



(43) International Publication Date
18 December 2014 (18.12.2014)

- (51) International Patent Classification:
G01L 5/00 (2006.01)
- (21) International Application Number:
PCT/US2014/042335
- (22) International Filing Date:
13 June 2014 (13.06.2014)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
61/834,466 13 June 2013 (13.06.2013) US
- (71) Applicant: **NORTHEASTERN UNIVERSITY** [US/US];
360 Huntington Avenue, 960 Renaissance Park, Boston,
MA 02115-5000 (US).
- (72) Inventors: **WEINBERG, Brian**; 5648 Madra Avenue,
San Diego, CA 92120 (US). **PIETRUSISNKI, Maciej**; 18
Bigelow Street, Cambridge, MA 02139 (US). **MAVROID-
IS, Constantinos**; 898 Massachusetts Avenue, Arlington,
MA 02476 (US).
- (74) Agents: **LEE, Yvonne** et al.; Wilmer Cutler Pickering
Hale Dorr LLP, 60 State Street, Boston, MA 02109 (US).
- (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, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, 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, 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).

Published:

- with international search report (Art. 21(3))
- before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments (Rule 48.2(h))

(54) Title: CAM DRIVEN COMPLIANT TORQUE SENSOR

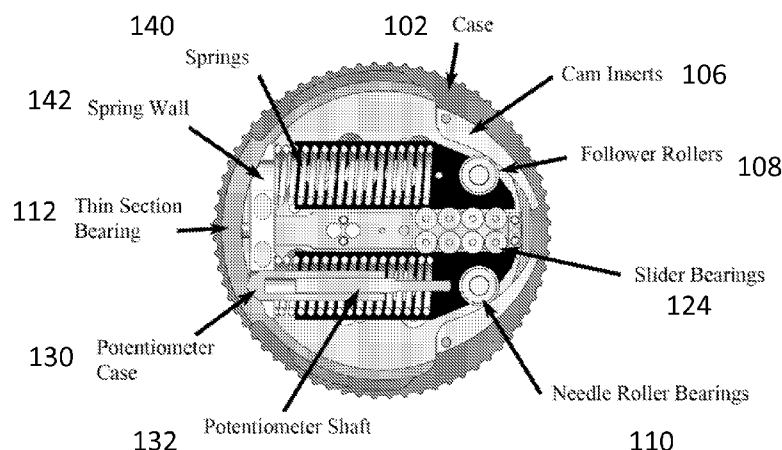


FIG. 1A

(57) Abstract: An apparatus for compliant torque sensing, the apparatus comprising a casing, said casing capable of rotating in re-
sponse to a force, a first cam and first follower mounted on a first interior portion of the casing to provide a first cam/follower set, a
second cam and second follower mounted on a second interior portion of the casing to provide a second cam/follower set, a first dis-
placement element secured to the first cam/follower set; and a second displacement element secured to the second cam/follower set,
wherein the first cam/follower set and second cam/follower set are positioned and arranged to move in response to a rotational force
applied to the casing, further wherein the movement causes a displacement of the first and second displacement elements.



CAM DRIVEN COMPLIANT TORQUE SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/834,466, entitled “Cam Driven Compliant Torque Sensor,” filed June 13, 2013, the contents of which are incorporated in their entirety herein.

BACKGROUND

[0002] In many human centered robotic applications where high accuracy force control needs to be combined with backdrivable powertrains, “series-elastic” elements have been proposed as an additional component to high speed reduction transmissions. In force-controlled robots, compliant components are generally placed between the end point and the environment to help stabilize the interface, by making the environment appear softer than it really is.

[0003] Traditional series compliance elements generally occupy a non-negligible amount of space between the load and an actuator. An optimum series elastic mechanism uses a spring length and stiffness that balance compliance with the frequency response of the device. For rotary devices that require compact packaging, there is not enough room for a spring of acceptable length.

SUMMARY

[0004] In some embodiments, an apparatus for compliant torque sensing is disclosed, the apparatus comprising a casing, said casing capable of rotating in response to a force; a first cam and first follower mounted on a first interior portion of the casing to provide a first cam/follower set; a second cam and second follower mounted on a second interior portion of the casing to provide a second cam/follower set, a first displacement element secured to the first cam/follower set; and a second displacement element secured to the second cam/follower

set, wherein the first cam/follower set and second cam/follower set are positioned and arranged to move in response to a rotational force applied to the casing, further wherein the movement causes a displacement of the first and second displacement elements.

[0005] In some embodiments, the apparatus further comprises at least one sensor for measuring the amount of displacement of the first and second displacement elements, the displacement correlating to an amount of rotational force applied on the casing. In some embodiments, the sensor is mounted in at least one of the first interior portion and second interior portion of the casing. In some embodiments, the first and second cams are in a fixed position and the cam followers are capable of movement in response to an applied force. In some embodiments, the first and second cam followers are in a fixed position and the cams are capable of movement in response to an applied force. In some embodiments, the first displacement element comprises a first spring connected to the first follower; the second displacement element comprises a second spring connected to the second follower, wherein the rotational force applied in a clockwise direction on the casing causes the first spring to contract and the second spring to elongate, and the rotational force applied in a counter clockwise direction on the casing causes the first spring to elongate and the second spring to contract; and the at least one sensor is capable of measuring an amount of displacement in the first spring, the displacement correlating to an amount of rotational force applied on the casing. In some embodiments, the apparatus further comprises a first slider and a second slider, such that the first spring moves along the first slider, and the second spring moves along the second slider, the first slider connected to the first follower, and the second slider connected to the second follower. In some embodiments, the first displacement element is integral with the first cam and comprises a flexible member capable of changing shape upon an application or release of pressure; the second displacement element is integral with the second cam and comprises a flexible member capable of displacement upon an application or

release of pressure; and the at least one sensor is capable of measuring the strain induced by the displacement in the flexible member, the displacement correlating to an amount of rotational force applied on the casing. In some embodiments, the first follower comprises a first follower roller, such that first follower roller rolls along a radially outward surface of the first cam, and the second follower comprises a second follower roller, such that the follower roller rolls along a radially outward surface of the second cam. In some embodiments, the first and second cams are comprised of a piezoelectric material. In some embodiments, the sensor is selected from the group consisting of potentiometers, linear sensors, and strain sensors. In some embodiments, the casing comprises a case and a base, wherein the first and second cams are secured to one of the case or base and the first and second followers are secured to the other of the case or base. In some embodiments, the first follower comprises a first follower roller including a first needle bearing, such that the first needle bearing rolls along a radially inward surface of the first cam, and the second follower comprises a second follower roller including a second needle bearing, such that the second needle bearing rolls along a radially inward surface of the second cam. In some embodiments, the exterior of the case includes grooves, the grooves facilitating a remote connection with one of an actuator or end effector. In some embodiments, the casing includes mounting holes, the mounting holes facilitating an inline connection with one of an actuator or end effector. In some embodiments, the actuator is a rotary actuator. In some embodiments, the rotary actuator is a gear bearing drive. In some embodiments, the apparatus further comprises a conversion module converting the amount of displacement in the first spring measured by the sensor into a signal compatible with a gear bearing drive, such that upon receiving the signal, the gears of the gear bearing drive are driven based on the signal. In some embodiments, the sensor comprises a strain gauge attached to a combination of the first cam and the second cam, the strain gauge measuring an amount of displacement in a combination of the first cam and the

second cam, the displacement correlating to an amount of rotational force applied on the casing.

BRIEF DESCRIPTION OF FIGURES

[0006] Figure 1A is a diagram of an interior view of a compliant torque sensor, according to some embodiments of the present disclosure.

[0007] Figure 1B is a diagram of an exterior view of a compliant torque sensor, according to some embodiments of the present disclosure.

[0008] Figure 2A is an illustration of an interior view of the compliant torque sensor with no torque applied to the device, according to embodiments of the present disclosure.

[0009] Figure 2B is an illustration of an interior view of the compliant torque sensor when there is a counterclockwise torque applied to the device, according to some embodiments of the present disclosure.

[0010] Figure 2C is an illustration of an interior view of the compliant torque sensor when there is a clockwise torque applied to the device, according to some embodiments of the present disclosure.

[0011] Figure 3A is a side view of a compliant torque sensor, according to some embodiments of the present disclosure.

[0012] Figure 3B is an illustration of the outer casing of a complaint torque sensor, according to some embodiments of the present disclosure.

[0013] Figure 3C is an illustration of an interior of a compliant torque sensor, according to some embodiments of the present disclosure.

[0014] Figure 4 is an illustration depicting forces applied to a compliant torque sensor, according to some embodiments of the present disclosure.

