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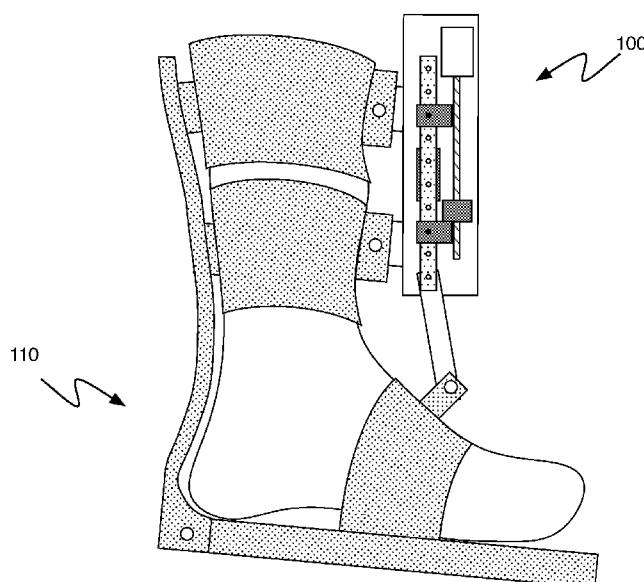


FIGURE 1

(57) Abstract: An actuator system for extending and flexing a joint, including a multi-motor assembly for providing a rotational output, a rotary-to-linear mechanism for converting the rotational output from the multi-motor assembly into an extension and flexion of the joint, and a controller for operating the actuator system in several operational modes. The multi-motor assembly preferably combines power from two different sources, such that the multi-motor assembly can supply larger forces at slower speeds ("Low Gear") and smaller forces at higher speeds ("High Gear"). The actuator has been specifically designed for extending and flexing a joint (such as an ankle, a knee, an elbow, or a shoulder) of a human. The actuator system may, however, be used to move any suitable object through any suitable movement (linear, rotational, or otherwise).

## **ACTUATOR SYSTEM WITH A MULTI-MOTOR ASSEMBLY FOR EXTENDING AND FLEXING A JOINT**

### **TECHNICAL FIELD**

**[0001]** This invention relates generally to the actuator field, and more specifically to a new and useful actuator system with a multi-motor assembly in the actuator field.

### **BACKGROUND**

**[0002]** Motors and actuators are used in a wide variety of applications. Many applications, including robotics and active orthotics, require characteristics similar to human muscles. The characteristics include the ability to deliver high force at a relatively low speed and to allow free-movement when power is removed, thereby allowing a limb to swing freely during portions of the movement cycle. This may call for an actuator that can supply larger forces at slower speeds and smaller forces at higher speeds, or a variable ratio transmission (VRT) between the primary driver input and the output of an actuator.

**[0003]** VRTs have been conventionally implemented as Continuously Variable Transmissions (CVTs). The underlying principle of most previous CVTs is to change the ratio of one or more gears by changing the diameter of the gear, changing the place where a belt rides on a conical pulley, or by coupling forces between rotating disks with the radius of the intersection point varying based on the desired ratio. Prior art CVTs have drawbacks in efficiency and mechanical complexity.

**[0004]** Motors have been used in a variety of applications, but typically a single motor is directly or indirectly coupled to provide motion for each output direction. Use of a single motor limits the speed/torque range or requires the extra cost and complexity of a transmission between the motor and output. Thus, there is a need in the actuator field to create a new and useful actuator system that can supply larger forces at slower speeds and smaller forces at higher speeds, but that minimizes or avoids the disadvantages of the conventional CVTs. This invention provides such a new and useful actuator system.

#### BRIEF DESCRIPTION OF THE FIGURES

**[0005]** FIGURE 1 is a schematic of the actuator system of the preferred embodiment in an orthotic that extends and flexes a joint of a user.

**[0006]** FIGURE 2 is a schematic of the actuator system of the preferred embodiment, with the first variation of the multi-motor assembly and with both the extension stop and the flexion stop of the rotary-to-linear mechanism in the force positions.

**[0007]** FIGURE 3 is a schematic of the actuator system of the preferred embodiment, with the second variation of the multi-motor assembly.

**[0008]** FIGURES 4a and 4b are schematics of the actuator system of the preferred embodiment, with the extension stop in the pass position and the flexion stop in the pass position, respectively.

**[0009]** FIGURE 5 is a flow diagram of the operation modes for the controller of the actuator system of the preferred embodiment.

**[0010]** FIGURE 6 is an exemplary current ramping scheme for the controller of the actuator system of the preferred embodiment.

**[0011]** FIGURE 7 is a chart of the speed / force profile of the first motor subsystem, the second motor subsystem, and the combination of the first and second motor subsystems.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

**[0012]** The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art of actuator systems to make and use this invention.

**[0013]** As shown in FIGURES 1 and 2, the actuator system 100 of the preferred embodiments for extending and flexing a joint 110 of a user includes a multi-motor assembly 120 for providing a rotational output, a rotary-to-linear mechanism 150 for converting the rotational output from the multi-motor assembly 120 into a linear motion that ultimately extends and flexes the joint, and a controller for operating the actuator system 100 in several operational modes. The multi-motor assembly 120 preferably combines power from two different sources, such that the multi-motor assembly 120 can supply larger forces at slower speeds (“Low Gear”) and smaller forces at higher speeds (“High Gear”). The actuator has been specifically designed for extending and flexing a joint 110 (such as an ankle, a knee, an elbow, or a shoulder) of a

human or robot. The actuator system 100 may, however, be used to move any suitable object through any suitable movement (linear, rotational, or otherwise).

1. Multi-motor assembly

**[0014]** As shown in FIGURE 2, the multi-motor assembly 120 of the preferred embodiments functions to provide rotational output to the rotary-to-linear mechanism 150. The multi-motor assembly 120 includes a drive shaft 122, a first motor subsystem 124, and a second motor subsystem 126. The drive shaft 122 functions to deliver the rotational output from the multi-motor assembly 120. The first motor subsystem 124 functions to provide a component of the rotational output of the multi-motor assembly 120. The first motor subsystem 124 includes a first motor 128, a first output shaft 130, and a first transmission 132. The second motor subsystem 126 functions to provide another component of the rotational output of the multi-motor assembly 120. The second motor subsystem 126 includes a second motor 134, a second output shaft 136, and a second transmission 138.

**[0015]** The first motor 128 of the first motor subsystem 124 functions to provide a first source of power, and the first output shaft 130 functions to deliver this power to the other elements of the first motor subsystem 124. The first motor 128 is preferably a three phase brushless electric motor with an outer rotor and seven pole pairs. The first motor 128, which is preferably supplied by Hyperion under the model number G2220-14, has a peak current of 35A and a peak power of 388W. The first motor 128 may, of

course, be a different type with different specifications and parameters depending on the design of the actuator system 100.

**[0016]** The first transmission 132 of the first motor subsystem 124 functions to transmit the power from the first output shaft 130 to the drive shaft 122. The first transmission 132 preferably includes two pulleys (one mounted on the first output shaft 130 and one mounted on the drive shaft 122) and a belt or chain connecting the two pulleys. The first transmission 132 may alternatively include gears or any other suitable device or method that transmits the power from the first output shaft 130 to the drive shaft 122. The first transmission 132 also preferably functions to define a first gear ratio of the rotation of the drive shaft 122 to the rotation of the first output shaft 130. In the preferred embodiment, the pulley (or gear) mounted to the first output shaft 130 is smaller than the pulley (or gear) mounted to the drive shaft 122, such that the first gear ratio is less than 1:1 (e.g., 1:4). In alternative embodiments, the first gear ratio may be 1:1 or may be greater than 1:1 (e.g., 4:1) depending on the design of the actuator system 100.

