The upper wheel **73** has a circular shape and is configured to enter channel **25** (the same channel holding upper wheel **63**) of the links **12** and travel along it within it (when spinning). The second wheel assembly **72** is placed distally to wheel assembly **62** and aligned with it in the distal-proximal axis. The lower wheel gear **74** has a circular shape and comprises peripheral teeth at its edge. Wheel assembly **72** is mounted at its center on an axle pin (not shown) fixed to the surface **51** (said axle pin extending upwards) and configured to spin around the axis of the axle pin. Both upper wheels **63** and **73** are positioned horizontally.

A wheel gear **80** is mounted at its center on an axle pin (not shown) fixed to the surface **51** (said axle pin extending upwards) and configured to spin around the axis of the axle pin. The wheel gear **80** has a circular shape and comprises peripheral teeth at its edge. The wheel gear **80** meshes with lower wheel gear **64** and lower wheel gear **74**

such that when lower wheel gear **64** is rotated it rotates wheel gear **80** which rotates lower wheel gear **74**.

The mobile actuator **50** comprises a wheel **90** having a circular shape and is placed and configured to enter channel **25** of the links **12** (at the side channel **25** opposite to the side channel holding upper wheels **63** and **73**) and travel along it within it (when spinning). Wheel **90** is mounted at its center on an axle pin (not shown) fixed to an elevated surface **92** which is fixed on surface **51**. The axle pin extends upwards and wheel **90** is configured to spin around the axis of the axle pin. The elevated surface **92** is such that that the wheel **90** is at the same height as upper wheels **63** and **73**. Thus when motor **60** spins shaft **60s** in one direction the mobile actuator **50** travels distally, and when motor **60** spins shaft **60s** in the other direction the mobile actuator **50** travels proximally.

According to another embodiment of the present invention, the angle adjusting between the links at the joints is according to a rack and pinion mechanism. Fig. 5A shows a robot **110** with this adjusting mechanism comprising connected links **112**, mobile actuator **150** and end effector **103** connected to the most distal link (wherein the proximal base is not shown here). Fig. 5B shows a side view of robot **110**.

Fig. 6A shows the robot **110** with some adjusted angles. Figs. 6B and 6C show a top and bottom view of robot **110** respectively.

Figs. 7A-7B show an embodiment of a single link **112** of the robot **110**. Link **112** comprises a rectangular cuboid body comprising distal and proximal surfaces extending therefrom that assist in connecting with adjacent links in a supportive and stable manner. The link **112** comprises a flat surface **115** having a thickness, extending distally from the body of the link **112**. Flat surface **115** preferably comprises a round half circular shape and an aperture **115a** at the circle center.

Fig. 7B shows another angle of the embodiment of Fig. 7A. The link **112** comprises a flat surface **117** having a thickness, extending proximally from a top surface of link **112**. Flat surface **117** is on a plane that is parallel to the plane that surface **115** is on. Flat surface **117** is paced above the plane surface **115** is on. The link **112** comprises a flat surface **118** having a thickness, extending proximally from a low portion of link **112**. Flat surface **118** is on a plane that is parallel to the planes that surfaces **117** and **115** are on, and is placed beneath the plane surface **115** is on. Flat surfaces **117** and **118** (which are parallel) each comprise an aperture **117a** and **118a** respectively (shown in Fig. 7C), being aligned with each other such that a shaft can be inserted therethrough.

The link **112** comprises two side channels **125** along the link **112** bottom portion sides thus forming a track/rail to enable the traveling of the wheels of the mobile actuator thereon. Link **112** is preferably symmetric (except for the torsion spring) and one channel will be explained here and it is correct for the other channel. The bottom of channel **125** is a surface **126**. The top of channel **125** is a surface

(not shown) aligned and in continuation with the bottom of surface **118** (wherein the connection between the links form a small gap between adjacent (distal-proximal) channels that do not affect the wheels traveling therein even in cases with a large angle between the links, thus a substantial continuous channel is formed).

Channels **125** further comprise an inward side wall surface **120** having a thickness, common to both side channels (and separates them from one another) extending along the length of link **112**. Side wall **120** distal end is placed beneath the most proximal edge portion of aperture **115a**. Side wall **120** proximal end is placed beneath the most distal edge portion of aperture **118a**. Optionally, the channels **125** comprise two curved surfaces, one at the attachment line between side wall **120** and surface **126** and one between the attachment line between top surface of channel **125** and side wall **120**.

The link **112** further comprises two proximal side ears **130** that extend upwards from the top of link **112** (at the proximal side of the link, distally to surface **117**). Each side ear **130** comprises an aperture (not shown). The apertures are aligned with one another. A shaft **132** is inserted within both apertures. A torsion spring **140** is mounted on the shaft **132** between side ears **130**.

A fixation element **141** rests on a portion of surface **117** and is connected to the shaft **132** by means of two arms **142** extending distally from the main body portion of fixation element **141**. The arms **142** each comprise apertures at their distal ends that are aligned with one another. Shaft **132** passes through the apertures of arms **142** such that each of

them is placed between one of the ears **130** and one side of the torsion spring **140**. Thus the fixation element **141** is movable around the axis of shaft **132**.

Fixation element **141** comprises a proximal holding element surface being a clamp **141e** (having a thickness) extending (preferably proximally and then) downwards from the fixation element **141** proximal end. The bottom of clamp **141e** is configured to engage the top of its proximal adjacent link **112** and apply pressure by pushing down on it such that it maintains fixation and is secured tightly and fastened, i.e. such that the position between the adjacent links is maintained (by preventing movement between the clamp **141e** and the top of its proximal adjacent link **112**). One end of the torsion spring is fixed to surface **117**. Figure 7C shows a protruding section **144** comprising a hollow bore **145** for receiving one end of the torsion spring **140** being fixed thereto. Fore simplicity, the torsion spring **140** is not shown in Fig. 7C. The other end of the torsion spring **146** (Fig. 7A) is placed above fixation element **141** such that the torsion force applies a downward force to it. Optionally said other end of the torsion spring **146** is placed in a receiving channel **147** on top of fixation element **141** for a better fixation. The torsion spring **146** applies a strong downward force on fixation element **141** such that is presses down on the top of proximal link **112** maintaining its adjacent link's position one in relation to the other.

Optionally To increase the friction force sand papers may be attached to the top of links **112** (at the areas that

engage with the clamp **141e**) and a metal screw attached to the clamp, engageable with the sand papers.

Fig. 7D shows a side view of link **112**. Figs. 7E and 7F show a side view and a diagonal view of two adjacent links **112** respectively where the respective heights of the parallel surfaces can be seen. For simplicity, only the connection portion including the distal portions of the proximal link and the proximal portions of the distal link are numbered. The adjacent links are connected such that the following apertures are aligned from top to bottom – **117a** (of distal link), **115a** (of proximal link) and **118a** (of distal link). A connecting shaft (not shown) is inserted through all three apertures connecting the links together allowing the joint angle between the links to vary, thus being a rotational joint wherein the distal link is rotationally displaceable (with respect to the axis being the shaft) in relation the proximal link.

With respect to two connected adjacent links, preferably, the thickness of surface **115** (of the distal link) is such that it is tightly fitted between surface **117** (of proximal link) and surface **118** (of proximal link). Preferably the thickness of surface **118** (of distal link) is tightly fitted within the space between surface **115** (of the proximal link) and the top of wall **120** (of the proximal link). These tight fittings contribute to the stability of the connection of the links and to the joint angle change while maintaining a position on the same aligned plane.

Preferably, at the connection area between two adjacent links, the space between surfaces **117** and **115** is curved and

complementary to surface **115**. Preferably, the space between surface **115** and top of wall **125** is curved and complementary to surface **118**.

Figures 8A-8C show an embodiment (at different angles) of the mobile actuator **150** movable on the connected links. The mobile actuator **150** is hollow and when in motion the connected links pass through the hollow portion. The connected links are surrounded by the mobile actuator **150** elements. Mobile actuator **150** comprises a bottom surface **151** having a thickness and two side arm surfaces **152** having a thickness, extending upwards from the sides of surface **151**. The top portion of mobile actuator **150** comprises a rack and pinion mechanism. The mobile actuator **150** comprises a first motor **155** configured to generating rotational movement. The motor **155** is connected to the top portion and is fixed thereto (typically passing through the top portion and protruding outwards). The motor **155** is configured to rotate the pinion element **156** (of the rack and pinion mechanism) which moves the rack element **157** accordingly. The pinion element **156** and the rack element **157** are a pair of gears which convert rotational motion into linear motion. The circular pinion element **156** engages teeth on a linear "gear" bar being the rack element **157**. Rotational motion applied to the pinion element **156** causes the rack element **157** to move relative to the pinion, thereby translating the rotational motion of the pinion into linear motion.

Figs. 8D-8F show the rack and pinion mechanism elements. The pinion element **156** has a circular shape and comprises peripheral teeth at its edge. The rack element **157** is

straight and comprises teeth on its top portion that mesh with the pinion teeth. When the pinion element **156** is rotated its teeth (meshing with the rack **157** teeth) move the rack **157** sideways either to the left or right depending on the rotation direction. The rack element comprises two spaced apart protrusion elements **158** extending downwards therefrom. The protrusion elements **158** are spaced apart such that top portions of the links **112** can pass therebetween when mobile actuator **150** is in motion. Fig. 8G shows an example of motor **155** with a rotating shaft cross-section configured to being tightly fit with the pinion's **156** inner aperture (Fig. 8H) and rotate the pinion **156**.

The mobile actuator **150** is engageable with a position-determining element being clamp **141e**. When the mobile actuator **150** is in position to change the angle between two links **112**, the motor **155** rotates the pinion **156** which moves the rack **157** sideways thus one of the protrusion elements **158** pushes the clamp **141e** sideways thus changing the angle (around the connecting shaft axis) between two adjacent links **112**. Actually the distal link and thus the entire robot **110** from the distal link distally onward changes its angle according to how much the protrusion elements **158** pushes. It should be noted that the motor **155** force that causes the protrusion elements **158** pushing, is greater than the torsion force (of the torsion spring **140**) that pushes down on the proximal link top portion for fixation. After the rotation/pushing is carried out and a desired angle between the links is obtained, the rack **157** is returned such that the protrusions are placed such that top portions of the links **112** can pass therebetween when mobile actuator **150** is in motion. When wanting to change the angle in the

opposite direction – the motor **155** rotates in the opposite direction and thus the rack **157** moves sideways in the opposite direction and thus the other protrusion **158** moves the clamp **141e** sideways in the opposite direction causing an angle change in the opposite direction.

The mobile actuator **150** further comprises a second motor **160** configured to generate rotational movement for causing spinning motion of wheels that cause the traveling of the mobile actuator **150** distally and proximally along the connected plurality of links **112**. Optionally, the motor **160** may be connected to the bottom surface **151** and is fixed thereto (typically passing through the surface **151** and protruding downwards), in a similar manner as in the embodiment of motor **60**. Optionally, the motor is placed on the top of mobile actuator **150** (like in Figs. 8A-8C) and rotates a first gear which rotates a second gear which rotates a third gear (shown on the bottom of mobile actuator **150** in Fig. 8A). The third gear may be equivalent to the lower wheel gear **64** that rotates the wheel **163**, in a similar manner as explained hereinabove relating to motor **60** and wheel assembly **62** mutatis mutandis.

The mobile actuator **150** comprises a second wheel **173** mounted at its center on an axle pin (not shown) fixed to the surface **151** (said axle pin extending upwards) and configured to spin around the axis of the axle pin. Both upper wheels **163** and **173** are positioned horizontally.

The wheels **163** and **173** have a circular shape and are configured to enter channels **125** along both sides of wall **120** of the links **112** and travel along it within them (when

spinning). When motor **160** rotates wheel **163** in one direction the mobile actuator **150** travels distally, and when motor **160** rotates wheel **163** in the other direction the mobile actuator **150** travels proximally. According to one embodiment, the side wheels **163** and **173** are mounted such that they (preferably tightly) press wall **120** when mobile actuator **150** travels on the links **112** (and the same for the three wheels configuration of Figs. 3A-3B) contributing to efficient maneuverability.

Figs. 9A-9C show an embodiment of a mobile actuator comprising a gripper **250**. The gripper **250** according to this embodiment is connected to a supportive top portion **255** of the mobile actuator. The use of the gripper could be for obtaining an item at the distal end of the robot.

According to another embodiment of the present invention, other elements (e.g. a magnet, a welding power supply (welding unit), a scissors, an illumination unit, etc.) may be connected to the mobile actuator. This is advantageous as the robot links (after the distal link is positioned in the required location) remain in their position without needing to change their position, while the mobile actuator carries the elements for use at the distal destination and back to the proximal base. This may be advantageous as there is no need to move links which saves in maneuvering/energy, and may be faster.

Optionally, the base **4** may connect to a stable end effector of an additional robot or to a movable actuator of an additional robot.

The maneuvering of the MASR may be according to a joystick, e.g. a two channel joystick, one channel used to drive the mobile actuator forward and backward along the links and the other to rotate the links clockwise or counter clockwise. According to this embodiment the mobile actuator comprises a receiver to receive the joystick commands and a controller coupled thereto that is coupled to the motors for providing the operational joystick commands to the motors. The user decides in real time which joint to adjust and how much to adjust it.

According to another embodiment of the present invention, the maneuvering of the robot is carried out by a motion planning. In this embodiment the mobile actuator comprises a processing unit (e.g. processor, controller) that comprises a memory for storing and carrying out operational commands to the motors of the mobile actuator for traveling to the required joints and carrying out the required positioning between the desired relative links. The processing unit is coupled to the motors of the mobile actuator. Optionally the processing unit is also coupled to a receiver configured to receive operational commands regarding the links positioning and control the motors accordingly.

According to one embodiment, the memory remembers all the history of the adjusted links position and carries out the new commands in accordance with the current position state of the joint (that has been stored in the memory).

According to another embodiment of the present invention, the mobile actuator and the links comprise position

encoders (e.g. angle transducers/sensors) for determining the current position between the links. The position data is received from encoders, e.g. a rotary encoder (a shaft encoder) configured to detect the angular position between two adjacent links. For example an encoder unit comprising one identifiable element attached on one link (e.g. on its proximal side) and another identifiable element on the adjacent link (e.g. on its distal side). The encoder sensor, attached to the mobile actuator, reads the relative angle between those two parts when arriving at the joint between the links.

According to this embodiment, it is enough for the memory only to remember the requested current angles without needing to remember the link positioning history since the requested joint angle (to be adjusted) can be read and adjusted in accordance with the current reading.

The mobile activator and the links may comprise elements of a linear encoder so that the mobile actuator can travel to the precise location on the joint in order to carry out the position adjusting. The mobile actuator comprises a sensor/transducer or readhead that can be paired with a scale that encodes position/location. When the sensor reads and acknowledges the scale it informs the controller which stops the motor driving the mobile actuator, thus the mobile actuator stops. The sensor may be placed at a location across from a corresponding scale on the link where it can read said corresponding scale on the link. For example, the sensor (also coupled to the processing unit/controller) may be placed on top of surface **51** facing upwards and the corresponding scales (each scale may have a

different reading indicating a different joint/link) may be placed beneath surface **18** facing downwards such that they become aligned when the mobile actuator is in a position engageable with a position-determining element (gear wheels **35**, clamp **141e**) of the respective link. Optionally a dedicated sensor may be used for the linear scale and the position/angle encoding.

According to another embodiment of the present invention, the mechanical mechanisms causing the positioning between adjacent links can vary (e.g. based on revolute, spherical, planar, cylindrical, edge slider, point slider mechanisms etc.).

According to an embodiment of the present invention, the orientation between two adjacent links may be adjusted by the mobile actuator in the three dimensional space (e.g. sideways horizontally and also vertically). The motion of the robot can be extended into three dimensional space. This can be achieved in multiple methods. Optionally, this can be carried out without modifying the mobile actuator and by fixing some of the axes of the joints to be non-parallel to each other. This will allow to move out of the imaginary plane that the links are disposed on (as explained herein). An optional embodiment may include the axes of two successive joints being perpendicular to each other.

