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Hollow
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[54] LOAD POSITIONING SYSTEM WITH GRAVITY COMPENSATION

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[73] Assignee: The United States of America as represented by the Administrator of the National Aeronautics and Space Administration, Washington, D.C.

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[51] Int. Cl.[4] G05D 23/275
[52] U.S. Cl. 318/632; 318/8; 318/48; 318/663
[58] Field of Search 318/48, 632, 8, 5, 663, 318/625

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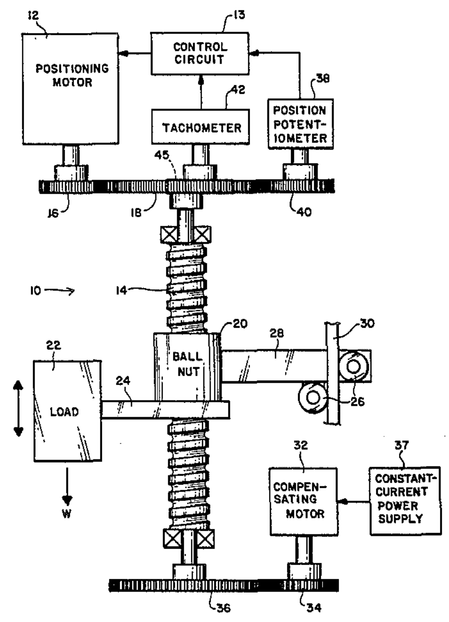
Attorney, Agent, or Firm—Darrell G. Brekke; John R. Manning; Robert D. Marchant

[57] ABSTRACT

A load positioning system with gravity compensation has a servo-motor (12), position sensing feedback potentiometer (38) and velocity sensing tachometer (42) in a conventional closed-loop servo arrangement to cause lead screw (14) and ball nut (20) to vertically position load (22). Gravity compensating components comprise the DC motor (32), gears (34) and (36), which couple torque from motor (32) to the lead screw (14), and constant-current power supply (37). The constant weight of the load (22) applied to the lead screw (14) via the ball nut (20) tends to cause the lead screw (14) to rotate, the constant torque of which is opposed by the constant torque produced by motor (32) when fed from the constant-current source (37). The constant current is preset as required by potentiometer (54) to effect equilibration of the load (22) which thereby enables the positioning servo-motor (12) to "see" the load (22) as weightless under both static and dynamic conditions. Positioning acceleration and velocity performance are therefore symmetrical.

