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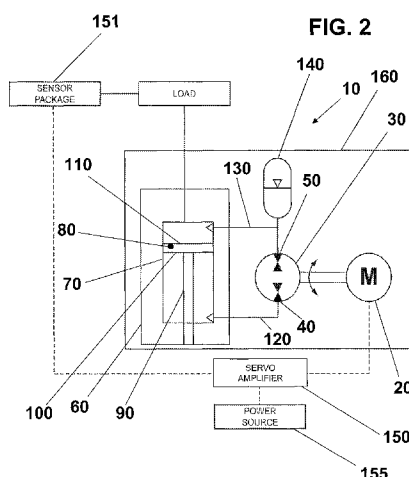
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(57) **Abstract:** Actuators suited for use with, for example, vehicular suspension systems. In some embodiments, the present actuators include a reversible hydraulic pump configured to produce variable hydraulic pressure; a hydraulic cylinder assembly (60) having a cylinder bore, and a piston (80) positioned within the cylinder bore (70) that is axially movable relative to the cylinder bore; an a hydraulic circuit hydraulically coupling the reversible hydraulic pump (30) to the hydraulic cylinder assembly. In these embodiments, actuated axial motion of the piston relative to the cylinder bore is accomplished without the use of check valves, pressure regulating valves, or actively controlled valves.

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DESCRIPTION

ACTUATORS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Patent Application Serial No. 11/674,600,
5 filed February 13, 2007, the entire disclosure of which is specifically incorporated herein by
reference.

BACKGROUND

1. Field

The present invention relates generally to actuators, and more particularly to hydraulic
10 actuator devices suited for use in land vehicle suspension systems.

2. Description of Related Art

The use of servo actuators to control motion in land vehicle suspension systems offers
the potential for improving performance, especially for off road application. For example,
developers of military vehicles have been particularly interested in this technology to enable
15 faster movement of military vehicles over rough battlefield terrain. Active suspension
systems provide a smoother ride and greater maneuvering stability in both off-road and on-
road vehicles than passive suspension systems.

Linear electromechanical actuators have been employed in active suspension system
designs. Typical linear electromechanical actuators for active suspension systems consist of
20 a rotary electric motor, an efficient means of providing mechanical advantage and converting
rotary motion to linear motion, and a means of controlling the torque of the motor. For
example, in one example of an active suspension electromechanical actuator, the mechanical
advantage is a set of reduction gears and a rack and pinion pair to convert the rotary
electromechanical torque to linear force. Typically, the linear actuator is supplemented by a
25 passive spring (steel coil, air, or other) to support vehicle static weight. Although this

combination rack and pinion based electromechanical actuator and supplemental spring works well, it is relatively long (poor ratio of actuator stroke to actuator length). This makes the rack and pinion actuator difficult to integrate into existing land vehicle suspension systems.

5 An alternate design approach utilizes hydraulic servo systems. Typical hydraulic servo systems have an electric motor, a hydraulic pump, a fluid reservoir, servo valves, flow passages, a hydraulic cylinder, and an array of pressure sensors and limit switches to control motion. This arrangement generally provides a good range of motion and can be configured to operate in all four control quadrants. The servo valve throttles the flow of fluid to control
10 cylinder force, and in its best form controls fluid flow rate to the cylinder in a proportional manner by partially opening or throttling. In four quadrant systems, four-way servo valves are used to direct hydraulic pressure to one side of the cylinder and to vent the other side to the fluid reservoir. This arrangement is satisfactory in systems where motion is intermittent and where duty cycle is relatively low, such as construction equipment. In systems with high
15 duty cycles, the conventional servo system offers low efficiency due to two major sources of losses. The first source of energy loss is in the servo valve, where throttling action is lossy, reducing pressure by dissipating energy. The second source of energy loss is in supply pressure regulation, typically accomplished by bleeding off or bypassing some of the flow to the reservoir to control the output pressure from the hydraulic pump. In systems where
20 energy efficiency is important, pressure regulation is accomplished with a variable displacement hydraulic pump. However, this increased efficiency is at the expense of size, complexity and cost.

SUMMARY

Embodiments of the present actuators are well-suited for use in an active suspension
25 system for off-road or on-road vehicles. In some embodiments, the present actuators include,

consist of, or consist essentially of a reversible hydraulic pump configured to produce variable hydraulic pressure; a hydraulic cylinder assembly comprising a cylinder bore and a piston positioned within the cylinder bore that is axially movable relative to the cylinder bore; and a hydraulic circuit hydraulically coupling the reversible hydraulic pump to the hydraulic cylinder assembly. In these embodiments, actuated axial motion of the piston relative to the cylinder bore is accomplished without the use of check valves, pressure regulating valves, or actively controlled valves. Land vehicles may employ some of these embodiments in a suspension system.

Some embodiments of the present actuator may include a servomechanism coupled to the reversible hydraulic pump. In some embodiments, the actuator is configured such that the reversible hydraulic pump is back drivable. Some embodiments may include as part of the hydraulic circuit a fixed-volume hydraulic accumulator that is at least partially filled with a compressible gas being held at a pressure greater than or equal to ambient pressure. Other embodiments may include a hydraulic accumulator having variable volume. Land vehicles may employ some of these embodiments in a suspension system.

In some embodiments, the reversible hydraulic pump, the hydraulic cylinder assembly, and the hydraulic circuit are structurally integrated as a modular unit that has an outer surface. Some embodiments also include a fixed-volume hydraulic accumulator that is structurally integrated as part of the modular unit. In some of these embodiments, actuated axial motion of the piston relative to the cylinder bore of the actuator requires no hydraulic communication with any component external to the outer surface of the modular unit. Land vehicles may employ some of these embodiments in a suspension system.

In other embodiments, the present actuators include, consist of, or consist essentially of a reversible motor configured to produce variable torque; a hydraulic transducer that is coupled to the reversible motor and has a first port and a second port; a hydraulic cylinder

assembly comprising a cylinder bore, a piston positioned within the cylinder bore that is axially movable relative to the cylinder bore and has a rod-end side and a cylinder-end side, and a piston rod connected to the piston at the rod-end side of the piston; a first flow conduit hydraulically coupling the first port of the hydraulic transducer to the rod-end side of the piston; a second flow conduit hydraulically coupling the second port of the hydraulic transducer to the cylinder-end side of the piston; and a hydraulic accumulator hydraulically coupled to the cylinder-end side of the piston. The coupling of the hydraulic transducer to the reversible motor may be achieved through direct mechanical contact of the components, mechanical contact of the components through intermediate components, magnetic coupling, or other methods of energy transfer. In these embodiments, actuated axial motion of the piston relative to the cylinder bore is accomplished without the use of check valves, pressure regulating valves, or actively controlled valves. Land vehicles may employ some of these embodiments in a suspension system.

Some embodiments of the present actuator may include a reversible electric motor capable of variable torque. Some embodiments may include a servo amplifier electrically coupled to the reversible electric motor. In some embodiments, the actuator may be configured such that the reversible electric motor is back drivable. In some embodiments, the hydraulic accumulator may have a fixed volume that is at least partially filled with a compressible gas being held at a pressure greater than or equal to ambient pressure. Land vehicles may employ some of these embodiments in a suspension system.

In some embodiments, the reversible motor, the hydraulic transducer, the hydraulic cylinder assembly, the first flow conduit, and the second flow conduit are structurally integrated as a modular unit that has an outer surface. In some embodiments, the first flow conduit and the second flow conduit are routed within the piston rod and have no hydraulic tubing routed external to the outer surface of the modular unit. In some of these

embodiments, actuated axial motion of the piston relative to the cylinder bore of the actuator requires no hydraulic communication with any component external to the outer surface of the modular unit. Land vehicles may employ some of these embodiments in a suspension system.

5 Some embodiments of the actuator may be configured to provide full four-quadrant operation, whereby the actuator can produce force in each of the two directions of travel, and do so either in support of, or in resistance to, the actuator direction of travel.

Details associated with the embodiments described above and others are presented below. Other embodiments of the present actuators are possible.

10

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings illustrate by way of example and not limitation. They are drawn to scale (in terms of proportions). Identical reference numerals do not necessarily indicate an identical structure. Rather, the same reference numeral may be used to indicate a similar feature or a feature with similar functionality. Not every feature of each embodiment is labeled in every figure in which that embodiment appears, in order to keep the figures clear.

15

FIG. 1 is a perspective view of one embodiment of the present actuators.

FIG. 2 is a schematic view of the actuator shown in **FIG. 1**.

FIG. 3 is a perspective cross-sectional view of the actuator shown in **FIG. 1** and taken at plane 3-3 of **FIG. 1**.

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FIG. 4 is a cross-sectional view of the actuator shown in **FIG. 1** and taken at plane 4-4 of **FIG. 1**.