Another embodiment comprises the joints of the links having more than one degree of freedom such as a U joint of spherical joint. In such a case the mobile actuator will be fitted with two or three motors (excluding the motor that

advances over the links) to actuate the U joints of the spherical joints.

Other embodiments may include one motor for the horizontal axis (e.g. the motor powers a gear engageable with a horizontal position-determining element on the link moving the distal link sideways on the same imaginary plane as described hereinabove) and another motor that powers an element (e.g. an additional gear at a different place on the link) engageable with a vertical position-determining element on the link (at a corresponding place) that is configured move the link vertically (e.g. moving the distal link upwards/downwards on the vertical axis). Other embodiments may include one motor for the horizontal and vertical positioning wherein the engageable element powered by the motor engages the horizontal position-determining element at a certain location about the joint and engages the vertical position-determining element at a different location about the joint. Appropriate encoders (e.g. as explained herein) are provided at the necessary locations so that the mobile actuator will stop at the appropriate locations to activate the desired actions.

A non-limiting example may be the worm gear mechanism explained hereinabove further comprising a vertical half worm wheel on a proximal link meshing with a corresponding vertical worm screw on its distal adjacent link. This example comprises three motors, one for driving the mobile actuator, the second for rotational displacement on the same plane (as in the embodiment explained hereinabove) and the third motor powering a gear that meshes with additional wheel gears that activates the vertical wheel gear

mechanism, thus repositioning the distal link upwards or downwards (on the vertical axis) in relation to the initial imaginary plane the links were disposed on.

Optionally the actuator may distance two adjacent links from each other or bring them closer together based on a prismatic joint mechanism.

According to an embodiment of the present invention, worn out motors may be easily replaced with new stronger motors. Optionally, the motors may be chargeable and thus recharged.

The present invention may be comprised of various materials according to a dedicated application. For example, the links (including surfaces) may be comprised from plastics or 3D printing materials, e.g. Verogray material (for example by using an Objet Connex 350 3D printer). The gears (e.g. gear wheels) may be comprised of plastics. The wheel arrangements may be comprised of plastics. The wheel portions that engage the channels (e.g. **63, 73, 163, 173**) and travel therethrough may comprise tires comprising rubber. The Actuator arms and bottom surface, the worm screw and the Rack **157** and Pinion **156** elements are preferably comprised of plastic. The shafts **32, 132, 39, 54,** the fixation element **141** and torsion spring are preferably comprised of steel.

The sizes of the robot may vary from millimeters to dozens of meters. For some specific applications the length of each link may be from 3cm to 10 cm, or from 10cm to 15 cm,

or from 15cm to 20 cm. The elements of the link and the size of the mobile actuator may vary accordingly.

The motors of the present invention may be, for example, Pololu - 1000:1 Micro Metal Gearmotor HPCB 12V with Extended Motor Shaft. The battery powering the motor may be, for example, Lithium Ion batteries 3.7Volts.

The controller of the present invention may be, for example, teensy 3.2. The encoder assembly of the present invention may be, for example, Pololu - Magnetic Encoder Pair Kit for Micro Metal Gearmotors, 12 CPR, 2.7-18V (HPCB compatible).

Examples with highly redundant configurations

Example 1

To demonstrate the capabilities of the MASR, a motion planning situation was simulated with obstacles as summarized in Fig. 10. The planning was performed by a human operator. The MASR in this example comprises a base and ten links and joints (10 DOF) actuated by one mobile actuator. The goal of the robot is to grab the circle and bring it back to the robot's original configuration.

The task is composed of two main challenges. The first is going through the narrow pass of 15cm, and the second is reaching the target with the small section of the robot that went through the opening. Throughout the whole task, the robot must avoid colliding with the obstacles.

The robot accomplishes this task by having the mobile actuator translate and adjust the angles of the joints one at a time. The robot first passes through the narrow pass by transforming its second half into an arc like shape. Then, the mobile actuator passes through the pass and then rotates the links to reach the target. Since four joints and links went through the pass, the robot had four degrees of freedom to reach its target (only three are required in a 2D space to reach location and orientation). In total, only eight translational steps for the motor are required in each direction, demonstrating the dexterity and maneuverability of the MASR.

Table 1: Motion Summary of MASR. During each action, the mobile actuator rotates a specific joint by an angle θ or advances from joint (start) to another (end).

STEP	Turning [degrees] (joint/angle)	Translation (start-end)
Reaching the target		
1	+45	(1-1)
2	+45	(1-2)
3	-45	(2-6)
4	-45	(6-7)
5	-45	(7-9)
6	-45	(9-2)
7	+45	(2-9)
8	+30	(9-10)
Returning after grasping		
9	-75	(10-10)
10	-60	(10-9)
11	+90	(9-2)
12	+30	(2-10)
13	+30	(10-9)
14	+45	(9-7)
15	+45	(7-6)
16	-45	(6-2)
17	-45	(2-1)
total (absolute)	**840 [degrees]**	**48 L**

As shown in Table I, each stage of motion consists of rotating the given joint by the turning angle, then translating the actuator to the desired joint, and repeating the process. There are a total of eight actions required to reach the object, one action to grasp it, and another eight actions required to return to its initial state with the grasped object in hand.

Figure 10 shows snapshots of the animation of MASR equipped with a single mobile actuator reaching its target. Starting at (a), the mobile actuator advances to the center after rotating the base link (b). At (c), the mobile actuator rotates the six top links to make an arc shape and then returns to the base (d) to rotate the links and penetrate through the small cavity. The actuator travels again to the top links to rotate them towards the target (e). After reaching its target, the robot makes the inverse plan of a-b-c-d-e to return to its original configuration (f).

The bottom row of Table I shows that the sum total of degrees that the links rotate equals 840°, and the actuator translates a total of 48 link-spans. The total time of the maneuver thus equals the time required to perform both modes of action.

Example 2

To prove the feasibility of the MASR, a mobile actuator was designed and manufactured, with 10 links and a base. The robot parts were 3D printed using Object Connex 350 with nominal accuracy of nearly 50 microns using "Verogray"

material. In this version, the joint angle is passively locked by a spring applying a friction force. To increase the friction force sand papers were glued to the links and a metal screw was attached to the clamp. Fig. 11A shows a top and bottom view of two adjacent links. The relative orientation between the links is passively fixed by the clamps. At their bottom, the links have a track which allows the mobile actuator to travel along them to reach and actuate a desired joint. Each of the links is 2 cm wide and 5 cm long, giving the active section of the snake robot a total length of 50 cm. The weight of the mobile actuator is 102 grams, whereas the average weight of a links including the clamp and joint is nearly 25 grams. A magnet was attached to the tip of the last link in order to grasp the target. However, other grasping mechanisms can be added.

The mobile actuator (shown in Fig. 11B) has two motors. One motor actuates the wheels to drive the mobile actuator along the tracks of the links (thus traveling upon the links), and a second motor to rotate the links. The rotational motor is attached to a linear gear mechanism (rack and pinion), allowing the teeth to disconnect from the links or push them for rotation. The maximum relative angle between the links is 45 degrees. A 4 Volts Lithium-ion battery was used to actuate the motors. The speed of the locomotion is nearly 3 cm/s and the rotational speed is nearly 18 degrees/s. The robot is very modular and the number of mobile actuators and links is easily changeable. Motors with 1000:1 gear ratio were used which can produce 0.9 Nm of torque at 32 rpm. This torque is necessary to

overcome the friction torque between the different links and other external forces to produce motion.

During all of the experiments, the mobile actuator was remotely controlled by a human operator. The operator had a two channel joystick. One channel was used to drive the mobile actuator forward and backward along the links and the other to rotate the links clockwise or counter clockwise.

The system is passively locked with friction and the mobile actuator fitted with a strong motor overcomes the friction to rotate the links.

Example 3

In order for the robot to operate as planned, it must be able to perform the following mechanical operations:

1. Travel freely over the links forward and backward.
2. Travel over curved joints without changing their orientation (the links are passively locked).
3. Rotate the links.

The basic experiment is presented in Fig. 12A. The mobile actuator was tested going towards the end of the links and returning back with and without bending the links. In both cases, the robot had no difficulty travelling over the links or rotate them to either direction.

Starting at (a), the robot advances towards its tip (b-c), then returns to the center (d). The robot then rotates the links clockwise (e) and counter clockwise (f). The robot then travels over the curved joint (g) and rotates its tip

clockwise (h) and counter clockwise (i). The robot then moves to the tip (j).

As the joints can be rotated by 45 degrees to each direction, the robot can make a "C" shape (half a circle) by rotating 4 links in the same direction (counter clockwise). This experiment is illustrated in Fig. 12B.

Example 4

Fig. 13 shows the robot penetrating through a small pass to reach a target behind the wall. In the following experiment, the robot comprises 10 links. The robot is very modular and adding additional links can be done very fast. With this longer version, a task was performed in a similar manner to that of the example relating to Fig. 10.

Following a similar algorithm, the robot successfully reached its desired target. However, it was found that since the robot is made of printed material, it slightly cured downwards by nearly 1 cm. Even though the weight of the robot is larger and the torque acting on the links substantially increased, the links remained locked during the experiment.

Example 5

A snapshot of the MASR end effectors attempting to draw the letter Z (under maximum angular deviation of $\delta = 0.2$ rad) is shown in Fig. 14. For robot applications where the end effectors are tasked with tracing a path, this result has significant implications for the selection of actuators of

the MASR. The actuator, represented by the rectangle (at the left joint), translates from joint to joint.

While some of the embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be carried into practice with many modifications, variations and adaptations, and with the use of numerous equivalents or alternative solutions that are within the scope of a person skilled in the art, without departing from the spirit of the invention, or the scope of the claims.

CLAIMS:

1. A robot device comprising a chain comprising a plurality of fixedly connected links and a mobile actuator movable thereon configured to change a position of a link relative to a position of an adjacent link;
wherein said mobile actuator comprises at least a first motor to drive it along said chain of connected links; and
wherein said mobile actuator is engageable with a position-determining element in said link.

2. The robot device according to claim 1, wherein each of said links is responsive to a rotational movement generated in said actuator by a second motor coupled to said actuator such that said rotational movement affects the position of the link in relation to its adjacent link.

3. The robot device according to claim 1, wherein the changing of a position of a link relative to a position of an adjacent link is carried out by a worm gear mechanism.

4. The robot device according to claim 1, wherein the connection between two adjacent links comprises a shaft inserted in an aperture on a surface extending proximally from the distal adjacent link and in an aperture on a surface extending distally from the proximal adjacent link.

5. The robot device according to claim 1, wherein the changing of a position of a distal link of two adjacent links of the chain of links relative to a position of the proximal link of said two adjacent links is carried out by a worm gear mechanism;

wherein the proximal link of the two adjacent links comprises a worm wheel surface extending distally therefrom that engages with a worm screw attached on the proximal side of the distal link.

6. The robot device according to claim 5, wherein the worm screw is mounted on a rotatable horizontal shaft fixed on the proximal side of the distal link.

7. The robot device according to claim 6, further comprising at least one wheel gear fixedly mounted on the shaft such that when the wheel gear rotates the shaft rotates respectively.

8. The robot device according to claim 7, wherein the mobile actuator comprises a horizontal rotatable axle mounted thereon and at least one spinning gear element fixedly mounted on said horizontal rotatable axle such that the spinning gear element is engageable with the wheel gear.

9. The robot device according to claim 8, further comprising a second motor coupled to the mobile actuator configured to generate a rotational movement that rotates the horizontal rotatable axle.

10. The robot device according to claim 1, wherein the links further comprise two side channels along their length wherein each side channel is substantially continuous with its corresponding side channel of its adjacent link thus forming a track;

wherein the mobile actuator comprises two wheels mounted thereon configured to drive along said track.

11. The robot device according to claim 1, wherein the links are disposed on an imaginary plane; and
wherein the change of a position of a link relative to a position of its adjacent link is such that one of said adjacent links is rotationally displaceable, with respect to an axis substantially perpendicular to said imaginary plane, in relation the other adjacent link.

12. The robot device according to claim 1, wherein the changing of a position of a link relative to a position of an adjacent link is carried out by a rack and pinion mechanism.

13. The robot device according to claim 1, wherein the changing of a position of a distal link of two adjacent links of the chain of links relative to a position of the proximal link of said two adjacent links is carried out by a rack and pinion mechanism;
wherein the distal link of the two adjacent links comprises a fixation element extending proximally therefrom;
wherein said fixation element comprises a clamp extending downwards from said fixation element proximal end;
wherein said clamp is engageable with a top portion of the distal link, pushing down on it maintaining fixation therebetween.

14. The robot device according to claim 13, further comprising a torsion spring fixed at one of its ends to a portion of the distal link and fixed at its other end on

top of the fixation element such that the torsion force of the torsion spring applies a downward force causing the clamp to push down on the top portion of the distal link.

15. The robot device according to claim 14, further comprising a rotatable horizontal shaft fixed to the distal link;
wherein the torsion spring is mounted on said shaft; and
wherein the fixation element comprises at least one distal arm fixedly mounted on said shaft such that said fixation element is rotationally displaceable with respect to said shaft axis.

16. The robot device according to claim 13, wherein the mobile actuator comprises a circular pinion element and a linear rack element engageable therewith such that a rotational movement that rotates said pinion element around its central axis causes said rack element to move linearly;
said device further comprising a second motor coupled to the mobile actuator configured to generate a rotational movement that rotates said pinion element around its central axis;
wherein said linear rack element comprises two spaced apart protrusion elements extending downwards therefrom engageable with the clamp.

17. The robot device according to claim 16, wherein the protrusion elements are configured to push the clamp sideways when engaged therewith, upon a linear movement of the rack element causing said changing of a position.

18. The robot device according to claim 1, further comprising a second motor coupled to the mobile actuator and a controller coupled to the first and second motor configured to activate them.

19. The robot device according to claim 18, further comprising an encoder;
said encoder comprising a sensor attached to the mobile actuator and coupled to the controller and scales that encode location placed on or near the joints between two adjacent links.

20. The robot device according to claim 18, further comprising a rotary encoder;
said rotary encoder comprising a sensor attached to the mobile actuator and coupled to the controller, and pairs of two identifiable elements placed on or near the joints between two adjacent links;
wherein one of the identifiable elements of each pair is placed on the distal link of the adjacent links and the other identifiable elements of each pair is placed on the proximal link of the adjacent links.