6 Claims, 5 Drawing Figures



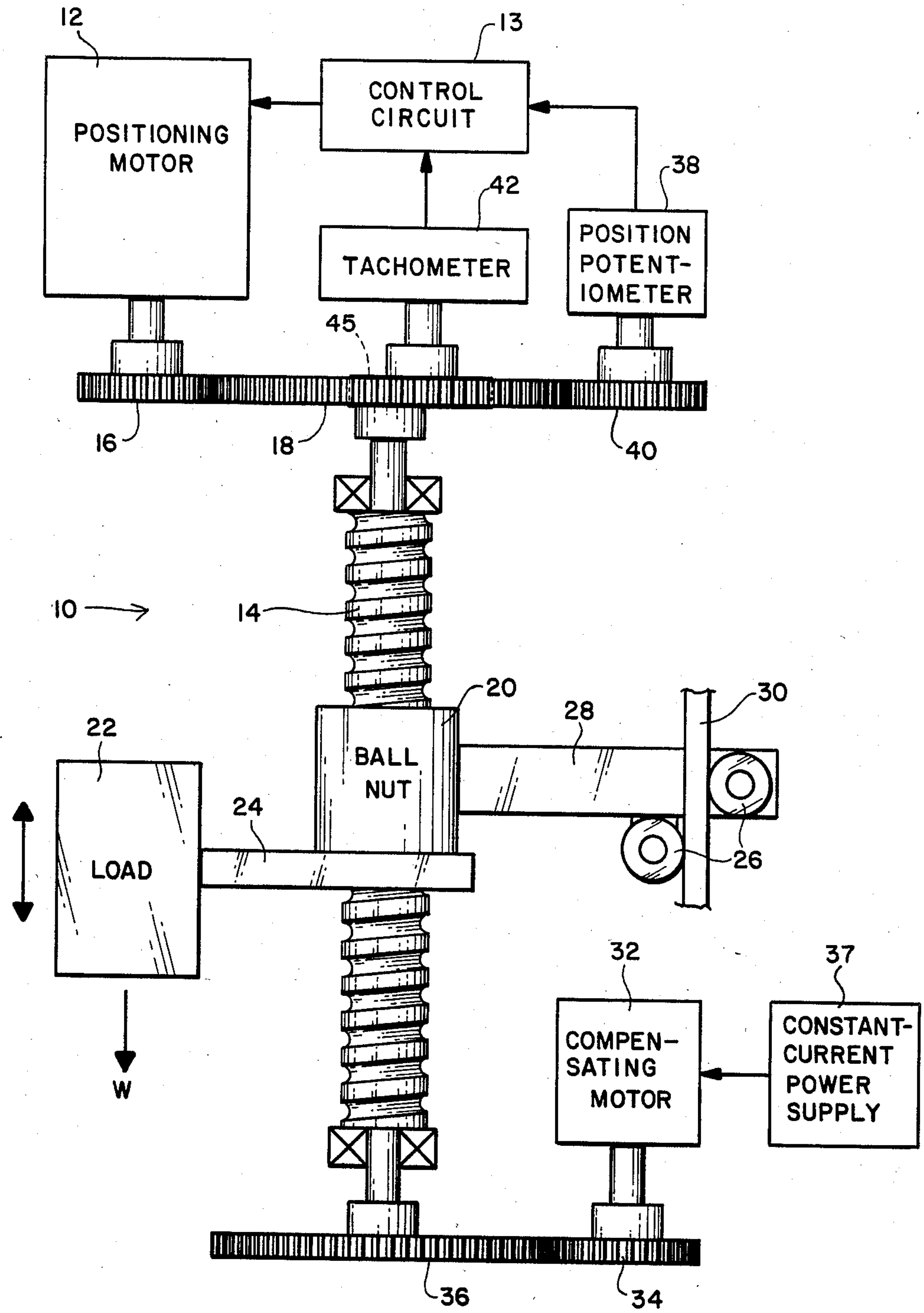

12
13
CONTROL CIRCUIT
POSITIONING MOTOR
42
38
TACHOMETER
POSITION POTENT-IOMETER
45
16
18
40
10
14
20
30
28
22
BALL NUT
24
LOAD
26
W
32
37
COMPEN-SATING MOTOR
CONSTANT-CURRENT POWER SUPPLY
36
34

