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DESCRIPTION

TITLE OF INVENTION

Linear Reciprocating Actuator Utilizing A Brushless DC Motor

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FIELD OF INVENTION

This invention concerns a device that provides linear reciprocating motion powered by a brushless DC motor.

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BACKGROUND OF INVENTION

Conventional motorized linear actuators found in the market today are driven by either a stepper or a hybrid motor. The stepper version is used for light applications while the stronger and more costly hybrid is used for heavier applications. A major drawback of these two motors is linear speed limitation.

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This linear actuator invention is powered by a conventional brushless DC (BLDC) motor and is able to produce high force at high reciprocating speeds. An internal nut and a lead screw convert the rotational motion of the BLDC motor to linear motion. In addition to the typical circuit that drives the BLDC motor, a position sensor and microcontroller are used to switch the motor clockwise and counter-clockwise at the correct instance.

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BRIEF DESCRIPTION OF PRIOR ART

The brushless DC motor, also known as the BLDC motor is a rotating electric machine which can be found in many applications, from toy cars to photocopier machines. They are generally preferred compared to other DC motors because of their longer life, higher efficiency, low EMI (electromagnetic interference), lower temperature rise, excellent instantaneous speed variation and low audible noise.

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The typical BLDC motor has a 3-phase stator coil that generates a magnetic field that “pulls” the rotor which essentially is made of permanent magnets formed into the shape of a ring. When the stator is energized in the correct sequence, the rotor rotates and moves as quickly as the rotating electro-
5 magnetic field. Hall sensors are commonly employed as the “brushless” commutation (electronic commutation) of the motor. They are placed next to the rotating rotor magnets and provide the “position” information of the rotor to the motor drive circuitry. This motor driver controls the smooth rotational movement of the rotor by “firing” (energizing) the correct set of stator coils
10 based on the rotor position.

These motors also have controller features such as tachometer output, motor enable and direction input. The tachometer output is represented by a square wave (also known as tach pulses) which provides information on motor speed
15 and number of rotations. The wave is generated when the magnetic field of circular-shaped magnet (tach magnet) which is attached to the rotor, cuts the path of a conductor that is laid onto the drive PC board. The motor enable feature functions like a switch that “enables” (turns on) and “disables” (turns off) the motor. Direction input is another switch that controls the direction of
20 rotation.

Linear actuators are used in applications such as medical equipment, pumps, x-y tables, automation of any kind, valve control and many others. There are literally hundreds of types of linear actuator products in the motion control
25 industry. Each type provides specialty in various parameters such as speed, accuracy, price range, thrust load, direct load, size constraints, axes of motion, etc. Linear actuators fall under different classes. This invention is in the class that provides reciprocating motion used in applications such as vacuum pumps, compressors, engines, etc.

Hall position sensors are usually used as an integral part of a closed loop feedback control system. They are used in a variety of fields such as industrial automation, automotive components, semiconductor manufacturing, robotics and the like. As mentioned above, they are also used
5 for electronic commutation in the BLDC motor.

The microcontroller is essentially a "special purpose mini computer" that executes one specific program that is stored in its memory. They have input and output ports that receive and send signals to the device that it is
10 controlling, in this case the BLDC motor. They are often small, low cost and require very little power to run.

SUMMARY OF THE INVENTION

This linear actuator invention produces high linear force at high speeds and is
15 powered by a conventional brushless DC (BLDC) motor. Instead of a regular rotating shaft found in the normal BLDC motor, this "modified" motor has a shaft that extends and retracts in a reciprocating motion. Devices to be driven are attached to the end of this shaft.

20 The main components that make up this invention are the BLDC motor, lead screw assembly, position feedback assembly and the microcontroller circuit.

The Brushless DC Motor

The BLDC motor used here is a conventional type which comprises a wound
25 stator, an outside-spin rotor with permanent magnets bonded to it, the electronics required to drive the motor, a mounting plate and a shaft that is coupled to the rotor and rotates with it. The shaft used in this actuator however, is slightly different. It is made hollow with a larger outside

diameter and is hidden from the end user. Inside this “hollow shaft” there is an internal screw thread.