Fig 1A

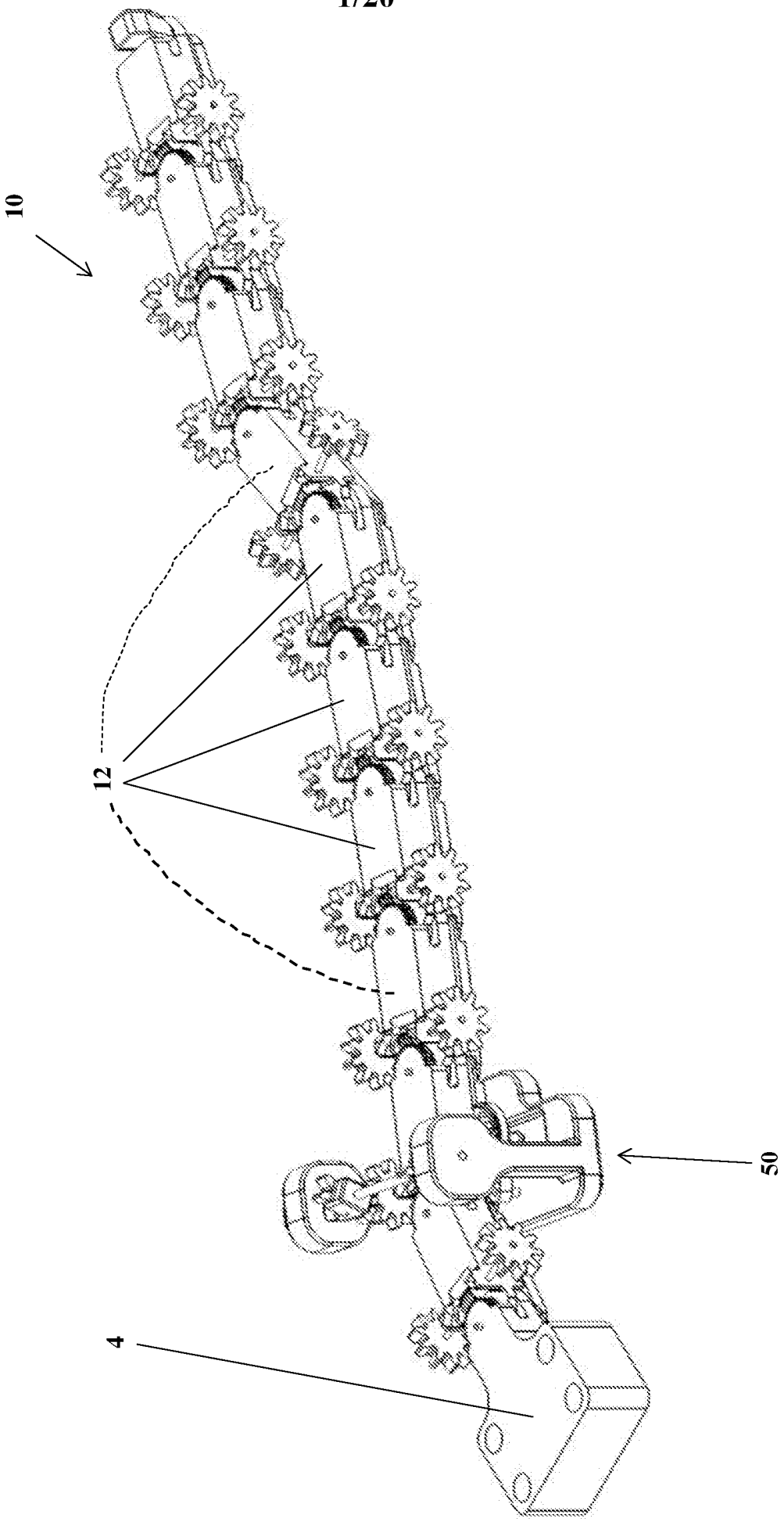

Fig 1B

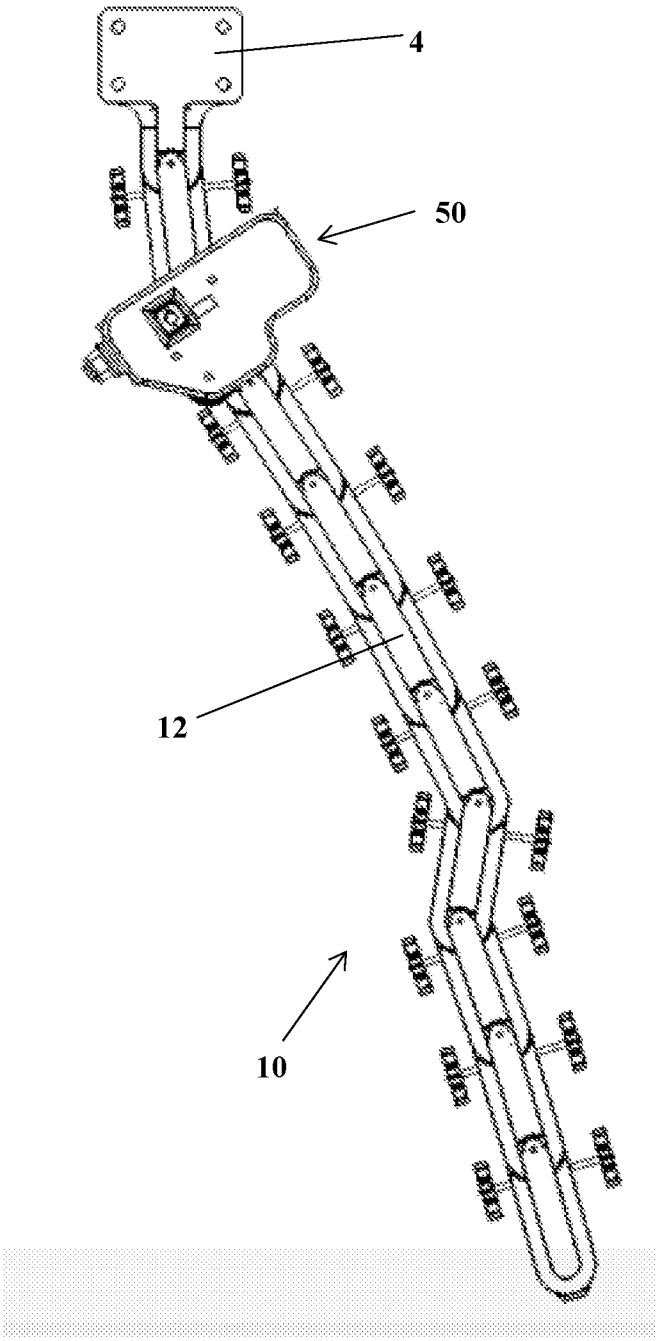

Fig 1C

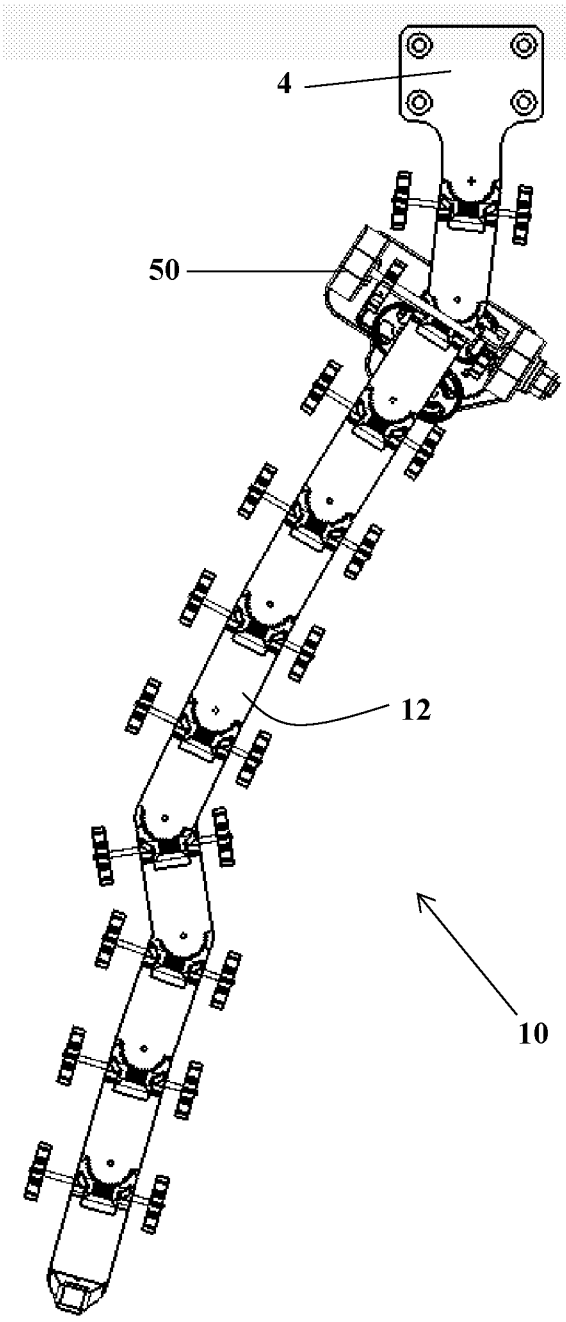

Fig 2A

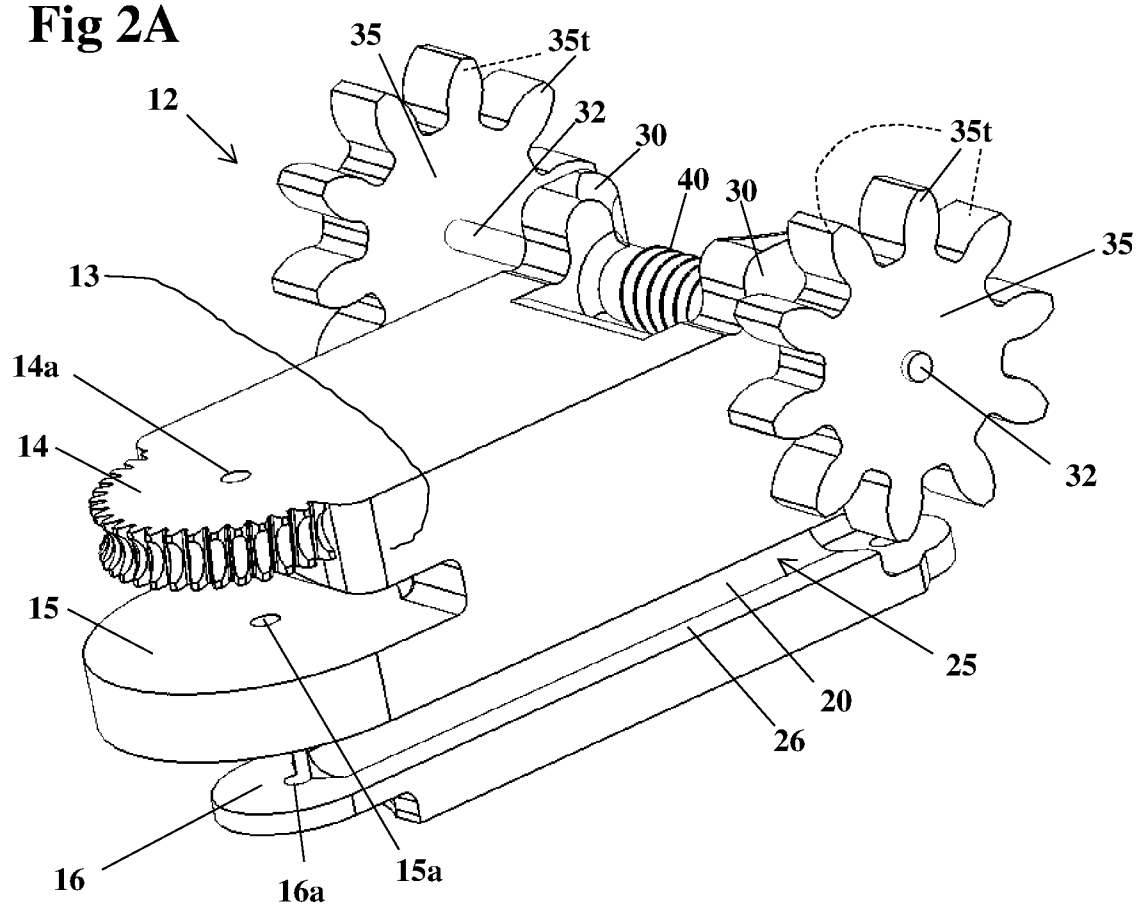
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Fig 2B

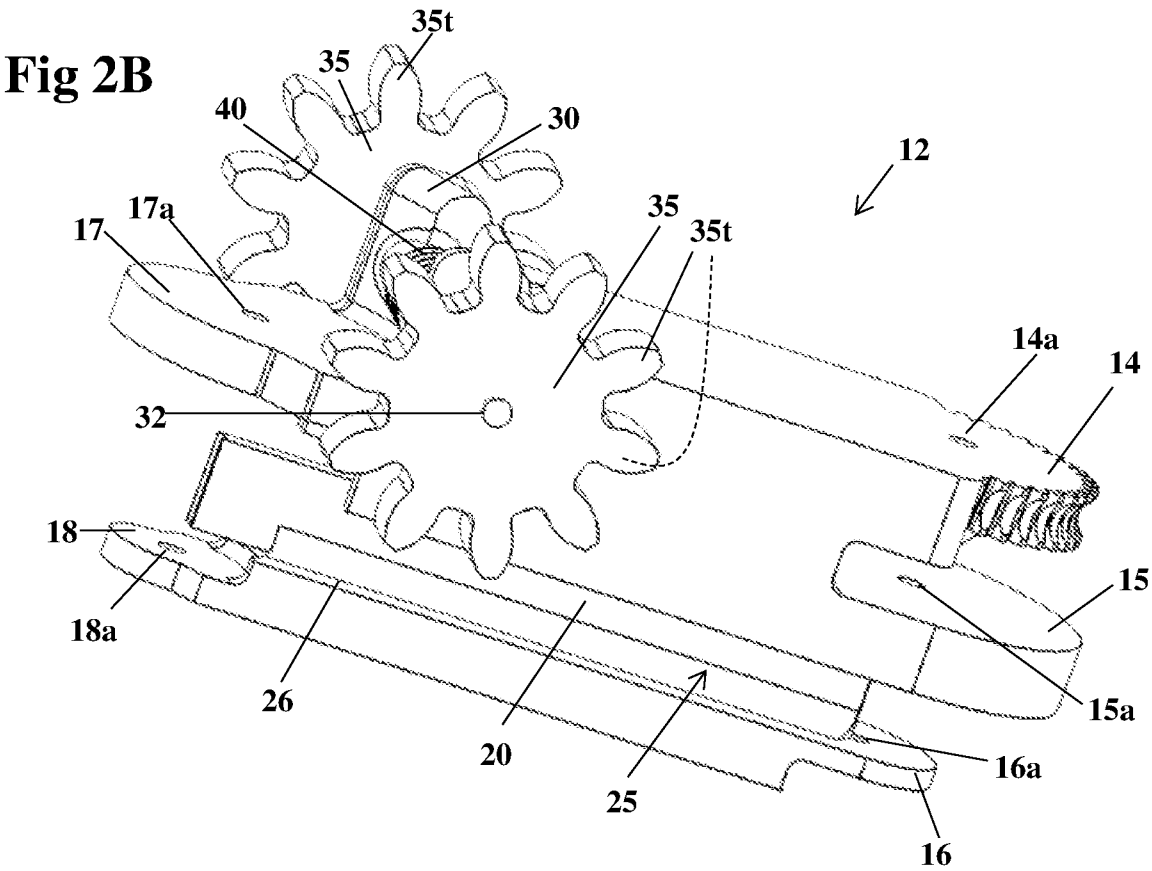
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Fig 2C