FIG. 1

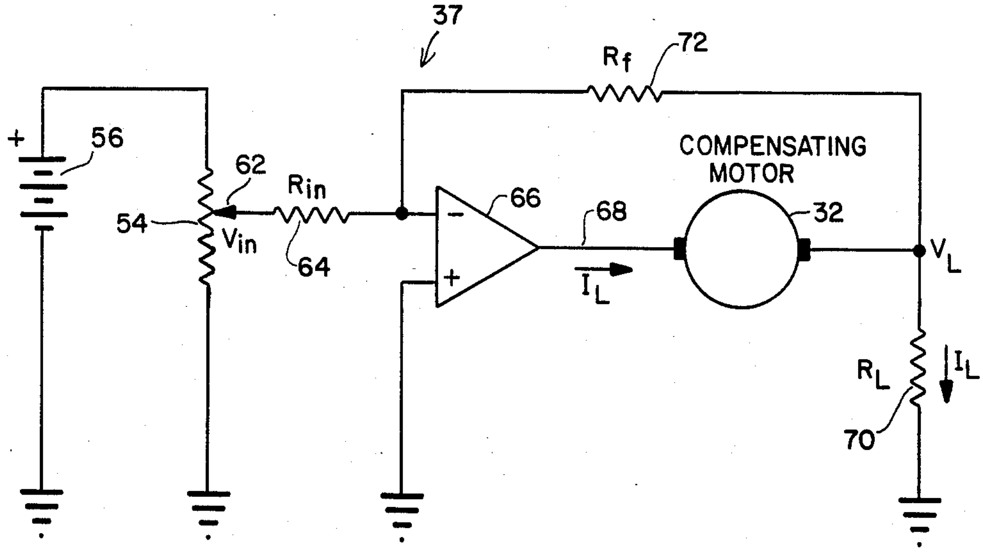

37
R_f
72
+
56
62
R_{in}
54
V_{in}
64
66
68
COMPENSATING
MOTOR