FIG. 5A is a cross-sectional view of the actuator shown in **FIG. 1** and taken at plane 5-5 of **FIG. 1**.

FIGS. 5B-5C are partial cross-sectional views showing additional detail of the cross-sectional view shown in **FIG. 5A**. Hydraulic fluid flow paths and examples of hydraulic fluid flow direction are illustrated.

FIG. 6 is a partial perspective cross-sectional view showing the piston, cylinder bore, and accumulator of the actuator shown in **FIG. 1**.

FIG. 7 is a cross-sectional view of the actuator shown in **FIG. 1** and taken at plane 7-7 of **FIG. 1**. The hydraulic transducer, a gear pump in this embodiment, is shown.

FIG. 8 is a front view of an embodiment of the present actuators that does not have the hydraulic accumulator, hydraulic transducer, or reversible motor structurally integrated with the cylinder assembly.

FIG. 9 is a cross-sectional view of an embodiment of the present actuators illustrating possible placement of a resolver and a linear variable displacement transducer.

FIG. 10 is a perspective view of an embodiment of the present actuators employed in a suspension system of a land vehicle.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The terms “comprise” (and any form of comprise, such as “comprises” and “comprising”), “have” (and any form of have, such as “has” and “having”), “contain” (and any form of contain, such as “contains” and “containing”), and “include” (and any form of include, such as “includes” and “including”) are open-ended linking verbs. As a result, a system or method that “comprises,” “has,” “contains,” or “includes” one or more elements possesses those one or more elements, but is not limited to possessing only those one or more elements or steps. Likewise, an element of a system or method that “comprises,” “has,”

“contains,” or “includes” one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a structure that is configured in a certain way must be configured in at least that way, but also may be configured in a way or ways that are not specified.

5 The terms “a” and “an” are defined as one or more than one unless this disclosure explicitly requires otherwise. The terms “substantially” and “about” are defined as at least close to (and includes) a given value or state (preferably within 10% of, more preferably within 1% of, and most preferably within 0.1% of). Metric units may be derived from the English units provided by applying a conversion and rounding to the nearest millimeter.

10 A preferred embodiment of the present actuator appears in perspective in **FIG. 1**. Actuator **10** includes hydraulic cylinder assembly **60**, reversible motor **20** capable of variable torque, and hydraulic transducer **30**.

 Reversible motor **20** of the actuator **10** is a reversible electric motor capable of variable torque, which may be driven by a servo amplifier. For example, the schematic
15 diagram of **FIG. 2** shows servo amplifier **150** electrically coupled to reversible motor **20**. In this embodiment, servo amplifier **150** provides a command signal for reversible motor **20** based on information from sensor package **151**. One of ordinary skill in the art will recognize that the sensor package may include few or numerous measurement devices, such as force transducers, pressure transducers, linear variable displacement transducers, and
20 resolvers. **FIG. 9** is a cross-sectional view of an alternate embodiment of actuator **10** showing an example of a resolver **152** configured to measure the rotation of hydraulic transducer **30**, and a linear variable displacement transducer **153** configured to measure relative linear motion between piston **80** and cylinder bore **70**.

Hydraulic transducer **30** of the preferred embodiment is gear pump **31** having first port **40**, second port **50**, and two spur gears **32** as illustrated in **FIG. 7**. In alternate embodiments, the hydraulic transducer may be any hydraulic transducer capable of bi-directional operation. “Bi-directional” operation with respect to the hydraulic transducer is defined as the ability to increase fluid pressure in at least two directions through the hydraulic transducer and to increase fluid flow rate in at least two directions through the hydraulic transducer. For example, in **FIG. 7**, rotational motion of spur gears **32** in a specific direction will result in hydraulic fluid flow away from gear pump **31** through the hydraulic transducer’s first port **40** and to gear pump **31** through the hydraulic transducer’s second port **50**. Rotational motion of spur gears **32** of gear pump **31** in the opposite direction will result in hydraulic fluid flow to gear pump **31** through first port **40** and away from the gear pump **31** through second port **50**. Similarly, torque applied to spur gears **32** in a specific direction will result in an increase in fluid pressure to first port **40**, whereas torque applied to spur gears **32** in the opposite direction will result in an increase in fluid pressure to second port **50**.

Returning to the schematic diagram of **FIG. 2**, hydraulic transducer **30** is coupled to reversible motor **20**, thereby allowing the transfer of energy between these two components. This coupling may be achieved through direct mechanical contact of the components, mechanical contact of the components through intermediate components, magnetic coupling, or other methods of energy transfer.

Hydraulic transducer **30** is hydraulically coupled to components of hydraulic cylinder assembly **60**. “Hydraulic coupling” of components means that the components are in hydraulic communication with each other, either directly or through other components.

One of ordinary skill in the art will recognize that the coupling of hydraulic transducer **30** with reversible motor **20** configured to produce variable torque, combined with the hydraulic coupling of hydraulic transducer **30** with hydraulic cylinder assembly **60**, will

result in a structure that can act as a reversible hydraulic pump capable of producing variable hydraulic pressure. Other embodiments may include other reversible hydraulic pump designs that are configured to produce variable hydraulic pressure. The reversible hydraulic pump may be coupled to a servomechanism to facilitate motion control.

5 Reversible motor **20** and hydraulic transducer **30** may be configured such that reversible motor **20** is back drivable. "Back drivable" denotes that energy can flow from the motor (or back drivable pump in alternate embodiments) to the cylinder assembly (e.g., hydraulic cylinder assembly **60**) or vice versa. When hydraulic energy flows from the cylinder assembly to the motor (or pump), the motor (or pump) functions as a generator that
10 can provide energy that can be stored or used by other components. For example, in the preferred embodiment shown in **FIG. 2**, hydraulic energy from cylinder assembly **60** may enter hydraulic transducer **30**, which can then convert it to mechanical rotational energy. Back drivable reversible electric motor **20**, which is coupled to hydraulic transducer **30**, acts as a generator and converts the mechanical rotational energy to electrical energy
15 (regeneration). The regenerated electrical energy can be stored or used by supporting power source **155**. Servo amplifier **150** of a back drivable actuator is designed to allow energy to flow in both directions.

One of ordinary skill in the art will understand that embodiments of the present actuators may include a servomechanism, reversible motor, and hydraulic transducer
20 configured such that the actuator is capable of four-quadrant operation. Four-quadrant operation exists when the actuator is capable of controlled operation in all four control quadrants. The preferred embodiment of the present actuators is capable of four-quadrant operation.

FIGS. 3-4 are cross-sectional views showing additional detail of hydraulic cylinder
25 assembly **60**. Hydraulic cylinder assembly **60** comprises cylinder bore **70**, piston **80**

positioned within cylinder bore **70**, and piston rod **90**. Piston **80** is axially movable relative to cylinder bore **70**. Piston **80** has rod-end side **100** and an opposite cylinder-end side **110**. Piston rod **90** is connected to piston **80** at rod-end side **100**. Within cylinder bore **70** is a hydraulic fluid-filled volume that is divided by piston **80**.

5 Hydraulic cylinder assembly **60** and its included components shown in **FIG. 3** have circular cross sections when viewed from a plane normal to their longitudinal axis. Other embodiments may have components that have non-circular cross-sectional shapes. For example, the cylinder bore may be rectangular, hexagonal, triangular, or irregularly shaped in cross section. The cylinder bore cross section may be any shape that allows for a piston to be
10 positioned within the cylinder bore and axially movable relative to the cylinder bore. Likewise, the piston can be any suitable shape that satisfies this relationship between cylinder bore and piston. The piston rod may be any structure, or combination of structures, that connects to the rod-end side of the piston and fixes the piston to other components. The piston rod may have any suitable cross-sectional shape.

15 A hydraulic circuit hydraulically couples hydraulic transducer (or reversible hydraulic pump) **30** to hydraulic cylinder assembly **60**. An example of a suitable hydraulic circuit is shown schematically in **FIG. 2**, where first flow conduit **120** hydraulically couples first port **40** of hydraulic transducer **30** to rod-end side **100** of piston **80**, second flow conduit **130** hydraulically couples second port **50** of the hydraulic transducer **30** to the cylinder-end side
20 **110** of piston **80**, and hydraulic accumulator **140** is hydraulically coupled to hydraulic cylinder assembly **60** such that the accumulator is in hydraulic communication with the cylinder-end side **110** of piston **80**. As a result of using such a hydraulic circuit, rod-end side **100** of piston **80** is in hydraulic communication with first port **40** of hydraulic transducer **30**, and cylinder-end side **110** of the piston **80** is in hydraulic communication with second port **50**
25 of the hydraulic transducer **30** and hydraulic accumulator **140**. In alternate embodiments, the

hydraulic accumulator may be hydraulically coupled to the hydraulic cylinder assembly at a different location, such as being configured such that the hydraulic accumulator is in hydraulic communication with the rod-end side **100** of piston **80**.