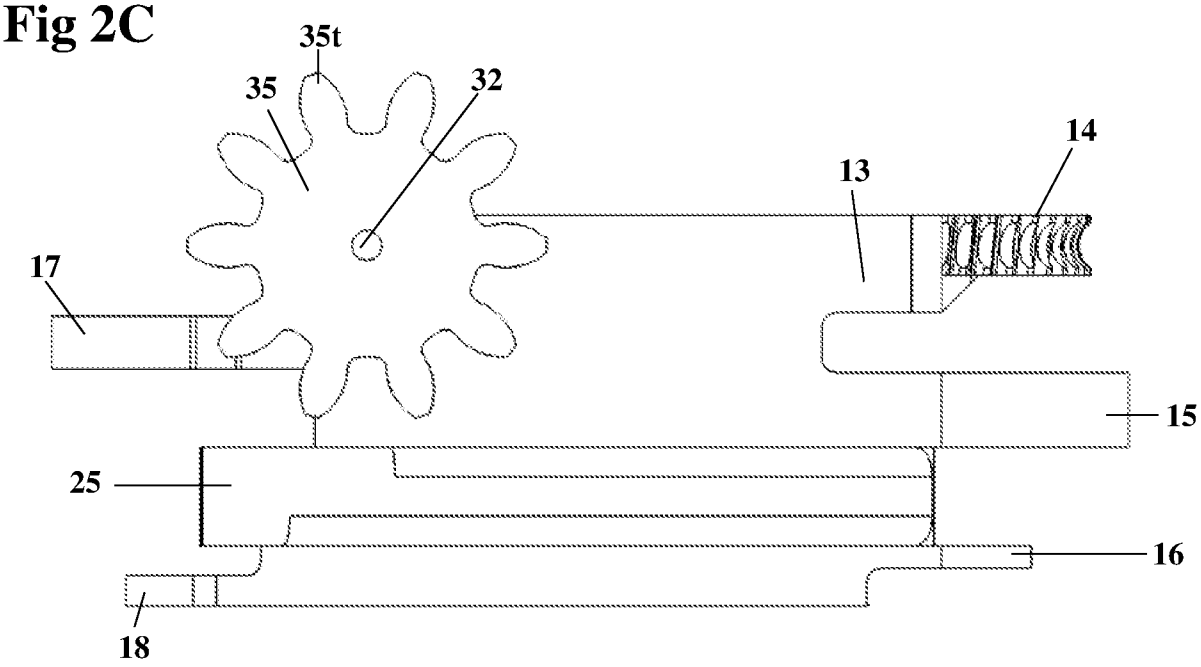


Fig 2D

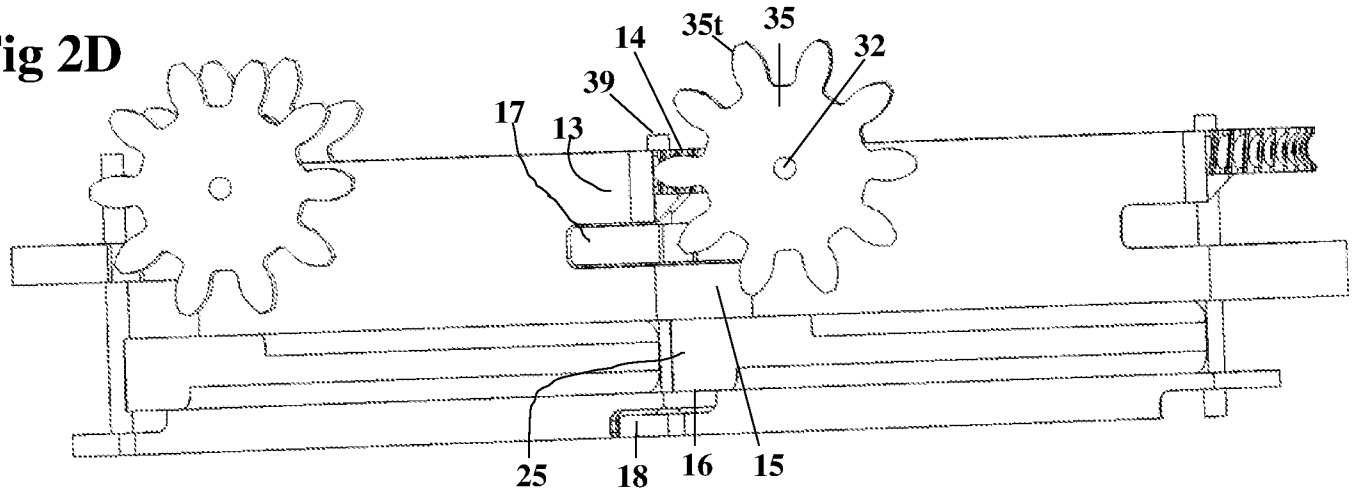


Fig 2E

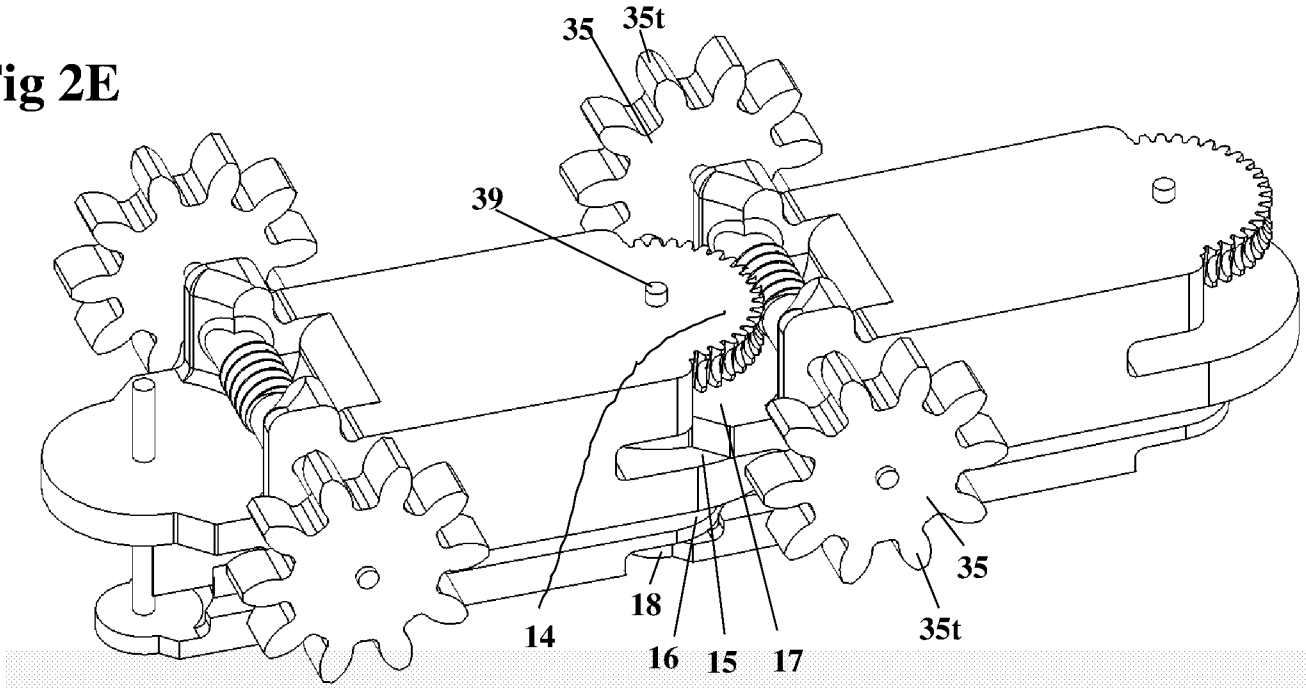


Fig 3A

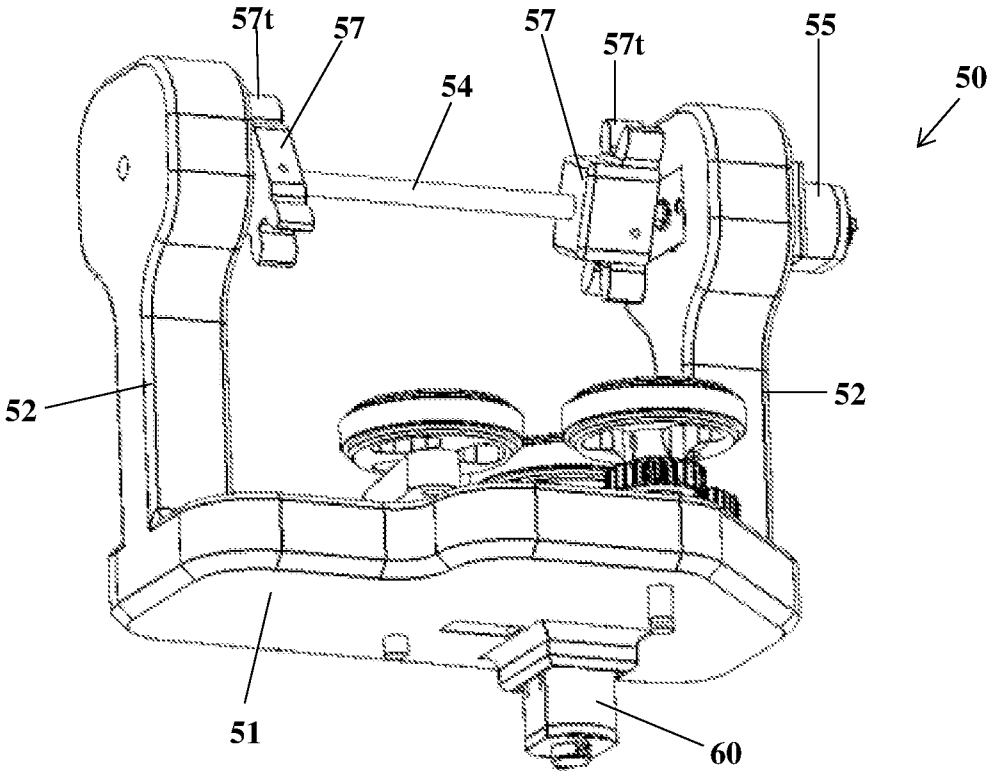
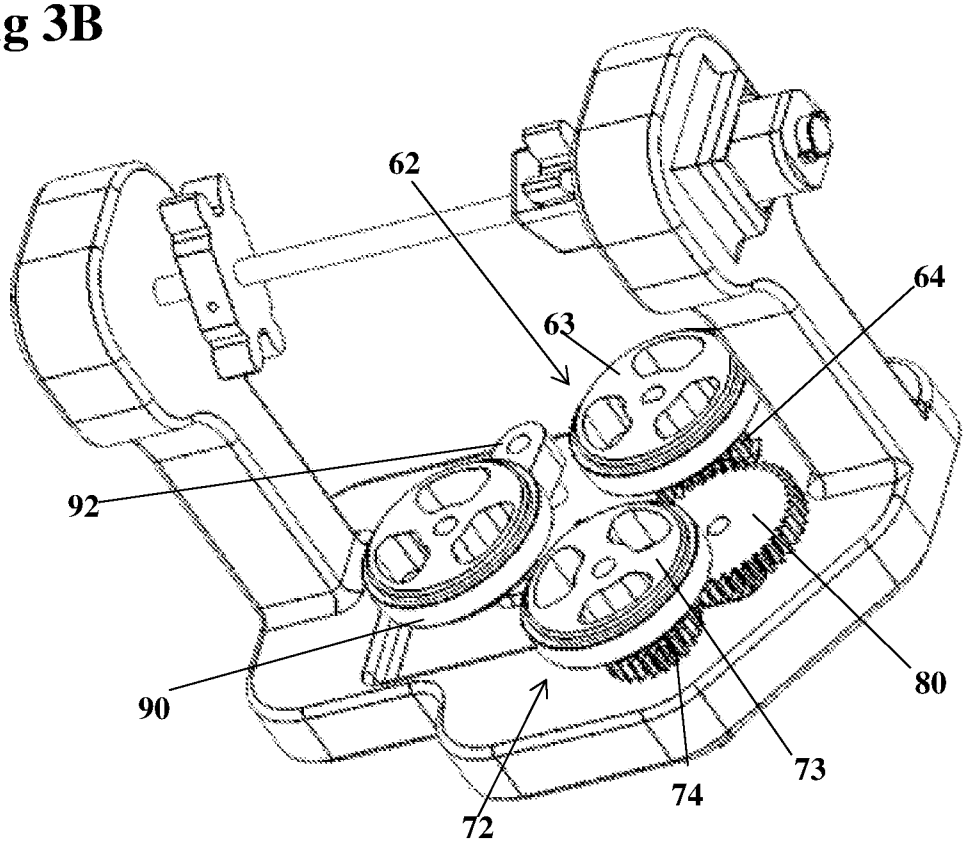


Fig 3B



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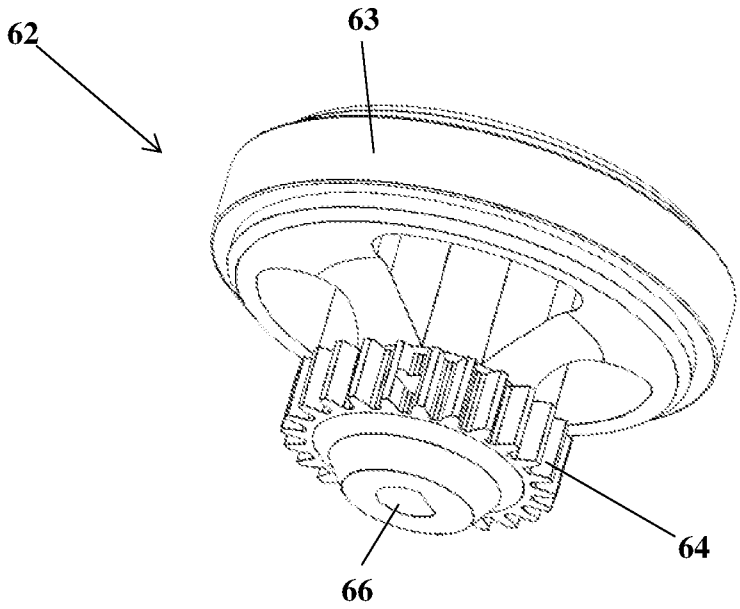


Fig 4B

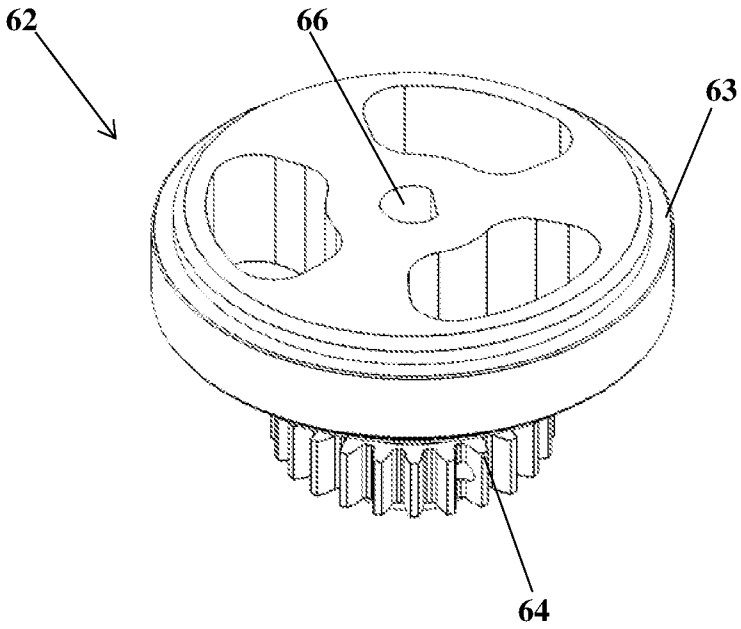
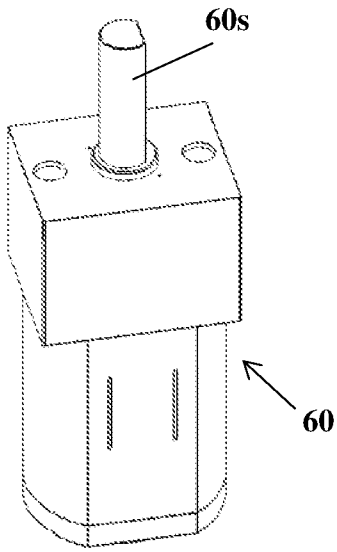


