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Dual-system hydraulic actuator

Abstract

An actuator includes a primary piston and a secondary piston axially movable together in a cylinder assembly; a plurality of chambers comprising: a first chamber, a second chamber, a third chamber, and a fourth chamber, wherein when fluid flows into the first chamber the primary piston extends and when fluid flows into the second chamber the primary piston retracts, wherein an extension fluid force applied by fluid in the third chamber to extend the secondary piston is different from a retraction fluid force applied by fluid in the fourth chamber to retract the secondary piston; and a force-balance chamber configured to receive fluid from the third chamber or the fourth chamber to apply a balancing force on the secondary piston to either oppose fluid force acting on the secondary piston or add to the fluid force acting on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATION (1) The present application is a U.S. National Phase Application pursuant to 35 U.S.C § 371 of International Application No. PCT/US2023/061811 filed on Feb. 2, 2023, which claims priority to U.S. Provisional patent application No. 63/310,679, filed on Feb. 16, 2022, the entire contents of all of which are herein incorporated by reference as if fully set forth in this description.

BACKGROUND

(1) A hydraulic cylinder actuator includes a cylinder that uses hydraulic power to facilitate mechanical operation. Particularly, a hydraulic cylinder actuator includes a hollow cylindrical tube inside which a piston can slide. The piston can divide the cylinder into two chambers. When pressurized fluid is provided to one chamber, the piston moves. A double acting actuator has a piston that can move in both directions. Any difference in fluid pressure between the two sides of the piston moves the piston inside the cylinder.

(2) Hydraulic actuators can be used in a variety of applications such as controlling implements of hydraulic machinery (e.g., excavators, loaders, etc.) and moving control surfaces of an aircraft. For instance, an aircraft typically includes a plurality of flight control surfaces (fixed wing aircraft) or one or more cyclic pitch control swashplates (rotary aircraft) that, when controllably positioned, guide the movement of the aircraft.

(3) In some critical applications, such as aircraft control systems, it may be desirable to have redundant controls, e.g., multiple actuators for moving a control surface, such that if control of one actuator is lost, the other actuators can safely move the control surface. Further, forces of these actuators can be additive, thereby increasing the force that the actuator can exert.

(4) In some applications, such as military applications, it may further be desirable to configure the actuator to be ballistic-tolerant such that the actuator may continue to work even if parts of it are damaged. It may be desirable to have the actuator be ballistic-tolerant without increasing the weight of the actuator substantially.

(5) It is with respect to these and other considerations that the disclosure made herein is presented.

SUMMARY

(6) The present disclosure describes implementations that relate to a dual-system hydraulic actuator.

(7) In a first example implementation, the present disclosure describes an actuator. The actuator includes: a primary piston that is disposed at least partially within a cylinder assembly; a secondary piston that is disposed at least partially within the cylinder assembly, wherein the primary piston and the secondary piston are configured to move together axially within the cylinder assembly; a plurality of chambers formed within the cylinder assembly and comprising: (i) a first chamber, wherein when fluid flows to the first chamber, the primary piston extends, (ii) a second chamber, wherein when fluid flows to the second chamber, the primary piston retracts, (iii) a third chamber, wherein when fluid flows to the third chamber, the secondary piston extends, (iv) a fourth chamber, wherein when fluid flows to the fourth chamber, the secondary piston retracts, and wherein an extension fluid force applied by fluid in the third chamber to extend the secondary piston is different from a retraction fluid force applied by fluid in the fourth chamber to retract the secondary piston; and a force-balance chamber configured to receive fluid from the third chamber or the fourth chamber to apply a balancing force on the secondary piston to either oppose fluid force acting on the secondary piston or add to the fluid force acting on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

(8) In a second example implementation, the present disclosure describes a method of operating the actuator of the first example implementation.

(9) In a third example implementation, the present disclosure describes a hydraulic system including a source of fluid, a fluid reservoir, the actuator of the first example implementation, and one or more manifolds controlling fluid flow from the source of fluid to the actuator and from the

actuator to the fluid reservoir.
(10) The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, implementations, and features described above, further aspects, implementations, and features will become apparent by reference to the figures and the following detailed description.

Description

BRIEF DESCRIPTION OF THE FIGURES
(1) The novel features believed characteristic of the illustrative examples are set forth in the appended claims. The illustrative examples, however, as well as a preferred mode of use, further objectives and descriptions thereof, will best be understood by reference to the following detailed description of an illustrative example of the present disclosure when read in conjunction with the accompanying Figures.
(2) FIG. **1** illustrates a perspective view of an actuator, in accordance with an example implementation.
(3) FIG. **2** illustrates a cross-sectional side view of the actuator of FIG. **1**, in accordance with another example implementation.
(4) FIG. **3** illustrates another cross-sectional side view of the actuator of FIG. **1**, in accordance with an example implementation.
(5) FIG. **4** is a flowchart of a method for operating an actuator, in accordance with an example implementation.
DETAILED DESCRIPTION
(6) The present disclosure relates to a dual-system hydraulic actuator. In some applications, multiple hydraulic cylinder actuators can be used to provide redundancy if control of one actuator is lost, and also to increase the force that can be exerted on a member (e.g., a rotor of a helicopter or control surface of a fixed-wing aircraft) being controlled by the actuators.
(7) In one example, an actuator can include two systems staggered in line such that a long cylinder accommodates several pistons, e.g., two pistons coupled to a common rod. In such a configuration, however, it may be difficult to armor such a long cylinder to protect the pistons against ballistic damage. Further, in such an actuator damage to one system can propagate to the other system, leading to loss of control of the entire actuator.
(8) In another example, an actuator can include three separate pistons, where a central piston is controlled by one system, and two outer pistons, one on each side of the central piston, are controlled by a second system. In this example, if the system associated with the central piston does not work, the second system can operate the other two pistons to enable the actuator to continue working. While damage to one system might not propagate to the other system, such a configuration leads to a large package, which may be undesirable in some applications. Further, armoring three separate cylinder can cause the actuator to much heavier.
(9) Further, in such a three-piston configuration, the pistons are coupled to a common yoke. The outer two pistons have an indirect load path acting on the yoke, which may lead to a reduced stiffness, rendering the actuator more susceptible to damage from vibration. Further, mismatch in force between the outer pistons can lead to bending and side loading.
(10) It may thus be desirable to have a dual-system hydraulic actuator that provides redundancy. Further, it may be desirable for such dual-system actuator to preclude propagation of damage from one system to another. This way, if one system fails, the other system can continue to work. It may also be desirable to have such dual-system actuator configured in a smaller package (e.g., smaller end-to-end length) compared to a three-piston configuration. Such actuator can have higher stiffness, leading to enhanced vibration performance.