Hydraulic accumulator **140** compensates for hydraulic fluid volume variation within cylinder bore **70**, which variation is piston-location dependent. This variation results from volume occupied by piston rod **90**. For example, in the depicted embodiment, an actuator position that places a minimum piston rod volume within the cylinder bore results in maximum hydraulic fluid volume within the cylinder bore, whereas an actuator position that places a maximum piston rod volume within the cylinder bore results in minimum hydraulic fluid volume within the cylinder bore. Hydraulically coupling hydraulic accumulator **140** to hydraulic cylinder assembly **60** allows hydraulic fluid to enter and exit cylinder bore **70** as required to compensate for cylinder bore fluid volume changes. Although the preferred embodiment utilizes a hydraulic accumulator, alternate embodiments may include no hydraulic accumulator. Persons of ordinary skill in the art will recognize that embodiments with two piston rods (one connected to each side of the piston) do not have fluid volume variation that is piston-location dependent.

FIG. 3 illustrates that the preferred embodiment has a fixed-volume hydraulic accumulator **140**. The fixed-volume hydraulic accumulator may be partially filled with a compressible gas at a pressure greater than ambient. This pressurization of the fixed-volume accumulator results in variable hydraulic pressure within the actuator, even when reversible motor **20** and hydraulic transducer **30** (or reversible hydraulic pump in alternate embodiments) is inactive. The variable hydraulic pressure is dependent on the position of the piston, thus creating a passive air spring. The passive air spring is a desirable characteristic for some applications of embodiments of the present actuators. For example, the preferred embodiment for implementation of the actuator in an active suspension system for land

vehicles (illustrated in **FIG. 10**) utilizes a fixed-volume hydraulic accumulator partially filled with a compressible gas at positive pressure.

Continuing with the preferred embodiment shown in **FIG. 3**, fixed-volume hydraulic accumulator **140** is integrated with hydraulic cylinder assembly **60**. However, alternate
5 embodiments may include a hydraulic accumulator located differently, or no hydraulic accumulator. Other embodiments may include a hydraulic accumulator having variable volume.

FIGS. 5A-5C and **6** illustrate the preferred embodiment's hydraulic circuit configuration, which routes first flow conduit **120** and second flow conduit **130** through
10 piston rod **90**. Both flow conduits (**120, 130**) comprise portions that are routed axially along the length of piston rod **90**. Second flow conduit **130** comprises a circular passage routed through the center of the piston rod **90**, intersecting the cylinder-end side **110** of piston **80** at opening **131**. First flow conduit **120** comprises an annular passage concentric with second flow conduit **130**. First flow conduit **120** is in hydraulic communication with the rod-end
15 side **100** of piston **80** via multiple openings **121** located on the radial surface of piston rod **90**. Multiple openings **141** located radially on the cylinder bore facilitate hydraulic communication between cylinder-end side **110** of piston **80** and hydraulic accumulator **140**. This preferred embodiment illustrates one efficient and compact configuration for the hydraulic circuit. Other routings, either through the piston rod or otherwise, will be
20 recognized by one of skill in the art.

The preferred embodiment of the present actuators depicted in **FIG. 1** is a modular unit **160**, having outer surface **170**. "Modular unit" is defined as a component or group of components having a common outer surface. The "outer surface" may be one or more surfaces depending on the geometry of the modular unit, and must form one continuous
25 closed volume. The definition of "outer surface" does not include cabling or tubing.

Components that are “structurally integrated” as part of a modular unit are either located within the outer surface of the modular unit, or are part of the outer surface. Elements that are said to be “part of” a modular unit, or “structurally integrated as” a modular unit, denote an open-ended listing of elements of the modular unit. Other non-listed elements may also be members of the modular unit.

Referring to **FIG. 4**, all hydraulic circuit elements are structurally integrated as part of modular unit **160**. In the preferred embodiment, reversible motor **20**, hydraulic transducer **30**, hydraulic cylinder assembly **60**, hydraulic accumulator **140**, first flow conduit **120**, and second flow conduit **130** are structurally integrated as modular unit **160**. The preferred embodiment comprises no hydraulic tubing routed external to outer surface **170** of modular unit **160**, and no hydraulic communication occurs between components within modular unit **160** and any component external to modular unit **160**. Alternate embodiments may include a reversible hydraulic pump, hydraulic cylinder assembly, and hydraulic circuit structurally integrated as a modular unit. In other alternate embodiments, components may be not structurally integrated as a modular unit. **FIG. 8** illustrates an embodiment of the actuator where reversible motor **20**, hydraulic transducer **30**, hydraulic accumulator **140**, and hydraulic cylinder **60** are not structurally integrated as a modular unit, as no common outer surface exists.

Referring to **FIGS. 2-3**, an example of actuated motion of the preferred embodiment of the present actuators involves reversible motor **20** turning hydraulic transducer **30** in response to a current applied by the servo amplifier **150**. This current can be any value up to the maximum allowed by the motor, and can be in either direction. The turning of hydraulic transducer **30** creates a pressure differential between first port **40** of hydraulic transducer **30** and second port **50** of the hydraulic transducer **30**. As a result of the portion of the hydraulic circuit (flow conduits **120**, **130**) coupling hydraulic transducer **30** to hydraulic cylinder

assembly **60**, a pressure differential is created across piston **80**. The pressure differential creates force on piston **80**, which is independent of the direction of the piston velocity and dependent only on the direction of the motor current. As piston **80** moves in the axial direction relative to cylinder bore **70**, hydraulic fluid flows between the volume within the cylinder bore **70** and accumulator **140** to compensate for piston rod displacement.

The preferred embodiment of the present actuators accomplishes actuated motion without using any valves. Valve operation is required only during the initial or maintenance filling of the actuator with hydraulic fluid. The preferred embodiment is controlled by modulating motor torque to modulate the output force of the actuator, rather than by controlling fluid flow with servo-valves (as is typical of hydraulic actuators). Actuated motion of the piston relative to the cylinder bore is accomplished without the use of any check valves, pressure regulating valves, or actively controlled valves. The absence of valves reduces complexity, reduces cost, increases reliability, and improves performance.

* * *

It should be understood that the present actuators are not intended to be limited to the particular forms disclosed. Rather, they are to cover all modifications, equivalents, and alternatives falling within the scope of the claims. For example, although the present actuators have been illustrated and described as working well in land vehicle suspension systems, those of ordinary skill in the art will understand that the present actuators can efficiently and reliably transmit large amounts force in a short response time, and accordingly are suited to many applications, such as compact, high-efficiency actuators for use in aircraft control systems, weapons pointing systems, robotics, and precision machining equipment.

Furthermore, although the components of hydraulic cylinder assembly **60** of the preferred embodiment have been shown as being cylindrically shaped, the components may be of any shape. Additionally, while reversible motor **20** of the preferred embodiment is an

electric motor, any type of reversible motor may be used, and need not be a rotational motor. Also, the coupling of reversible motor **20** to hydraulic transducer **30** of the preferred embodiment need not be a direct mechanical coupling. Alternately, a reversible hydraulic pump that does not have a separately identifiable reversible motor and hydraulic transducer components may be used.

The claims are not to be interpreted as including means-plus- or step-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase(s) “means for” or “step for,” respectively.

CLAIMS

1. An actuator comprising:

a reversible hydraulic pump configured to produce variable hydraulic pressure;

a hydraulic cylinder assembly comprising:

5 a cylinder bore; and

a piston positioned within the cylinder bore, the piston being axially movable
relative to the cylinder bore, and the piston having a rod-end side and a
cylinder-end side;

a hydraulic circuit hydraulically coupling the reversible hydraulic pump to the

10 hydraulic cylinder assembly;

wherein actuated axial motion of the piston relative to the cylinder bore is

accomplished without the use of check valves, pressure regulating valves, or
actively controlled valves.

2. The actuator of claim 1 further comprising a servomechanism coupled to the

15 reversible hydraulic pump.

3. The actuator of claim 1 configured such that the reversible hydraulic pump is back
drivable.

4. The actuator of claim 1, wherein:

the reversible hydraulic pump, the hydraulic cylinder assembly, and the hydraulic

20 circuit are structurally integrated as a modular unit;

the modular unit has an outer surface; and

actuated axial motion of the piston relative to the cylinder bore of the actuator

requires no hydraulic communication with any component external to the
outer surface of the modular unit.

25 5. The actuator of claim 1, wherein:

the hydraulic circuit further comprises a fixed-volume hydraulic accumulator; and
the fixed-volume hydraulic accumulator is at least partially filled with a compressible
gas, the compressible gas being held in the fixed-volume hydraulic
accumulator at a pressure greater than or equal to ambient pressure.