Fig 4C



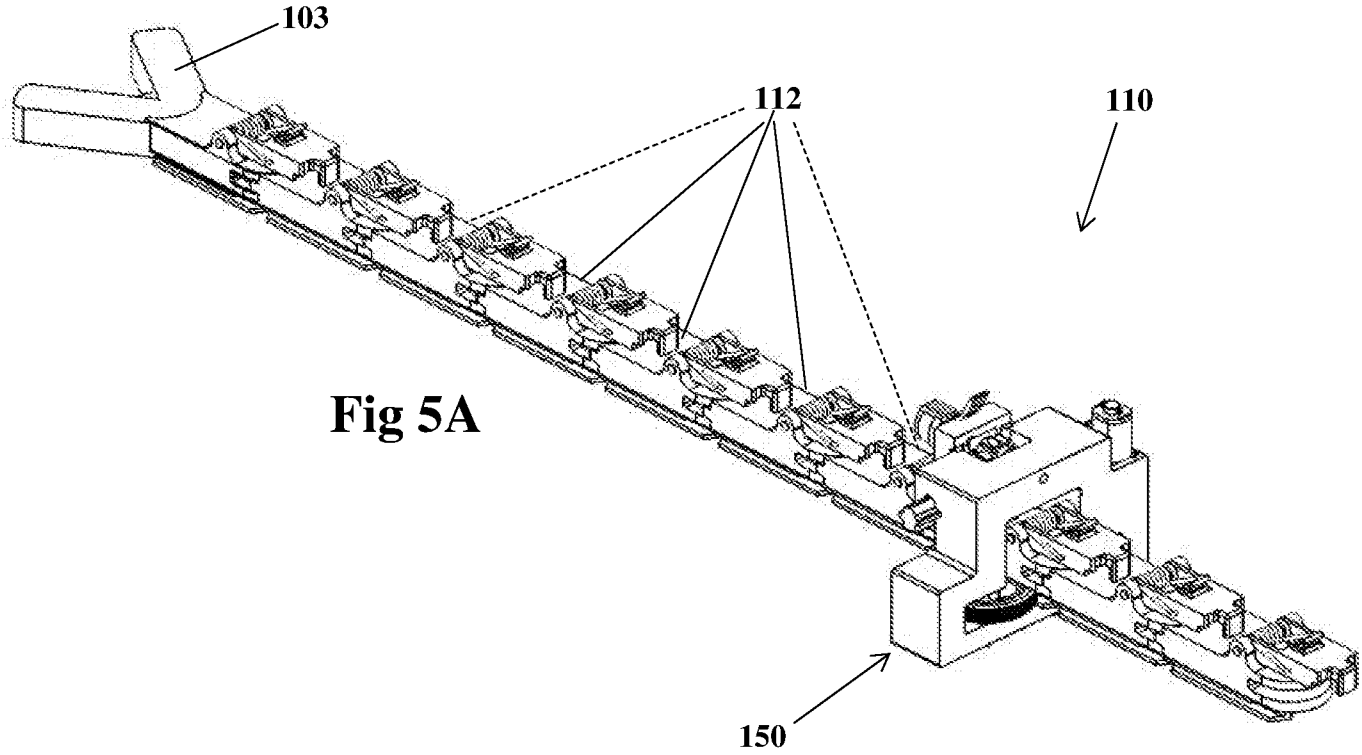


Fig 5A

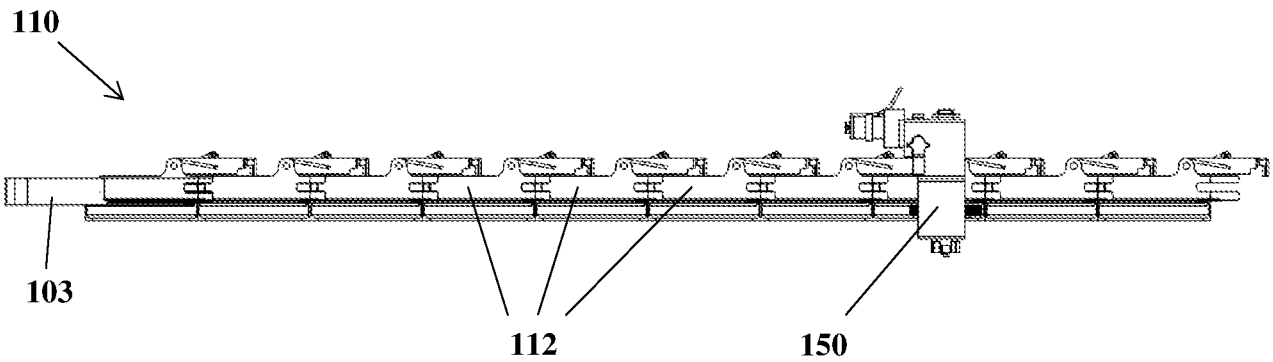
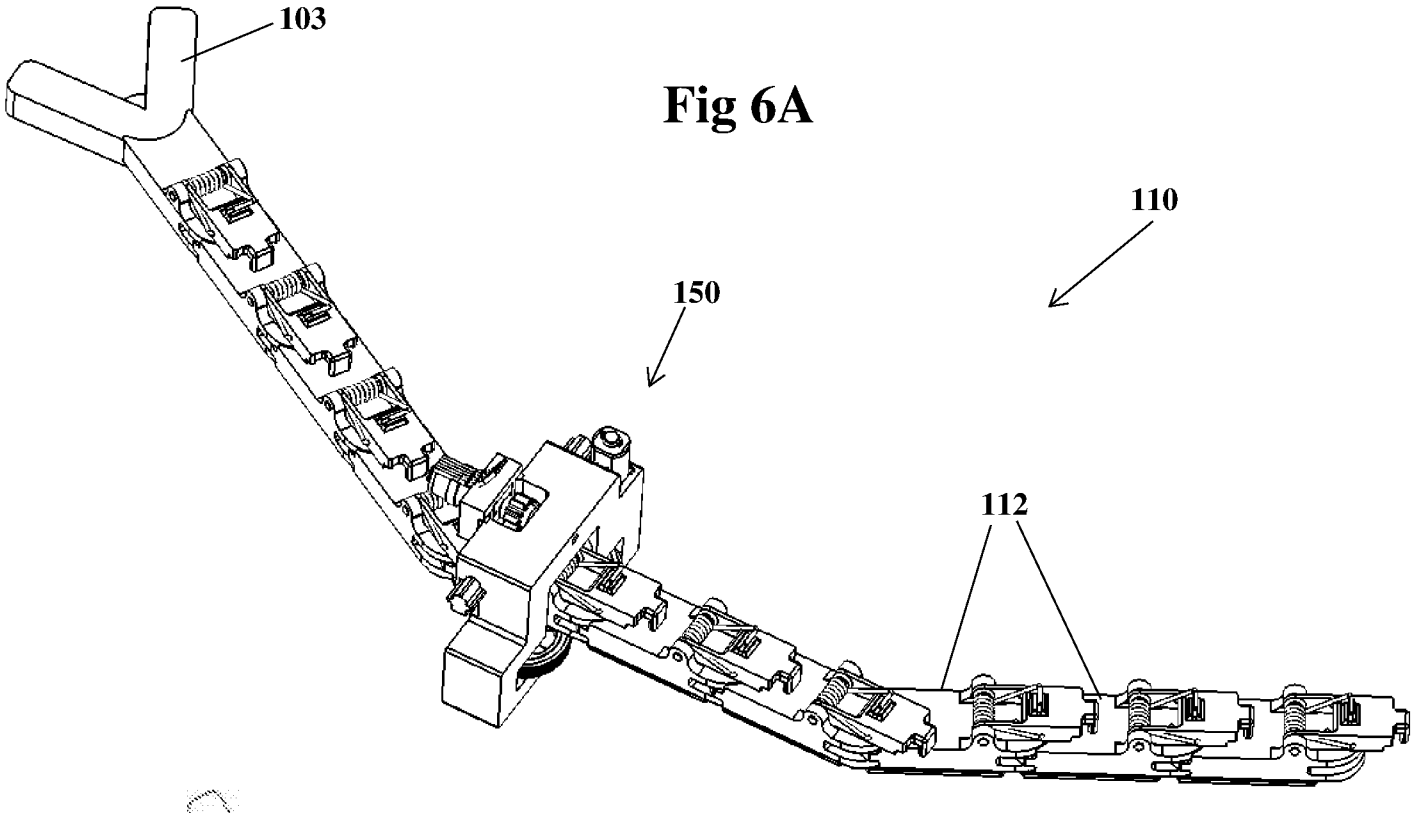


Fig 5B



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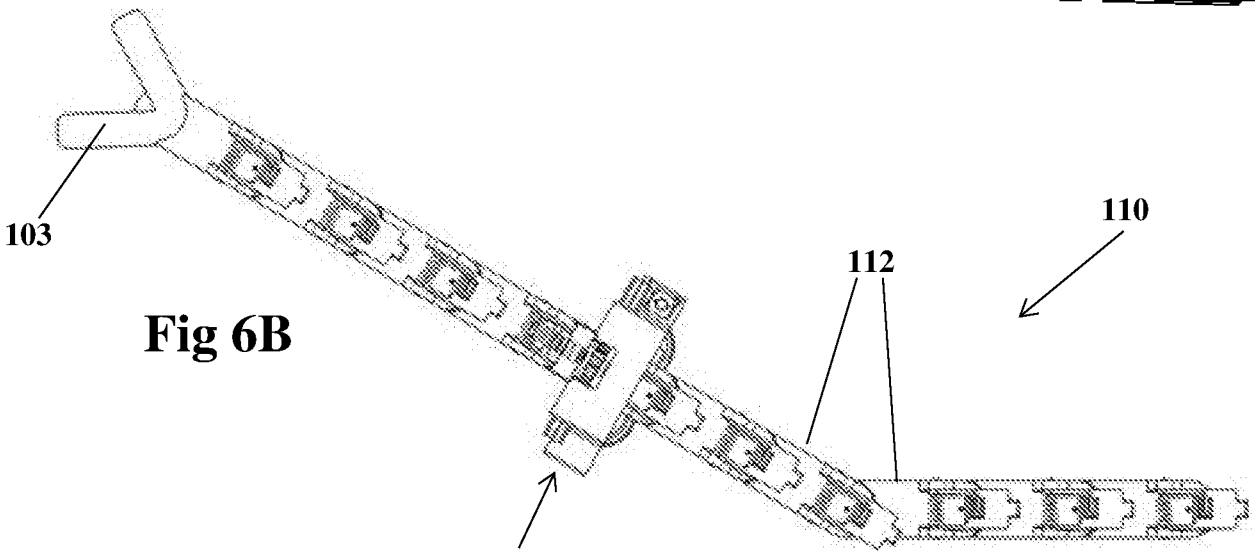


Fig 6B

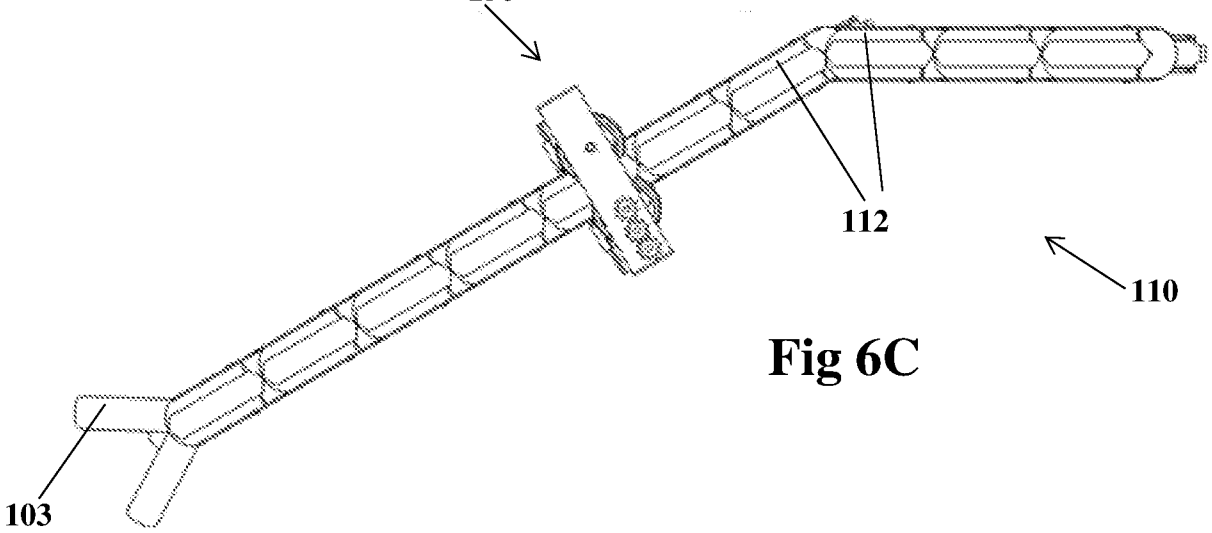
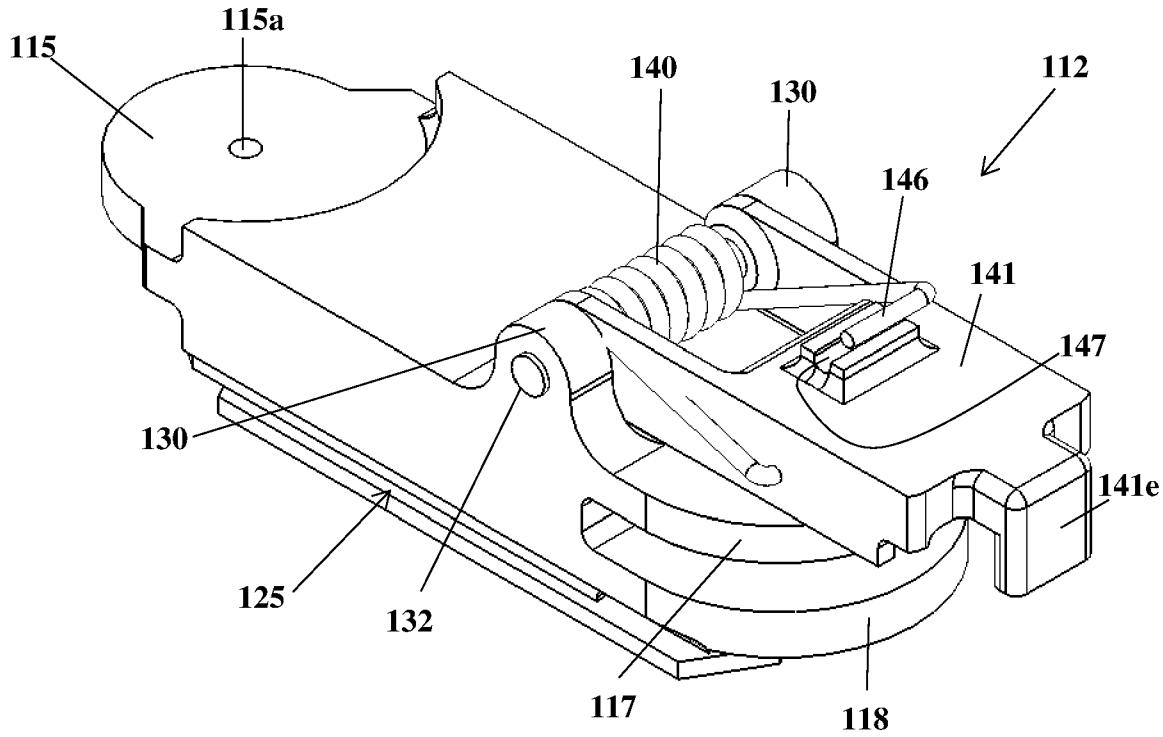


Fig 6C

Fig 7A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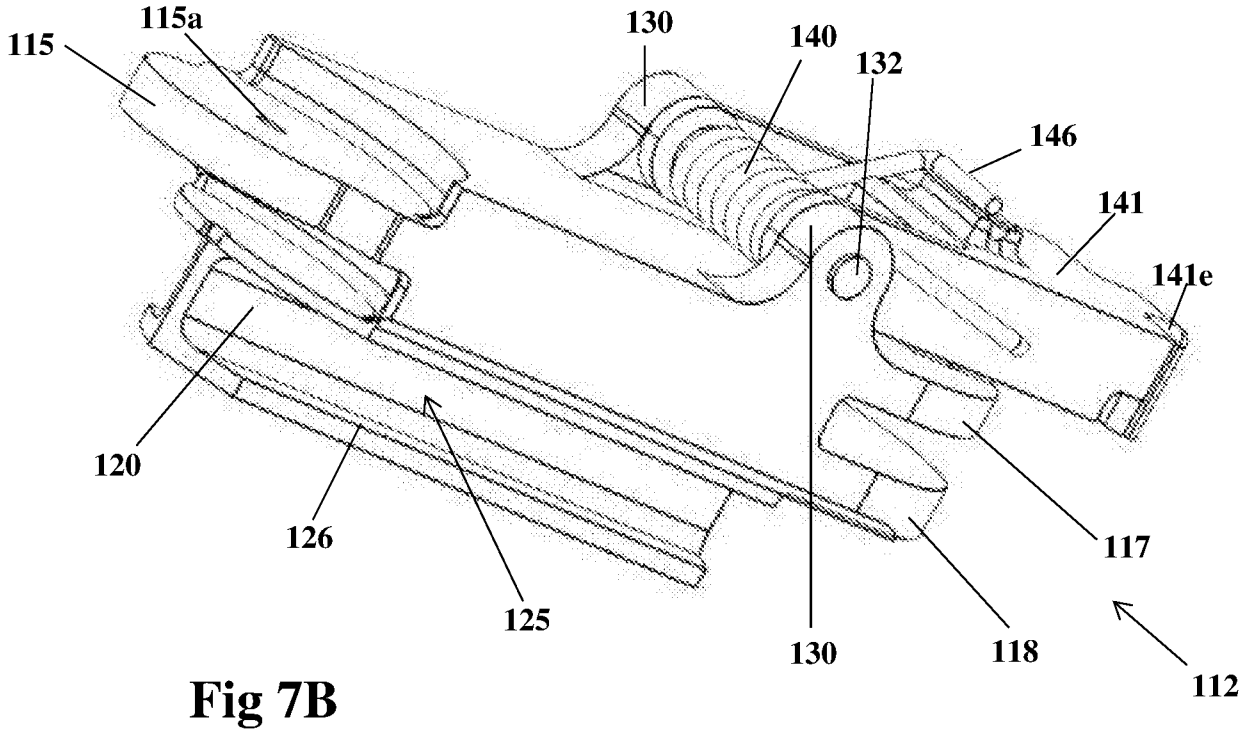
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Fig 7B