(11) FIG. **1** illustrates a perspective view of an actuator **100**, in accordance with an example implementation. The actuator **100** can include a cylinder assembly **102** and a piston rod **104**. The piston rod **104** is slidably-accommodated within the cylinder assembly **102**. The term "slidably accommodated" is used herein to indicate that a first component (e.g., a piston) is positioned relative to a second component (e.g., a cylinder) with sufficient clearance therebetween, enabling movement of the first component relative to the second component in the proximal and distal directions.
(12) A proximal end of the cylinder assembly **102** has a connection portion **106** having a hole **107** through which a pin can be disposed to couple the cylinder assembly **102** to a frame or structure (e.g., to a frame of an aircraft). Similarly, a distal end of the piston rod **104** has a connection portion **108** having a hole **109** through which a pin can be disposed to couple the piston rod **104** to a movable member, such as a control surface of an aircraft or a rotor of a helicopter.
(13) In an example implementation, the cylinder assembly **102** can include a primary cylinder **200** and a secondary cylinder **202**. The primary cylinder **200** is separate from the secondary cylinder **202**.
(14) The primary cylinder **200** can have a flange **204**, and the secondary cylinder **202** can have a respective flange **206**. The flange **204** is coupled to the flange **206** via a plurality of fasteners (e.g., bolts) such as fastener **208**, disposed in a circular array about the cylinder assembly **102**. Beneficially, as the cylinder assembly **102** comprises two separate cylinders, if one of them (e.g., the primary cylinder **200**) is damaged, the other cylinder (e.g., the secondary cylinder **202**) may remain operational.
(15) FIG. **2** illustrates a cross-sectional side view of the actuator **100**, and FIG. **3** illustrates another cross-sectional side view of the actuator **100**, in accordance with an example implementation. The cross-section of FIG. **3** is taken across a plane that is perpendicular to the plane of the cross-sectional view of FIG. **2**.
(16) The actuator **100** has a central gland **300** disposed at the interface between the primary cylinder **200** and the secondary cylinder **202**. In an example, the central gland **300** can include two portions, a first gland portion **302** and a second gland portion **304**. The central gland **300** separates the primary cylinder **200** and the secondary cylinder **202**, and is coupled thereto via the fasteners (e.g., the fastener **208**) that couple the primary cylinder **200** to the secondary cylinder **202**.
(17) The central gland **300** operates as a seal carrier. For example, the central gland **300** can have several internal annular grooves in which seals (e.g., O-rings, T-seals, etc.) can be disposed. This allows slidable components such as pistons to move relative to the central gland **300**, while sealing fluid chambers from each other. Further, as described in more detail below, the central gland **300** isolates a first system controlling a primary piston from a second system controlling a secondary piston.
(18) The primary cylinder **200** and the secondary cylinder **202** together form a cylindrical cavity therein in which a primary piston **306** and a secondary piston **308** are, at least partially, disposed. The primary piston **306** and the secondary piston **308** are axially-movable within the cylinder assembly **102**.
(19) The primary piston **306** and the secondary piston **308** are both hollow. Particularly, the primary piston **306** has a longitudinal cylindrical cavity formed therein in which a portion of the secondary piston **308** is disposed and through which a portion of the piston rod **104** is disposed as well.
(20) The secondary piston **308** is coupled to the piston rod **104** such that the secondary piston **308** and the piston rod **104** move together. For example, the piston rod **104** can have threads formed on its exterior surface at its proximal end, and the secondary piston **308** can have corresponding threads formed in its interior surface at its distal end. This way, the piston rod **104** can be threaded to the secondary piston **308** at threaded region **309**.
(21) Further, a proximal end of the primary piston **306** rests against or interfaces with a shoulder **310** formed by the secondary piston **308**, while a distal end of the primary piston **306** interfaces

with the piston rod **104**. This way, the primary piston **306**, the secondary piston **308**, and the piston rod **104** move together. Particularly, if a force is applied to the primary piston **306**, such force is transmitted to the secondary piston **308** and the piston rod **104** as well. If a force is applied to the secondary piston **308**, such force is transmitted to the primary piston **306** and the piston rod **104** as well.

(22) The primary piston **306** has a piston head **312** on which fluid acts (i.e., applies a fluid force) to move the primary piston **306**. The primary piston **306** is slidably-accommodated within the primary cylinder **200**, such that the piston head **312** slides along the interior surface of the primary cylinder **200** as the primary piston **306** moves axially.