32
V_L
I_L
R_L
I_L
70

FIG. 2

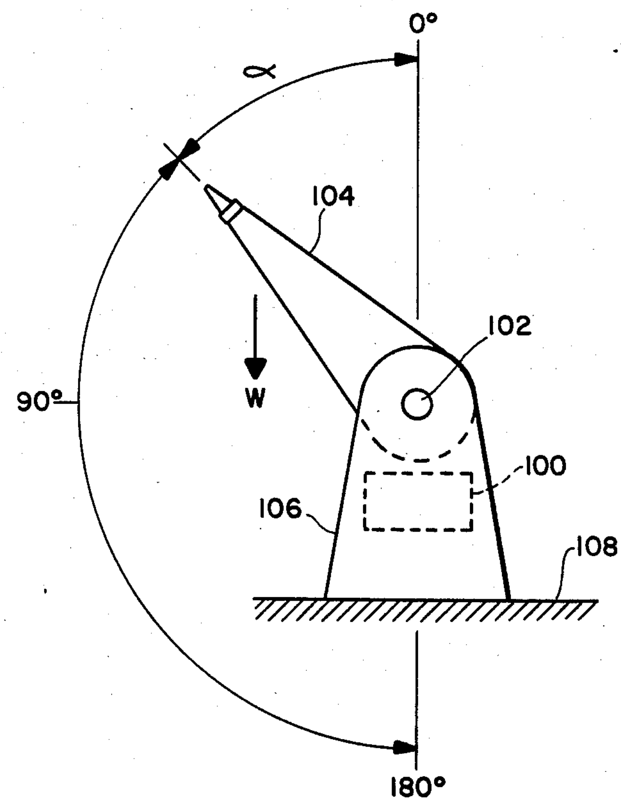
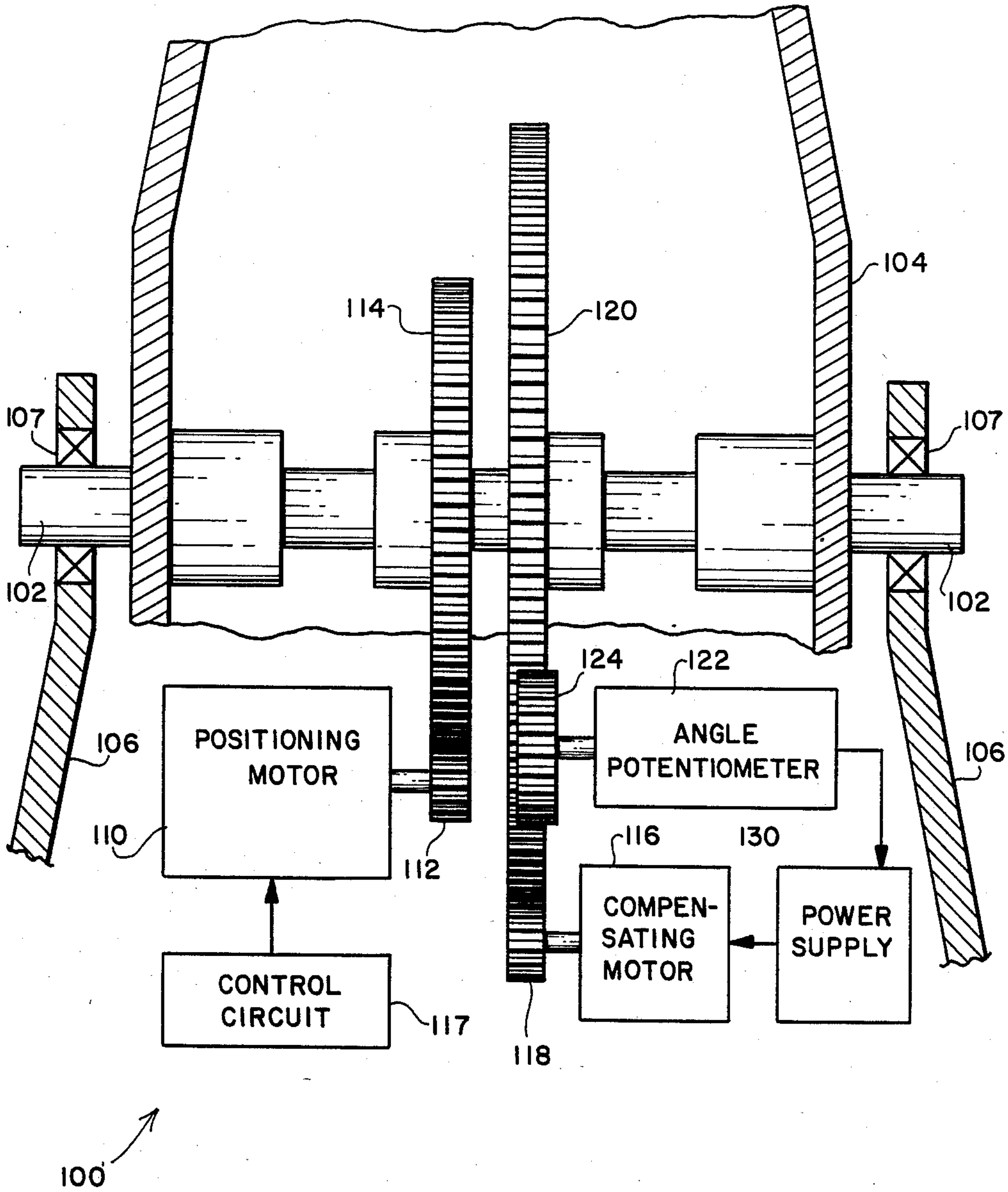