5 6. The actuator of claim 5, wherein:

the reversible hydraulic pump, the hydraulic cylinder assembly, the hydraulic circuit,
and the fixed-volume hydraulic accumulator are structurally integrated as a
modular unit;

the modular unit has an outer surface; and

10 actuated axial motion of the piston relative to the cylinder bore of the actuator
requires no hydraulic communication with any component external to the
outer surface of the modular unit.

7. The actuator of claim 6, further comprising a servomechanism coupled to the
reversible hydraulic pump, and wherein the actuator is configured such that the reversible
15 hydraulic pump is back drivable.

8. A land vehicle equipped with the actuator of claim 1.

9. A land vehicle equipped with the actuator of claim 6.

10. A land vehicle equipped with the actuator of claim 7.

20 11. An actuator comprising:

a reversible motor configured to produce variable torque;

a hydraulic transducer coupled to the reversible motor, the hydraulic transducer

having a first port and a second port;

a hydraulic cylinder assembly comprising:

25 a cylinder bore;

a piston positioned within the cylinder bore, the piston being axially movable relative to the cylinder bore, and the piston having a rod-end side and a cylinder-end side; and

a piston rod connected to the piston at the rod-end side of the piston;

5 a first flow conduit hydraulically coupling the first port of the hydraulic transducer to the rod-end side of the piston;

a second flow conduit hydraulically coupling the second port of the hydraulic transducer to the cylinder-end side of the piston; and

a hydraulic accumulator hydraulically coupled to the hydraulic cylinder assembly;

10 wherein actuated axial motion of the piston relative to the cylinder bore is accomplished without the use of check valves, pressure regulating valves, or actively controlled valves.

12. The actuator of claim 11, wherein the reversible motor is a reversible electric motor configured to produce variable torque.

15 13. The actuator of claim 12 further comprising a servo amplifier electrically coupled to the reversible electric motor.

14. The actuator of claim 12 configured such that the reversible electric motor is back drivable.

15. The actuator of claim 11, wherein:

20 the reversible motor, the hydraulic transducer, the hydraulic cylinder assembly, the hydraulic accumulator, the first flow conduit, and the second flow conduit are structurally integrated as a modular unit;

the modular unit has an outer surface; and

actuated axial motion of the piston relative to the cylinder bore of the actuator
requires no hydraulic communication with any component external to the
outer surface of the modular unit.

16. The actuator of claim 15, wherein the first flow conduit and the second flow conduit
are routed within the piston rod, and the actuator comprises no hydraulic tubing that is routed
external to the outer surface of the modular unit.

17. The actuator of claim 15, wherein the reversible motor is a reversible electric motor
configured to produce variable torque.

18. The actuator of claim 11, wherein:

the hydraulic accumulator has a fixed volume; and

the hydraulic accumulator is at least partially filled with a compressible gas, the

compressible gas being held in the hydraulic accumulator at a pressure greater
than or equal to ambient pressure.

19. The actuator of claim 17, further comprising a servo amplifier electrically coupled to
the reversible motor, and wherein:

the actuator is configured such that the reversible electric motor is back drivable;

the hydraulic accumulator has a fixed volume; and

the hydraulic accumulator is at least partially filled with a compressible gas, the

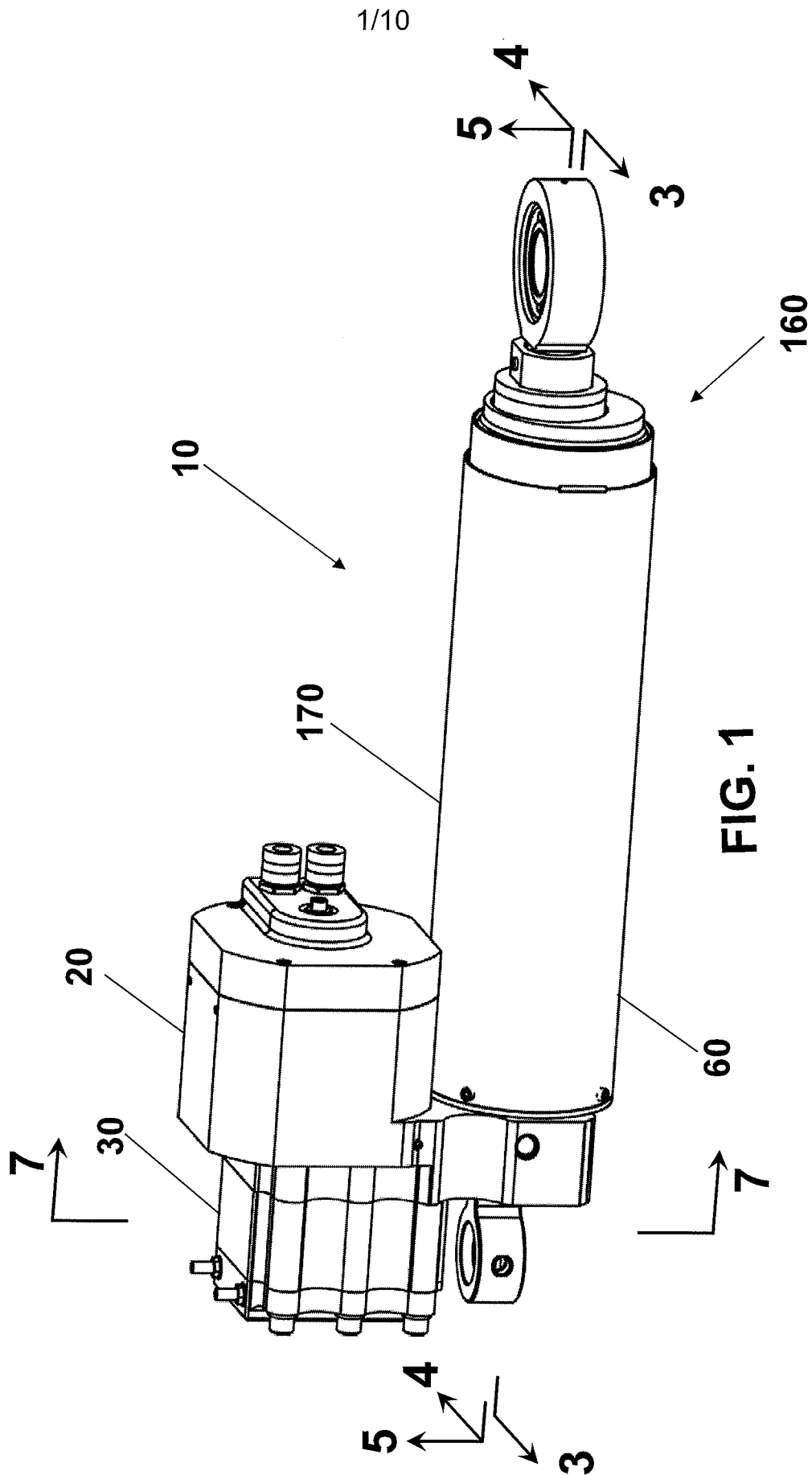
compressible gas being held in the hydraulic accumulator at a pressure greater

than or equal to ambient pressure.