**[0017]** The second motor 134 of the second motor subsystem 126 functions to provide a second source of power, and the second output shaft 136 functions to deliver this power to the other elements of the second motor subsystem 126. The second motor 134, like the first motor 128, is preferably a three phase brushless electric motor with an outer rotor and seven pole pairs. The second motor 134, which is preferably supplied by Hyperion under the model number G2220-14, has a peak current of 35A and a peak power of 388W. The second motor 134 is preferably identical to the first motor 128 in design and performance characteristics, which functions to reduce part count and

manufacturing complexity. The second motor 134 may, however, be a different type with different specifications and parameters depending on the design of the actuator system 100. The second output shaft 136 functions to deliver the power of the second motor 134 to the other elements of the second motor subsystem 126.

**[0018]** The second transmission 138 of the second motor subsystem 126 functions to transmit the power from the second output shaft 136 to the drive shaft 122. The second transmission 138 preferably includes two pulleys (one mounted on the second output shaft 136 and one mounted on the drive shaft 122) and a belt or chain connecting the two pulleys. The second transmission 138 may alternatively include gears or any other suitable device or method that transmits the power from the second output shaft 136 to the drive shaft 122. The second transmission 138 also preferably functions to at least partially define the second gear ratio of the rotation of the drive shaft 122 to the rotation of the second output shaft 136. In the preferred embodiment, the pulley (or gear) mounted to the second output shaft 136 is smaller than the pulley (or gear) mounted to the drive shaft 122, such that the second gear ratio is less than 1:1 (e.g., 1:4). In alternative embodiments, the second gear ratio may be 1:1 or may be greater than 1:1 (e.g., 4:1) depending on the design of the actuator system 100.

**[0019]** The power from the first motor subsystem 124 and the power from the second motor subsystem 126 preferably have different characteristics, such that the multi-motor assembly 120 can supply larger forces at slower speeds (“Low Gear”) and smaller forces at higher speeds (“High Gear”). This may be accomplished by using different motors in the first motor subsystem 124 and the second motor subsystem 126.

In the preferred embodiment, however, this is accomplished by using identical motors, but with transmissions that define different gear ratios for the first motor subsystem 124 and the second motor subsystem 126. The second gear ratio is preferably lower than the first gear ratio, but the actuator system 100 may be re-arranged such that the second gear ratio is higher than the first gear ratio.

**[0020]** The second transmission 138 of the second motor subsystem 126 preferably connects the second output shaft 136 to the first output shaft 130. With this arrangement, the power from the second motor 134 is transmitted through both the second transmission 138 and the first transmission 132 before reaching the drive shaft 122. Thus, the second transmission 138 and the first transmission 132 cooperatively define the second gear ratio. The effective gear ratio from motor 134 to the drive shaft 122 is a product of the first transmission 132 and the second transmission 138. For example, if the gear ratios of both the first transmission 132 and the second transmission 138 were 1:3, then the effective gear ratio from motor 134 to the drive shaft 122 would be 1:9. By leveraging the first transmission 132, this variation provides a compact form factor. Using the example, the system would be able to provide an effective gear ratio of 1:9 without the need for a large pulley or gear system.

**[0021]** As shown in FIGURE 3, a second transmission 238 of a variation of the second motor subsystem 226 connects the second output shaft 236 to the drive shaft 122. In this variation, the power from the second motor 234 is transmitted through only the second transmission 238 before reaching the drive shaft 122 (and, thus, the second transmission 238 defines the second gear ratio). By separately connecting the first

motor 128 and the second motor 234 to the drive shaft 122, the first gear ratio and the second gear ratio may be specifically tailored for the actuator system 100.

**[0022]** As shown in FIGURE 2, the multi-motor assembly 120 of the preferred embodiment also includes a one-way clutch 140 located between the second motor 134 and the drive shaft 122. The one-way clutch 140 functions to facilitate the following motor modes:

- High Gear motor mode – the first motor subsystem 124 provides powers in a first direction without spinning the second output shaft 136 and imparting drag from the second motor subsystem 126,
- Low Gear motor mode – the second motor subsystem 126 provides power in the first direction (with drag from the first motor subsystem 124),
- Combined motor mode – the first motor subsystem 124 and the second motor subsystem 126 provide power in the first direction, and
- High Gear motor mode – the first motor subsystem 124 provides power in an opposite direction (with drag from the second motor subsystem 126).

In a first variation of the multi-motor assembly 120, as introduced above, the one-way clutch 140 is preferably located within the second transmission 138 and, more specifically, in the pulley mounted on the first output shaft 130. In other variations, the one-way clutch 140 may be mounted in any suitable location between the second motor 134 and the drive shaft 122.

**[0023]** The multi-motor assembly 120 of the preferred embodiment also includes a power source (not shown). The power source is preferably six lithium polymer battery

cells, supplied by Emerging Power under the model number 603462H1. The battery cells are preferably arranged in both series and parallel (3S2P) to provide a voltage of 11.1V (nominal) and a capacity of 2640 maH. The power source may, however, be any suitable type, including both power supplied by the power grid and other portable sources (e.g., fuel cells), depending on the design of the actuator system 100.

2. **Rotary-to-linear mechanism**

**[0024]** The rotary-to-linear mechanism 150 of the preferred embodiment functions to convert the rotational output from the multi-motor assembly 120 into a linear movement that ultimately extends and flexes the joint of the user. In the preferred embodiment, the rotary-to-linear mechanism 150 includes a ball screw 152 that accepts the rotational output of the multi-motor assembly 120 and a ball nut 154 that connects to the ball screw 152 and cooperates with the ball screw 152 to convert rotational movement of the ball screw 152 to linear movement of the ball nut 154. The drive shaft 122 of the multi-motor assembly 120 and the ball screw 152 of the rotary-to-linear mechanism 150 are preferably different sections of the same shaft. One section includes a pulley (or gear) from the first transmission 132, while another section includes a semi-circular, helical groove of the ball screw 152. The drive shaft 122 and the ball screw 152 may, however, be separate shafts connected in any suitable manner, such as through a pulley or gear arrangement. In alternative embodiments, the rotary-to-linear mechanism 150 may include any suitable device or method that converts the rotational output from the multi-motor assembly 120 into an extension and flexion of the joint.

**[0025]** The rotary-to-linear mechanism 150 of the preferred embodiment also includes a linear slide 156 with a moving rail 158 that moves in a flexion direction and an extension direction. The linear slide 156 functions to provide a supported structure when the joint is fully flexed, and a compact structure when the joint is fully extended. The linear slide 156 preferably includes stationary wheels and moving wheels, but may alternatively include any suitable device or method to allow the moving rail 158 to move in the flex and extended directions.

**[0026]** As shown in FIGURES 2 and 4a, the moving rail 158 of the linear slide 156 preferably includes an extension stop 160, which functions to translate linear movement of the ball nut 154 in an extension direction into an extension of the joint. In the preferred embodiment, the extension stop 160 is movable between a force position (shown in FIGURE 2) that allows the ball nut 154 to apply force against the extension stop 160, and a pass position (shown in FIGURE 4a) that prevents the ball nut 154 from applying force against the extension stop 160. The extension stop 160 is preferably U-shaped and pivotally mounted on the moving rail 158, but may alternatively be shaped and mounted in any manner to allow movement from the force position to the pass position. In an alternative embodiment, the extension stop 160 may be permanently (or semi-permanently) fixed or fastened in the force position.

**[0027]** In a first variation, as shown in FIGURES 2 and 4b, the moving rail 158 of the linear slide 156 also includes a flexion stop 162, which functions to translate linear movement of the ball nut 154 in a flexion direction into a flexion of the joint. In the preferred embodiment, the flexion stop 162 is movable between a force position (shown

in FIGURE 2) that allows the ball nut 154 to apply force against the flexion stop 162, and a pass position (shown in FIGURE 4b) that prevents the ball nut 154 from applying force against the flexion stop 162. The flexion stop 162, like the extension stop 160, is preferably U-shaped and pivotally mounted on the moving rail 158, but may alternatively be shaped and mounted in any manner to allow movement from the force position to the pass position. In an alternative embodiment, the flexion stop 162 may be permanently (or semi-permanently) fixed or fastened in the force position.