0°
α
104
102
90°
W
100
106
108
180°

FIG. 3



104
114
120
107
107
102
102
124
122
106
POSITIONING
MOTOR
ANGLE
POTENTIOMETER
106
110
112
116
130
COMPEN-
SATING
MOTOR
POWER
SUPPLY
CONTROL
CIRCUIT
117
118
100

FIG. 4

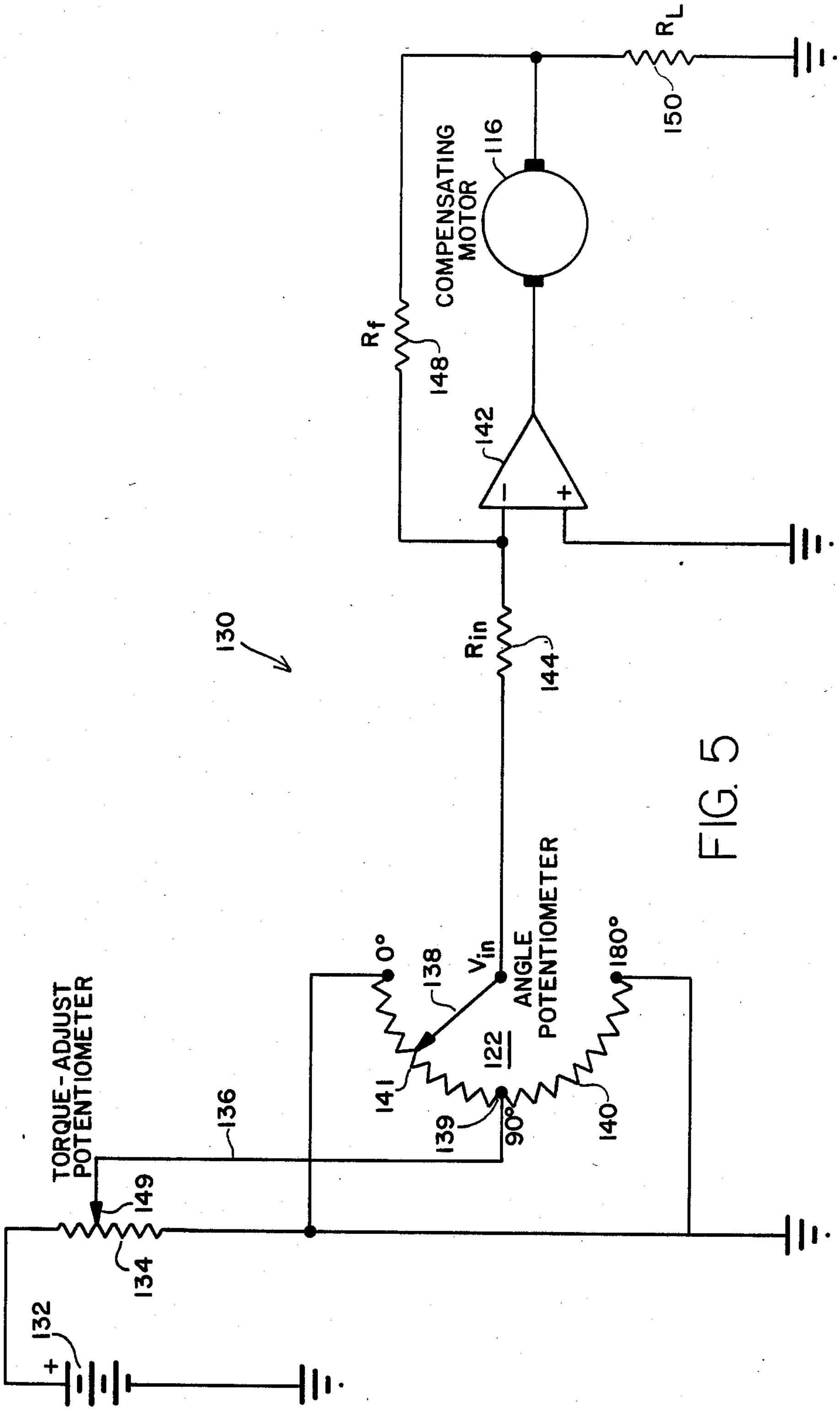

R_L
150
COMPENSATING MOTOR
116
R_f
148
142
130
R_{in}
144
V_{in}
ANGLE POTENTIOMETER
0°
138
180°
122
141
139
90°
140
136
TORQUE-ADJUST POTENTIOMETER
149
134
132

FIG. 5

LOAD POSITIONING SYSTEM WITH GRAVITY COMPENSATION

DESCRIPTION

Origin of the Invention

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 USC 2457).

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to load positioning systems used for moving a load in a gravity field and particularly to apparatus for compensating for the gravity force in a manner permitting symmetrical load acceleration and velocity with low cost, weight and space penalties.

2. Description of the Prior Art

In load positioning systems it is known to compensate for the effects of gravity on the load by means of a counterbalance or counterweight, a constant-force spring, or a pneumatic equilibrator.

A counterweight is often undesirable due to its large size or to the weight/inertia that it adds to the system. For example, in a typical three degrees-of-motion system with X, Y and Z axes, the mass of the Z counterweight often degrades the performance of either or both of the X and Y drives, which leads to the necessity for more power. Additional power translates to more apparatus cost, weight, and volume.

In many situations a constant force spring is not capable of generating a sufficient compensating force. These springs have innately high stresses which induce metal fatigue. Consequently, the springs have a relatively short dynamic life span.

The disadvantage of pneumatic equilibrators is that they are long and bulky and generally have to be made on a custom basis.

In a load positioning system with a servomechanism it is known to bias the servo amplifier in an attempt to compensate for the force of gravity. This procedure is not optimum inasmuch as it only reduces the steady-state error. When the bias is added, the maximum acceleration and maximum velocity remain asymmetrical—that is, the acceleration and the velocity in the direction opposite the gravity vector are less than the acceleration and the velocity in the direction of the gravity vector. Motor selection must therefore be made according to the performance demands of the worst case. This results in greater apparatus cost, volume and weight.

A limited scale patent search on the subject invention uncovered these patents, not one of which even recognizes the problem solved by the present invention. U.S. Pat. Nos. 4,105,961; 4,200,828; and 4,301,528 disclose phonograph arms wherein motors are utilized to adjust styli forces and facilitate groove tracking. Gravity measuring devices are described in U.S. Pat. Nos. 3,408,868; 3,991,625; and 4,022,064. U.S. Pat. No. 3,854,378 discloses an apparatus for stabilizing an oscillating mass such as an artillery gun and U.S. Pat. No. 2,789,260 sets forth a device for electronically indicating deviation from the earth's gravity vector.