The Lead Screw Assembly

5 The lead screw assembly converts the rotational movement of the rotor to linear motion. It is made up of two different portions. The threaded portion of the lead screw assembly mates with the internal thread of the hollow shaft. A small magnet, which makes up one part of the position feedback system, is attached to this end of the lead screw assembly. The other portion of the lead
10 screw is a shaft that has a cross-section that is shaped to prevent rotational movement. This part of the lead screw assembly extends out of the motor through a hole with a shape that matches with the lead screw cross-section. Devices that require the reciprocating action are attached to the end of this shaft.

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The Position Feedback System

The position feedback assembly comprises a hall effect sensor and the disc magnet (mentioned earlier) which is attached to one end of the lead screw assembly. The hall sensor is placed in a position where the disc magnet is
20 able to toggle its state when the lead screw is at the retracted end of the stroke.

The Microcontroller Circuit

The microcontroller circuit basically consists of the microcontroller chip and
25 its supporting electronic devices and is typically integrated into a printed circuit board (PCB). The circuit is wired to the position hall sensor and the main BLDC drive board. The microcontroller, which acts as the “brain” of this system senses the various signals and executes the necessary tasks based on the firmware (program codes) that has been pre-programmed into it such

as “commanding” the motor to start, stop or reverse its direction. Actuator stroke variation caused by rotor inertia or changing loads can also be fixed by incorporating a correction feature in the program. Additional features such as those related to safety can also be included.

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Actuator Operation

During operation the rotor rotates like a regular motor. The rotary motion of the rotor is transferred to the internal hollow shaft. The internal screw thread inside this hollow shaft converts the rotational motion into linear movement
10 of the mating lead screw.

When the actuator is first switched on, the controller commands the motor to rotate in a direction that causes the lead screw to retract. When the lead screw reaches the retracted end of the stroke, the hall sensor detects the
15 presence of the disc magnet (placed at the end of the moving lead screw) and this signal is captured by the microcontroller chip. The controller then commands the rotor to reverse its direction of rotation causing the lead screw to move in the opposite direction (extend). During shaft extension, the controller keeps track of the traverse length by counting the tach pulses.

20 When it reaches a preset value, the controller tells the rotor to change its direction again. The lead screw will now begin to retract and this cycle is repeated as long as power is supplied to the circuitry.

However due to inertia, the rotor does not stop instantaneously. This may
25 cause the reciprocating shaft to overshoot its intended stop position. In view of this potential problem, the firmware is programmed to correct this phenomenon.

By changing the size of the BLDC motor and using various thread configurations, this actuator can be designed for various loads and speeds to suit various applications.

5 REFERENCES TO THE DRAWINGS

Figure 1 shows the overall view of the linear actuator.

Figure 2 shows another view of the linear actuator.

Figure 3 is a sectional view of the actuator showing the internal structure.

Figure 4 is a view of the hall effect sensor mounted at the rear of the actuator.

10 Figure 5 shows the part of the lead screw that is shaped to prevent rotational movement.

Figure 6 shows the anti-rotation hole feature of the mounting plate.

Figure 7 shows the microcontroller printed circuit board which is attached to the main drive board.

15 Figure 8 is the overall view of the actuator with the enclosure and mounting plate shown transparent.

Figure 9 is a close-up view of the position feedback control components.

Figure 10 shows the actuator unit with the enclosure removed.

Figure 11 shows the enclosure with sensor PC board mounted.

20 Figure 12 shows the rotor assembly with hollow shaft.

Figure 13 is the printed circuit board showing the serpentine-like trace

Figure 14 shows the lead screw assembly.

Figure 15 shows the cross-sectional view of the linear actuator.

Figure 16 shows the layout of the magnetic poles around the tach magnet.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description below describes the best mode presently utilized for producing the invention for industrial use. They will be described in detail with references to Figures 1 through 16.