**[0028]** In a second variation, as shown in FIGURE 4c, the moving rail 158 of the linear slide 156 may additionally or alternatively include a latch 262, which functions to translate linear movement of the ball nut 154 in both the flexion and extension directions into a flexion and extension of the joint. In the preferred embodiment, the latch 262 is movable between an engaged position (shown in FIGURE 4c) that allows the ball nut 154 to move the latch 262 and the moving rail, and a disengaged position (not shown) that prevents the ball nut 154 from applying force against the latch 262. The latch 262, unlike the extension stop 160, is preferably mounted to engage in slidable manner with the ball nut 154, but may alternatively be shaped and mounted in any manner to allow movement from the engaged position to the disengaged position.

**[0029]** In a third variation, the flexion stop 162 and latch 262 may be omitted to allow unpowered flexion of the joint.

**[0030]** The extension stop 160 and the flexion stop 162 are preferably located relatively far from each other, which allows the joint of the user to experience “free movement”, essentially moving the moving rail 158 back and forth between the

extension stop 160 and the flexion stop 162 without the need to move the ball nut 154 or back-drive the multi-motor assembly 120. In a variation, the extension stop 160 and the flexion stop 162 are located relatively close to each other, which prevents the joint of the user from experiencing little or no “free movement”. In other words, movement of the moving rail 158 will move the ball nut 154 and back-drive the multi-motor assembly 120.

**[0031]** As shown in FIGURE 1, the actuator system 100 of the preferred embodiments for extending and flexing a joint 110 of a user includes a rotary-to-linear mechanism that functions to convert the linear movement of the moving rail into an extension and flexion (both rotational movements) of the joint of the user. In other variations, the actuator system 100 may include gears, pulleys, or any other suitable mechanism to ultimately extend and flex the joint of the user.

### 3. Controller

**[0032]** The controller of the preferred embodiment functions to operate the actuator system 100 in one of several operation modes. The controller preferably includes sensors (such as encoders on the first motor 128 and the second motor 134) to estimate the position of the moving rail 158, and sensors on the ball nut 154 to estimate the force either provided by the multi-motor assembly 120 or applied to the joint through external factors (such as gravitational force on the body of the user). The controller may also include other sensors to predict or determine future forces applied to the joint or needed by the multi-motor assembly 120. The controller may, however, use any suitable method or device to estimate the position of the moving rail 158 and the force needed by the multi-motor assembly 120.

**[0033]** Based on the position of the moving rail 158 and the force needed by the multi-motor assembly 120, the controller provides current to the first motor subsystem 124, the second motor subsystem 126, or both the first motor subsystem 124 and the second motor subsystem 126. As shown in FIGURE 5, the controller preferably operates the multi-motor assembly 120 of the actuator system 100 in the following operation modes: High Gear Flexion mode, High Gear Extension mode, Low Gear Extension mode, and Continuously Variable Transmission Extension mode.

**[0034]** In the High Gear Flexion mode, the controller provides current only to the first motor subsystem 124 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150. The ball screw 152 is driven in the direction such that the ball nut 154 applies a force against the flexion stop 162 (if positioned in the force position) and drives the moving rail 158 in the flexion direction. The High Gear Flexion mode supplies a smaller force at a higher speed to quickly flex the joint of the user.

**[0035]** The High Gear Extension mode is similar to the High Gear Flexion mode, except the first motor subsystem 124 is driven in the opposite direction. In the High Gear Extension mode, the controller provides current only to the first motor subsystem 124 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150 and the ball nut 154 applies a force against the extension stop 160. The ball screw 152 is driven in the direction such that the ball nut 154 applies a force against the extension stop 160 (if positioned in the force position) and drives the

moving rail 158 in the extension direction. The High Gear Extension mode supplies a smaller force at a higher speed to quickly extend the joint of the user.

**[0036]** The Low Gear Extension mode is similar to the High Gear Extension mode, except the second motor subsystem 126 is driven instead of the first motor subsystem 124. In the Low Gear Extension mode, the controller provides current only to the second motor subsystem 126 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150 and the ball nut 154 applies a force against the extension stop 160. The ball screw 152 is driven in the direction such that the ball nut 154 applies a force against the extension stop 160 (if positioned in the force position) and drives the moving rail 158 in the extension direction. The Low Gear Extension mode supplies a larger force at a lower speed to forcefully extend the joint of the user.

**[0037]** In the Continuously Variable Transmission Extension mode, the controller provides current to both the first motor subsystem 124 and the second motor subsystem 126 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150 and the ball nut 154 applies a force against the extension stop 160. In this mode, as exemplified in FIGURE 6, the controller varies the ratio of current provided to the first motor subsystem 124 and current provided to the second motor subsystem 126 to achieve a desired rotational output in the Continuously Variable Transmission Extension mode. As the controller senses an increased force needed by the multi-motor assembly 120, the controller preferably first ramps up the current to the first motor subsystem 124 (the High Gear or “HG”), then ramps down the current to the

first motor subsystem 124 while ramping up the current to the second motor subsystem 126 (the Low Gear or “LG”). The Continuously Variable Transmission Extension mode can supply both a smaller force at a higher speed to quickly extend the joint of the user (“High Gear”), and a larger force at a lower speed to forcefully extend the joint of the user (“Low Gear”). More importantly, as shown in FIGURE 7, by varying the ratio of current provided to the first motor subsystem 124 and current provided to the second motor subsystem 126, the controller can achieve a desired force and speed from the multi-motor subsystem that is outside the range of possible forces and speeds supplied by just the first motor 128 or the second motor 134. The actuator system 100 provides these advantages and features without providing a conventional multi-gear transmission or conventional CTV (with gears, conical pulleys, etc.).

**[0038]** As shown in FIGURE 5, the controller of the preferred embodiment also operates the actuator system 100 in a Free Movement mode. In one variation of the Free Movement mode, the controller provides current to the first motor subsystem 124 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150 and the ball nut 154 moves away from the extension stop 160. In another variation of the Free Movement mode, the controller provides current to the first motor subsystem 124 such that the multi-motor assembly 120 provides a rotational output to the rotary-to-linear mechanism 150 and the ball nut 154 maintains a general position between – but not contacting – the extension stop 160 or the flexion stop 162.

#### 4. Further Embodiments

**[0039]** As a person skilled in the art of actuator system 100s will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims. As a first example, while the actuator system 100 has been described to include a multi-motor assembly 120 with a first motor 128 and a second motor 134, the multi-motor assembly 120 may include additional motors (with or without additional one-way clutches 140). As an additional example, while the actuator system 100 has been described to include a rotary-to-linear mechanism 150, it is possible that the rotational output of the multi-motor assembly 120 may be used without a mechanism that converts the rotational output to a linear output.

## CLAIMS

We Claim:

1. An actuator system for extending and flexing a joint, comprising:
  - a multi-motor assembly for providing a rotational output;
  - a rotary-to-linear mechanism for converting the rotational output from the multi-motor assembly into an extension and flexion of the joint; and
  - a controller for operating the actuator system in several operational modes.
2. The actuator system of Claim 1, wherein the multi-motor assembly includes:
  - a drive shaft that provides the rotational output to the rotary-to-linear mechanism;
  - a first motor subsystem having a first output shaft and a first transmission connecting the first output shaft to the drive shaft; and
  - a second motor subsystem having a second output shaft and a second transmission coupling the second output shaft to the drive shaft.
3. The actuator system of Claim 2, wherein the first transmission defines a first gear ratio of the rotation of the drive shaft to the rotation of the first output shaft, and wherein the second transmission at least partially defines a second gear ratio of the rotation of the drive shaft to the rotation of the second output shaft, wherein the second gear ratio is different than the first gear ratio.

4. The actuator system of Claim 3, wherein the second gear ratio is lower than the first gear ratio.
5. The actuator system of Claim 3, wherein the second transmission connects the second output shaft to the first output shaft, and wherein the second transmission and the first transmission cooperatively define the second gear ratio.
6. The actuator system of Claim 5, wherein the second motor subsystem further includes a one-way clutch located between the second motor and the first motor.
7. The actuator system of Claim 3, wherein the second transmission connects the second output shaft to the drive shaft, and wherein the second transmission defines the second gear ratio.
8. The actuator system of Claim 7, wherein the first motor subsystem includes a first motor, wherein the second motor subsystem includes a second motor, and wherein the first motor and the second motor have substantially identical performance characteristics.