SUMMARY OF THE INVENTION

Accordingly, it is an object of this invention to provide a load positioning system having symmetrical velocity and acceleration performance through an improved gravity compensation means.

It is another object of the invention to provide such a load positioning system wherein the power demand of the primary drive means is minimized.

It is a further object to provide a load positioning system in which symmetrical velocity and acceleration performance is achieved with gravity compensation apparatus that is less expensive and/or lighter weight and/or more compact than prior gravity compensation devices.

It is still further an object of the invention to provide a load positioning system wherein electromechanical means apart from the primary drive means are employed to cancel the force on the load induced by gravity.

The attainment of these and related objects may be achieved through the use of the novel load positioning system herein disclosed. Generally, in accordance with the invention, a primary drive means, such as a motor, is mechanically coupled to the load to be positioned. The torque imposed on the coupling means as a result of gravity is counteracted with an equal and opposite torque generated by a second motor. In practice, the second motor, the gravity compensating motor, need not generate as much torque as the primary motor. By eliminating the effect of gravity-induced torque in this manner, the load positioning motor effectively "sees" a weightless load under both static and dynamic conditions and the load positioning motor is permitted symmetrical velocity and acceleration performance.

For further comprehension of the invention, and of the objects and advantages thereof, reference will be made to the following description and accompanying drawings and to the appended claims in which the various novel features of the invention are more particularly set forth.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic side view of a load positioning system in accordance with the invention.

FIG. **2** is a schematic diagram of a power supply circuit used in the system of FIG. **1**.

FIG. **3** is a diagrammatic side view of another embodiment of a load positioning system in accordance with the invention.

FIG. **4** is a front view showing more detail of the positioning system of FIG. **3**.

FIG. **5** is a schematic diagram of a circuit used in the load positioning system of FIGS. **3** and **4**.

DETAILED DESCRIPTION OF THE INVENTION

Turning now to the drawings, more particularly to FIG. **1**, there is shown a load positioning system which includes gravity compensation in accordance with the invention. The output shaft of motor **12** is coupled to lead screw **14** by means of meshing gears **16** and **18**. A conventional control circuit **13** controls the rate and direction of rotation of the output shaft of motor **12**. It is preferred that positioning motor **12** be a part of a conventional closed-loop servo system wherein feedback signals representative of lead screw position and rate data are generated by transducers such as position potentiometer **38** and tachometer **42**, respectively. Position potentiometer **38** is coupled to the lead screw by means of gears **18** and **40** and tachometer **42** is coupled to lead screw **14** by meshing gears **18** and **45**.

As lead screw **14** is rotated, ball nut **20** traverses to and fro along the lead screw. For one direction of rotation of lead screw **14**, ball nut **20** moves upward, that is, in the direction toward gear **18**. Conversely, when the lead screw is rotated in the opposite direction, the ball nut **20** moves downward and away from gear **18**. Load **22** is fixedly attached to the ball nut **20** by member **24**. Rollers **26** are attached to ball nut **20** by member **28** and engage guide member **30** to prevent cocking forces being applied to the ball nut during traversal on lead screw **14**. The force w of gravity on load **22** applies a constant torque to lead screw **14** and tends to cause it to rotate. A motor **32** is coupled to lead screw **14** by means of engaging gears **34** and **36** to provide an equal and opposite torque to lead screw **14** to compensate for the gravity induced torque applied to the lead screw **14** by load **22**. Although the compensating motor **32** is shown depicted coupled to the end of lead screw **14** opposite motor **12**, it is to be understood that both motors may be coupled to either end of lead screw **14** or that the positions of the motors may be reversed (motor **32** at the upper end of lead screw and motor **12** at the lower end). The gearing for motor **32** is chosen to give a torque multiplication ratio to enable the use of a minimum size motor and minimum power supply. Also the motor dynamics and gear ratio combination is chosen so that the motor rotor and gears will accelerate at a sufficiently high rate to keep motor **12** from driving motor **32**.