(23) As depicted in FIGS. **2-3**, a first chamber **314** is formed between, or bounded by, an exterior peripheral surface of the secondary piston **308** and an interior peripheral surface of the primary cylinder **200**, and between the piston head **312** and the first gland portion **302**. The first chamber **314** is an annular chamber as depicted. When pressurized fluid is provided to the first chamber **314**, the primary piston **306** extends. The term “extend” or “extension” is used herein to refer to movement in the distal direction (e.g., to the right in FIGS. **2-3**), whereas the term “retract” or “retraction” is used herein to refer to movement in the proximal direction (e.g., to the left in FIGS. **2-3**).

(24) Further, a second chamber **316** is formed between, or bounded by, an exterior peripheral surface of the primary piston **306** and an interior peripheral surface of the primary cylinder **200**, and between the piston head **312** and an end gland **318**. The second chamber **316** is also an annular chamber. When pressurized fluid is provided to the second chamber **316**, the primary piston **306** retracts.

(25) The end gland **318** is disposed at a distal end of the primary cylinder **200** between the primary piston **306** and the primary cylinder **200**. The end gland **318** can have internal annular grooves in which seals are disposed. This way, the primary piston **306** can move or slide axially relative to the end gland **318**, while the seals preclude leakage from the second chamber **316** to the external environment of the actuator **100**. The second chamber **316** is referred to as a retraction chamber because when pressurized fluid is provided thereto, the primary piston **306** retracts.

(26) The actuator **100** has a first port **320** formed in the primary cylinder **200** and configured to provide fluid to and receive fluid from the first chamber **314**. The actuator **100** further has a second port **322** formed in the primary cylinder **200** and configured to provide fluid to and receive fluid from the second chamber **316**.

(27) For example, if pressurized fluid is provided from a source of fluid (e.g., a pump) through the first port **320** to the first chamber **314**, the fluid applies a fluid force on the piston head **312** in the distal direction, and the primary piston **306** extends (moves in the distal direction). Fluid discharged from the second chamber **316** as the primary piston **306** extends flows through the second port **322** to a fluid reservoir, for example.

(28) On the other hand, if pressurized fluid is provided from the source of fluid through the second port **322** to the second chamber **316**, the fluid applies a fluid force on the piston head **312** in the proximal direction, and the primary piston **306** retracts (moves in the proximal direction). The primary piston **306** can retract (i.e., move in the proximal direction) until it reaches the first gland portion **302** of the central gland **300** (i.e., bottoming of the primary piston **306** during retraction takes place as it reaches the first gland portion **302**).

(29) Fluid discharged from the first chamber **314** as the primary piston **306** retracts flows through the first port **320** to the fluid reservoir. As mentioned above, movement of the primary piston **306** causes the piston rod **104** and the secondary piston **308** to move therewith.

(30) Referring to FIG. **3**, an outer diameter of the piston head **312** of the primary piston **306** (or inner diameter of the primary cylinder **200**) is labelled “D.sub.1,” while the outer diameter of the rest of the primary piston **306** is labelled “D.sub.2.” An outer diameter of the secondary piston **308** through a portion that bounds the first chamber **314** is also equal to D.sub.2. With this

configuration, the annular surface area of the primary piston **306** in the first chamber **314** on which fluid acts to extend the primary piston **306** is equal to the annular surface area of the primary piston **306** in the second chamber **316** on which fluid acts to retract the primary piston **306**.
(31) Thus, the primary piston **306** is balanced, i.e., the fluid force acting on the primary piston **306** when extending is equal to the fluid force acting on the primary piston **306** when retracting. Assuming pressure level of supply fluid provided to the first chamber **314** is P.sub.S, while return fluid in (fluid being discharged from) the second chamber **316** is P.sub.R, then the fluid force acting on the primary piston **306**, whether the primary piston **306** is extending or retracting, is
(32) $F_1 = P_S(\pi\frac{D_1^2}{4} - \pi\frac{D_2^2}{4}) - P_R(\pi\frac{D_1^2}{4} - \pi\frac{D_2^2}{4}) = (P_S - P_R).(\pi\frac{D_1^2}{4} - \pi\frac{D_2^2}{4})$.
As an example, the supply pressure level P.sub.S can be a high pressure level such as 3000-5000 psi, whereas the return pressure level P.sub.R can be a low pressure level, e.g., 50-100 psi.
(33) The primary cylinder **200**, the primary piston **306**, and the associated fluid chambers can be considered a first system that controls extension and retraction of the piston rod **104**. The actuator **100** further has a second system that includes the secondary piston **308** and associated fluid chambers that controls extension and retraction of the piston rod **104** (via the secondary piston **308**). This way, the actuator **100** is a dual-system actuator where if one system does not work, another system can safely operate the movable member (e.g., aircraft control surface or rotor) being controlled by the actuator **100**.
(34) The secondary piston **308** has a piston head **324** on which fluid acts (i.e., applies a fluid force) to move the secondary piston **308**. The secondary piston **308** is slidably-accommodated within the secondary cylinder **202**, such that the piston head **324** slides along the interior surface of the secondary cylinder **202** as the secondary piston **308** moves axially.
(35) The secondary piston **308** is hollow as depicted in FIGS. **2-3** and includes a longitudinal cylindrical cavity formed therein. The actuator **100** includes a balance tube **326**, an inner cylinder **328**, and a static piston **330** that are received, at least partially, within the longitudinal cylindrical cavity of the secondary piston **308**.
(36) The static piston **330** is coupled to the secondary cylinder **202** such that the static piston **330** remains stationary or fixedly-disposed within the secondary cylinder **202**. For instance, a proximal end of the static piston **330** can be threaded into or retained by a retaining ring to the secondary cylinder **202**.
(37) The balance tube **326** is coupled to the static piston **330** via a retaining ring **332** (e.g., a wire ring or a retaining O-ring), such that the balance tube **326** also remains stationary. The inner cylinder **328** is slidable about an exterior surface of the static piston **330**. Particularly, the inner cylinder **328** is slidably-accommodated between the balance tube **326** and the static piston **330** such that the inner cylinder **328** can move axially relative to the balance tube **326** and the static piston **330**.
(38) A force-balance chamber **334** is formed between the exterior peripheral surface of the static piston **330** and the interior peripheral surface of the inner cylinder **328**, between an enlarged distal end **335** of the static piston **330** and a proximal end **336** of the inner cylinder **328**. The proximal end **336** of the inner cylinder **328** has external grooves and internal grooves in which seals can be disposed to preclude fluid leakage from the force-balance chamber **334** as the inner cylinder **328** moves axially about the exterior surface of the static piston **330**. As depicted in FIGS. **2-3**, the balance tube **326** is interposed (radially) between the inner cylinder **328** and the secondary piston **308**. The secondary piston **308** is configured to move axially about the exterior surface of the balance tube **326** as the secondary piston **308** extends or retracts.
(39) Further, as depicted in FIGS. **2-3**, a third chamber **338** is formed between, or bounded by, an exterior peripheral surface of the balance tube **326** and an interior peripheral surface of the secondary cylinder **202**, and between the piston head **324** and an interior proximal surface of the secondary cylinder **202**. Also, a fourth chamber **340** is formed between, or bounded by, an exterior peripheral surface of the secondary piston **308** and an interior peripheral surface of the secondary