9. The actuator system of Claim 3, wherein the controller operates the actuator system in the following motor modes:

- Continuously Variable Transmission motor mode – in which the controller provides current to both the first motor subsystem and the second motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism; and
- High Gear motor mode – in which the controller provides current only to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism.

10. The actuator system of Claim 9, wherein the controller varies the ratio of current provided to the first motor subsystem and current provided to the second motor subsystem to achieve a desired rotational output in the Continuously Variable Transmission motor mode.

11. The actuator system of Claim 1, wherein the rotary-to-linear mechanism includes a screw that accepts the rotational output of the multi-motor assembly; a nut that connects to the screw; wherein the screw and the nut cooperate to convert rotational movement of the screw to linear movement of the nut.

12. The actuator system of Claim 11, further comprising a moving rail having an extension stop that translates linear movement of the nut in an extension direction into linear movement of the moving rail in an extension direction.
13. The actuator system of Claim 12, wherein linear movement of the moving rail in the extension direction causes an extension of the joint.
14. The actuator system of Claim 12, wherein the extension stop is movable between a force position that allows the nut to apply force against the extension stop, and a pass position that prevents the nut from applying force against the extension stop.
15. The actuator system of Claim 12, wherein the moving rail also has a flexion stop that translates linear movement of the nut in a flexion direction into linear movement of the moving rail in a flexion direction.
16. The actuator system of Claim 15, wherein linear movement of the moving rail in the flexion direction causes a flexion of the joint.
17. The actuator system of Claim 15, wherein the flexion stop is movable between a force position that allows the nut to apply force against the flexion stop, and a pass position that prevents the nut from applying force against the flexion stop.

18. The actuator system of Claim 15, wherein the extension stop and the flexion stop are located such that they allow significant movement of the moving rail back and forth between the extension stop and the flexion stop without moving the ball nut or back-driving the multi-motor assembly.

19. The actuator system of Claim 12,

- wherein the multi-motor assembly includes
  - a drive shaft that provides rotational output,
  - a first motor subsystem having a first output shaft and a first transmission connecting the first output shaft to the drive shaft, and
  - a second motor subsystem having a second output shaft and a second transmission coupling the second output shaft to the drive shaft;
- wherein the controller operates the actuator system in the following operational modes:
  - Continuously Variable Transmission Extension mode – in which the controller provides current to both the first motor subsystem and the second motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop; and
  - High Gear Flexion mode – in which the controller provides current only to the first motor subsystem such that the multi-motor assembly provides a

rotational output to the rotary-to-linear mechanism and the nut applies a force against the flexion stop.

20. The actuator system of Claim 19, wherein the controller varies the ratio of current provided to the first motor subsystem and current provided to the second motor subsystem to achieve a desired rotational output in the Continuously Variable Transmission Extension mode.

21. The actuator system of Claim 19, wherein the controller also operates the actuator system in the following operational modes:

- Low Gear Extension mode – in which the controller provides current only to the second motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop;
- High Gear Extension mode – in which the controller provides current only to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop.

22. The actuator system of Claim 19, wherein the controller also operates the actuator system in the following operational mode:

- Free Movement mode – in which the controller provides current to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut moves away from the extension stop.

23. An actuator system for extending and flexing a joint, comprising:

- a multi-motor assembly including a drive shaft that provides rotational output, a first motor subsystem having a first output shaft and a first transmission connecting the first output shaft to the drive shaft, and a second motor subsystem having a second output shaft and a second transmission coupling the second output shaft to the drive shaft, wherein the first transmission defines a first gear ratio of the rotation of the drive shaft to the rotation of the first output shaft, and wherein the second transmission at least partially defines a second gear ratio of the rotation of the drive shaft to the rotation of the second output shaft, wherein the second gear ratio is lower than the first gear ratio;
- a rotary-to-linear mechanism including a screw that accepts the rotational output of the drive shaft, a nut that cooperates with the screw to convert rotational movement of the screw to linear movement of the nut;
- a moving rail including an extension stop that translates linear movement of the nut in an extension direction into an extension of the joint, and a flexion stop that

translates linear movement of the nut in a flexion direction into a flexion of the joint,

- a controller for operating the actuator system in the following operational modes:
  - Continuously Variable Transmission Extension mode – in which the controller provides current to both the first motor subsystem and the second motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop; and
  - High Gear Flexion mode – in which the controller provides current only to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the flexion stop.

24. The actuator system of Claim 23, wherein the second transmission connects the second output shaft to the first output shaft, wherein the second motor subsystem further includes a one-way clutch located between the second motor and the first motor, wherein the second transmission and the first transmission cooperatively define the second gear ratio, and wherein the drive shaft and the screw are axially connected as a unitary part.

25. The actuator system of Claim 23, wherein the controller varies the ratio of current provided to the first motor subsystem and current provided to the second motor subsystem to achieve a desired rotational output in the Continuously Variable Transmission Extension mode.

26. The actuator system of Claim 23, wherein the controller also operates the actuator system in the following operational modes:

- Low Gear Extension mode – in which the controller provides current only to the second motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop;
- High Gear Extension mode – in which the controller provides current only to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut applies a force against the extension stop.

27. The actuator system of Claim 23, wherein the controller also operates the actuator system in the following operational mode:

- Free Movement mode – in which the controller provides current to the first motor subsystem such that the multi-motor assembly provides a rotational output to the rotary-to-linear mechanism and the nut moves away from the extension stop.

28. A method for controlling an actuator system that extends and flexes a joint, the method comprising the steps of:

- providing a multi-motor assembly including a drive shaft, a first motor subsystem having a first output shaft, and a second motor subsystem having a second output shaft;
- coupling the first output shaft to the drive shaft with a first transmission;
- coupling the second output shaft to the drive shaft with a second transmission;
- providing current only to the first motor subsystem in High Gear mode; and
- providing current to both the first motor subsystem and the second motor subsystem in a Continuously Variable Transmission mode.

29. The method of Claim 28, wherein the step of providing current to both the first motor subsystem and the second motor subsystem includes varying the ratio of current provided to the first motor subsystem and current provided to the second motor subsystem to achieve a desired output.