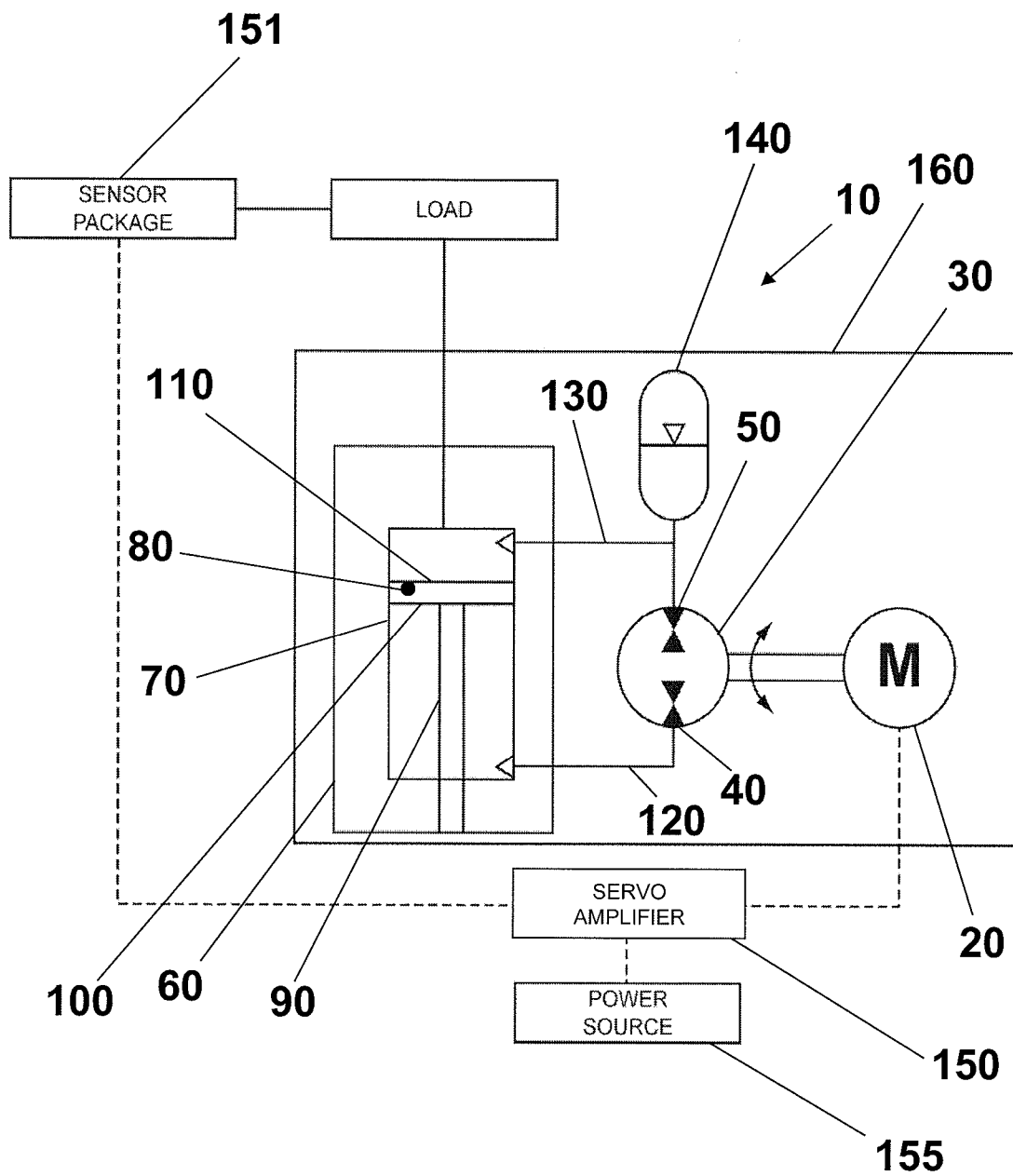
20. A land vehicle equipped with the actuator of claim 11.

21. A land vehicle equipped with the actuator of claim 17.

22. A land vehicle equipped with the actuator of claim 19.



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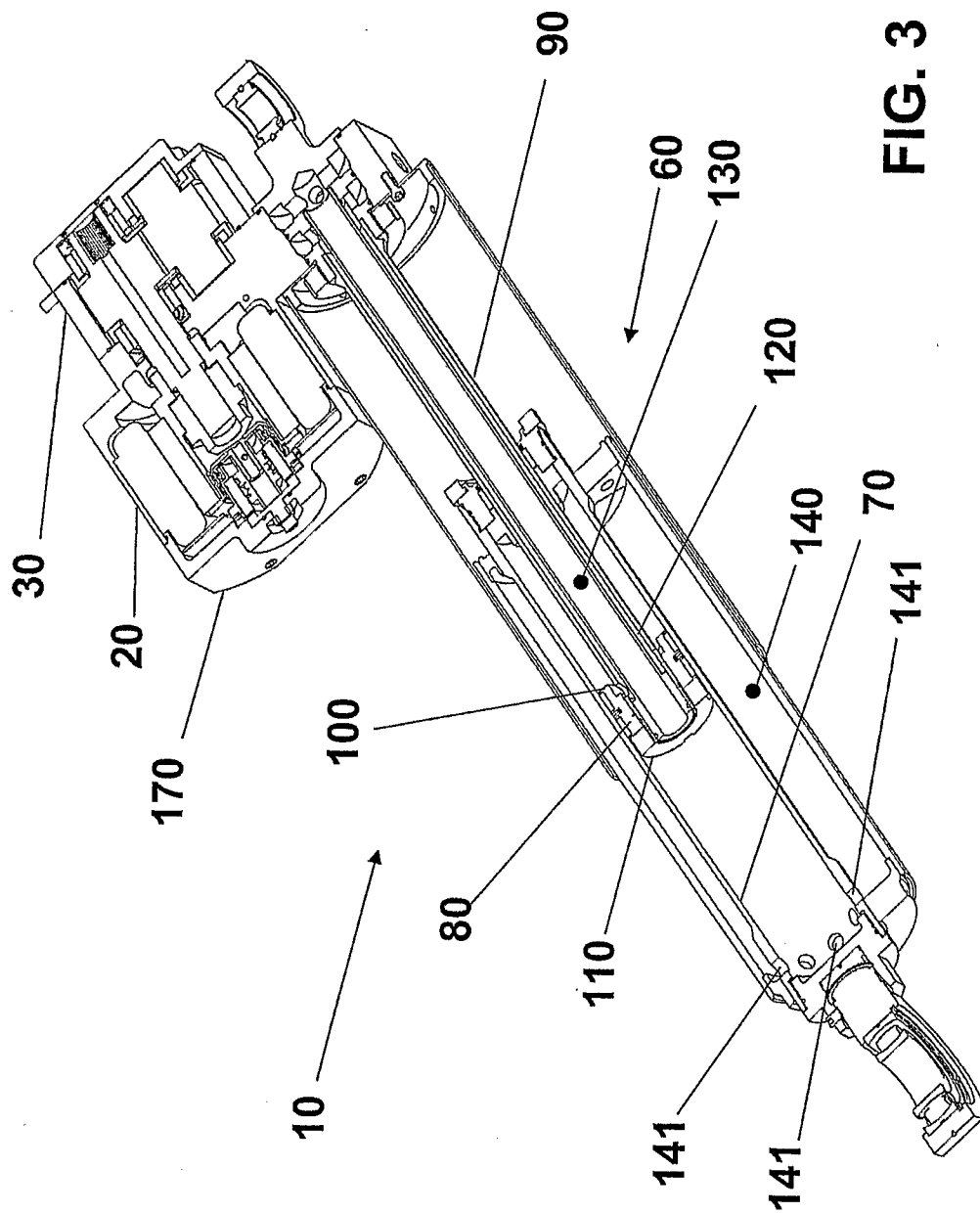