[0015] Figure 5 is a graph depicting applied torque versus potentiometer position parameterized by spring stiffness, according to some embodiments of the present disclosure.

[0016] Figure 6A is a model depicting overall results of a factor of safety test, according to some embodiments of the present disclosure.

[0017] Figure 6B is a model depicting the cam follower interface results of a factor of safety test, according to some embodiments of the present disclosure.

[0018] Figure 7A is a model depicting a testing platform for the compliant torque sensor, according to some embodiments of the present disclosure.

[0019] Figure 7B is a model depicting an encoder for a Gear Bearing Drive (GBD), according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0020] Some embodiments of the present disclosure provide a compliant torque sensor with a cam and follower mechanism to serve as an elastic element between an actuator and load. The compliant torque sensor can absorb shock resulting from a force exerted by an actuator. An actuator can be any combination of motors and gears combined to introduce motion in a system. In some embodiments, an actuator can be a rotary actuator (e.g., a gear bearing system). In some embodiments, the actuator can be a Gear Bearing Drive, as described in International Application No. PCT/US14/31566, entitled “Curved Bearing Contact System,” filed March 24, 2014; and as described in U.S. Application No. 11/821,095, entitled “Gear Bearing Drive,” filed June 21, 2007, issued as U.S. Patent No. 8,016,893, the contents of which are incorporated in their entirety herein. In some embodiments, the compliant torque sensor is also a rotary device that produces rotary motion or torque. By incorporating a cam and follower mechanism, e.g., a roller or roller bearing designed to follow cams, into a rotary device, an elastic element can be provided in a compactly packaged form. In addition, the incorporation of the cam follower in a rotary device allows the determination of an applied force by position determination. A position measurement

device is incorporated into a rotary device to measure the elastic element's deflection and thereby provide information relating to a force applied to the device.

[0021] Figure 1A is a diagram of an interior view of a compliant torque sensor, according to some embodiments of the present disclosure; the upper surface of the lower spring has been cut away to reveal the sensor elements housed within the spring. Figure 1B is a diagram of an exterior view of a compliant torque sensor, according to some embodiments of the present disclosure. Taken together, the figures show a case 102, a lid 104, cam insert 106, follower rollers 108, needle roller bearings 110, thin section bearing 112, sliders 120, slider bearing support 122, slider bearings 124, potentiometer case 130, potentiometer shaft 132, springs 140, a spring wall 142, and a mounting hole 150.

[0022] A compliant torque sensor 100 can comprise a cylindrical housing that includes a base (not shown), a case 102 and a lid 104. In some embodiments, a cam 106 can be secured to the case 102 of the rotary device. The case 102 rotates on a thin section bearing 112 at its base and another ball bearing (not shown) mounted in the lid 104. The movement of the case can be rotational, such that it can rotate clockwise or counter clockwise with respect to the cylindrical housing. The movement of the case 102 can cause the cam 106 to move accordingly. Some embodiments of the present invention provide two cam/follower sets are arranged such that they provide opposing torques on the case of a rotary device. In some embodiments, the cam/follower set can include a cam 106, a cam follower 108, springs 140 and sliders 120. One cam/follower set can be located on one portion, e.g., the 'upper' portion of the rotary device, and the second cam/follower set can be located on a second portion, e.g., the 'lower' portion of the rotary device. (Designation of 'upper' and 'lower' portions are arbitrary and are used herein only for clarity in describing the device.) In some embodiments, the follower 108 can be attached to a spring 140 and slider 120 (e.g., a linear motion device that reduces friction) such that the follower 108 and one end of the spring 140

move in the same direction and retain generally the same distance as they move. The cam follower 108, springs 140 and sliders 120 can be attached to the base, such that the cam follower 108, springs 140 and sliders 120 do not rotate with the case 102. Rotation of the case 102 can cause the cam 106 to move, such that the movement of the cam 106 causes movement of the follower 108. Movement of the follower 108 can also cause movement of the slider 120 and compression or elongation of the springs 140. Springs 140 can be pre-loaded and in an equilibrium position when there are no external forces acting on the springs 140. When an external torque is applied, rotating the case 102 relative to the base, the springs 140 (through a connection cam follower 108) can be displaced from their equilibrium position, extending one spring 140 and contracting the other spring 140, therefore creating a net torque imbalance or restoring torque on the case. By measuring the magnitude of the spring displacement using a potentiometer and comparing this value to a calibrated scale as a function of spring force, the applied torque can be determined.

[0023] A compliant torque sensor can be a rotary device. The case 102 rotates on a thin section bearing 112 at its base and another ball bearing mounted in the lid 104. The lid 104 can be fastened to the case 102 with screws or bolts or the lid 104 can be machined into the case 102. In some embodiments, the lid 104 and case 102 can comprise one piece. The lid 104 and case 102 can both be made from aluminum or any material capable of handling the stress and force intended for the device. In some embodiments, the case 102 comprises 2024 Aluminum and the lid 104 comprises 7075 Aluminum. The base can be mounted directly to an actuator's output or to an end effector. There are mounting holes 150 in the lid 104 for inline arrangements and an AT5 timing belt pulley pattern cut into the outside of the case 102 for mounting remotely. When the lid 104 and case 102 are one piece, the mounting holes 150 can be located on the case 102. In some embodiments, both the case 102 and the lid 104 can

be designed with manufacturing software (e.g., Camworks) and fabricated using a milling machine (e.g., 3 Axis Mill).

[0024] One of the components mounted (e.g., by bolts, screws, welding) on an interior side includes a cam insert 106. A cam insert 106 can be mounted on the radially inward side of the case 102. As described in more detail below, the cam insert 106 can be in the shape of an arc. Briefly, the cam insert 106 is shaped such that one end of the arc is closer to the center of the compliant torque sensor than the other end of the arc. The cam insert 106 can be made of steel or any material capable of handling the stress and force intended for the device. In some embodiments, the cam insert 106 comprises A2 Tool Steel. The cam insert can be hardened to 60 Rc (based on the Rockwell scale). In some embodiments, cam insert 106 can be designed with manufacturing software (e.g., Camworks) and fabricated using a milling machine.

[0025] In some embodiments, the radially inward side of the cam insert 106 is in contact with a follower roller 108. The follower roller 108 can include a bearing (e.g., roller bearing) to facilitate a smooth motion along the cam insert 106. One type of bearing that can be used is a needle roller bearing 110. The follower roller 108 can be made of steel or any material capable of handling the stress and force intended for the device. In some embodiments, the follower roller 108 comprises A2 Tool Steel and can be fabricated using a manual lathe.

[0026] The follower roller 108 is attached to a spring 140 and to a slider 120, which will be described in more detail below. Briefly, the slider 120 constrains the physical movement of the spring 140 and the follower roller 108 to one direction along a single axis. As described above, the cam insert 106 can be an arc with one end of the arc closer to the center of the compliant torque sensor as compared to the other end of the arc. The arc-shaped cam insert 106 is positioned such that when the compliant torque sensor is rotated in one direction, the cam insert 106 will cause the follower roller 108 and spring 140 to move along the axis in

a corresponding direction. For example, when a cam insert 106 pushes a follower roller 108 towards the center of the compliant torque sensor, the follower roller 108 will move in a linear direction along the slider 120 towards the center of the compliant torque sensor.

[0027] When the follower roller 108 moves along the slider 120 the attached spring 140 correspondingly contracts and elongates. For example, as the follower roller 108 moves radially inward along the slider 120, the corresponding spring 140 contracts. When the follower roller 108 moves radially outward along the slider 120, the corresponding spring elongates. Therefore, as the case 102 rotates, the cam insert 106 can either push the follower roller 108 radially inward along the slider 120, and having a corresponding spring 140 contract, or allows the follower roller 108 to move radially outward along the slider 120, being pushed by the elongation of the spring 140.

[0028] The spring 140 is held in alignment by the slider 120. The spring 140 is also attached at one end to a spring wall 142, which is attached to the base of the case 102. The configuration of the spring wall 142 allows the spring 140 to be changed and easily preloaded. The spring wall 142 can be made of steel or any material capable of handling the stress and force intended for the device. In some embodiments, the spring wall 142 comprises A2 Tool Steel. In some embodiments, spring wall 142 can be designed with manufacturing software (e.g., Camworks) and fabricated using a milling machine (e.g., 3 Axis Mill and a Manual Mill).