BLDC

This invention refers to a linear reciprocating actuator driven by a conventional brushless DC motor. The motor has a outside-spin rotor (fig 10) with a stationary stator mounted onto a spindle. A circular tach magnet (fig 12) that has been pre-magnetized into many poles around it (fig 16) is attached to the rotor. A printed circuit board (PCB) containing the drive electronics (fig 1) is integrated with the motor and placed closed to the tach magnet (fig 10). The PCB has a serpentine-like conductive trace on it (fig 13) that generates electric pulses when the magnetic fields from the tach magnet cuts through them when the rotor is rotating.

A mounting plate (fig 1) made of metal is assembled to the spindle via screws. There are two mounting holes at each end of the plate which are used for mounting the linear actuator. A small hole with a shape that matches the anti-rotation shaft is made at the area where the lead screw assembly protrudes out from the actuator (fig 5 and fig 6).

Hollow Shaft

A hollow shaft with an internal thread inside it is attached to the rotor (fig 12). The internal thread is made of engineering plastic such as glass reinforced PBT (polybutylene terephthalate) or PA46 (polyamide 4/6) that is able to withstand the high forces and high temperatures. The rotor is then assembled to the stator and spindle like a normal BLDC motor.

Lead Screw Assembly

The lead screw assembly (fig 14) is made up of two different shafts, the threaded shaft and the anti-rotation shaft. One end of the threaded shaft has a recess that will facilitate the assembly of the disc magnet. The anti-rotation shaft has a cross-section that is shaped such that it can prevent rotational motion when fit through with a matching hole. An attachment feature is made at the end of the anti-rotation shaft that will be used to attach to the

driven device. Examples of attachment features are screw threads (externally or internally threaded) and hooks. The two shafts are joined together either by interference fit, adhesives, screw or any other method that is strong enough to hold the two parts together. The holding strength must be greater
5 than the maximum linear force of the actuator. A 2-pole disc magnet is attached to the end of the threaded portion via adhesives.

Enclosure and the Hall Effect Sensor

To place the hall sensor at the rear end of the actuator, some kind of
10 stationary mounting surface is required. One possible method is to have a metal enclosure that envelopes the whole rotor (fig 1) and secured to the mounting plate. A small printed circuit board sits at the top of the enclosure (fig 4) secured by two screws. The position hall sensor is soldered to this PC board and positioned just outside the stroke path of the lead screw assembly.
15 When the magnet moves past the sensor, the change in the magnetic polarity toggles the sensor. Besides providing a mounting surface for the hall sensor, the enclosure also functions as a safety device that prevents human contact with the spinning rotor. Slots around the enclosure allow for air ventilation around the motor.

20 The sensor board has three wires running to the microcontroller printed circuit board (fig 7). These wires carry the signal from the hall sensor to the microcontroller chip. The microcontroller board contains the pre-programmed microcontroller and its supporting devices. The power input
25 terminals are also found in this board. This board is connected to the BLDC drive board by the use of header receptacle pins.

Stroke Correction Methodology

This method was developed to correct “shaft overshoot” and “shaft underrun”. Shaft overshoot is caused by rotor inertia which makes the shaft travel a little further than designed stroke. Both shaft overshoot and underrun
5 (i.e. actual stroke shorter than designed stroke) are caused by a load that is varying in magnitude. One example of this kind of load is the vacuum pump where the vacuum pressure (load) is built up over time as more and more air is pumped out. The correction methodology is described as follows.

10 Upon power-up, the controller is programmed to retract the shaft. When the shaft reaches the retracted end for the first time, the magnet toggles the hall effect sensor. The controller sets the tach count to zero at this instance and the motor direction is switched to rotate in the opposite direction. This causes the lead screw to move away from the sensor (extend stroke). As the
15 motor rotates and extending the shaft, the controller keeps track of the stroke distance by counting the pulses generated by the tach magnet. Each revolution of the rotor produces a fixed number of tach pulses. When the pulse count reaches a pre-set value, the controller commands the motor to stop. This pre-set value corresponds to the designed stroke length of the
20 actuator. For example, assume that the tach magnet has 45 pairs of magnetic poles that generates 45 pulses per rotor revolution, and the threaded shaft has a lead of 2.44 mm (i.e. the shaft moves forward/backward by this amount in one rotor revolution). If the required stroke length is 18.21 mm, then the number of pulses generated by the tach magnet during the entire stroke
25 traverse is $18.21 \times 45 \div 2.44 = 336$ pulses. This will be the pre-set value.