FIG. 3

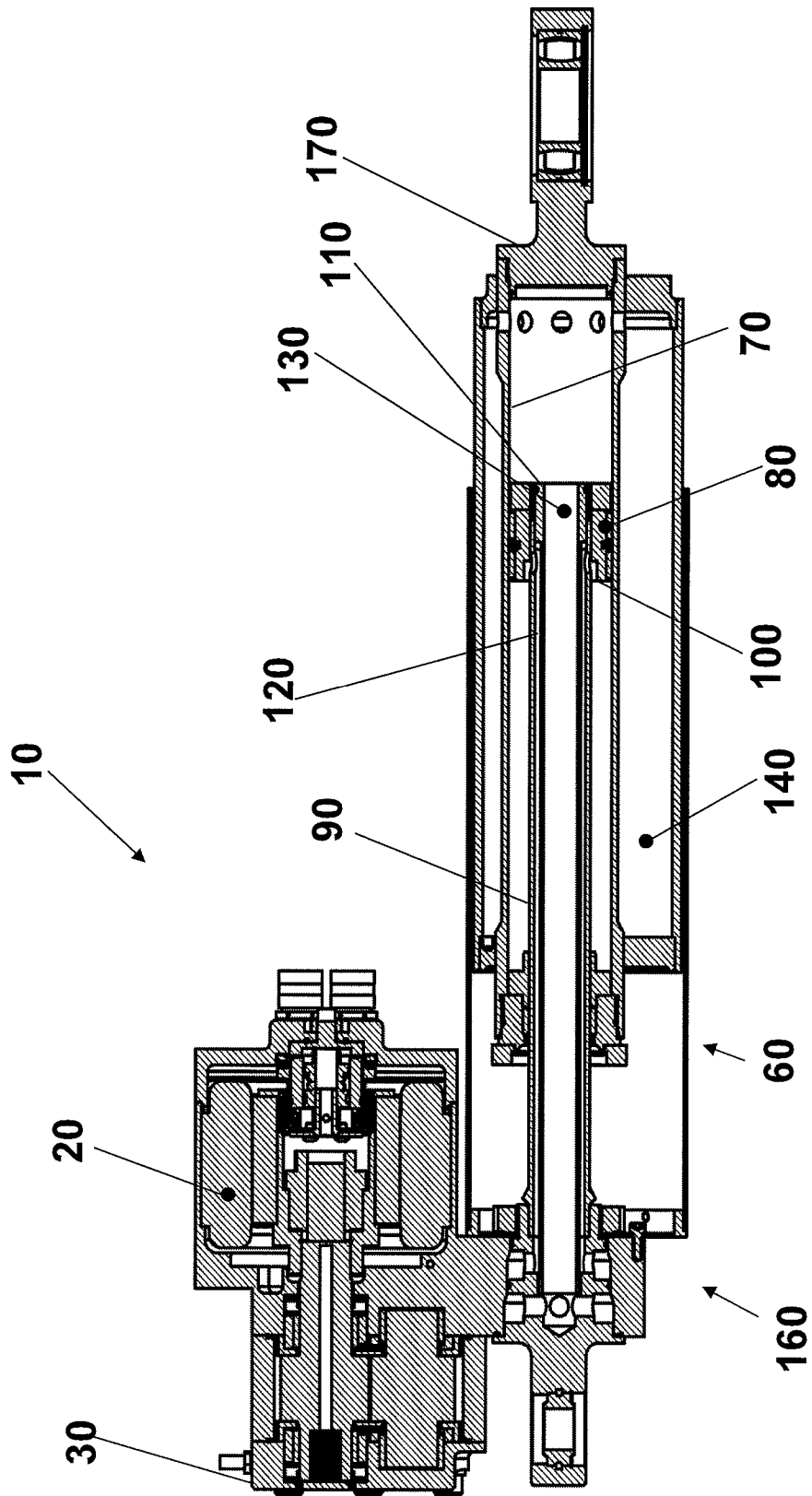
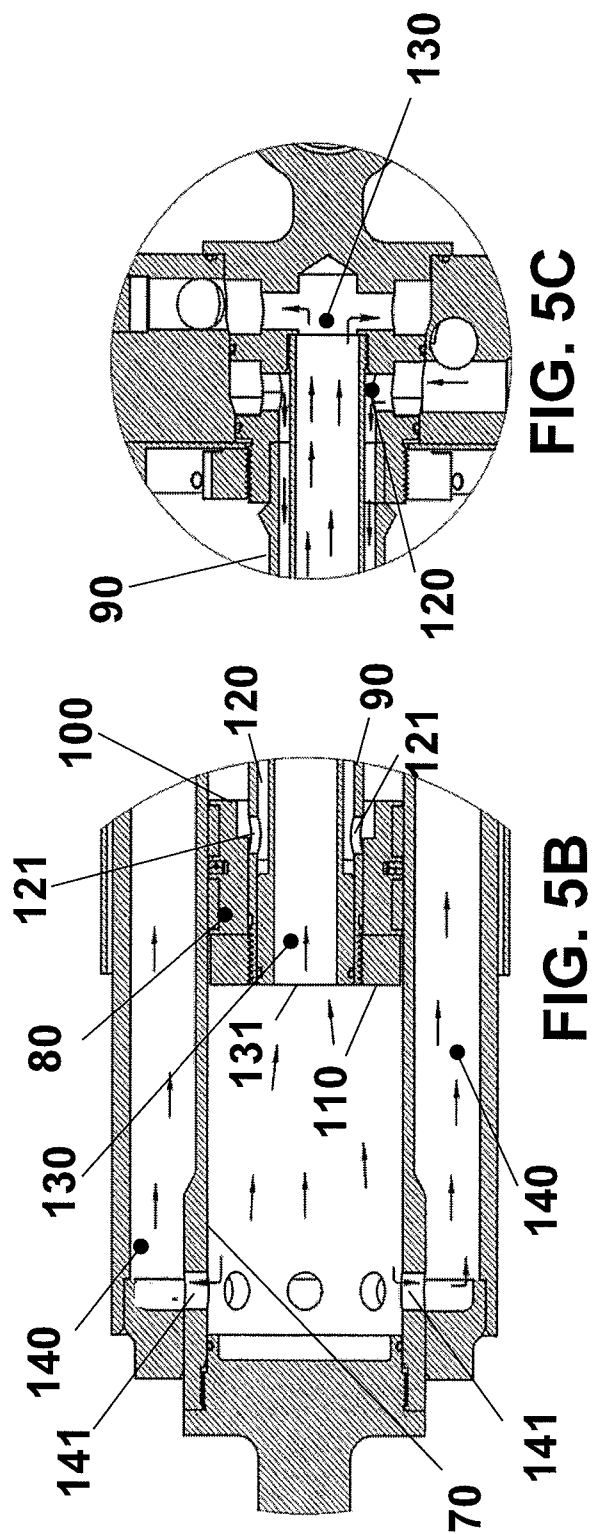
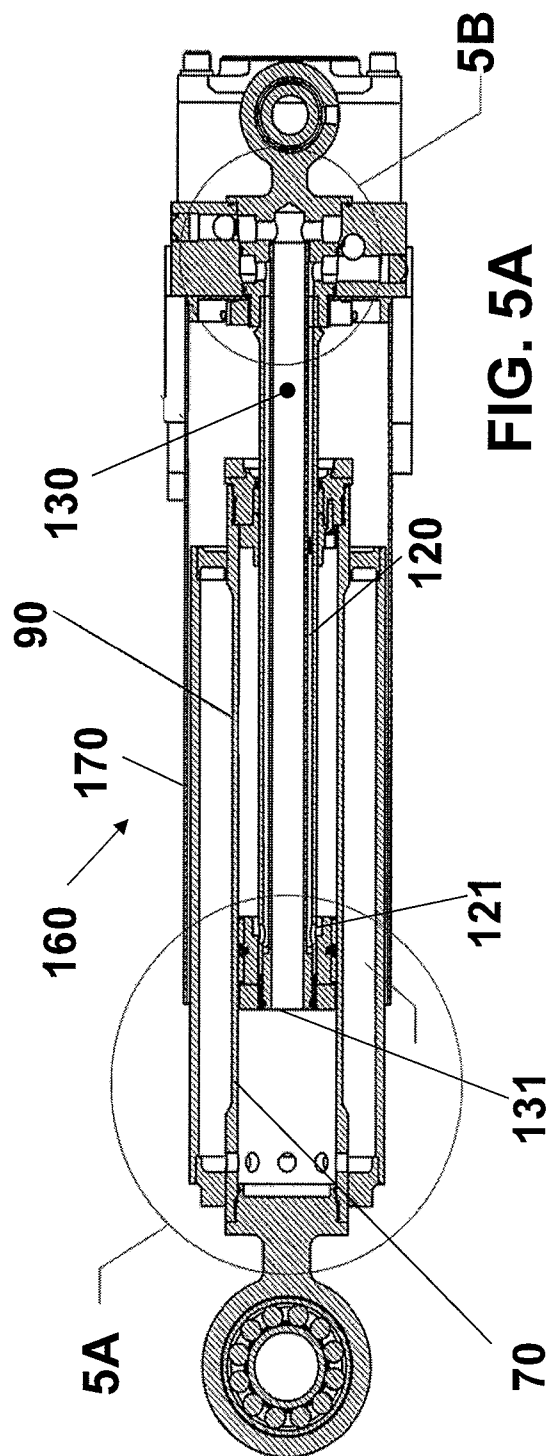


FIG. 4



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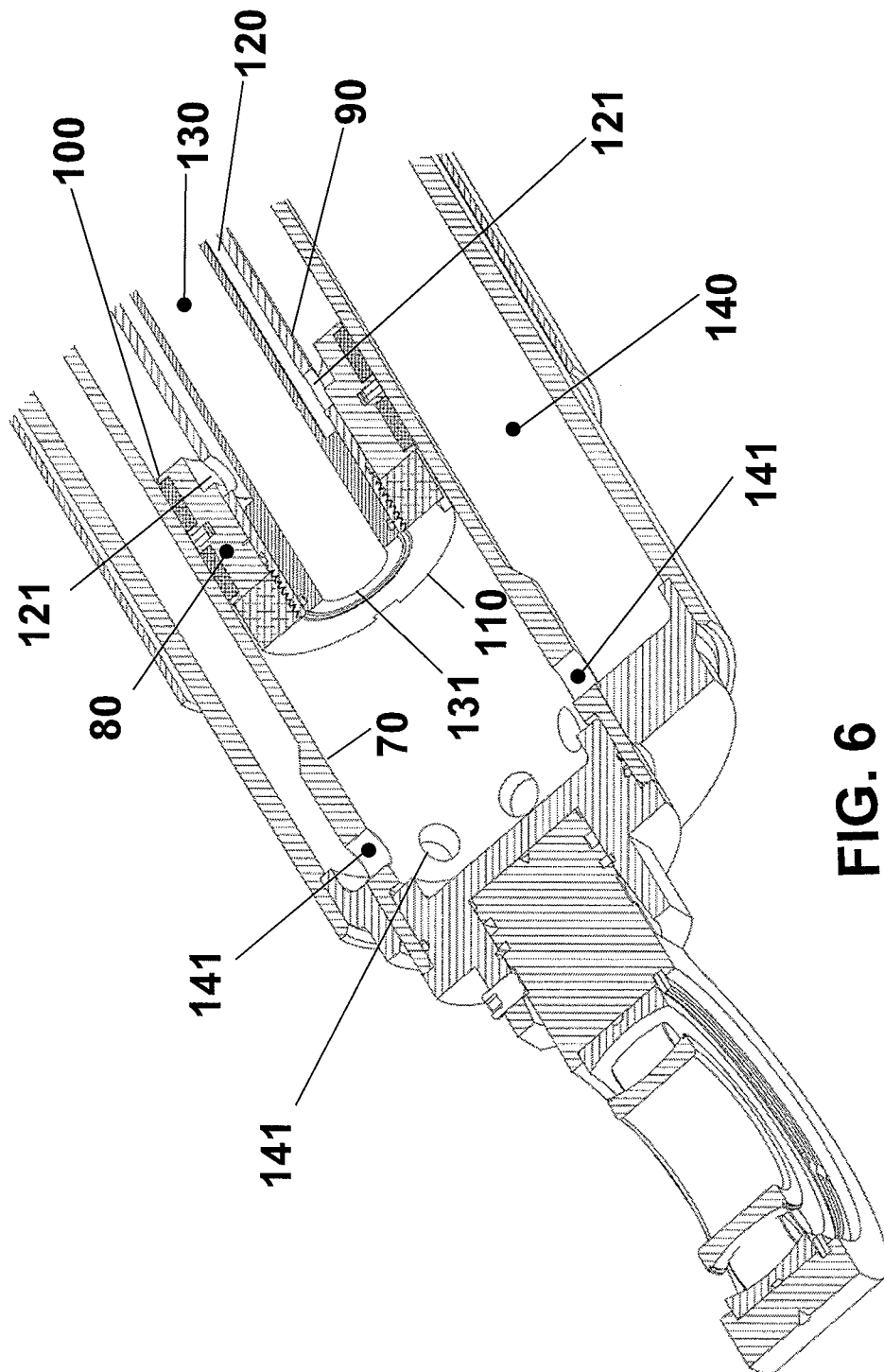