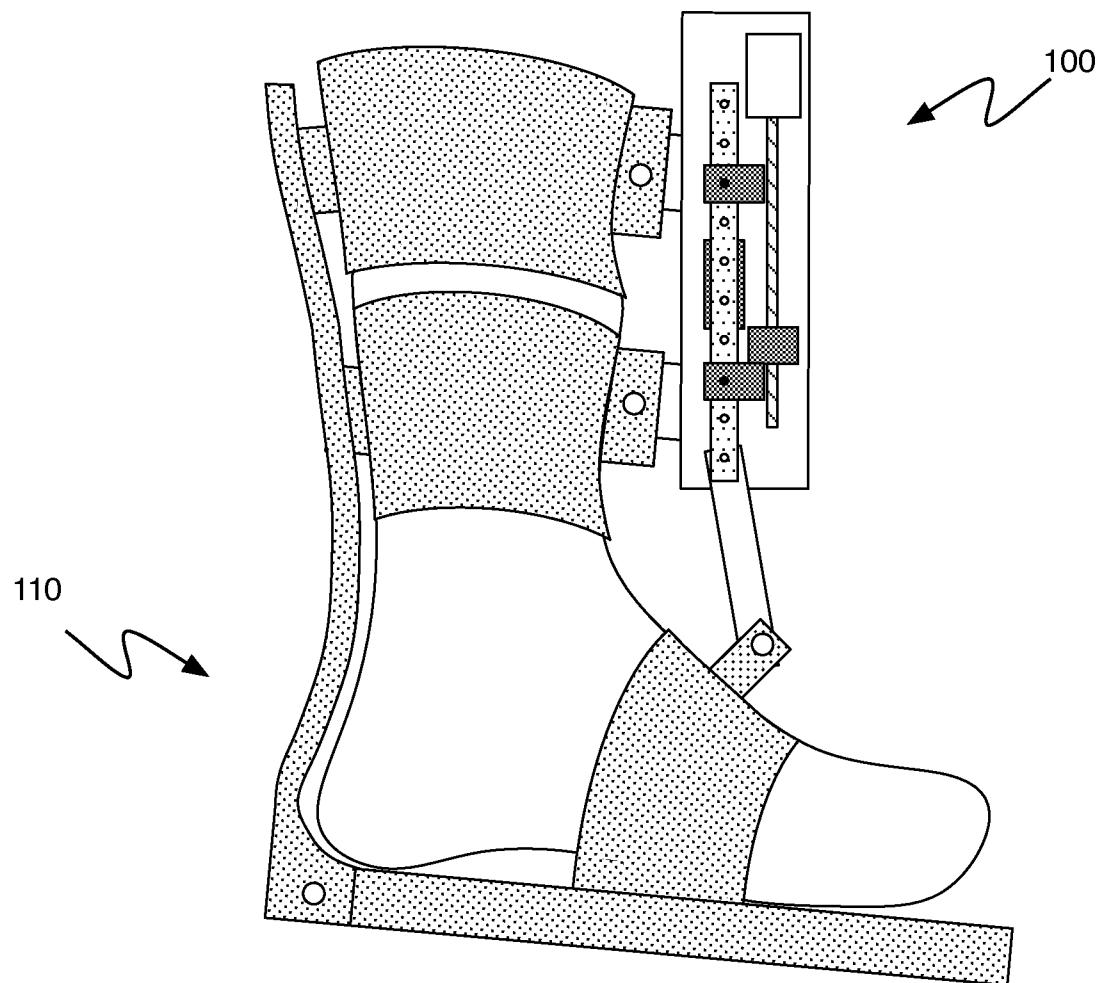


FIGURE 1

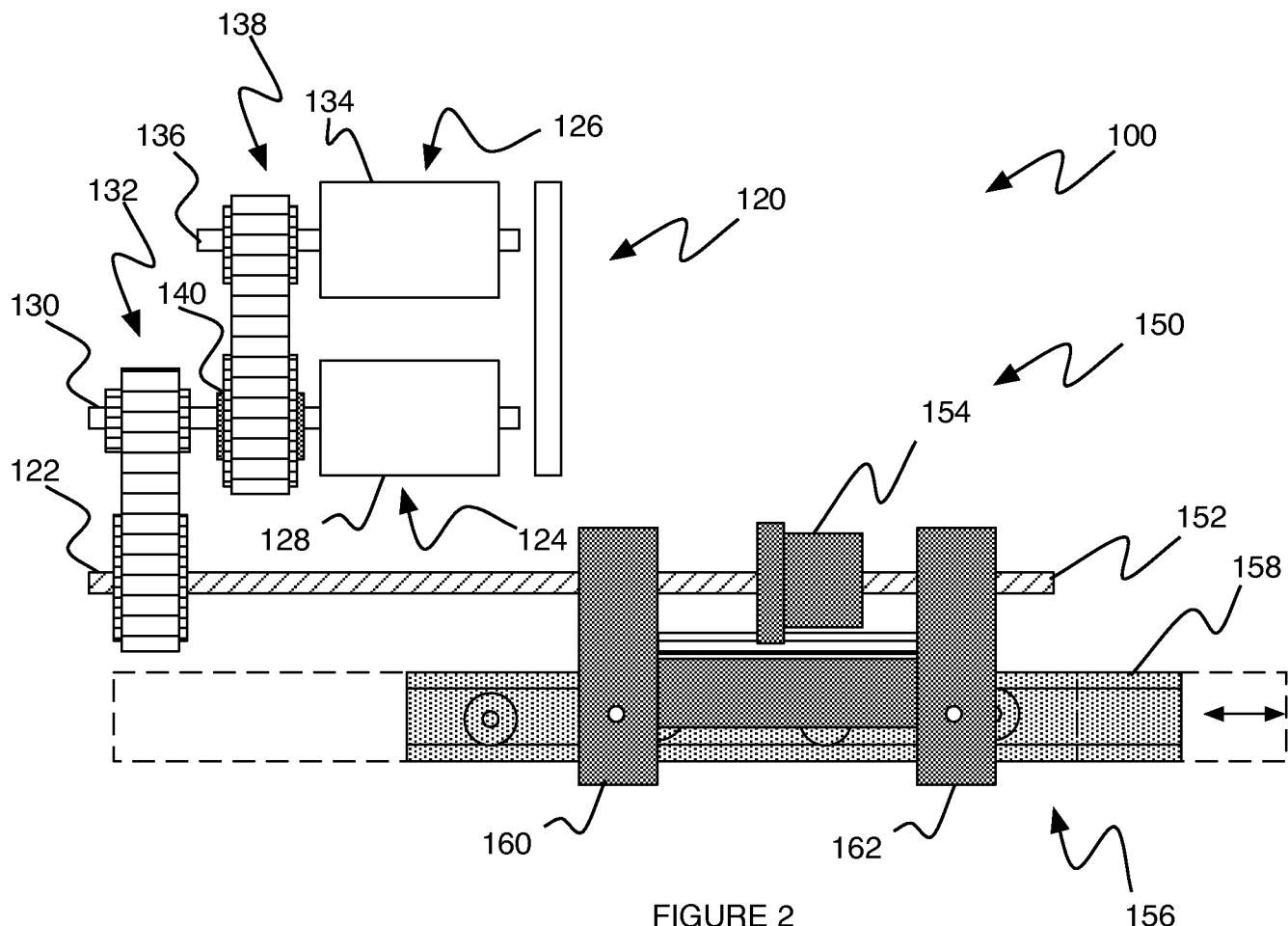