When the pulse count reaches 336, the controller sends the stop signal to the motor. However, due to inertia the rotor does not stop instantly when commanded to stop. It will continue to rotate and slowing down at the same

time. During this deceleration time the controller keeps on counting the tach pulses until the rotor comes to a complete stop. The difference between the actual number of tach pulses and the pre-set value represents the overshoot. The overshoot value is subtracted from the pre-set value and this result will be used as the “pulse count” in the next extension stroke. Based on the previous example, assume that the shaft overshoots the intended position when it first extends and the controller computes the overshoot value to be 67 pulses (i.e. 67 pulses beyond the designed 336). Therefore, the pulse count for the next extension stroke will be $336 - 67 = 269$.

At the next extension stroke, the motor will be commanded to stop when the pulse count reaches 269. Since this value is smaller than the first value, the motor will be commanded stop before the end of the actual stroke. Like before, inertia will cause the rotor to spin a little longer and will finally come to a complete stop at the desired position.

In some applications, the load is not constant but changes over time and this will also affect the stroke length. One characteristic of the BLDC motor is that its torque changes with the load. A heavy load will slow the motor down and vice versa. In the linear actuator, this attribute causes the stroke length to vary with the load. A load that has changed in magnitude from the previous stroke will affect the rotor deceleration time. Returning to our example, assume that the load has increased this time round and the rotor comes to a complete stop at pulse count 329 (Note: it would have been 336 if the load were constant). This is 7 counts less than the pre-set count of 336. This variation of 7 counts will be added to the pulse count (currently 269), making the new pulse count value equal to 276. At the end of the next following stroke, this correction is performed once again and this is repeated at the end

of every extension stroke. With this method, stroke length deviation caused rotor inertia or varying load is virtually eliminated.

Other Features

- 5 The actuator has a safety protection feature that switches the motor off when there is an overload, i.e. when the load is above the capacity of the motor. This is accomplished by analyzing the tach pulses from the motor. If the motor is commanded to rotate but there are no tach pulses after a certain time, a time-out is enabled that switches off the motor, thus preventing the motor
- 10 coils from burning out and damaging the drive electronics.

What is claimed is:

1. A linear actuator comprising:
 - a brushless direct current (BLDC) motor having a rotor, tach magnet,
5 stator, spindle and drive electronics
 - the said BLDC motor with built-in motor enable input feature, motor
direction input feature, PWM (pulse width modulation) input feature and
tach output feature
 - a hollow shaft with an internal thread coupled to the said rotor of the
10 BLDC motor
 - a lead screw assembly comprising an externally threaded shaft that mates
with the internal thread of the said hollow shaft, and a shaft with a cross-
section that has a shape that will prevent rotational motion when fitted
through a matching anti-rotation hole feature
 - 15 • a magnet attached to the threaded end of the said lead screw assembly
 - a mounting plate with an anti-rotation hole feature that is attached to the
BLDC motor
 - a hall effect sensor that is placed in a position where the said magnet can
toggle its digital state when the lead screw assembly is approaching the
20 retracted end of the stroke
2. A method of fabricating the linear actuator defined in claim 1 that consists
the steps of:
 - making an internal thread inside the hollow shaft
 - 25 • attaching the magnet to the end of the linear shaft
 - mounting the hall effect sensor at the retracted end of the stroke
3. Use of a microcontroller in combination with a contactless position sensing
device to control the reciprocating action of the linear actuator.

4. The method of correcting the actual stroke length to the designed stroke length dynamically by using the tachometer pulses in the form of a microcontroller algorithm.
 5. The method of sensing the complete stop of the said rotor by checking the absence of tachometer pulses after a small delay in the form of a microcontroller algorithm.
 5. The method of sensing overloads by checking the absence of the tachometer pulses and turning the motor off in the form of a microcontroller algorithm.
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