The torque produced by a DC motor is proportional to the field flux and the armature current. There are many DC motors that have a constant flux and thus produce a torque directly proportional to the armature current. When the armature current is constant then the torque is constant. Shunt motors, permanent magnet motors, servomotors and torque motors are some of the types of DC motors that display these characteristics. In the preferred embodiment, motor **32** is such a motor supplied by a constant-current power supply **37**. FIG. **2** shows a typical power supply circuit **37** for supplying a constant current I_L to compensating motor **32** for different loads **22**. A variable resistor **54** is connected in shunt with a DC voltage source **56**. Input resistor **64** (R_{in}) is connected between the wiper contact **62** of potentiometer **54** and the inverting input of power amplifier **66**. The output of amplifier **66** is connected to one terminal of motor **32** by line **68** whereas the other motor terminal is connected to the node formed by resistors **70** (R_L) and **72** (R_f). One terminal of feedback resistor R_f is connected to the inverting input of amplifier **66** and one terminal of resistor R_L is grounded. The non-inverting input of amplifier **66** is grounded. The motor current I_L supplied by circuit **37** to DC motor **32** is defined by the equation

$$I_L = V_{in}\left(-\frac{R_F}{R_{in}}\cdot\frac{1}{R_L}\right) \text{ where } R_f >> R_L$$

In accordance with operational amplifier principles, if V_{in} and R_L remain constant, voltage V_L will remain constant and the current through the motor **32** will remain constant. The voltage V_{in} is selected by moving wiper **62** and is chosen to produce the necessary compensating torque for a particular load **22**.

In one specific embodiment of the invention the load **22** was a ship model for use in an aircraft simulator of the type disclosed in commonly assigned U.S. Pat. No. 4,055,004, Chase, Oct. 25, 1977. The ship had six degrees of freedom and the simulator trainee could practice landing an aircraft on the flight deck of a moving ship. The transversal of ball nut **20** along lead screw **14** accomplished ship motion along one axis of freedom. In that embodiment, wherein the load **22** had a weight of 4.5 pounds, the positioning motor **12** was implemented with an Inland DC motor type OT-0735 having a continuous stall torque of 6.3 ounce-inches, and compensating motor **32** was implemented with an Inland DC motor type NT-0726 having a continuous stall torque of 2.9 ounce-inches and a volume of approximately one cubic inch. These motors may be obtained from Inland Motor Specialty Products Division, Kollmorgen Corporation, Redford, VA 24141. The power amplifier **66** used for this embodiment was an Intersil ICH8510 manufactured by Intersil, Inc., Cupertino, Calif. Other parameters of system **10** were as follows:

Element	Parameter
Lead screw 14	8 threads per inch
Gear 16	42 teeth
Gear 18	42 teeth
Gear 34	42 teeth
Gear 36	200 teeth
Gear 40	140 teeth
Gear 45	28 teeth

From FIG. **1** it is apparent that load **22** follows a linear path parallel to lead screw **14**. The invention may also be employed to compensate for the force of gravity on a load that is angularly positioned.

FIG. **3** is a diagrammatic representation of a second embodiment of the present invention. A load **104**, a robotic arm, is supported by base **106** and caused to rotate about pivot **102** by positioning system **100** that includes two motors similar to those employed in system **10**. A primary motor rotates load **104** about pivot **102** while a gravity compensating motor generates a torque equal and opposite to the torque produced by gravity force w. Load **104** is continually subjected to gravity force w; however, as the load **104** is rotated from $\alpha=0°$ to $\alpha=90°$ (where α is the angle between the arm and the vertical plane) there is a substantial change in the torque applied to the pivot by load **104**. The secondary motor, the gravity compensating motor, alters its torque output as angle α is changed.

FIG. **4** is a front view of robotic arm **104** showing the details of positioning system **100**. Pivot **102**, a shaft, is supported at each end by a bearing **107** and the bearings are in turn supported by stand **106**. Positioning motor **110** is mechanically coupled to pivot **102** by intermeshing gears **112** and **114**. The rate and direction of rotation of positioning motor **110** is controlled by a conventional motor control circuit **117**. A gravity-compensating DC motor **116** of the same type as motor **32** is coupled to pivot **102** by gears **118** and **120** and angle potentiometer **122** is coupled to pivot **102** by gears **120** and **124**. As positioning motor **110** rotates, load **104** turns about pivot **102**. Positioning motor **110** may be, for example, a servo motor in a conventional closed-loop system servo system having negative feedback signals generated by a position potentiometer and tachometer (not shown).