[0029] The slider 120 can be made of steel or any material capable of handling the stress and force intended for the device. In some embodiments, the sliders 120 are precision machined and ground sliders that ride on bearings 124 to minimize friction and stiction. The slider 120 can be hardened to 61 Rc (based on the Rockwell scale). In some embodiments, the slider 120 can be designed with manufacturing software (e.g., Camworks) and fabricated using a milling machine (e.g., 3 Axis Mill and a Manual Mill).

[0030] The slider bearings 124 are mounted on a slider bearing support 122. The slider bearing support 122 is mounted onto the base of the compliant torque sensor. The slider bearing support 122 can be made of aluminum or any material capable of handling the stress and force intended for the device. In some embodiments, the slider bearing support comprises 7075 Aluminum and can be fabricated using a manual mill.

[0031] The second cam/follower set is generally identical to the first, except for placement. The first and second cam/follower set can be arranged such that when the compliant torque sensor is rotated in a clockwise direction, the spring corresponding to the first cam/follower set will contract and the spring corresponding to the second cam/follower set will elongate. Similarly, when the compliant torque sensor is rotated in a counter-clockwise direction, the spring corresponding to the first cam/follower set will elongate and the spring corresponding to the second cam/follower set will contract. One cam/follower set can be positioned in the upper portion of the compliant torque sensor, while the second cam/follower set can be positioned in the lower portion of the compliant torque sensor. In some embodiments, the first portion corresponds to a first half of the compliant torque sensor and the second portion corresponds to a second half of the compliant torque sensor.

[0032] A potentiometer case 130 can be attached to the case and be positioned parallel lengthwise to one of the cam/follower sets (shown here in the lower spring/slider). The potentiometer case 130 can include a potentiometer shaft 132. The potentiometer shaft 132 can be attached to a slider 120 at a certain point such that the potentiometer shaft 132 moves with slider 120. As discussed in more detail below, the potentiometer measures an amount of linear displacement that results when a rotational force is applied to the compliant torque sensor.

[0033] Figures 2A-2C demonstrate the operation of the compliant torque sensor under applied forces. Figure 2A is a diagram of an interior view of the compliant torque sensor

with no torque applied to the device, e.g., at rest, according to embodiments of the present disclosure. It shows a potentiometer output 202, a first cam/follower set 220, and a second cam/follower set 222.

[0034] In some embodiments, the potentiometer output 202 is set to approximately 0.5 when there is no torque applied to the compliant torque sensor. As shown in Figure 2A, the first cam/follower set 220 and the second cam/follower set 222 are in generally identical positions relative to a horizontal line bisecting the compliant torque sensor. The potentiometer output 202 is 0.4968.

[0035] Figure 2B is a diagram of an interior view of the compliant torque sensor when there is a counterclockwise torque applied to the device, according to some embodiments of the present disclosure. It shows a counterclockwise torque 230, potentiometer output 204, an angle of displacement 210, a first cam/follower set 220, and a second cam/follower set 222.

[0036] When a counterclockwise torque 230 is applied to the compliant torque sensor, the case 102 rotates in a counterclockwise direction relative to the base. The cam insert 106 in the second cam/follower set 222 pushes against the follower roller 108 in the second cam/follower set 222. The follower roller 108 moves inwardly, which causes the spring to compress. The compression of the spring and movement of the slider causes the potentiometer shaft to move into the potentiometer case. At the same time, the counterclockwise torque 230 allows the spring in the first cam/follower set 220 to release and elongate. The spring can release up to an amount the follower roller is blocked by a corresponding cam. As shown in Figure 2B, potentiometer output is smaller as compared to the potentiometer output when the compliant torque sensor is in equilibrium. In this particular embodiment, a counterclockwise rotation of 10.6 degrees corresponds to a potentiometer output of 0.2916. The case 102 can rotate counterclockwise up to 180 degrees relative to the base.

[0037] Figure 2C is a diagram of an interior view of the compliant torque sensor when there is a clockwise torque applied to the device, according to some embodiments of the present disclosure. It shows a clockwise torque 240, potentiometer output 206, an angle of displacement 212, a first cam/follower set 220, and a second cam/follower set 222.

[0038] When a clockwise torque 240 is applied to the compliant torque sensor, the case 102 rotates in a clockwise direction relative to the base. The cam insert 106 in the first cam/follower set 222 pushes against the follower roller 108 in the first cam/follower set 222. The follower roller 108 moves inwardly, which causes the spring to compress. At the same time, the clockwise torque 240 allows the spring in the second cam/follower set 222 to release and elongate. The spring can release up to an amount the follower roller is blocked by a corresponding cam. The elongation of the spring and movement of the slider in the second cam/follower set causes the potentiometer shaft to move out of the potentiometer case. As shown in Figure 2C, potentiometer output 212 is larger as compared to the potentiometer output when the compliant torque sensor is in equilibrium. In this particular embodiment, a clockwise rotation of 10.6 degrees corresponds to a potentiometer output of 0.6827. The case 102 can rotate clockwise up to 180 degrees relative to the base.

[0039] Figure 5 is a graph depicting applied torque versus potentiometer position parameterized by spring stiffness, according to some embodiments of the present disclosure. It shows parametric curves relating applied torque to relative potentiometer position, parameterized by spring stiffness.

[0040] In some embodiments, the shape of the cam and size and location of the followers and sliders, can be determined through a simulation software (e.g., SolidWorks and a COSMOSMotion simulation package). Springs can be sourced and entered into a model along with simulated static and dynamic loading. Virtual sensors can be placed to measure linear displacement of the slider and rotation of the case. A cam profile which yields a close-

to linear relationship between these two variables can be chosen. Parametric curves, as shown in Figure 5, of relative applied torque vs. potentiometer position can be generated based on the optimum cam profile. Spring stiffness parameters can be chosen based on a variety of factors, including component availability.

[0041] Figure 3A is a side view of a compliant torque sensor, according to some embodiments of the present disclosure, in which the relative positions of the cam and the follower are switched as compared to the compliant torque sensor in Figures 1A and 1B. Figure 3B is an illustration of the outer casing of a compliant torque sensor, according to some embodiments of the present disclosure. Figure 3C is an illustration of an interior of a compliant torque sensor, according to some embodiments of the present disclosure. Taken together, the figures show a base 302, case 304, cam 312 and follower 314.

[0042] In some embodiments, a compliant torque sensor can include a circular shaped base 302 and case 304. Together, the case 304 and the base 302 can form a cylindrical housing. The base 302 can rotate relative to the case 304. In some embodiments, bearings are located in between the base 302 and the case 304 to allow for smoother rotation. The interior of the circular casing can include a cam 312 and follower 314. A cam 312 can be attached to an interior portion of the base 302 and a follower 314 attached to an interior portion of the case 304. In some embodiments, there are two sets of cams 312 and followers 314 in the interior of the compliant torque sensor. One cam 312 and follower 314 set can be located in one portion of the interior of the compliant torque sensor, and another cam 312 and follower 314 set can be located in another portion of the interior of the compliant torque sensor.

[0043] In some embodiments, a follower 314 can be located further away from the center of the compliant torque sensor than a cam 312. A cam 312 can be arc-shaped such that one end of the arc is closer to the center of the compliant torque sensor as compared to the other

end of the arc. A follower 314 can include a roller generally positioned near the perimeter of the interior of the compliant torque sensor. The follower 314 can be in contact with a cam 312 on a radially outward side of the cam 312. In some embodiments, a cam 312 comprises a flexible member capable of changing shape upon an application or release of pressure. A cam 312 can comprise rigid, but deformable material (e.g., carbon fiber). In some embodiments, a cam 312 can comprise piezoelectric material. A cam 312 can move in both radially inward and radially outward directions based on the position of the follower 314 and a corresponding application or release of pressure on the cam 312.

[0044] Figure 4 is an illustration depicting forces applied to a compliant torque sensor, according to some embodiments of the present disclosure. It shows a first cam follower set 406, a second cam follower set 408, counterclockwise rotation 402 of the base relative to the case, clockwise rotation 404 of the base relative to the case, and cam action 412 414.

[0045] In some embodiments, the case 304 can rotate counterclockwise 402 relative to the base 302. A bearing element can be placed in between the case 304 and the base 302 to facilitate the rotation. When the counterclockwise rotation 402 occurs, the follower roller in the first cam follower set 406 pushes on the cam in the first cam follower set 406. At the same time, the roller in the second cam follower set 408 allows the cam in the second cam follower set 408 to expand. The resulting bending of the cam in the first cam follower set 406 and can be measured by a sensor (not shown). The resulting change in shape of the second cam follower set 408 can also be measured by a sensor. In some embodiments, the sensor can be a linear sensor or a strain gauge. A strain gauge can be mounted on the cam or a linear sensor can be mounted to the end of the cam. A sensor can also be located external to the device.