cylinder **202**, and between the piston head **324** and the second gland portion **304** of the central gland **300**.
(40) Both the third chamber **338** and the fourth chamber **340** are annular. When pressurized fluid is provided to the third chamber **338**, the secondary piston **308** extends. On the other hand, when pressurized fluid is provided to the fourth chamber **340**, the secondary piston **308** retracts.
(41) The piston head **324** can have an external annular groove in which a seal is disposed. This way, the secondary piston **308** can move or slide axially, while the seals preclude leakage between fourth chamber **340** and the third chamber **338**.
(42) The actuator **100** further has a third port **342** formed in the secondary cylinder **202** and configured to provide fluid to and receive fluid from the third chamber **338**. The actuator **100** also has a fourth port **344** formed in the secondary cylinder **202** and configured to provide fluid to and receive fluid from the fourth chamber **340**.
(43) If pressurized fluid is provided through the third port **342** to the third chamber **338**, the fluid applies a fluid force on the piston head **324** in the distal direction, and the secondary piston **308** extends (moves in the distal direction). The secondary piston **308** can extend (i.e., move in the distal direction) until it reaches the second gland portion **304** of the central gland **300** (i.e., bottoming of the secondary piston **308** during extension takes place as it reaches the second gland portion **304**). Fluid discharged from the fourth chamber **340** as the secondary piston **308** extends flows through the fourth port **344** to a fluid reservoir.
(44) On the other hand, if pressurized fluid is provided through the fourth port **344** to the fourth chamber **340**, the fluid applies a fluid force on the piston head **324** in the proximal direction, and the secondary piston **308** retracts (moves in the proximal direction). Fluid discharged from the third chamber **338** as the secondary piston **308** retracts flows through the third port **342** to the fluid reservoir. As mentioned above, as the secondary piston **308** moves, the piston rod **104** and the primary piston **306** move therewith.
(45) Referring to FIG. **3**, an outer diameter of the piston head **324** of the secondary piston **308** (or interior diameter of the secondary cylinder **202**) is labelled “D.sub.1,” and the outer diameter of the rest of the secondary piston **308** is labelled “D.sub.2.” An outer diameter of the balance tube **326** is labelled “D.sub.3,” which is smaller than D.sub.2. With this configuration, the annular surface area of the secondary piston **308** in the third chamber **338** on which fluid acts to extend the secondary piston **308** is larger than the annular surface area of the secondary piston **308** in the fourth chamber **340** on which fluid acts to retract the secondary piston **308**. As such, an extension fluid force applied by fluid in the third chamber **338** to extend the secondary piston **308** is different from a retraction fluid force applied by fluid in the fourth chamber **340** to retract the secondary piston **308**.
(46) Assuming that pressure level of fluid provided to the third chamber **338** to extend the secondary piston **308** is P.sub.S, whereas the pressure level in the fourth chamber **340** is P.sub.R, then the extension fluid force acting on the secondary piston **308** in the distal direction is
(47) $F_{2E} = P_S(\pi\frac{D_1^2}{4} - \pi\frac{D_3^2}{4}) - P_R(\pi\frac{D_1^2}{4} - \pi\frac{D_2^2}{4})$.
On the other hand, assuming that pressure level of fluid provided to the fourth chamber **340** to retract the secondary piston **308** is P.sub.S, whereas the pressure level in the third chamber **338** is P.sub.R, then the retraction fluid force acting on the secondary piston **308** in the distal direction is
(48) $F_{2R} = P_S(\pi\frac{D_1^2}{4} - \pi\frac{D_2^2}{4}) - P_R(\pi\frac{D_1^2}{4} - \pi\frac{D_3^2}{4})$.
As mentioned above, the supply pressure level P.sub.S can be a high pressure level such as 3000-5000 psi, whereas the return pressure level P.sub.R can be a low pressure level, e.g., 50-100 psi.
(49) Because D.sub.2 is larger than D.sub.3, then the extension fluid force is greater than the retraction fluid force, i.e., F.sub.2E>F.sub.2R. The actuator **100**, however, is configured to make up or compensate for the difference between F.sub.2E>F.sub.2R to balance the secondary piston **308**.
(50) The static piston **330** has a first set of cross-holes **346**, a longitudinal channel **348** formed therein, and a second set of cross-holes **350**. The term “hole” is used generally herein to indicate a