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Fig 7C

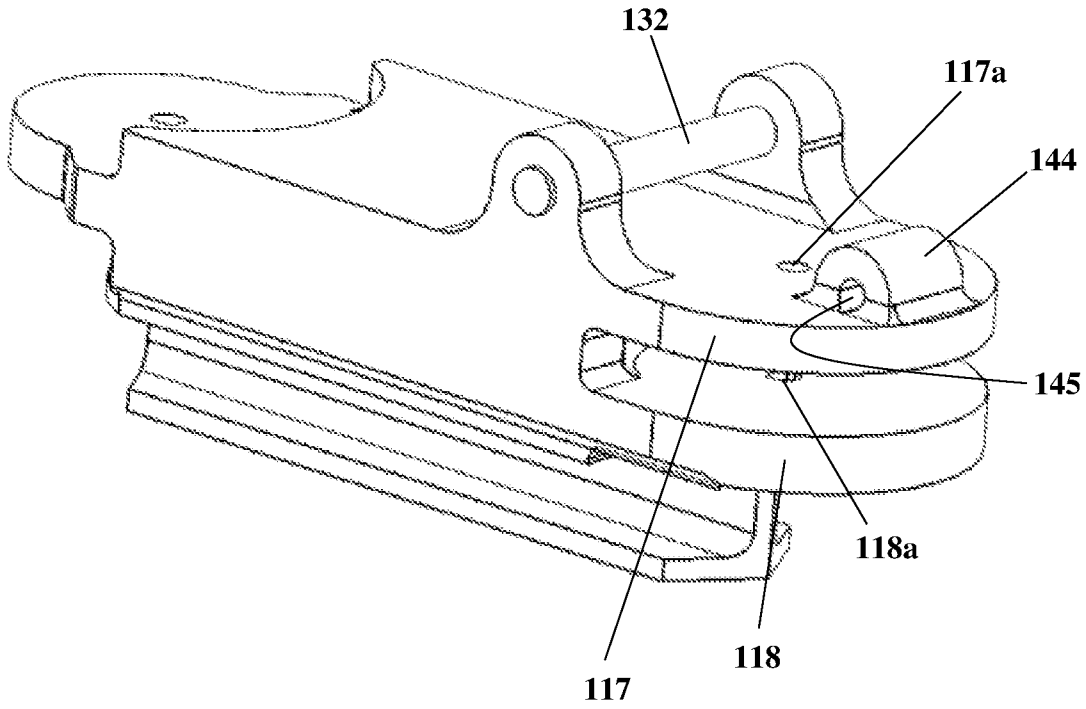
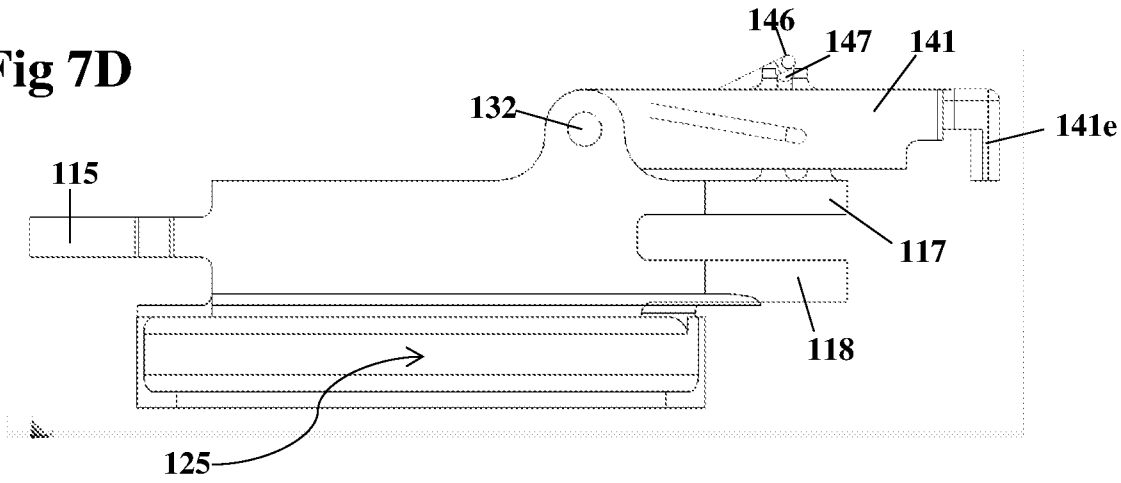


Fig 7D



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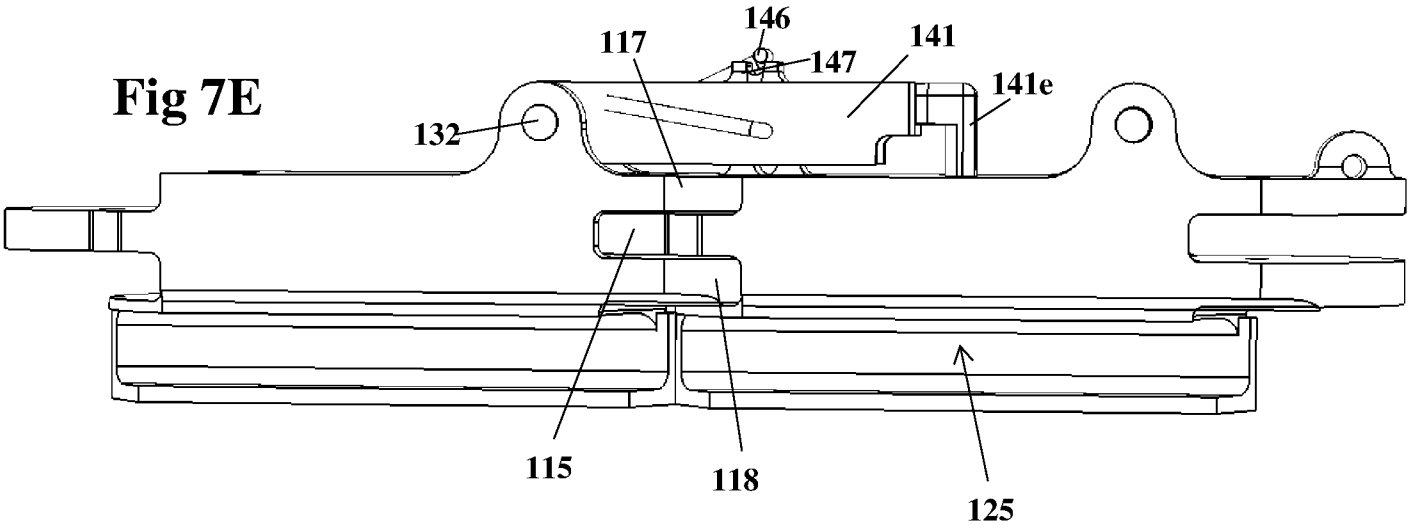


Fig 7F

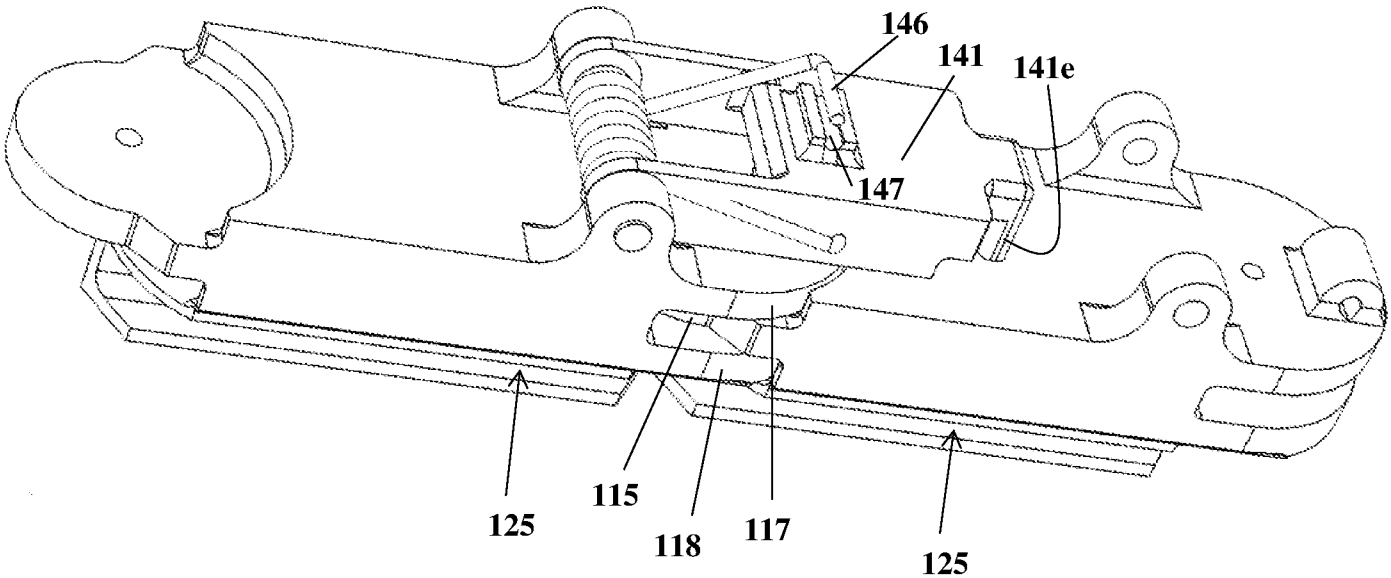
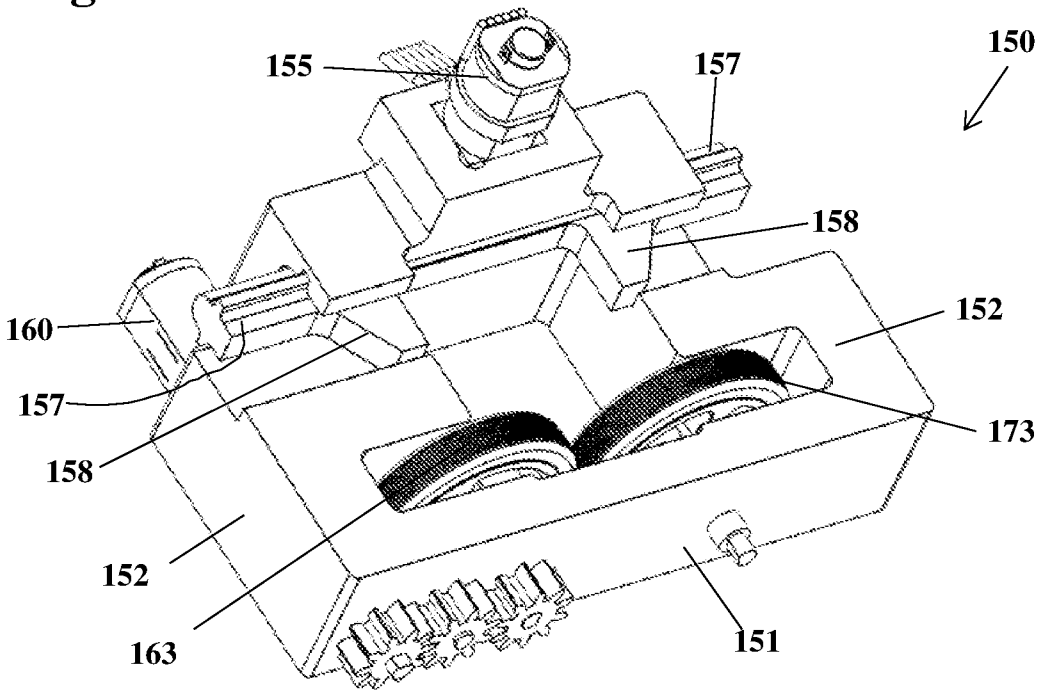


Fig 8A



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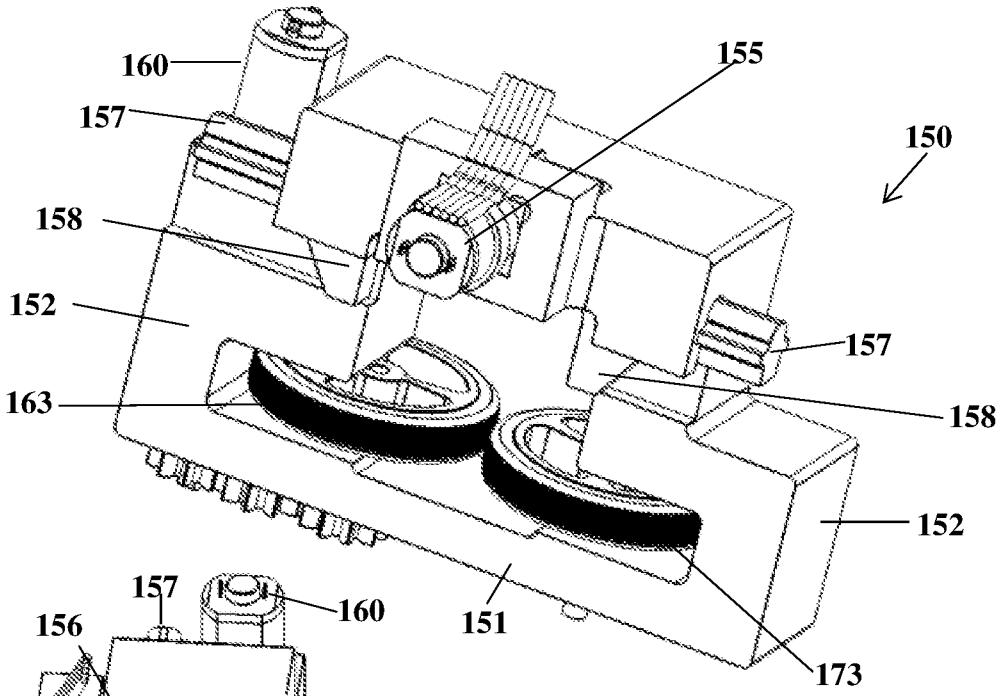

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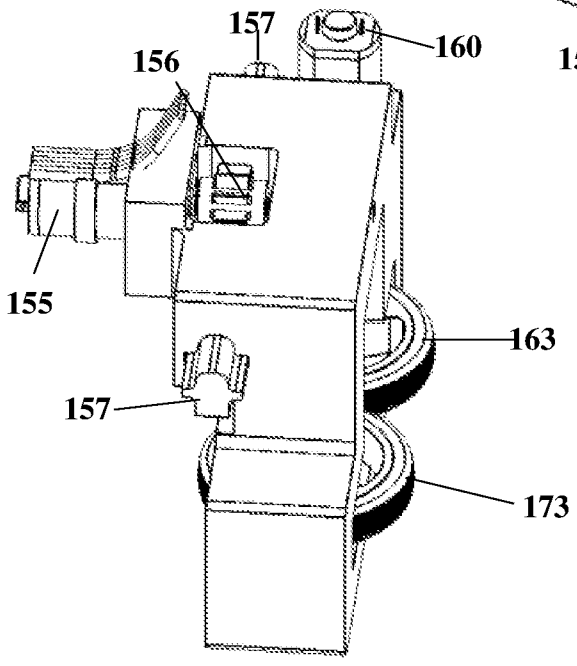