[0046] In some embodiments, the case 304 can rotate clockwise 404 relative to the base 302. When the clockwise rotation 404 occurs, the roller in the second cam follower set 408

pushes on the cam in the second cam follower set 406. At the same time, the roller in the first cam follower set 406 allows the cam in the first cam follower set 406 to expand. The resulting bending of the cam in the second cam follower set 408 and can be measured by a sensor. The resulting change in shape of the first cam follower set 406 can also be measured by a sensor. In some embodiments, the sensor can be a linear sensor or a strain gauge. A strain gauge can be mounted on the cam or a linear sensor can be mounted to the end of the cam.

[0047] Figure 6A is a model depicting overall results of a factor of safety test, according to some embodiments of the present disclosure. Figure 6B is a model depicting the cam follower interface results of a factor of safety test, according to some embodiments of the present disclosure.

[0048] The compliant torque sensor was modeled under maximum loading condition to determine the level of hardening that was needed for the cam and follower to prevent failure. The results from this analysis based on an A2 steel hardness of 60 Rc are shown in Figure 6A and Figure 6B. Additional weight savings were also realized based on the results of this analysis and removal of material.

[0049] Figure 7A is a side view illustration depicting a testing platform for the compliant torque sensor, according to some embodiments of the present disclosure. Figure 7B is a top view illustration depicting an encoder for a Gear Bearing Drive (GBD), according to some embodiments of the present disclosure. Taken together, the figures show a compliant torque sensor 702, a GBD 704, an end effector 706, a timing belt preload adjuster 708, a line encoder 710, and a timing belt 712.

[0050] A testing platform can be used to test a compliant torque sensor 702 with a GBD 704. Briefly, a GBD is a compact mechanism with two main abilities. It operates as an actuator providing torque and as a joint providing support. The GBD is a bearingless powered

joint with large power density. It utilizes a two stage planetary gear arrangement that allows a high reduction ratio while maintaining a compact form factor.

[0051] A compliant torque sensor 702 can be connected directly with a GBD 704 or remotely attached to a GBD 704. The testing platform shown in Figure 7A allows for remote testing and is useful because it closely mimics the configuration for certain human robotics applications (e.g., an actuated knee brace).

[0052] The testing platform includes a rigid mount for the compliant torque sensor 702 and GBD 704, a timing belt tensioning adjuster 708, and an attachment shaft for connecting various end effectors 706 to the compliant torque sensor. The timing belt tensioning adjuster 708 can be used to fit the timing belt properly over the GBD 704 and the compliant torque sensor 702. The attachment shaft can be used to place a variety of end effectors 706.

[0053] Some embodiments of the present disclosure facilitate a stable and robust force control of the Gear Bearing Drive (GBD) when used in human centered robotics systems such as in rehabilitation robotics. It includes features to allow for remote mounting via AT5 timing belt but can also be directly mounted to an actuator for an inline configuration.

[0054] Some embodiments of the present invention provide a back drivability function to an actuator otherwise unable to be back driven. It allows for accurate torque sensing and also allows for passive compliance, which is needed when non-back drivable actuators are used in human centered devices.

[0055] As described above, the compliant torque sensor can act not only as an elastic element, but can also act as a sensor providing a GBD with back driving capability. A conversion module can convert and channel output of the compliant torque sensor to an actuator. In some embodiments, the potentiometer output can be converted to a signal and sent to a servo drive. A servo drive can receive a signal from a control system (e.g., the potentiometer output) and convert it to an electric current, which can be sent to the GBD to

produce motion proportional to the signal. In some embodiments, an encoder 710 can be used to interface the GBD with the servo drive.

[0056] Although the disclosed subject matter has been described and illustrated in the foregoing exemplary embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the disclosed subject matter may be made without departing from the spirit and scope of the disclosed subject matter, which is limited only by the claims which follow.

CLAIMS

What is claimed is:

1. An apparatus for compliant torque sensing, the apparatus comprising:
 - a casing, said casing capable of rotating in response to a force;
 - a first cam and first follower mounted on a first interior portion of the casing to provide a first cam/follower set;
 - a second cam and second follower mounted on a second interior portion of the casing to provide a second cam/follower set,
 - a first displacement element secured to the first cam/follower set; and
 - a second displacement element secured to the second cam/follower set, wherein the first cam/follower set and second cam/follower set are positioned and arranged to move in response to a rotational force applied to the casing, further wherein the movement causes a displacement of the first and second displacement elements.
2. The apparatus of claim 1, further wherein the displacement of the first and second displacement elements absorbs shock resulting from the rotational force applied to the casing.
3. The apparatus of claim 1, further comprising at least one sensor for measuring the amount of displacement of the first and second displacement elements, the displacement correlating to an amount of rotational force applied on the casing.
4. The apparatus of claim 3, wherein the sensor is mounted in at least one of the first interior portion and second interior portion of the casing.
5. The apparatus of claim 1, wherein the first and second cams are in a fixed position and the cam followers are capable of movement in response to an applied force.
6. The apparatus of claim 1, wherein the first and second cam followers are in a fixed position and the cams are capable of movement in response to an applied force.

7. The apparatus of claim 4 or 5, wherein:
- the first displacement element comprises a first spring connected to the first follower;
- the second displacement element comprises a second spring connected to the second follower, wherein the rotational force applied in a clockwise direction on the casing causes the first spring to contract and the second spring to elongate, and the rotational force applied in a counter clockwise direction on the casing causes the first spring to elongate and the second spring to contract; and
- the at least one sensor is capable of measuring an amount of displacement in the first spring, the displacement correlating to an amount of rotational force applied on the casing.
8. The apparatus of claim 7, further comprising a first slider and a second slider, such that the first spring moves along the first slider, and the second spring moves along the second slider, the first slider connected to the first follower, and the second slider connected to the second follower.
9. The apparatus of claim 4 or 6, wherein:
- the first displacement element is integral with the first cam and comprises a flexible member capable of changing shape upon an application or release of pressure;
- the second displacement element is integral with the second cam and comprises a flexible member capable of displacement upon an application or release of pressure; and
- the at least one sensor is capable of measuring the strain induced by the displacement in the flexible member, the displacement correlating to an amount of rotational force applied on the casing.
10. The apparatus of claim 9, wherein the first follower comprises a first follower roller, such that first follower roller rolls along a radially outward surface of the first cam, and the second follower comprises a second follower roller, such that the follower roller rolls along a radially outward surface of the second cam.

11. The apparatus of claim 10, wherein the first and second cams are comprised of a piezoelectric material.
12. The apparatus of any one of claim 3-11, wherein the sensor is selected from the group consisting of potentiometers, linear sensors, and strain sensors.
13. The apparatus of any preceding claim, wherein the casing comprises a case and a base, wherein the first and second cams are secured to one of the case or base and the first and second followers are secured to the other of the case or base.
14. The apparatus of claim 1 or 7, wherein the first follower comprises a first follower roller including a first needle bearing, such that the first needle bearing rolls along a radially inward surface of the first cam, and the second follower comprises a second follower roller including a second needle bearing, such that the second needle bearing rolls along a radially inward surface of the second cam.
15. The apparatus of any preceding claim, wherein the exterior of the case includes grooves, the grooves facilitating a remote connection with one of an actuator or end effector.
16. The apparatus of any preceding claim, wherein the casing includes mounting holes, the mounting holes facilitating an inline connection with one of an actuator or end effector.
17. The apparatus as in any one of claims 15 or 16, in which the actuator is a rotary actuator.
18. The apparatus of claim 17, wherein the rotary actuator is a gear bearing drive.
19. The apparatus of claim 18, further comprising a conversion module converting the amount of displacement in the first spring measured by the sensor into a signal compatible with a gear bearing drive, such that upon receiving the signal, the gears of the gear bearing drive are driven based on the signal.
20. The apparatus of claim 9, wherein the sensor comprises a strain gauge attached to a combination of the first cam and the second cam, the strain gauge measuring an amount of

displacement in a combination of the first cam and the second cam, the displacement correlating to an amount of rotational force applied on the casing.