hollow place (e.g., cavity) in a solid body or surface, for example. The term "cross-hole" is used herein to encompass any type of opening (e.g., slot, window, hole, etc.) that crosses a path of, or is formed transverse relative to, another hole, cavity, or channel.
(51) With this configuration, fluid provided to the third chamber **338** is communicated through the first set of cross-holes **346**, the longitudinal channel **348**, and the second set of cross-holes **350** to the force-balance chamber **334**. Thus, pressurized fluid in the third chamber **338** applying a fluid force on the secondary piston **308** in the distal direction, also applies a force on the inner cylinder **328** in the proximal direction. The inner cylinder **328** is coupled to the secondary piston **308**, and therefore the force acting on the inner cylinder **328** in the proximal direction is transmitted to the secondary piston **308** and opposes the fluid force acting on the secondary piston **308** in the distal direction.
(52) The inner cylinder **328** is locked to the secondary piston **308**. Any locking or coupling mechanism can be used. As such, axial forces applied to the inner cylinder **328** are transmitted to the secondary piston **308** and vice versa. Further, the actuator **100** can include an anti-rotation feature (e.g., a pin) that precludes the primary piston **306** from rotating relative to the secondary piston **308** as they both move axially within the cylinder assembly **102**.
(53) Referring back to FIG. **3**, the inner diameter of the inner cylinder **328** is labelled "D.sub.4" and the outer diameter of the static piston **330** is labelled "D.sub.5." Referring to FIGS. **2-3** together, during extension of the secondary piston **308**, fluid communicated to the force-balance chamber **334** applies a fluid force on the proximal end **336** of the inner cylinder **328** in the proximal direction. The fluid force acting on the inner cylinder **328** in the proximal direction can be referred to as a balancing force and is determined as
(54) $F_B = P_S(\pi\frac{D_4^2}{4} - \pi\frac{D_5^2}{4})$.
(55) Notably, the inner cylinder **328** and the static piston **330** are configured such that D.sub.4 and D.sub.5 render the balancing force F.sub.B equal to the difference between F.sub.2E and F.sub.2R. In other words, F.sub.B=F.sub.2E−F.sub.2R.
(56) As such, the secondary piston **308** is balanced. When the secondary piston **308** extends, the balancing force F.sub.B opposes the extension force F.sub.2E, thereby reducing F.sub.2E to be equal to the retraction force F.sub.2R.
(57) Although in the example implementation illustrated in the Figures, pressurized fluid provided to the third chamber **338** is communicated to the force-balance chamber **334** to oppose extension of the secondary piston **308**, other configurations are possible. For example, rather than communicating fluid from the third chamber **338** to the force-balance chamber **334**, the actuator **100** can be configured such that fluid from the fourth chamber **340** is communicated to the force-balance chamber **334**. In this example, when the secondary piston retracts, the balancing force F.sub.B applied to the inner cylinder **328** via fluid in the force-balance chamber **334** is an additive force that is summed to the retraction force F.sub.2R of fluid in the fourth chamber **340**, such that F.sub.B+F.sub.2R=F.sub.2E.
(58) As such, the actuator **100** can be configured to either provide fluid from the third chamber **338** or from the fourth chamber **340** to the force-balance chamber **334**. In the first case, the force acting on the inner cylinder **328** opposes the extension force F.sub.2E acting on the secondary piston **308**, and in the second case, the force acting on the inner cylinder **328** is additive to the retraction force F.sub.2R acting on the secondary piston **308**.
(59) Thus, the actuator **100** is configured as a dual system actuator. If a first system stops working under any condition, a second system may continue working to move the piston rod **104**. This way, the actuator **100** provides for redundancy. Further, the force applied to the secondary piston **308** is additive to the fore applied to the primary piston **306**. In other words, pressurized fluid can be provided simultaneously to the first chamber **314** and the third chamber **338** to extend both the primary piston **306** and the secondary piston **308**, where the forces applied by both pistons **306**, **308** on the piston rod **104** are added. Similarly, pressurized fluid can be provided simultaneously to