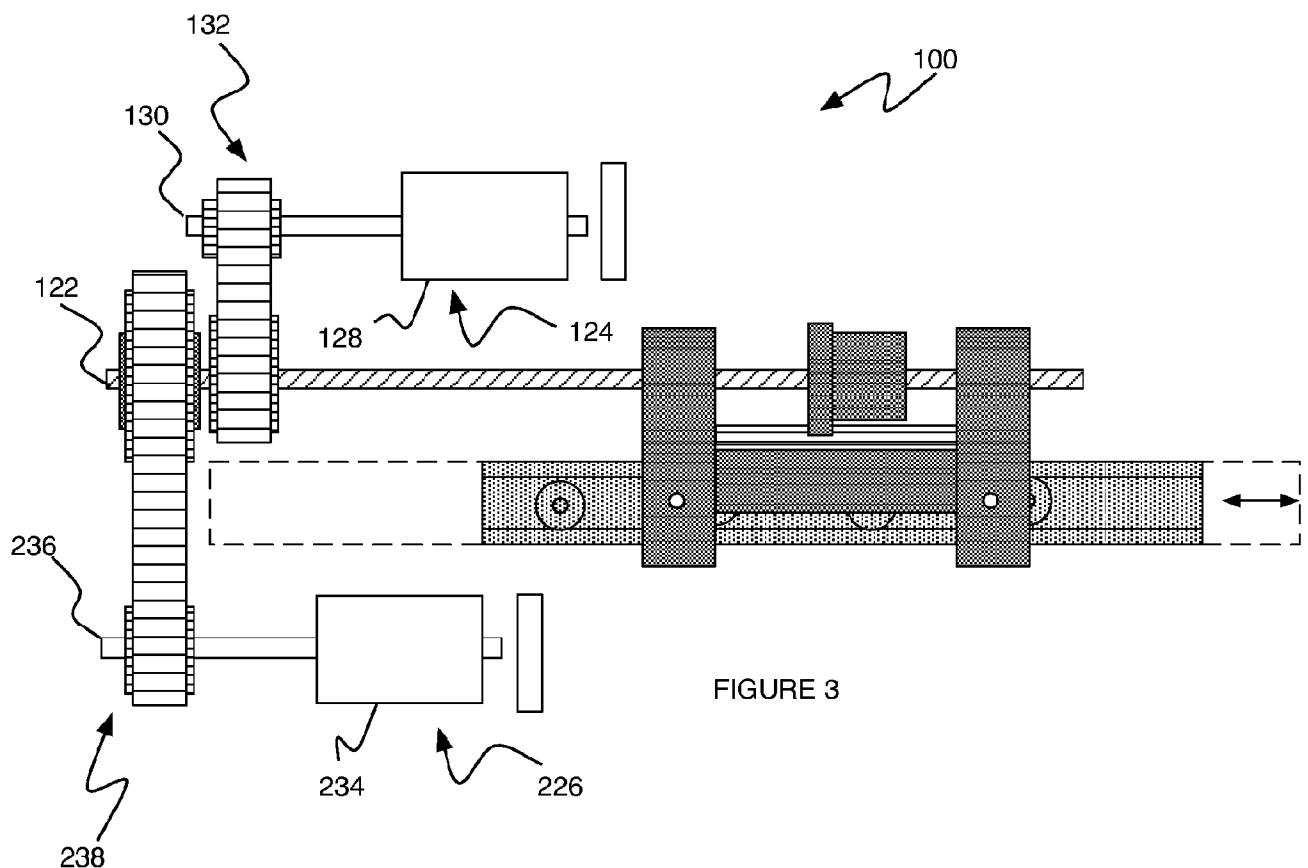
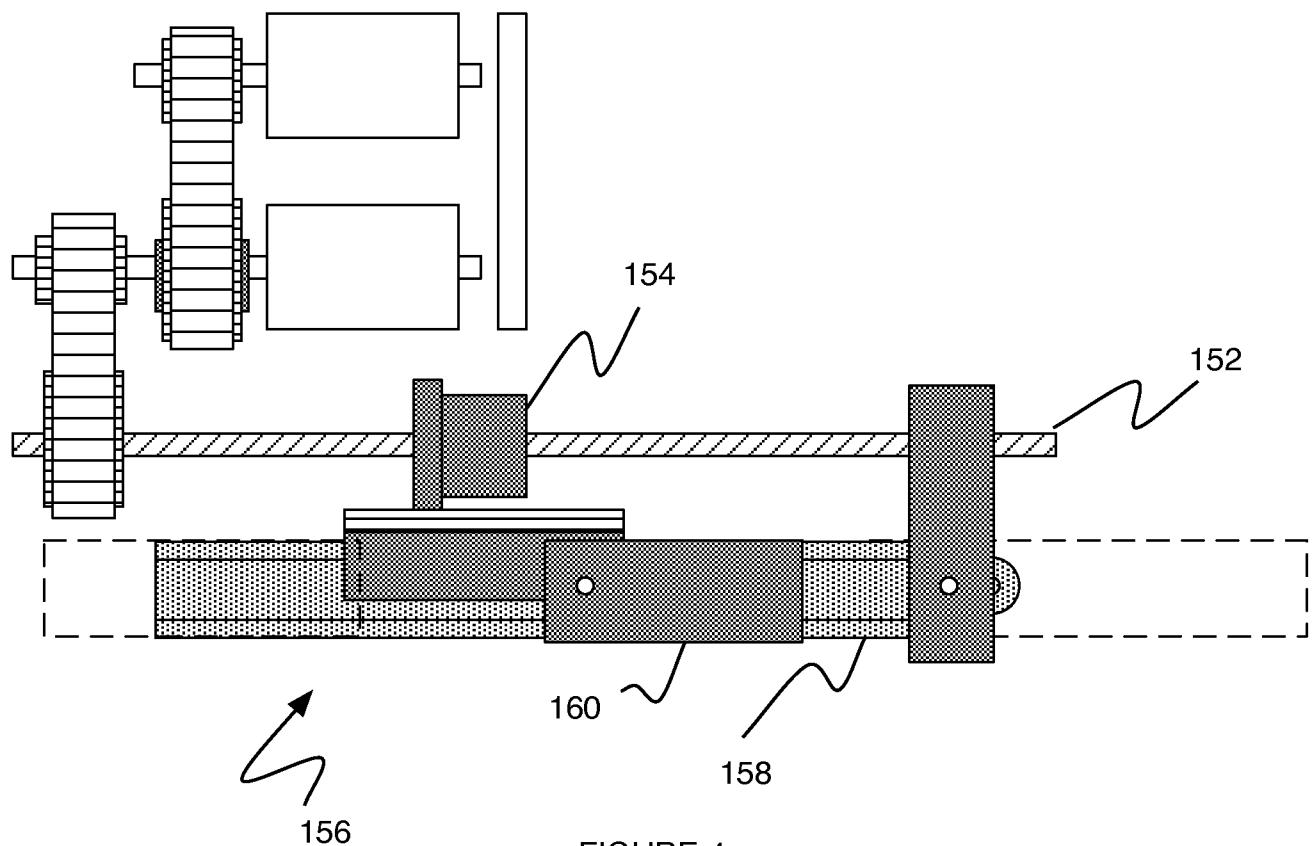