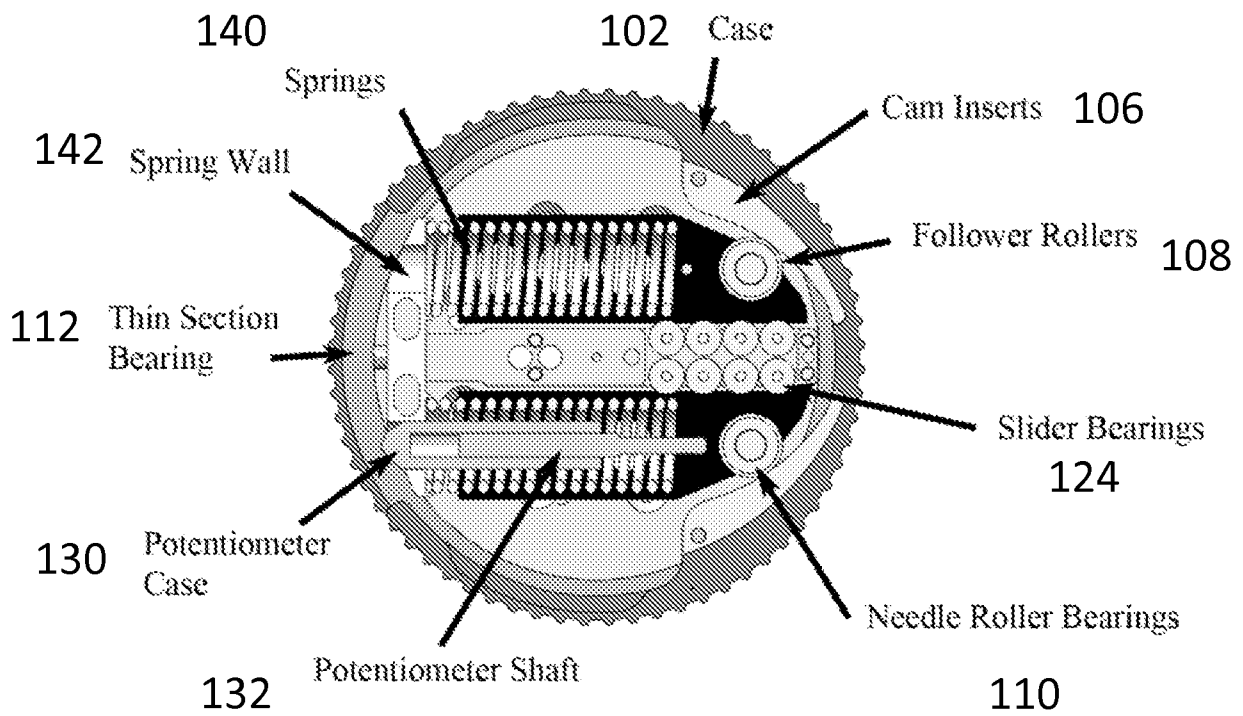


FIG. 1A

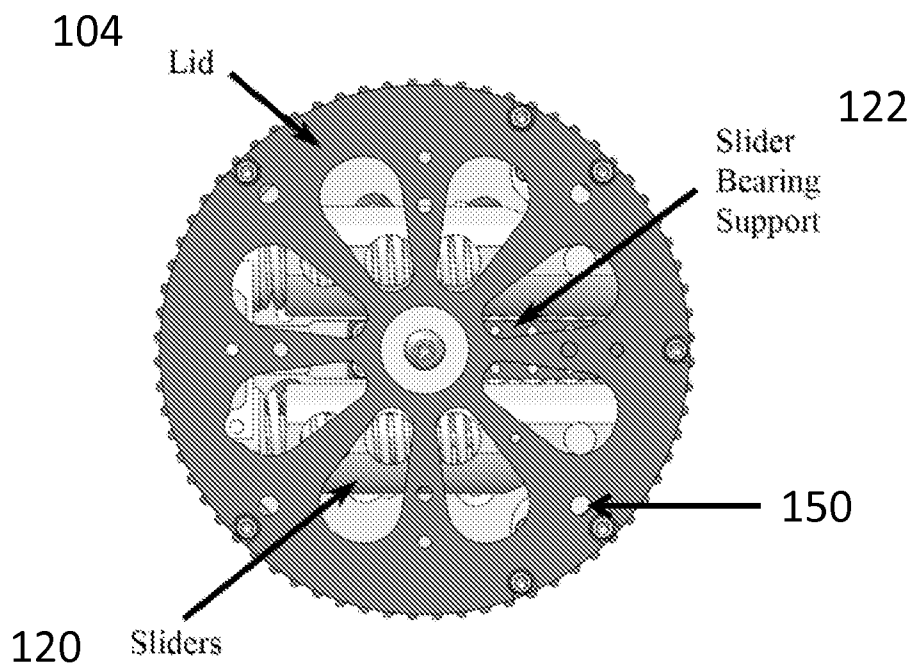


FIG. 1B

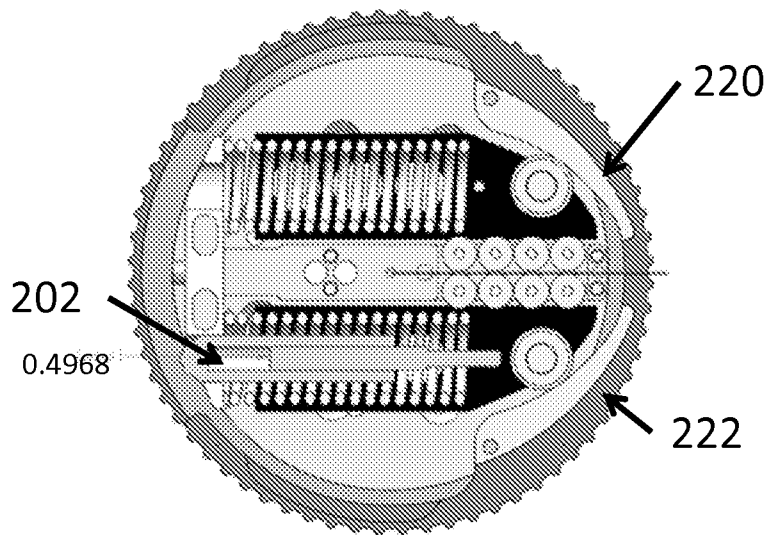


FIG. 2A

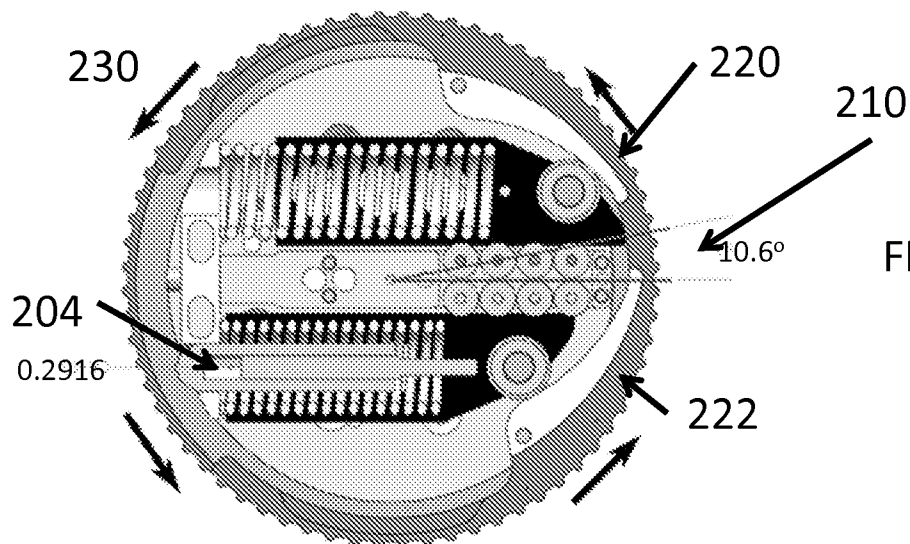


FIG. 2B

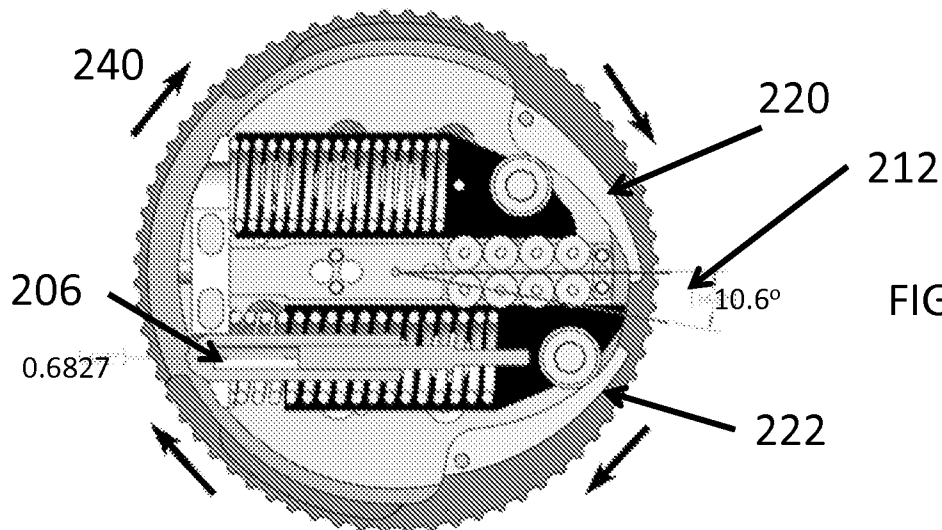


FIG. 2C

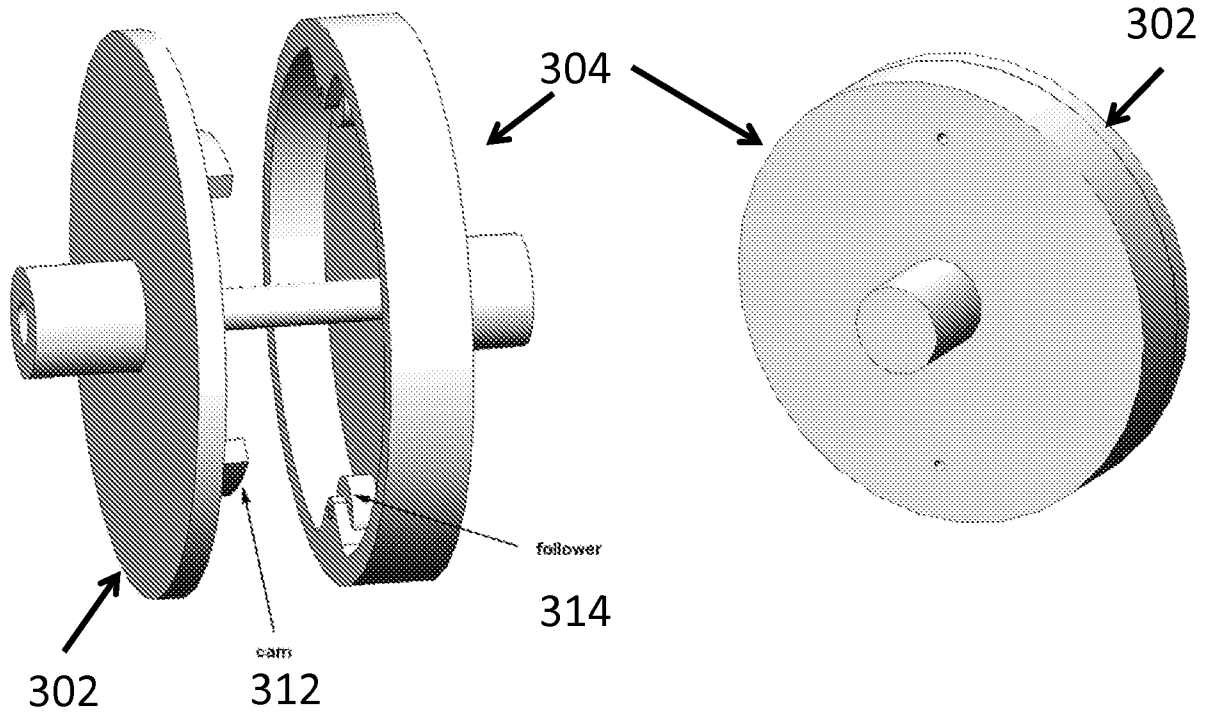


FIG. 3A

FIG. 3B

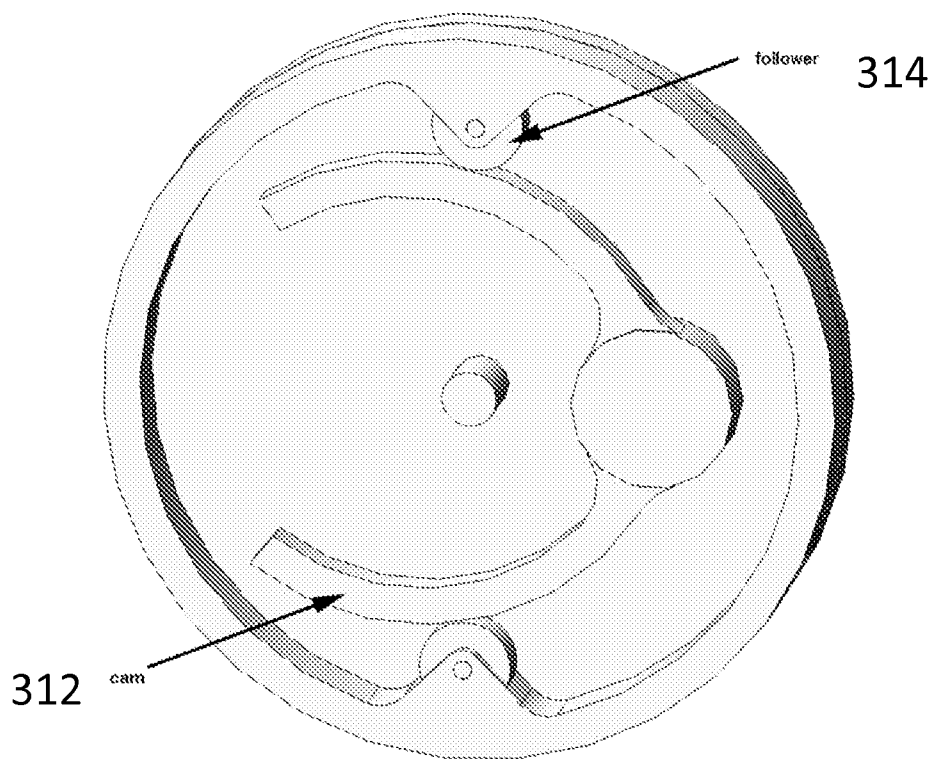


FIG. 3C

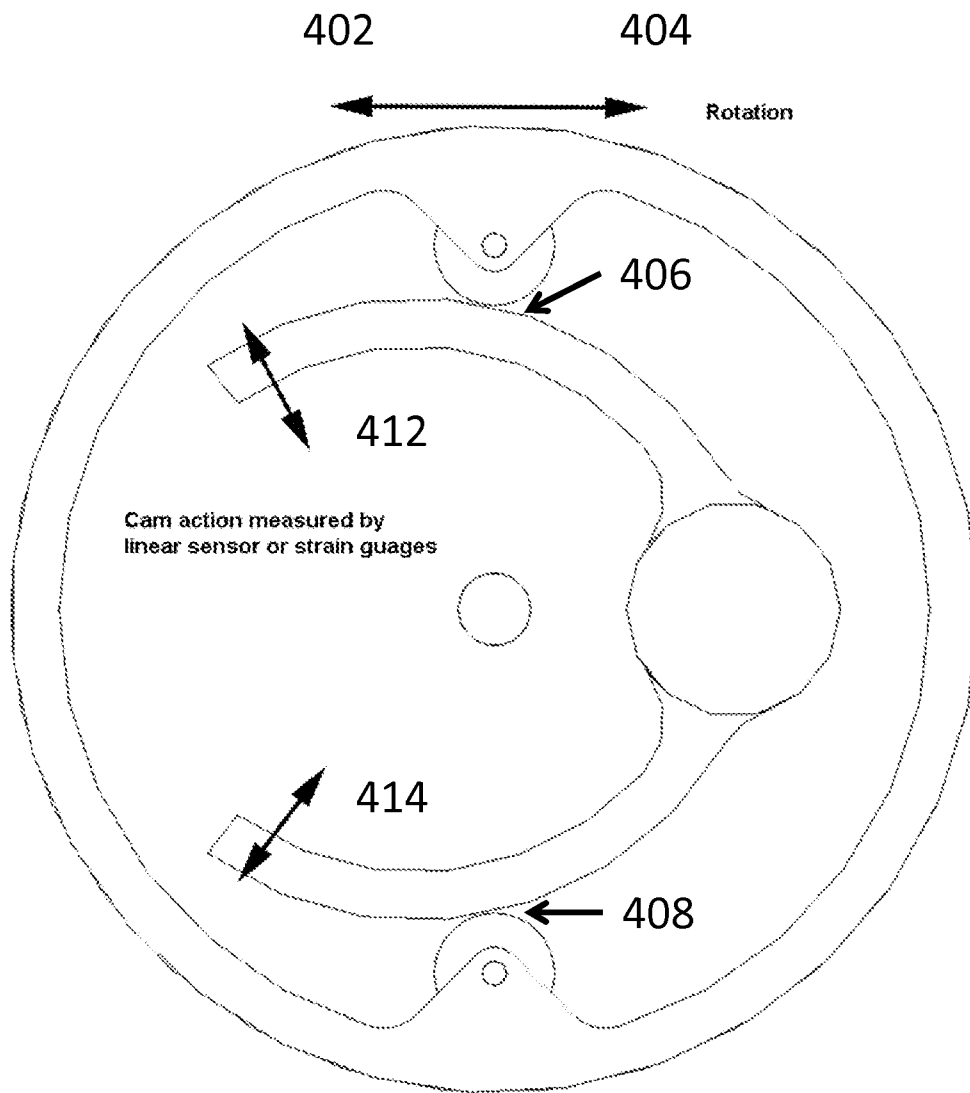


FIG. 4

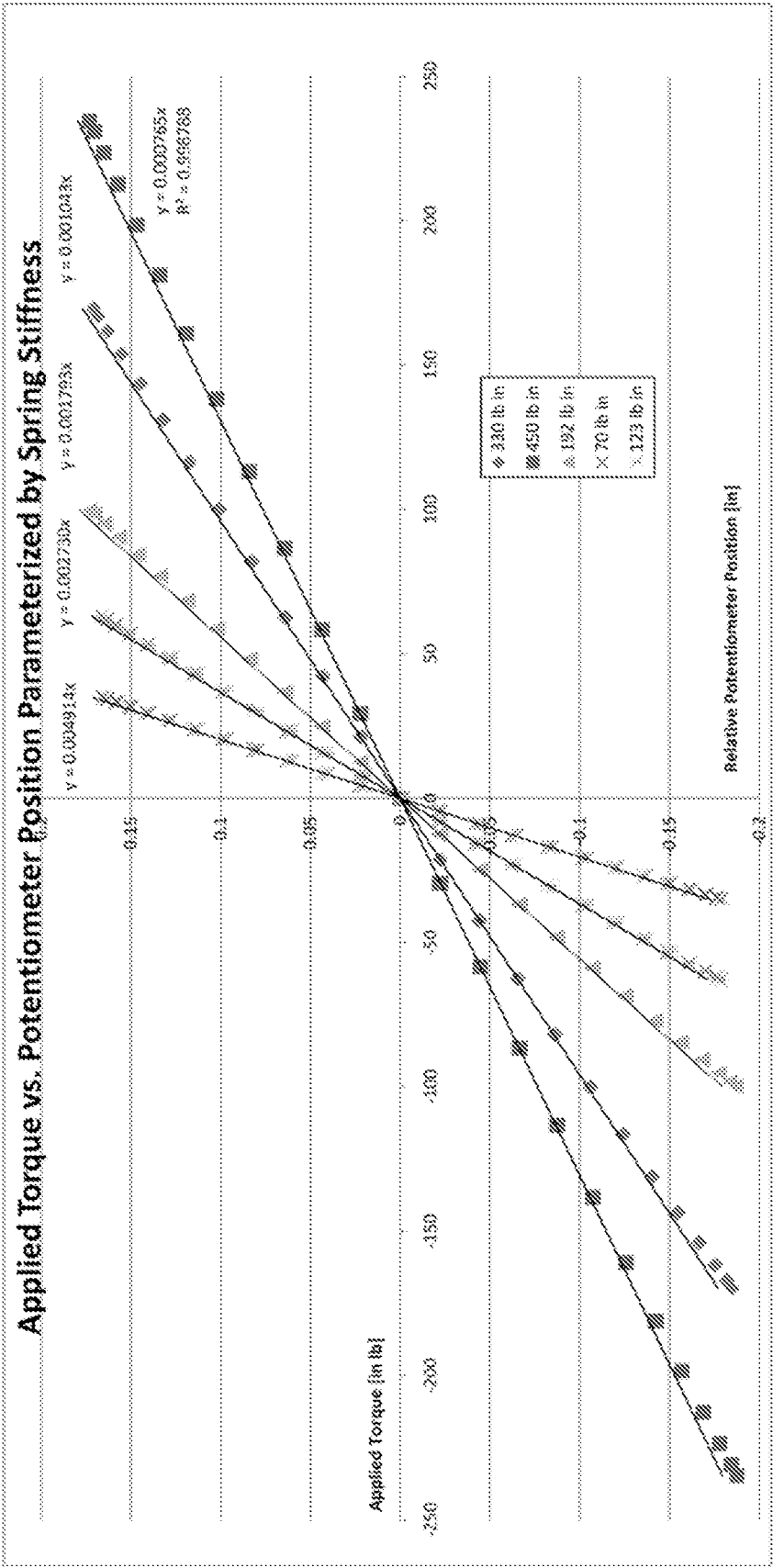


FIG. 5

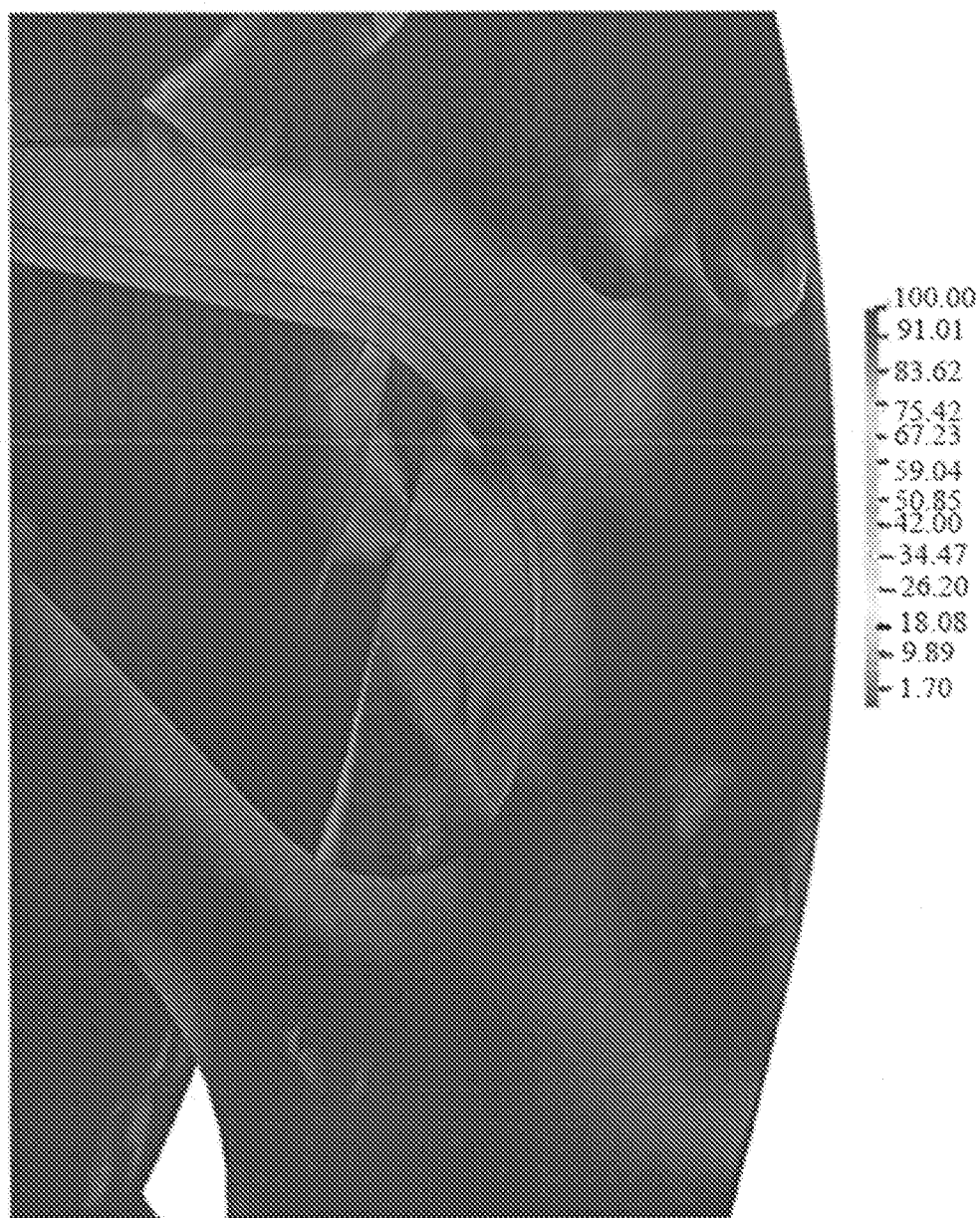


FIG. 6A