the second chamber **316** and the fourth chamber **340** to retract both the primary piston **306** and the secondary piston **308**, where the forces applied by both pistons **306**, **308** on the piston rod **104** are added.
(60) The configuration of the actuator **100** may offer several benefits over existing actuators. For example, the actuator **100** has two system for redundancy. A first hydraulic system (e.g., the first chamber **314**, the second chamber **316**, the first port **320**, the second port **322**, etc.) operates the primary piston **306** to move the piston rod **104**. At the same time, a second hydraulic system (e.g., the third chamber **338**, the fourth chamber **340**, the third port **342**, the fourth port **344**, etc.) operates the secondary piston **308**, which is coupled to the piston rod **104** and the primary piston **306**. If one system is damaged, the other system may continue working, thus providing a redundant configuration.
(61) Further, the actuator **100** is configured such that damage to one system might not propagate to the other. For example, the primary cylinder **200** is separate from the secondary cylinder **202**. Thus, if one cylinder is damaged, the other might not be. Particularly, if one cylinder is cracked, such a crack might not propagate to the other cylinder as the two cylinders are separated by the central gland **300**, which is composed of two separate portions (i.e., the first gland portion **302** and the second gland portion **304**). In other words, the crack is interrupted. Similarly, the primary piston **306** is a separate component from the secondary piston **308**. Thus, if one piston is damaged or cracked, such a crack might not propagate to the other piston.
(62) In an example, the end gland **318** may be configured as a frangible gland or component. As such, if the end gland **318** is damaged, as the primary piston **306** moves, the end gland **318** may disintegrate (e.g., may be fragmented) such that the primary piston **306** is not jammed. Even though damaging the end gland **318** may cause leakage and failure of the hydraulic system controlling the primary piston **306**, the hydraulic system controlling the secondary piston **308** might continue working, allowing the secondary piston **308** to safely position the piston rod **104**. Similarly, the first gland portion **302** and the second gland portion **304** of the central gland **300** may also be made as frangible components.
(63) In an example, to provide further protection against ballistic fragments that could damage the actuator **100**, one of the cylinders **200**, **202** may be armored (e.g., made of thick hardened steel that can withstand ballistic objects). Armoring one cylinder instead of both reduces the weight of the actuator **100**. At the same time, if the non-armored cylinder is damaged, the armored cylinder may continue protecting the respective piston and hydraulic system to enable the actuator **100** to continue functioning.
(64) Further, the configuration of the actuator **100** with, at least partially, concentric pistons, may render the actuator **100** stiffer compared to an actuator having three side-by-side pistons. Higher stiffness may render the actuator **100** more tolerant of vibrations. Further, the actuator **100** might not suffer from side loading or bending issues associated with a three-piston actuator.
(65) FIG. **4** is a flowchart of a method **900** for operating an actuator, in accordance with an example implementation. For example, the method **900** can be used for operating the actuator **100**.
(66) The method **900** may include one or more operations, or actions as illustrated by one or more of blocks **902-906**. Although the blocks are illustrated in a sequential order, these blocks may also be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation. It should be understood that for this and other processes and methods disclosed herein, flowcharts show functionality and operation of one possible implementation of present examples. Alternative implementations are included within the scope of the examples of the present disclosure in which functions may be executed out of order from that shown or discussed, including substantially concurrent or in reverse order, depending on the functionality involved, as would be understood by those reasonably skilled in the art.
(67) At block **902**, the method **900** includes providing fluid to the first chamber **314** and the third

chamber **338** of the actuator **100** to extend the piston rod **104** of the actuator **100**, wherein the actuator **100** comprises the primary piston **306** and the secondary piston **308**, wherein the secondary piston **308** is coupled to the piston rod **104**, and wherein the primary piston **306** is secured to the secondary piston **308** and the piston rod **104**, such that the primary piston **306**, the secondary piston **308**, and the piston rod **104** move together axially, wherein providing fluid to the first chamber **314** causes the primary piston **306** to extend, and wherein providing fluid to the third chamber **338** causes an extension fluid force to be applied to extend the secondary piston **308**.
(68) At block **904**, the method **900** includes providing fluid to the second chamber **316** and the fourth chamber **340** of the actuator **100** to retract the piston rod **104** of the actuator **100**, wherein providing fluid to the second chamber **316** causes the primary piston **306** to retract, and wherein providing fluid to the fourth chamber **340** causes a retraction fluid force to be applied to retract the secondary piston **308**, wherein the extension fluid force is different from the retraction fluid force.
(69) At block **906**, the method **900** includes providing fluid from the third chamber **338** or the fourth chamber **340** to the force-balance chamber **334** to apply a balancing force on the secondary piston **308** to oppose fluid force acting on the secondary piston **308** or add to the fluid force acting on the secondary piston **308**, thereby compensating for a difference between the extension fluid force and the retraction fluid force.
(70) The method can include other operations described herein.
(71) The detailed description above describes various features and operations of the disclosed systems with reference to the accompanying figures. The illustrative implementations described herein are not meant to be limiting. Certain aspects of the disclosed systems can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.
(72) Further, unless context suggests otherwise, the features illustrated in each of the figures may be used in combination with one another. Thus, the figures should be generally viewed as component aspects of one or more overall implementations, with the understanding that not all illustrated features are necessary for each implementation.
(73) Additionally, any enumeration of elements, blocks, or steps in this specification or the claims is for purposes of clarity. Thus, such enumeration should not be interpreted to require or imply that these elements, blocks, or steps adhere to a particular arrangement or are carried out in a particular order.
(74) Further, devices or systems may be used or configured to perform functions presented in the figures. In some instances, components of the devices and/or systems may be configured to perform the functions such that the components are actually configured and structured (with hardware and/or software) to enable such performance. In other examples, components of the devices and/or systems may be arranged to be adapted to, capable of, or suited for performing the functions, such as when operated in a specific manner.
(75) By the term “substantially” it is meant that the recited characteristic, parameter, or value need not be achieved exactly, but that deviations or variations, including for example, tolerances, measurement error, measurement accuracy limitations and other factors known to skill in the art, may occur in amounts that do not preclude the effect the characteristic was intended to provide
(76) The arrangements described herein are for purposes of example only. As such, those skilled in the art will appreciate that other arrangements and other elements (e.g., machines, interfaces, operations, orders, and groupings of operations, etc.) can be used instead, and some elements may be omitted altogether according to the desired results. Further, many of the elements that are described are functional entities that may be implemented as discrete or distributed components or in conjunction with other components, in any suitable combination and location.
(77) While various aspects and implementations have been disclosed herein, other aspects and implementations will be apparent to those skilled in the art. The various aspects and implementations disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims, along with the full scope of

equivalents to which such claims are entitled. Also, the terminology used herein is for the purpose of describing particular implementations only, and is not intended to be limiting.