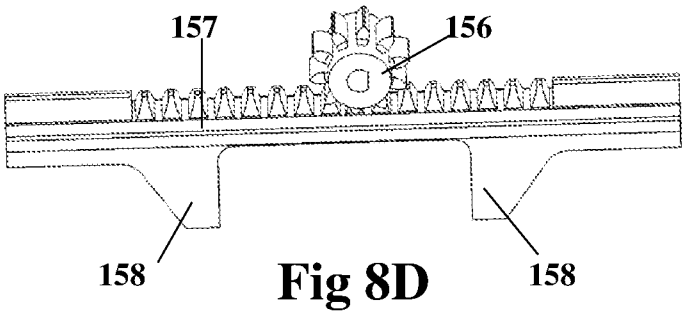


Fig 8D

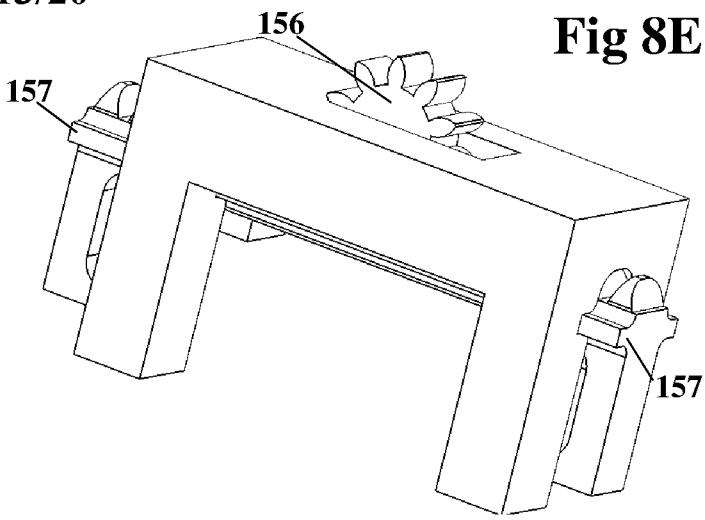
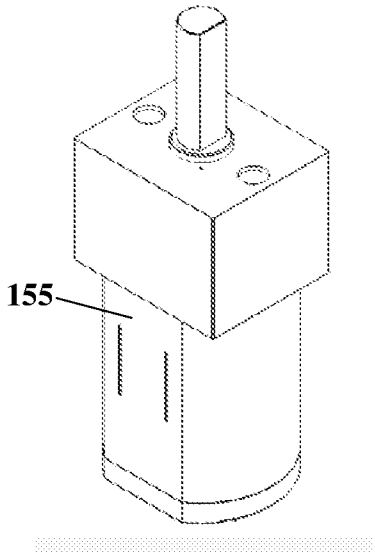


Fig 8E

Fig 8G



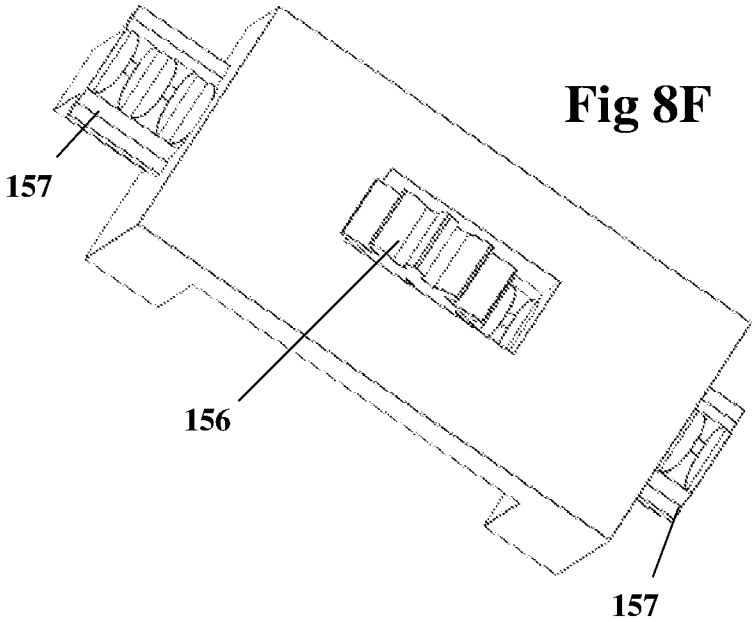
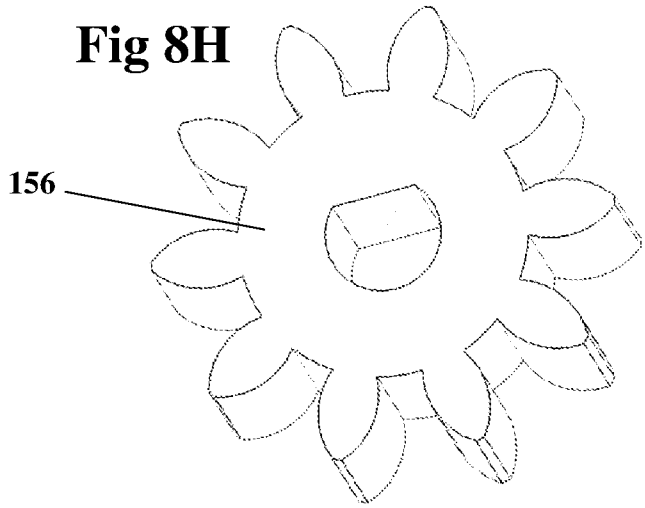


Fig 8F

Fig 8H



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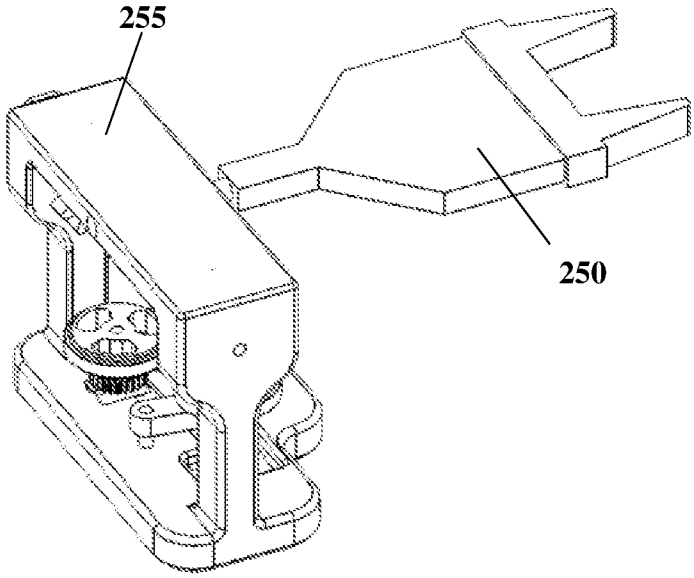

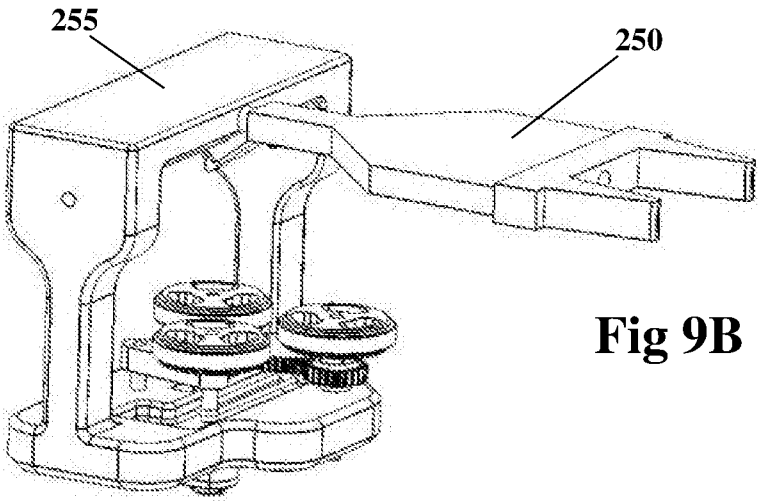

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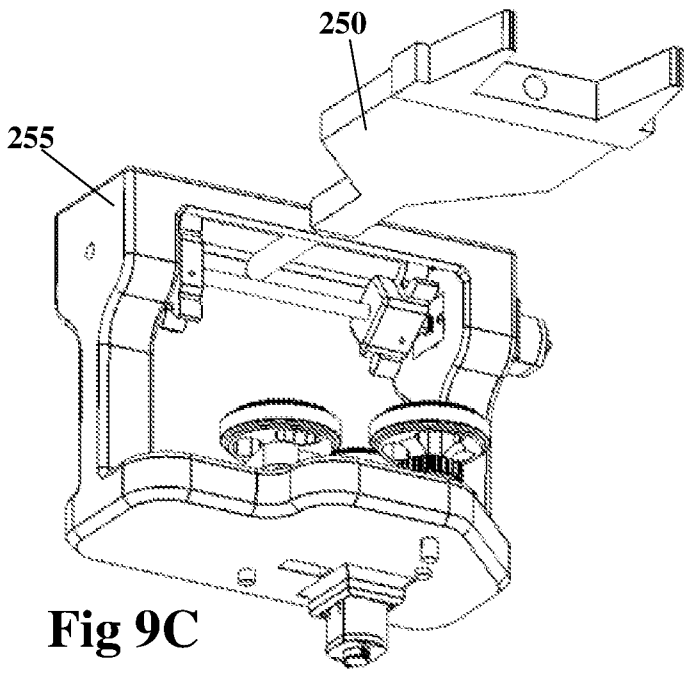
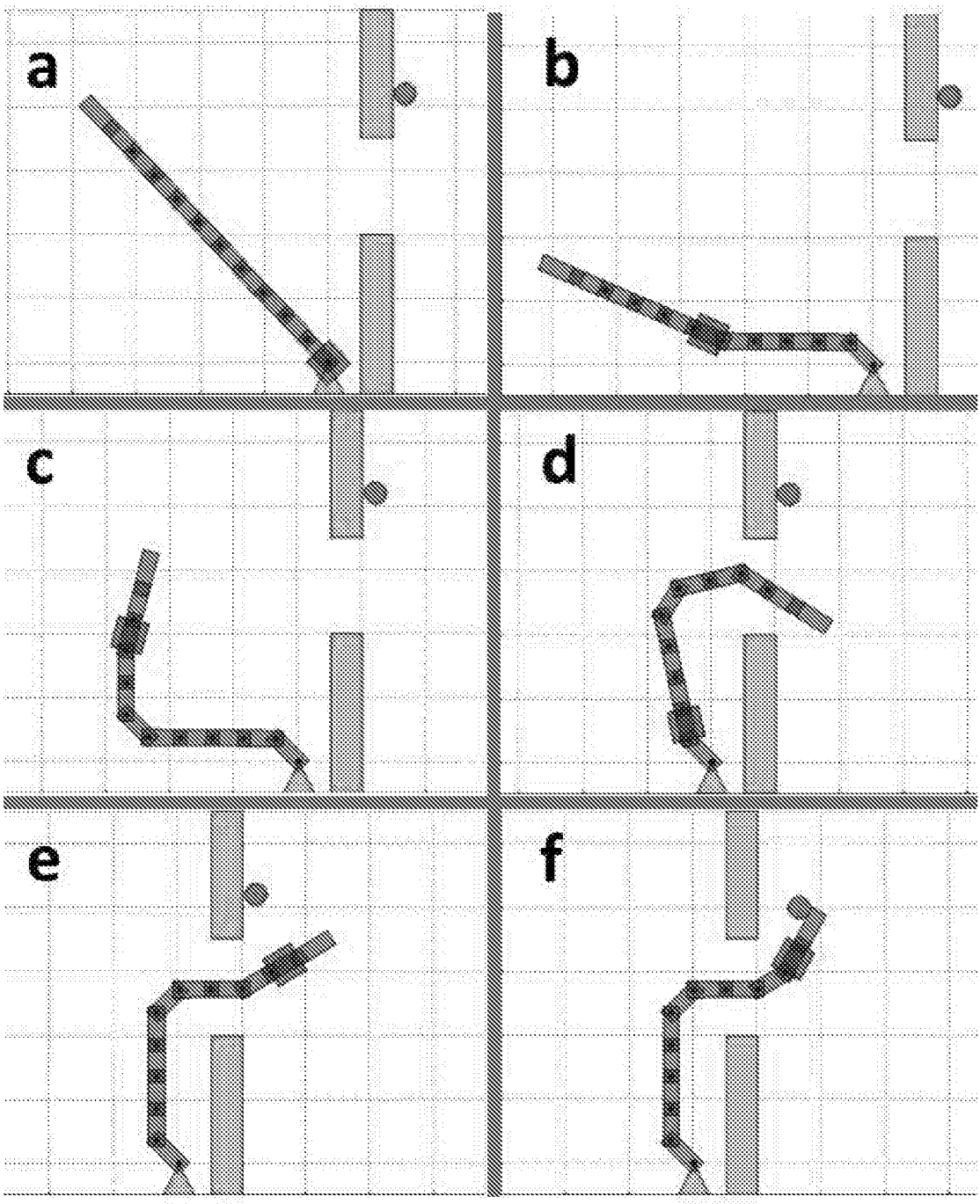
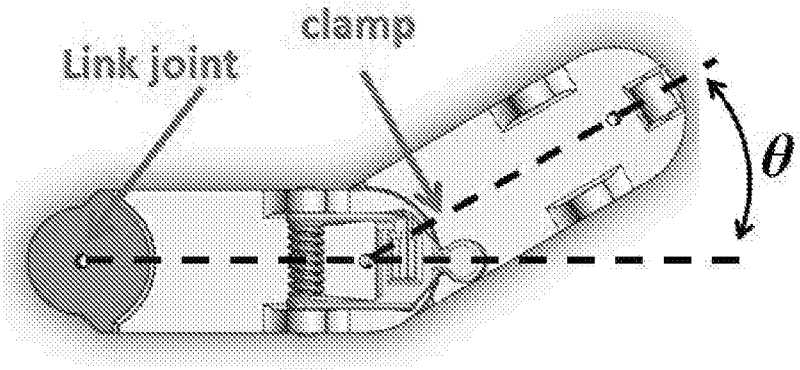


Fig 9C

Fig. 10





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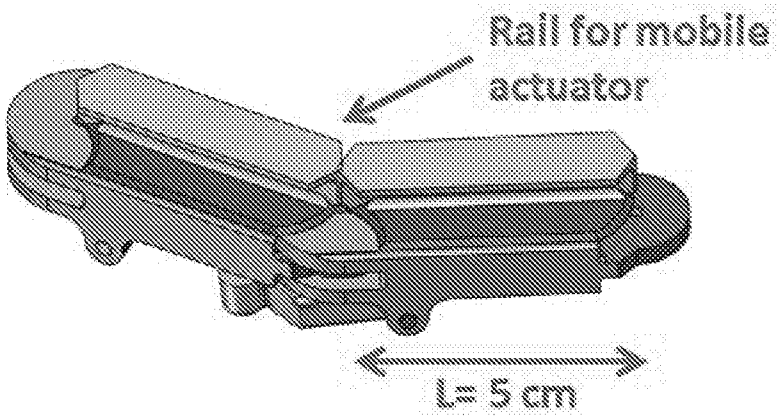