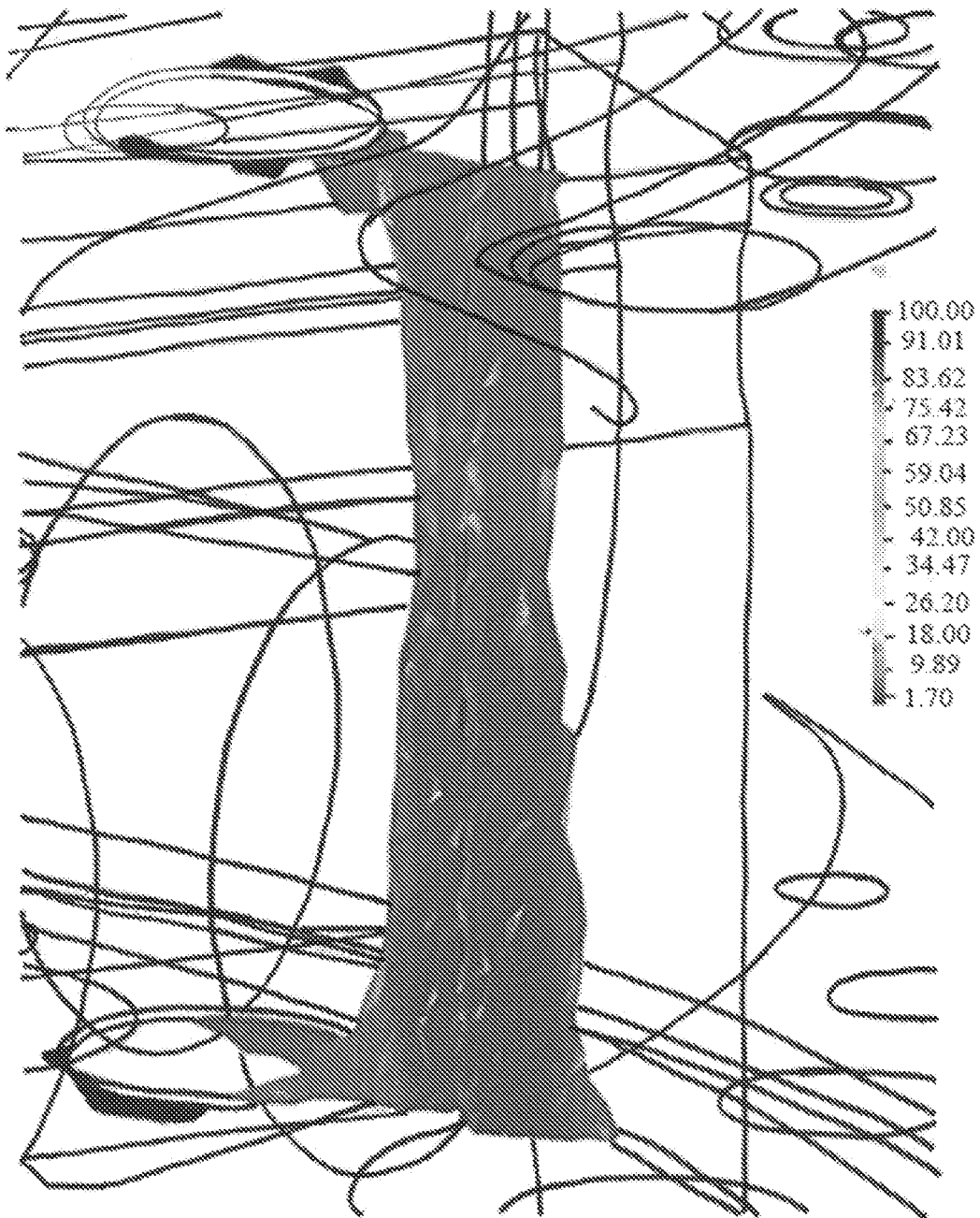


FIG. 6B

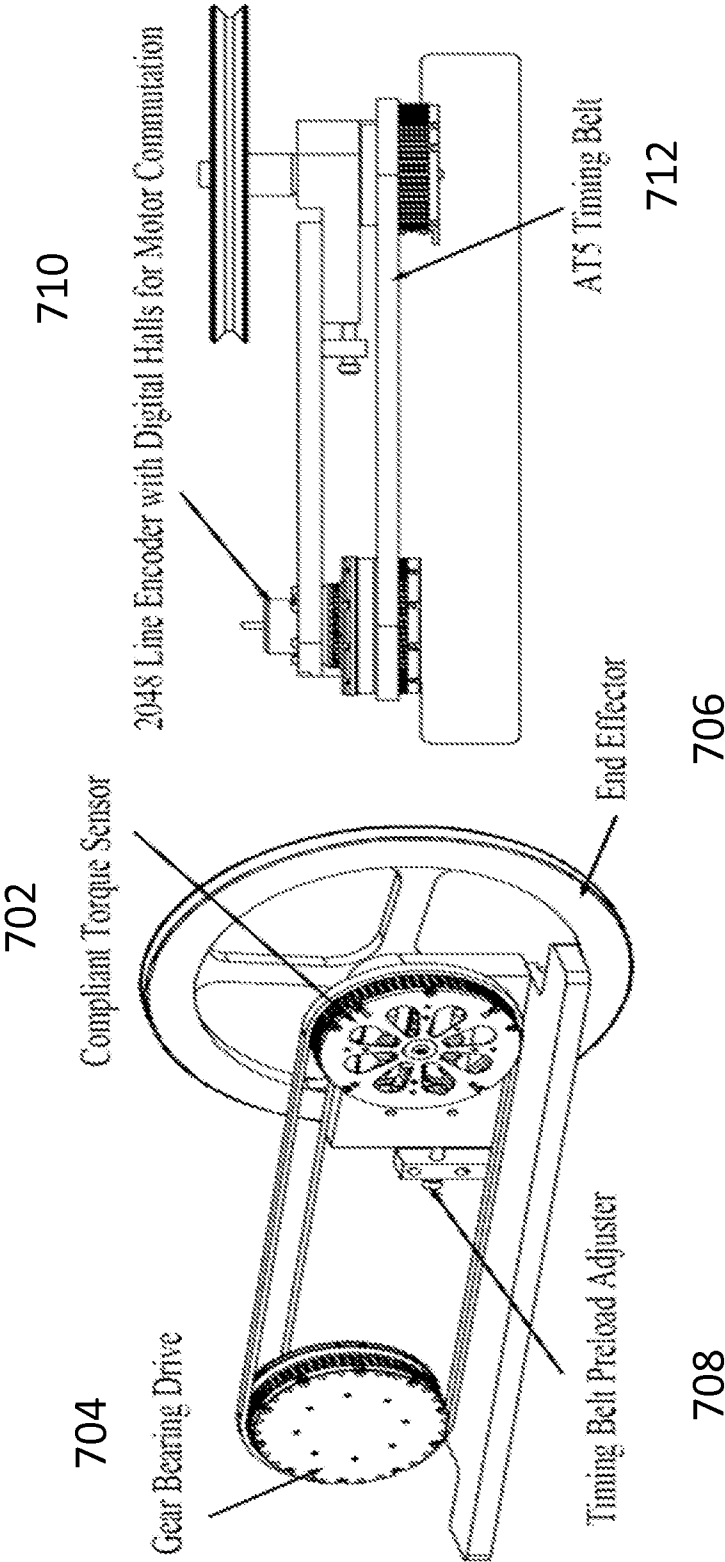


FIG. 7B

FIG. 7A

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2014/042335

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01L 5/00 (2014.01)

CPC - A61F 2002/7645 (2014.09)

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(8) - A61F 2/64, 2/76; G01L 1/20, 1/22, 3/00, 5/00, 5/16, 5/22 (2014.01)

CPC - A61F 2002/5072, 2002/7635, 2002/7645; G01L 3/1457, 5/16 (2014.09)

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

USPC - 338/2, 5; 474/19; 475/149

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

PatBase, Google Patents, Google

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008/0097269 A1 (WEINBERG et al) 24 April 2008 (24.04.2008) entire document	1-11,20
A	US 2011/0125290 A1 (LANGLOIS) 26 May 2011 (26.05.2011) entire document	1-11,20
A	US 8,211,042 B2 (GILBERT et al) 03 July 2012 (03.07.2012) entire document	1-11,20
A	US 2005/0166685 A1 (BOITEN) 04 August 2005 (04.08.2005) entire document	1-11,20

☐ Further documents are listed in the continuation of Box C.

* 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

30 September 2014

Date of mailing of the international search report

03 NOV 2014

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Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
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Authorized officer:

Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2014/042335

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 12-19
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.