FIG. 5 depicts a circuit **130** for supplying current to gravity-compensating motor **116**. A potentiometer **134** employed for torque adjustment purposes is connected in parallel with a DC voltage source **132**. Angle potentiometer **122** has a wiper **138** and a centertap terminal **139** coinciding with 90° rotation of wiper **138**. The resistance elements **140** and **141** each have a sine taper. Wiper **149** of torque-adjust potentiometer **134** is connected to centertap **139** by line **136**. A resistor **144** (R_{in}) is connected between wiper **138** and the inverting input of power amplifier **142**. The terminals of compensating motor **116** are connected to the output of amplifier **142** and the node formed by resistors **148** (R_f) and **150** (R_L), respectively. One terminal of feedback resistor **148** is connected to the inverting input of amplifier **142** and one terminal of resistor R_L is grounded, as is the non-inverting input of amplifier **142**.

The wiper **138** of potentiometer **122** is mechanically aligned to be at centertap **139** when $\alpha=90°$. The wiper **149** of potentiometer **134** is adjusted so that the torque supplied by motor **116** will be equal and opposite to the torque induced by gravity when $\alpha=90°$ and wiper **138** of potentiometer **122** is at centertap **139** (90°). The input voltage V_{in} supplied by angle potentiometer **122** is equal to the voltage at centertap **139** multiplied by the sine of angle α. V_{in} is therefore at a maximum when $\alpha=90°$ (the load **102** is parallel to ground **108**) and zero when $\alpha=0°$ or 180° (the load **104** is normal to ground **108**). Thus as the load **104** is positioned about pivot **102**, the wiper **138** of potentiometer **122** is slewed and the value of V_{in} is such that compensating motor **116** applies a torque to pivot **102** that is equal and opposite to the torque applied to load **104** by gravity. Circuit **130** provides for up to 180° rotation of load **104**. In situations requiring 360° rotation of load **104** it would merely be necessary to couple a second potentiometer, similar to potentiometer **122**, to the shaft of potentiometer **122**, connecting both in the same manner. The additional potentiometer would be staggered 180° with respect to potentiometer. It is to be understood that a potentiometer is only one of several position/angle sensing transducers that could be used for positioning system **100**.

As a result of the compensating torques provided by systems **10** and **100**, the positioning motors **12** and **110** act against a constant load regardless of the position of load **22** or load **104**. With the gravity forces equilibrated by motors **32**, **116**, the positioning motors **12**, **110** are therefore capable of providing symmetrical acceleration and velocity performance, with a minimum of static and dynamic errors. The gravity compensation is achieved through the use of apparatus that is economical, light weight and compact.

While I have illustrated and described the preferred embodiments of my invention, it is to be understood that I do not limit myself to the precise constructions herein disclosed and that various changes and modifications may be made within the scope of the invention as defined in the appended claims.

I claim:

1. A load positioning system for moving a load in a first direction and a second direction in the vertical plane subjected to the force of gravity comprising first motor means for moving said load in the first and second directions, means for mechanically coupling said first motor means to said load, said force of gravity on said load inducing a torque on said coupling means, and a second motor means coupled to said coupling means for applying a torque equal and opposite to said gravity induced torque, said second motor means compensating for said force of gravity, so that acceleration and velocity of said load produced by said first motor means is symmetrical in the first and second directions.

2. A load positioning system as set forth in claim **1** wherein said second motor means includes a DC motor supplied by a constant-current source.

3. A load positioning system as defined in claim **2** wherein said load is moved in a linear path by said first motor means.

4. A load positioning system as described in claim **3** wherein said coupling means includes a lead screw that is rotated by said first motor means.

5. A load positioning system as in claim **1** wherein said load is angularly moved by said first motor means.

6. A load positioning system as set forth in claim **5** wherein the torque generated by the second motor means varies as a function of the angular orientation of the load.

* * * * *