(78) Embodiments of the present disclosure can thus relate to one of the enumerated example embodiments (EEEs) listed below.

(79) EEE1 is an actuator comprising: a primary piston that is disposed at least partially within a cylinder assembly; a secondary piston that is disposed at least partially within the cylinder assembly, wherein the primary piston and the secondary piston are configured to move together axially within the cylinder assembly; a plurality of chambers formed within the cylinder assembly and comprising: (i) a first chamber, wherein when fluid flows to the first chamber, the primary piston extends, (ii) a second chamber, wherein when fluid flows to the second chamber, the primary piston retracts, (iii) a third chamber, wherein when fluid flows to the third chamber, the secondary piston extends, (iv) a fourth chamber, wherein when fluid flows to the fourth chamber, the secondary piston retracts, and wherein an extension fluid force applied by fluid in the third chamber to extend the secondary piston is different from a retraction fluid force applied by fluid in the fourth chamber to retract the secondary piston; and a force-balance chamber configured to receive fluid from the third chamber or the fourth chamber to apply a balancing force on the secondary piston to either oppose fluid force acting on the secondary piston or add to the fluid force acting on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

(80) EEE 2 is the actuator of EEE 1, wherein the cylinder assembly comprises: a primary cylinder; and a secondary cylinder coupled to the primary cylinder, wherein the primary cylinder and the secondary cylinder form a longitudinal cylindrical cavity in which the primary piston and the secondary piston are axially-movable.

(81) EEE 3 is the actuator of EEE 2, wherein the primary cylinder has a flange, wherein the secondary cylinder has a respective flange, and wherein the actuator further comprises: a central gland disposed between the flange of the primary cylinder and the respective flange of the secondary cylinder; and a plurality of fasteners coupling the flange of the primary cylinder, the respective flange of the secondary cylinder, and the central gland to each other.

(82) EEE 4 is the actuator of EEE 3, wherein the central gland comprises: a first gland portion interfacing with the flange of the primary cylinder; and a second gland portion separate from the first gland portion and interfacing with the respective flange of the secondary cylinder.

(83) EEE 5 is the actuator of any of EEEs 1-4, further comprising: a piston rod disposed partially within the cylinder assembly and coupled to the secondary piston, wherein the primary piston is secured between the secondary piston and the piston rod, such that the primary piston, the secondary piston, and the piston rod move axially together.

(84) EEE 6 is the actuator of any of EEEs 1-5, further comprising: a static piston that is coupled to the cylinder assembly such that the static piston remains stationary; and an inner cylinder that is coupled to the secondary piston and slidable about an exterior surface of the static piston, wherein the force-balance chamber is formed between the exterior surface of the static piston and an interior surface of the inner cylinder, such that the balancing force is applied to the inner cylinder, which transmits the balancing force to the secondary piston.

(85) EEE 7 is the actuator of EEE 6, wherein the force-balance chamber is fluidly-coupled to the third chamber via a longitudinal channel and one or more cross-holes formed in the static piston, such that the force-balance chamber receives fluid from the third chamber as the secondary piston extends, wherein fluid in the force-balance chamber applies the balancing force on the secondary piston to oppose the extension fluid force applied to the secondary piston by fluid in the third chamber.

(86) EEE 8 is the actuator of any of EEEs 6-7, wherein the force-balance chamber is fluidly-coupled to the fourth chamber, such that the force-balance chamber receives fluid from the fourth chamber as the secondary piston retracts, wherein fluid in the force-balance chamber applies the

balancing force on the secondary piston as an additive force to the retraction fluid force applied to the secondary piston by fluid in the fourth chamber.

(87) EEE 9 is the actuator of any of EEEs 6-8, further comprising: a balance tube that is coupled to the static piston and interposed radially between the inner cylinder and the secondary piston, wherein the secondary piston is configured to move axially about an exterior surface of the balance tube as the secondary piston extends or retracts.

(88) EEE 10 is a method comprising: providing fluid to a first chamber and a third chamber of an actuator to extend a piston rod of the actuator, wherein the actuator comprises a primary piston and a secondary piston, wherein the secondary piston is coupled to the piston rod, and wherein the primary piston is secured to the secondary piston and the piston rod, such that the primary piston, the secondary piston, and the piston rod move together axially, wherein providing fluid to the first chamber causes the primary piston to extend, and wherein providing fluid to the third chamber causes an extension fluid force to be applied to extend the secondary piston; providing fluid to a second chamber and a fourth chamber of the actuator to retract the piston rod of the actuator, wherein providing fluid to the second chamber causes the primary piston to retract, and wherein providing fluid to the fourth chamber causes a retraction fluid force to be applied to retract the secondary piston, wherein the extension fluid force is different from the retraction fluid force; and providing fluid from the third chamber or the fourth chamber to a force-balance chamber to apply a balancing force on the secondary piston to oppose fluid force acting on the secondary piston or add to the fluid force acting on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

(89) EEE 11 is the method of EEE 10, wherein the actuator further comprises: (i) a cylinder assembly in which the primary piston and the secondary piston are axially-movable, (ii) a static piston that is coupled to the cylinder assembly, such that the static piston remains stationary, and (iii) an inner cylinder that is coupled to the secondary piston and slidable about an exterior surface of the static piston, wherein applying the balancing force on the secondary piston comprises: applying the balancing force to the inner cylinder, which transmits the balancing force to the secondary piston.