Fig. 11B

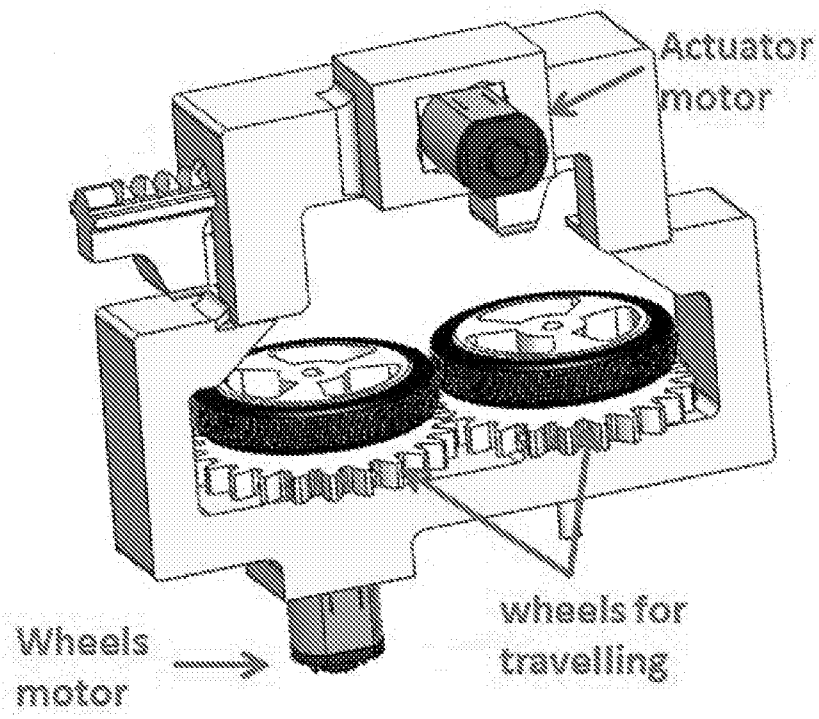
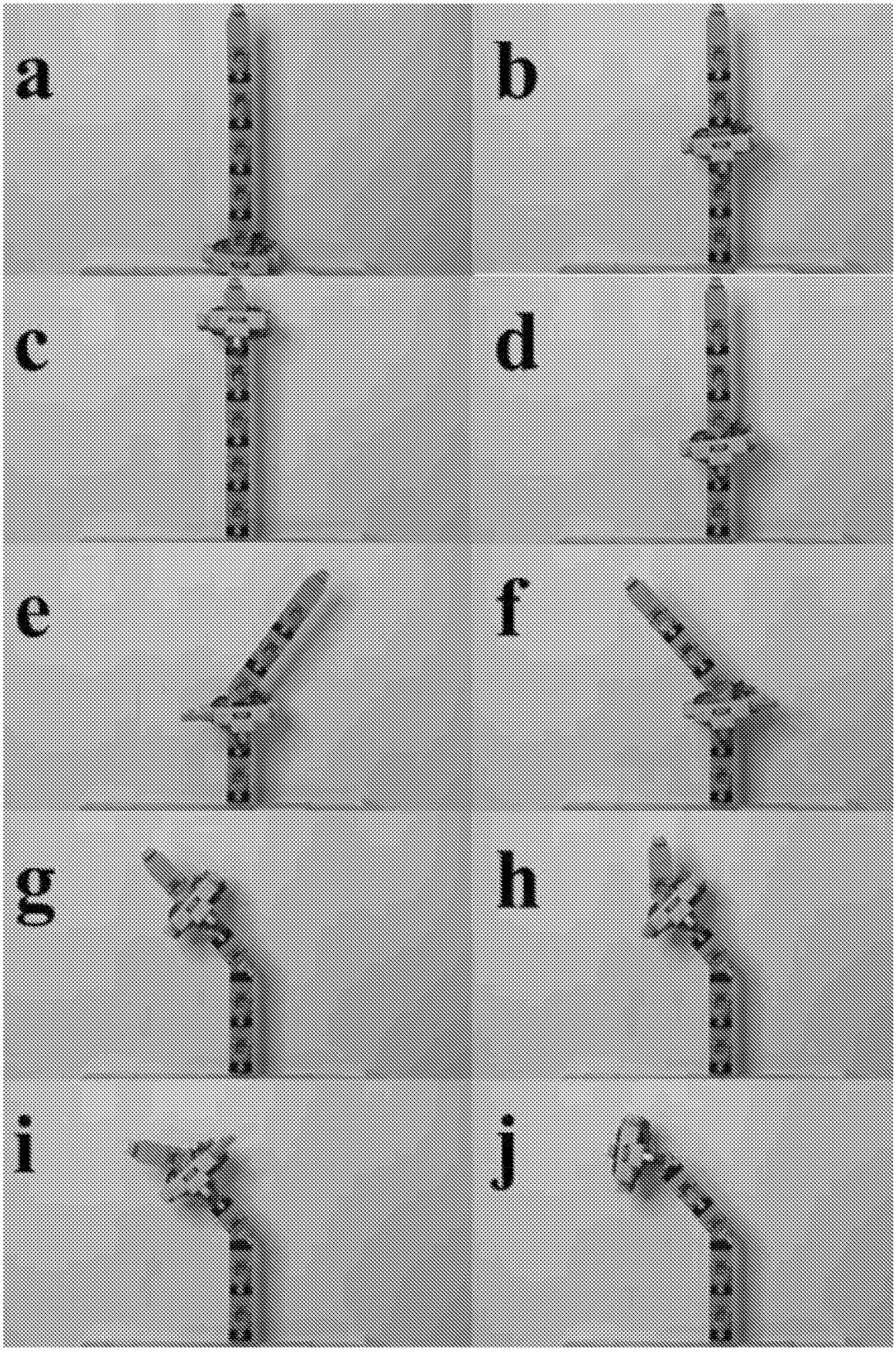


Fig. 12A



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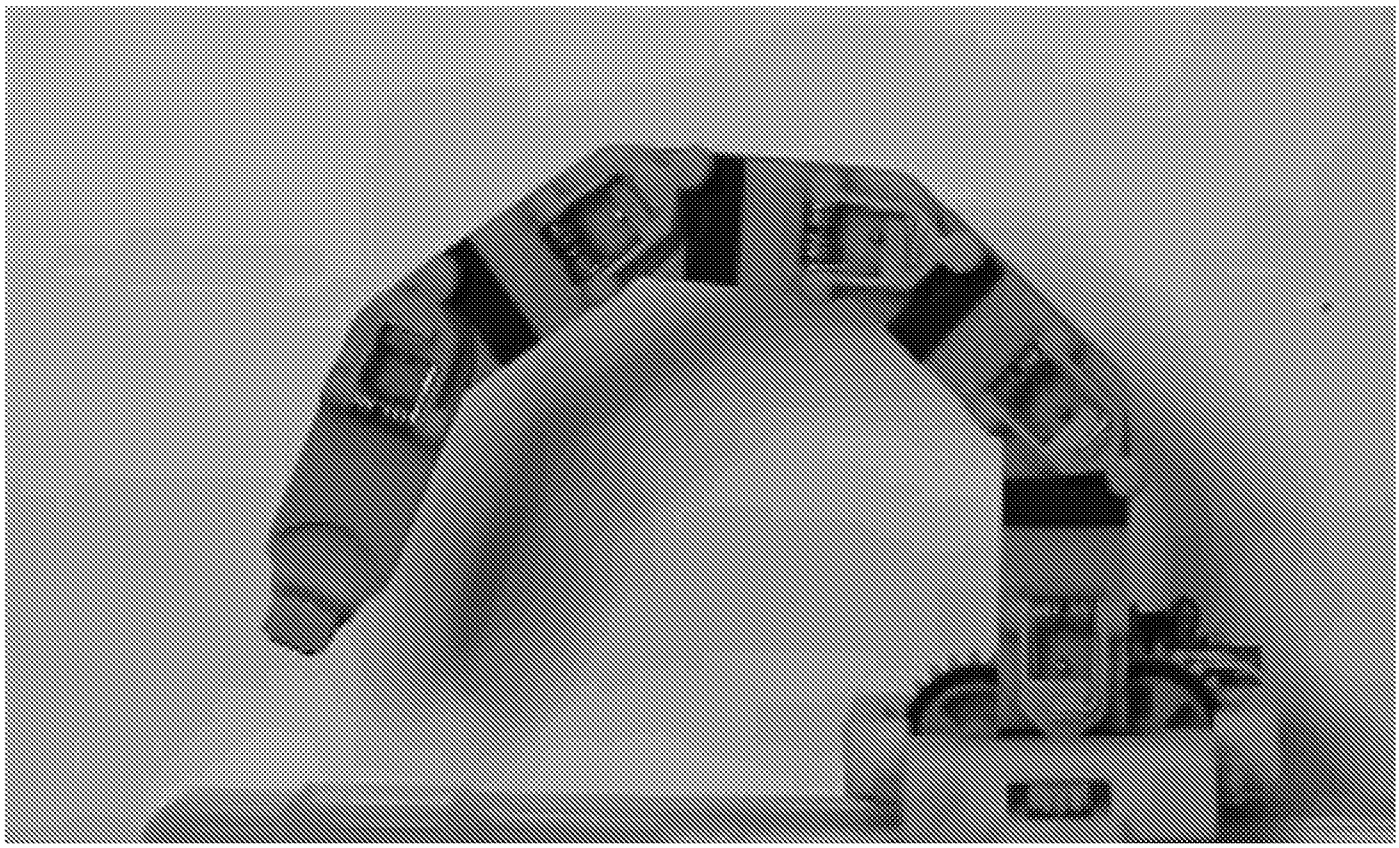

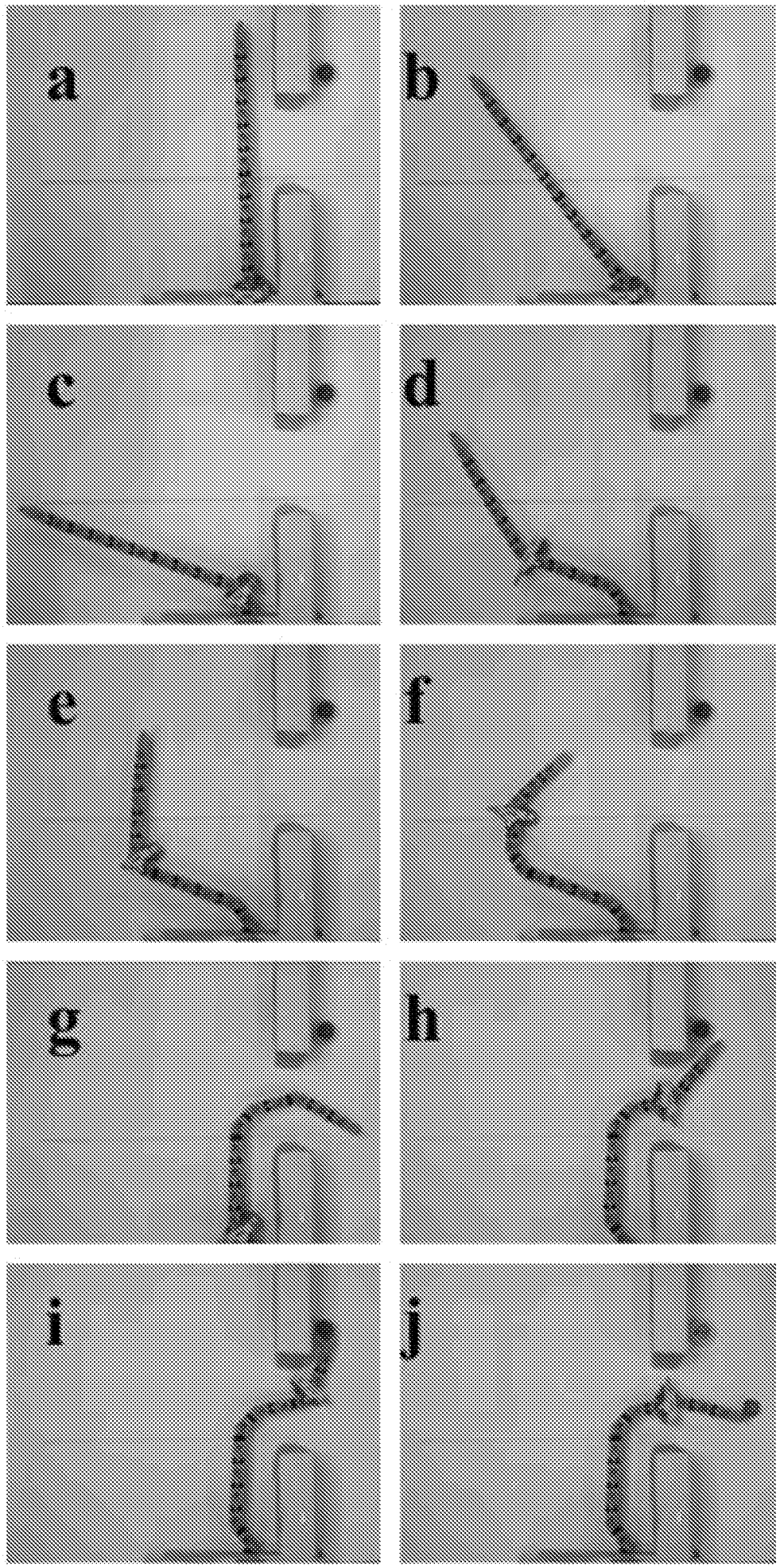

Fig. 13

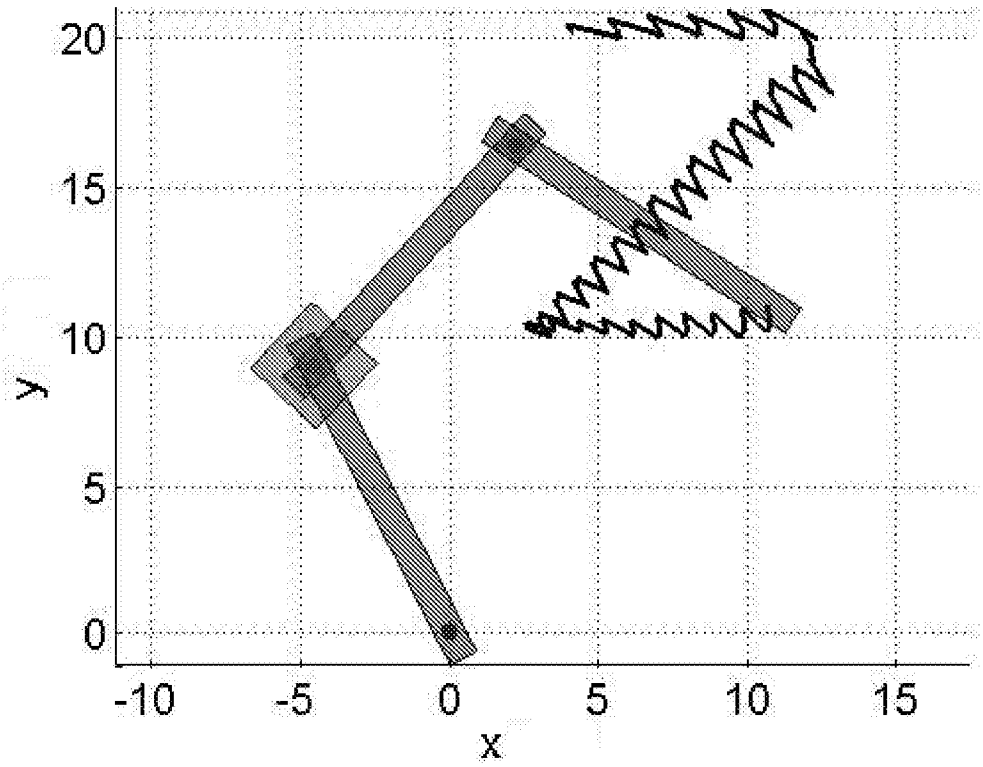

Fig. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2017/050376

A. CLASSIFICATION OF SUBJECT MATTER
IPC (2017.01) B25J 9/06, B25J 17/00

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)
IPC (2017.01) B25J 9/06, B25J 17/00

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)
Databases consulted: PATENTSCOPE, Esp@cenet, Google Patents, PatBase

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 20090222133 A BUCKINGHAM 03 Sep 2009 (2009/09/03) whole	1-20
A	US 20030004399 A BELSON 02 Feb 2003 (2003/02/02) whole	1-20

☐ 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	Date of mailing of the international search report
24 Jul 2017	26 Jul 2017
Name and mailing address of the ISA: Israel Patent Office Technology Park, Bldg.5, Malcha, Jerusalem, 9695101, Israel Facsimile No. 972-2-5651616	Authorized officer GUTKIN Solomon Telephone No. 972-2-5651763

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2017/050376

Patent document cited search report	Publication date	Patent family member(s)	Publication Date
US 20090222133 A	03 Sep 2009	NONE	
US 20030004399 A	02 Feb 2003	NONE	