FIG. 6

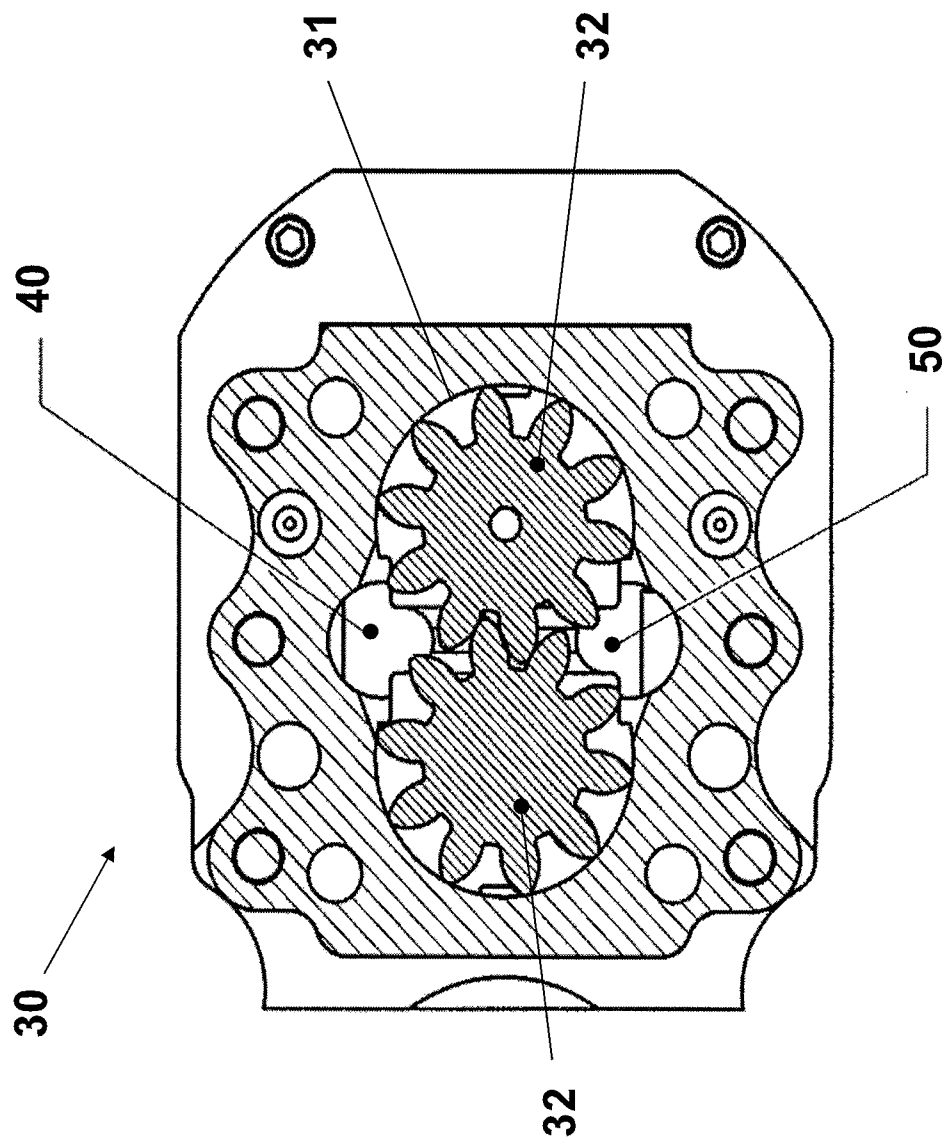


FIG. 7

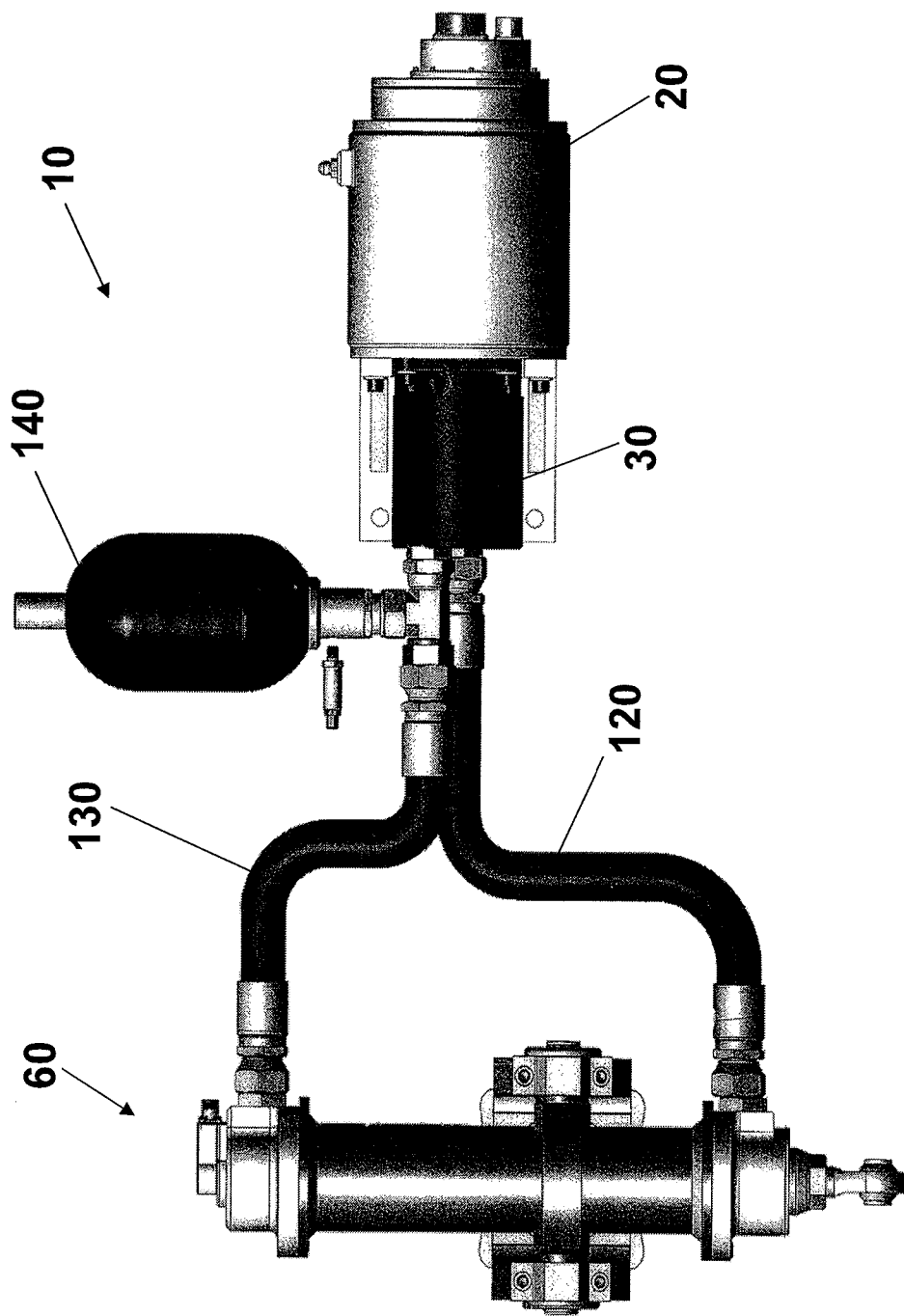


FIG. 8

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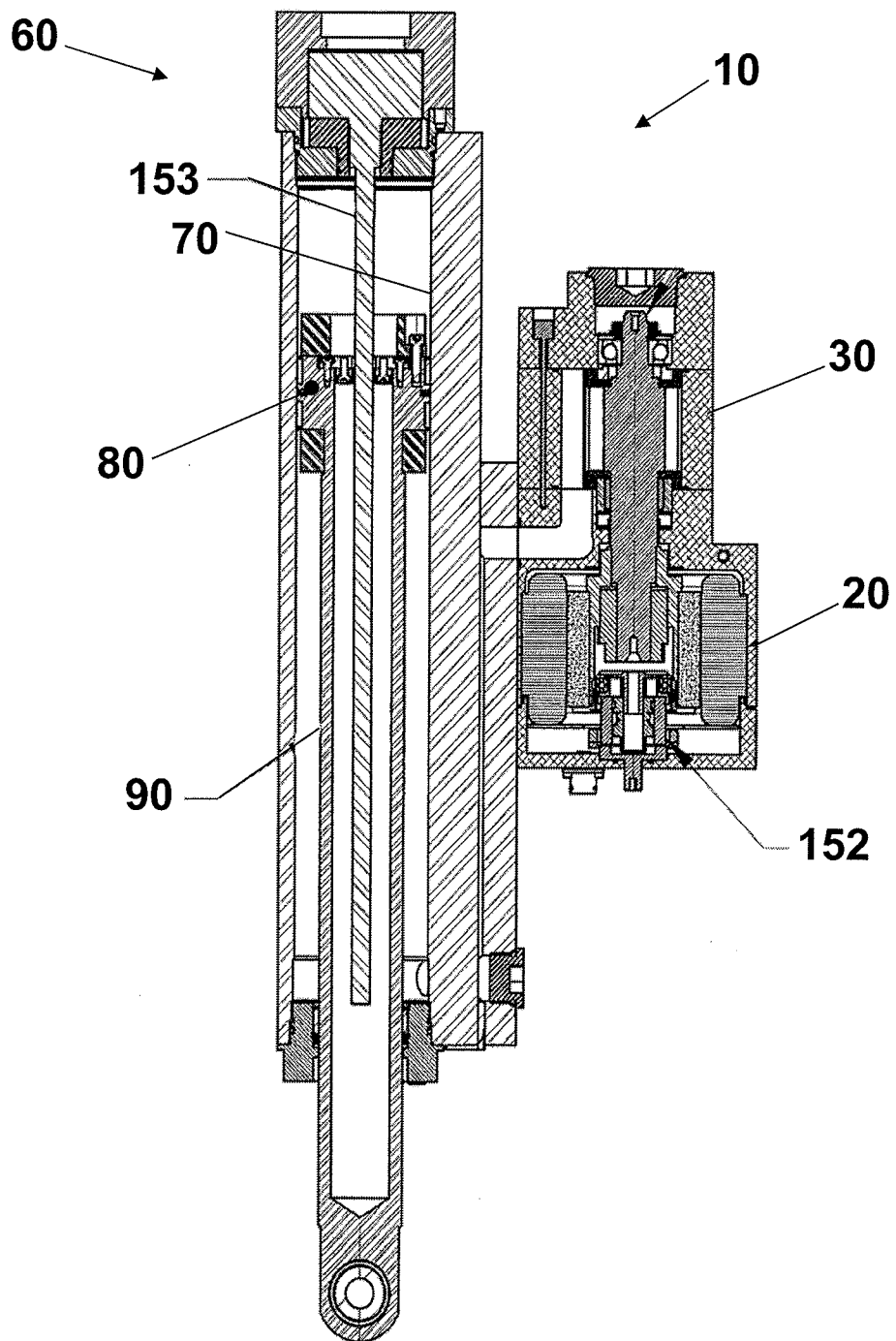


FIG. 9

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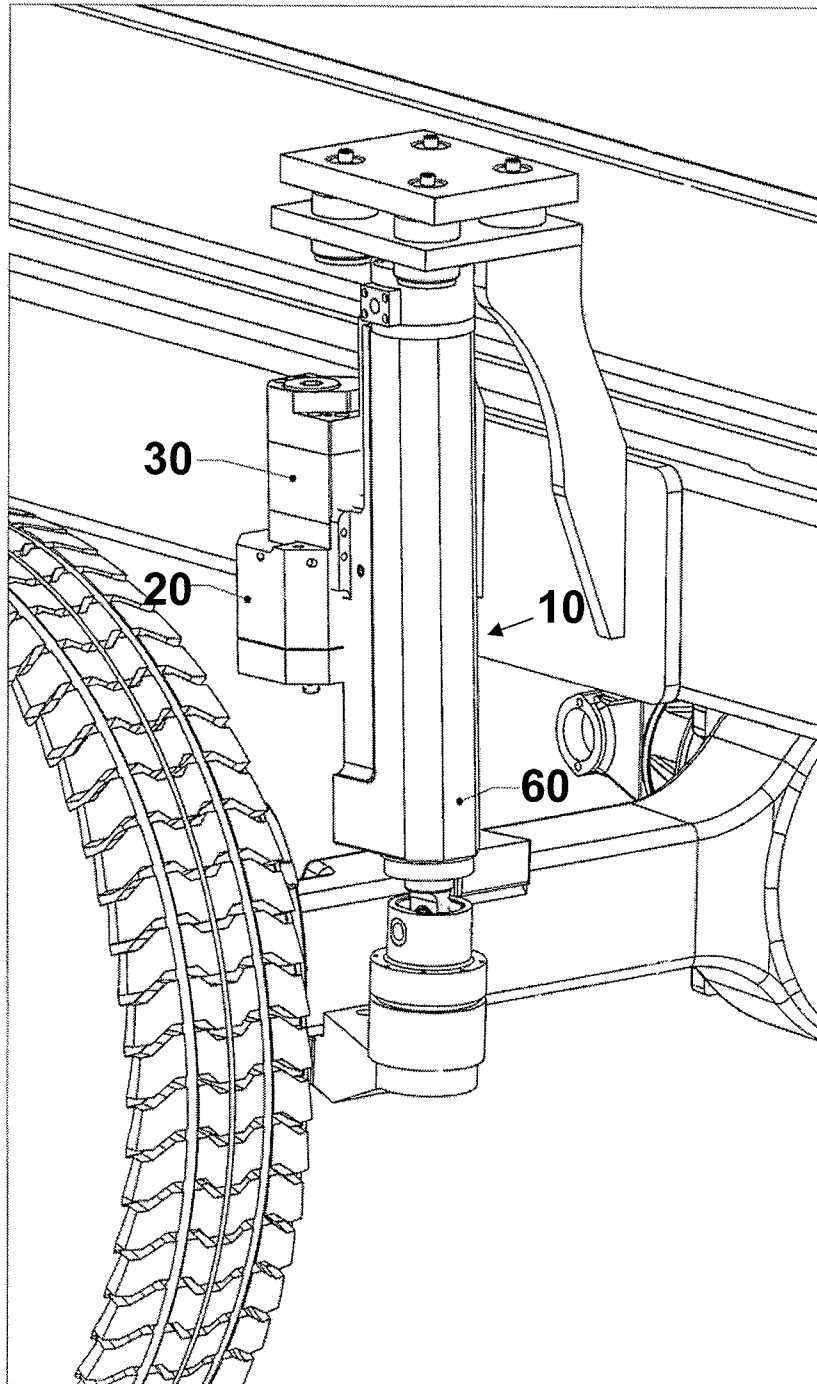


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/053499

A. CLASSIFICATION OF SUBJECT MATTER
INV. F15B7/00

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)

F15B

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 practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 306 560 A (SNECMA MOTEURS [FR]) 2 May 2003 (2003-05-02) paragraphs [0002], [0007] - [0010], [0012] - [0024]; figures 1-3	1-4, 6, 7, 11, 12, 14, 15, 17
Y		9, 10, 16, 19-22
X	WO 2005/059372 A (THALES UK PLC [GB]; GROSSART STUART JAMES CAMERON [FR]) 30 June 2005 (2005-06-30) page 38, line 14 - page 40, line 14; figure 3	1-3, 5, 11, 12, 14, 18
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

19 June 2008

Date of mailing of the international search report

04/07/2008

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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2008/053499

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT

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International application No

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