(90) EEE 12 is the method of EEE 11, wherein providing fluid to the force-balance chamber comprises: providing fluid from the third chamber through one or more cross-holes and a longitudinal channel formed in the static piston to the force-balance chamber as the secondary piston extends; and applying the balancing force on the secondary piston to oppose the extension fluid force applied to the secondary piston by fluid in the third chamber.

(91) EEE 13 is the method of any of EEEs 11-12, wherein providing fluid to the force-balance chamber comprises: providing fluid from the fourth chamber to the force-balance chamber as the secondary piston retracts; and applying the balancing force on the secondary piston as an additive force to the retraction fluid force applied to the secondary piston by fluid in the fourth chamber.

Claims

1. An actuator comprising: a primary piston that is disposed at least partially within a cylinder assembly; a secondary piston that is disposed at least partially within the cylinder assembly, wherein the primary piston and the secondary piston are configured to move together axially within the cylinder assembly; a plurality of chambers formed within the cylinder assembly and comprising: (i) a first chamber, wherein when fluid flows to the first chamber, the primary piston extends, (ii) a second chamber, wherein when fluid flows to the second chamber, the primary piston retracts, (iii) a third chamber, wherein when fluid flows to the third chamber, the secondary piston extends, (iv) a fourth chamber, wherein when fluid flows to the fourth chamber, the secondary piston retracts, and wherein an extension fluid force applied by fluid in the third chamber to extend the secondary piston is different from a retraction fluid force applied by fluid in the fourth chamber

to retract the secondary piston; and a force-balance chamber configured to receive fluid to apply a balancing force on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

2. The actuator of claim 1, wherein the cylinder assembly comprises: a primary cylinder; and a secondary cylinder coupled to the primary cylinder, wherein the primary cylinder and the secondary cylinder form a longitudinal cylindrical cavity in which the primary piston and the secondary piston are axially-movable.

3. The actuator of claim 2, wherein the primary cylinder has a flange, wherein the secondary cylinder has a respective flange, and wherein the actuator further comprises: a central gland disposed between the flange of the primary cylinder and the respective flange of the secondary cylinder; and a plurality of fasteners coupling the flange of the primary cylinder, the respective flange of the secondary cylinder, and the central gland to each other.

4. The actuator of claim 3, wherein the central gland comprises: a first gland portion interfacing with the flange of the primary cylinder; and a second gland portion separate from the first gland portion and interfacing with the respective flange of the secondary cylinder.

5. The actuator of claim 1, further comprising: a piston rod disposed partially within the cylinder assembly and coupled to the secondary piston, wherein the primary piston is secured between the secondary piston and the piston rod, such that the primary piston, the secondary piston, and the piston rod move axially together.

6. The actuator of claim 1, further comprising: a static piston that is coupled to the cylinder assembly such that the static piston remains stationary; and an inner cylinder that is coupled to the secondary piston and slidable about an exterior surface of the static piston, wherein the force-balance chamber is formed between the exterior surface of the static piston and an interior surface of the inner cylinder, such that the balancing force is applied to the inner cylinder, which transmits the balancing force to the secondary piston.

7. The actuator of claim 6, wherein the force-balance chamber is fluidly-coupled to the third chamber via a longitudinal channel and one or more cross-holes formed in the static piston, such that the force-balance chamber receives fluid from the third chamber as the secondary piston extends, wherein fluid in the force-balance chamber applies the balancing force on the secondary piston to oppose the extension fluid force applied to the secondary piston by fluid in the third chamber.

8. The actuator of claim 6, further comprising: a balance tube that is coupled to the static piston and interposed radially between the inner cylinder and the secondary piston, wherein the secondary piston is configured to move axially about an exterior surface of the balance tube as the secondary piston extends or retracts.

9. A method comprising: providing fluid to a first chamber and a third chamber of an actuator to extend a piston rod of the actuator, wherein the actuator comprises a primary piston and a secondary piston, wherein the secondary piston is coupled to the piston rod, and wherein the primary piston is secured to the secondary piston and the piston rod, such that the primary piston, the secondary piston, and the piston rod move together axially, wherein providing fluid to the first chamber causes the primary piston to extend, and wherein providing fluid to the third chamber causes an extension fluid force to be applied to extend the secondary piston; providing fluid to a second chamber and a fourth chamber of the actuator to retract the piston rod of the actuator, wherein providing fluid to the second chamber causes the primary piston to retract, and wherein providing fluid to the fourth chamber causes a retraction fluid force to be applied to retract the secondary piston, wherein the extension fluid force is different from the retraction fluid force; and providing fluid to a force-balance chamber to apply a balancing force on the secondary piston, thereby compensating for a difference between the extension fluid force and the retraction fluid force.

10. The method of claim 9, wherein the actuator further comprises: (i) a cylinder assembly in which

the primary piston and the secondary piston are axially-movable, (ii) a static piston that is coupled to the cylinder assembly, such that the static piston remains stationary, and (iii) an inner cylinder that is coupled to the secondary piston and slidable about an exterior surface of the static piston, wherein applying the balancing force on the secondary piston comprises: applying the balancing force to the inner cylinder, which transmits the balancing force to the secondary piston.

11. The method of claim 10, wherein providing fluid to the force-balance chamber comprises: providing fluid from the third chamber through one or more cross-holes and a longitudinal channel formed in the static piston to the force-balance chamber as the secondary piston extends; and applying the balancing force on the secondary piston to oppose the extension fluid force applied to the secondary piston by fluid in the third chamber.