FIGURE 2





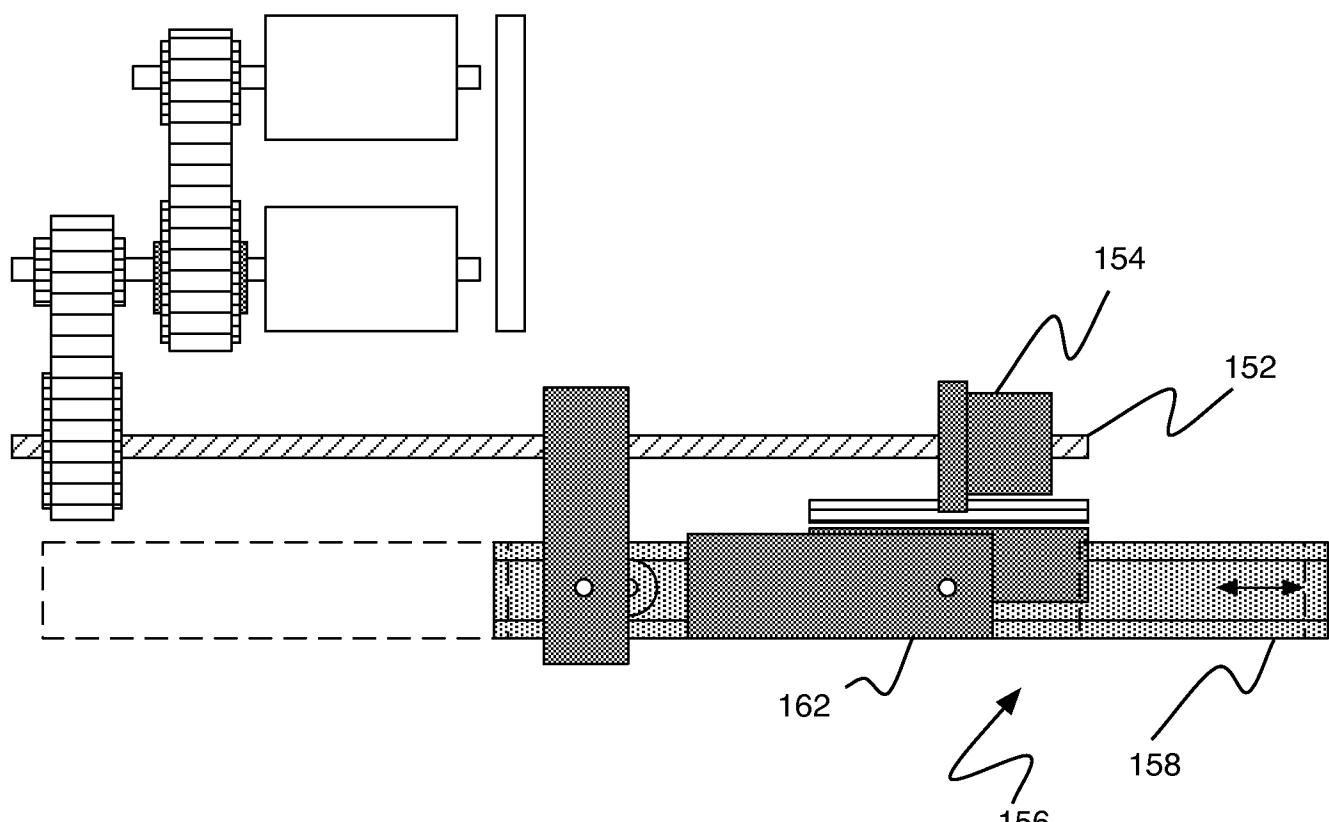
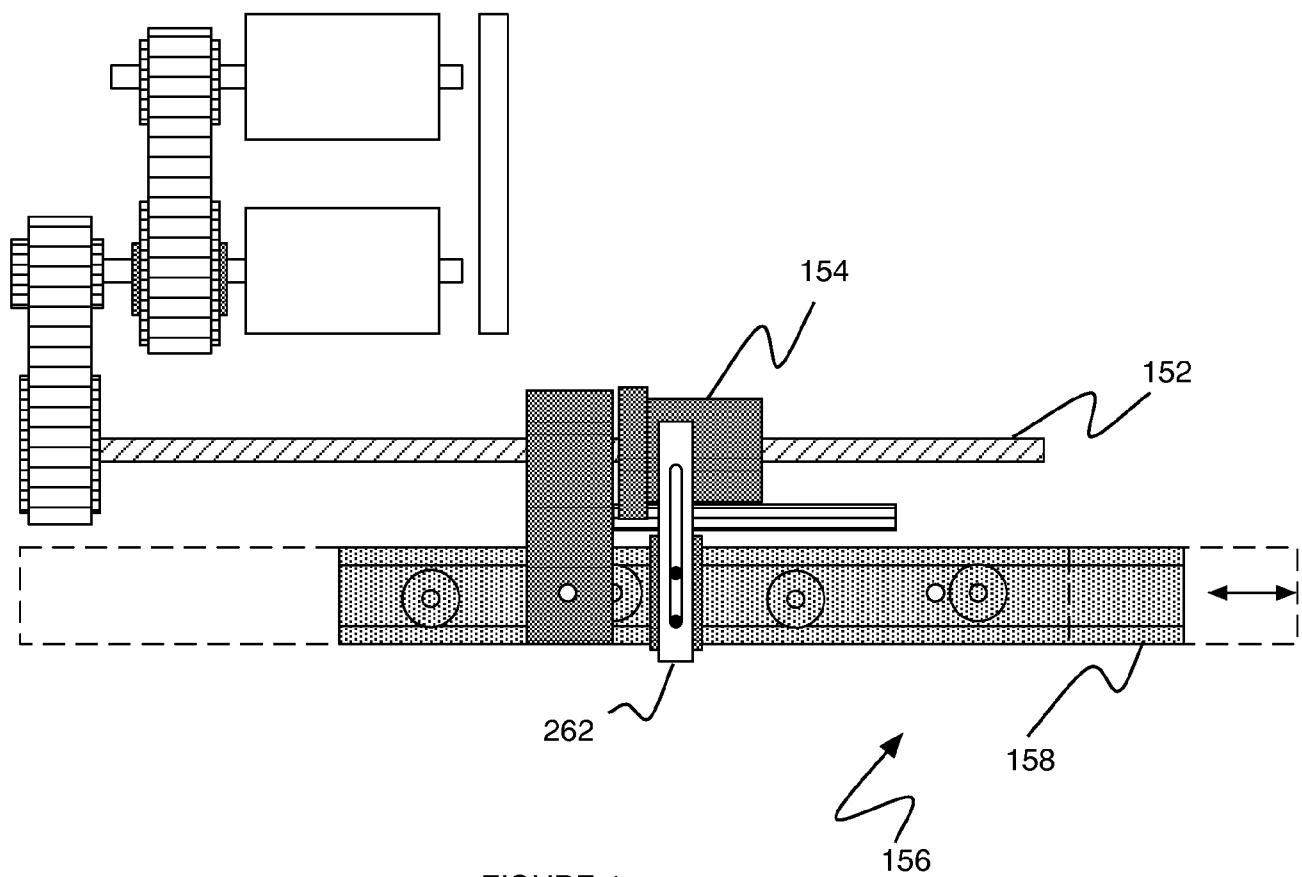
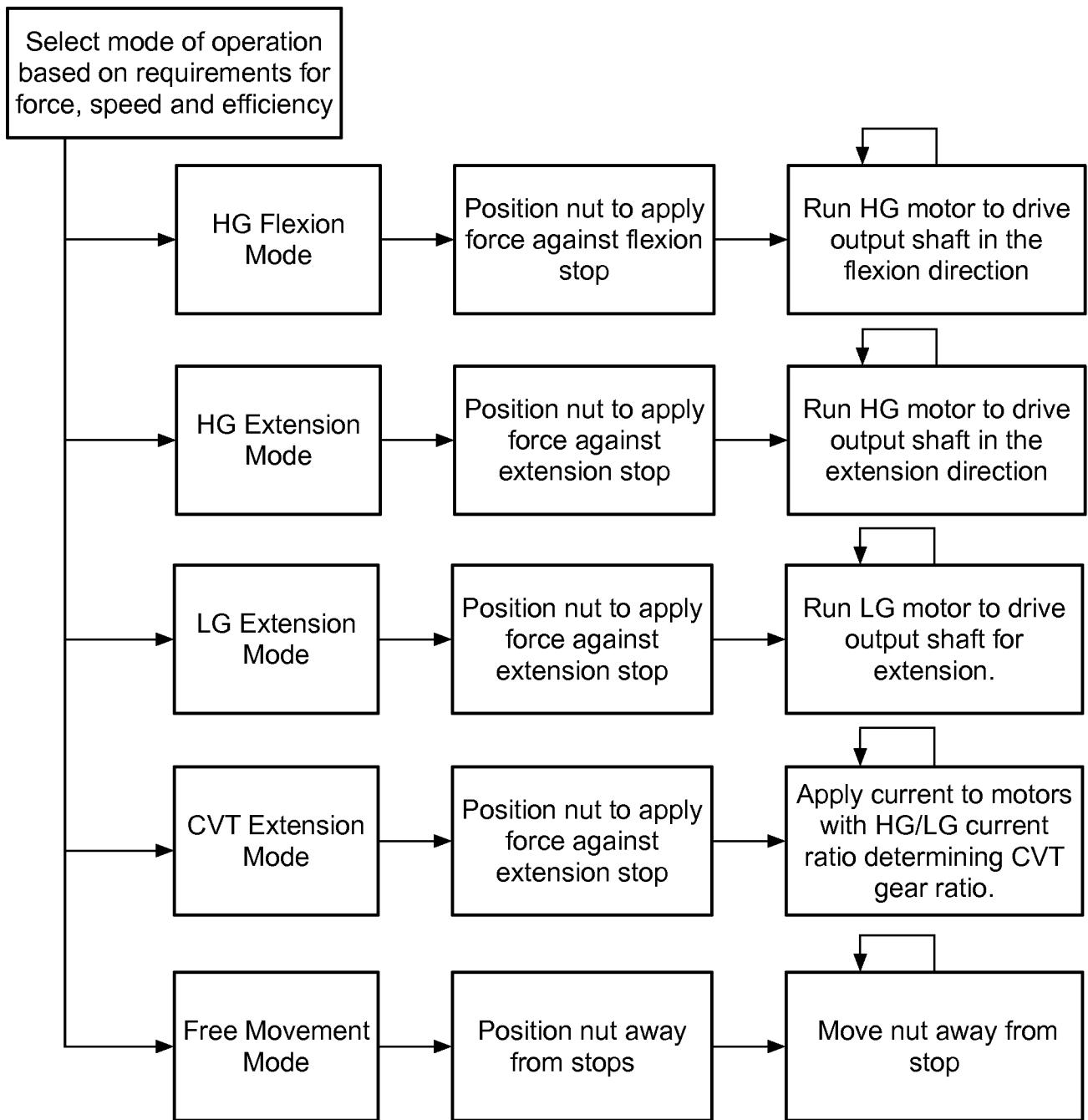


FIGURE 4b





## FIGURE 5

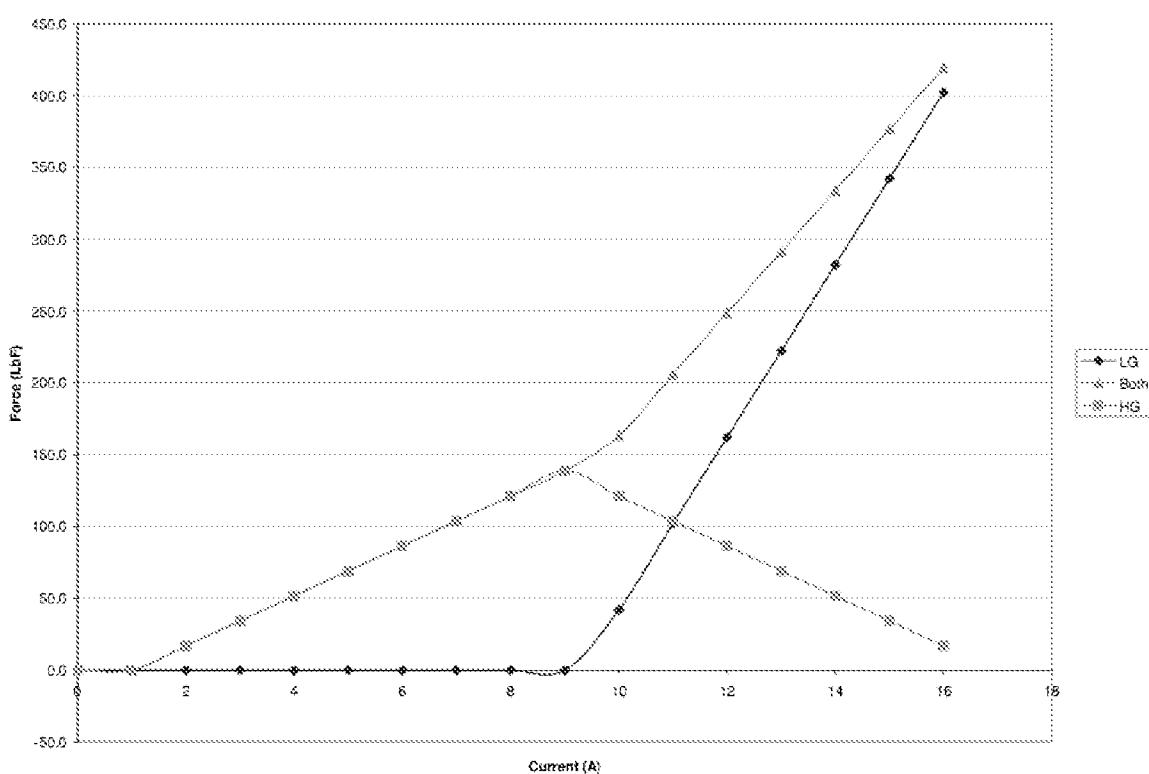


FIGURE 6

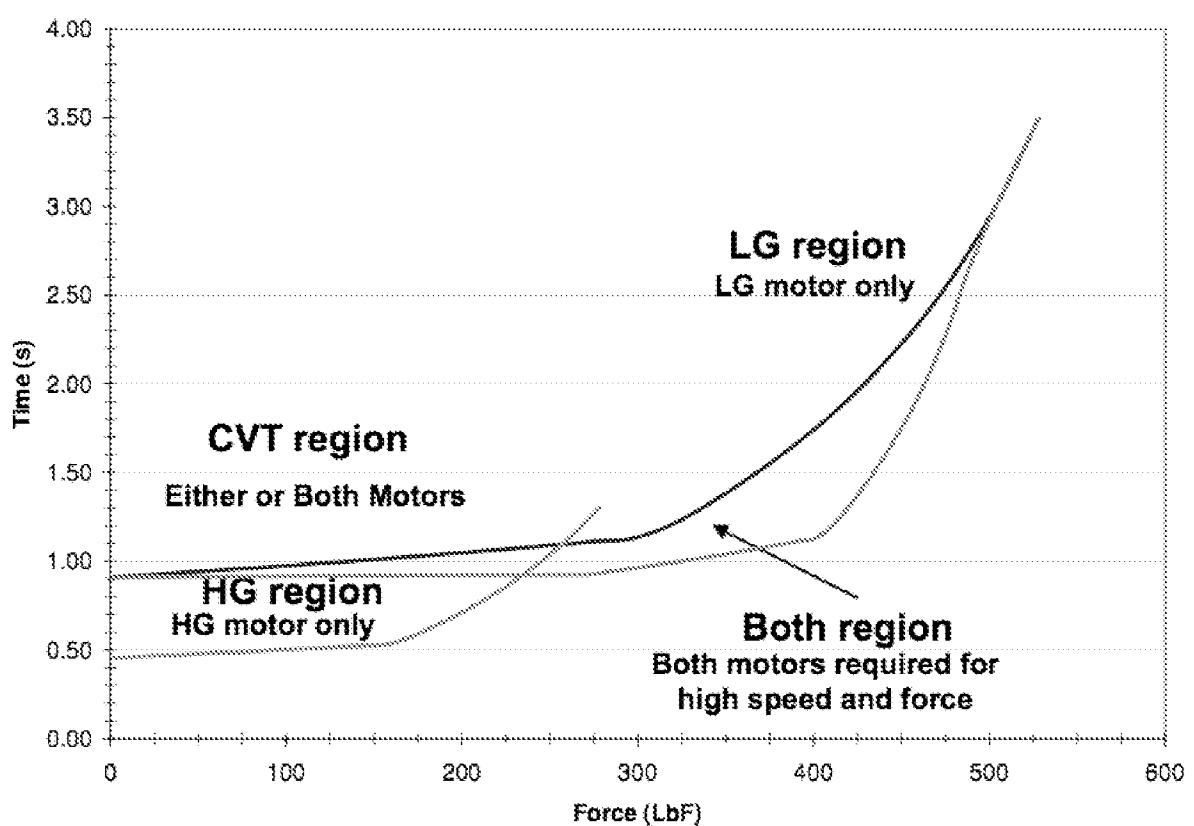


FIGURE 7

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 09/53939

A. CLASSIFICATION OF SUBJECT MATTER  
 IPC(8) - F16H 1/16 (2009.01)  
 USPC - 74/425.5

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)  
 USPC: 74/425.5

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
 USPC: 74/335; 74/508

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
 USPTO, PUBWEST (PGPB, USPT, USOC, EPAB, JPAB), Google

Search Terms Used: actuate, motor, gear, speed, ratio, adjust, variable, continuous, clutch, transmission, linear, bend, flex, joint

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X - Y	US 2008/0200994 A1 (Colgate et al.) 21 August 2008 (21.08.2008), para [0010]-[0052], Fig 3A	1, 2 ----- 3-29
Y	US 2007/0270265 A1 (Miller et al.) 22 November 2007 (22.11.2007), [0070]-[0072], [0076]-[0079], [0103], [0106], [0142]-[0183]	3-29
A	US 2007/0162152 A1 (Herr et al.) 12 July 2007 (12.07.2007), entire document	1-29
A	US 2004/0078091 A1 (Elkins) 22 April 2004 (22.04.2004), entire document	1-29

Further documents are listed in the continuation of Box C.

* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family
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Date of the actual completion of the international search  05 November 2009 (05.11.2009)	Date of mailing of the international search report  13 NOV 2009
Name and mailing address of the ISA/US  Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer:  Lee W. Young  PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774