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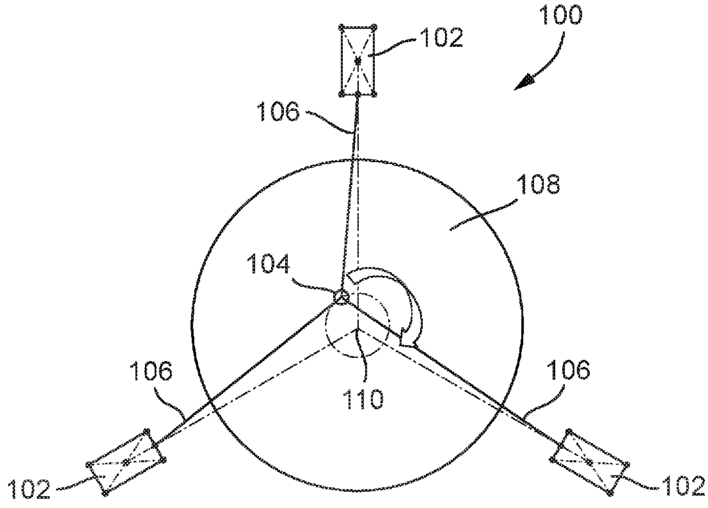
(54) **Title:** CONTINUOUS DRIVE SMA MOTOR

Fig. 1



(57) **Abstract:** Continuous drive motor driven by shape memory alloy (SMA) actuator wires. The SMA actuator wires rotate or control the position of a drive spindle, which in turn causes a rotor or other component of a motor to rotate. Fine control of the velocity of the rotation of the rotor/motor, and a continuous drive of the rotor/motor is enabled.

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Continuous Drive SMA Motor

The present techniques generally relate to a shape memory alloy (SMA) actuator assembly, and in particular to continuous drive motors that are driven by SMA actuator wires.

In a first approach of the present techniques, there is provided an actuator assembly comprising: a first component; a second component rotatable relative to the first component; a third component coupled to the second component at a position away from a central axis of rotation of the second component; and at least two shape memory alloy (SMA) actuator wires, each coupled at a first end to the first component and arranged to apply, upon contraction, a force to the third component, thereby driving rotation of the second component. In some cases, the third component may be a drive spindle, or may be one of a pair of magnets (where the other magnet may be provided on the first component).

In a further approach of the present techniques, there is provided an actuator assembly comprising: a first component; a second component rotatable relative to the first component; a third component coupled to the second component at a position away from a central axis of rotation of the second component; and at least two shape memory alloy (SMA) actuator wires, each coupled to the first component and to the third component and arranged to apply, upon contraction, a force to the third component, thereby driving rotation of the second component.

In a further approach of the present techniques, there is provided an actuator assembly comprising: a first component; a second component rotatable relative to the first component; a first magnet magnetically coupled to the second component at a position away from a central axis of rotation of the second component; a second magnet attached to the second component at a position away from a central axis of rotation of the second component; and at least two shape memory alloy (SMA) actuator wires, each coupled at a first end to the first component and at a second end to the first magnet and arranged to apply, upon contraction, a force to the first magnet, thereby driving rotation of the second component.

In a further approach of the present techniques, there is provided an actuator assembly comprising: a first component; a second component rotatable relative to the first component; a third component coupled to the second component at a position away from a central axis of rotation of the second component a third component moveable relative to the first component;, and coupled to the third component; and at least two shape memory alloy (SMA) actuator wires, each coupled at a first end to the first component and each coupled to the third component and arranged to apply, upon contraction, a force to the drive spindle, thereby driving rotation of the second component. Each SMA actuator wire may be connected to the third component at the second end, or may be connected to the third component at a point along the length of the SMA wire.

In a further approach of the present techniques, there is provided an actuator assembly comprising: a support structure; a rotating part that is rotatable relative to the support structure about a rotation axis, the rotating part comprising an eccentric portion; a movable component that is movable relative to the support structure along at least one movement axis that is orthogonal to the rotation axis; and at least two SMA wires arranged to move the movable component relative to the support structure along the at least one movement axis, to thereby drive movement of the eccentric portion and continuous rotation of the rotating part relative to the support structure.

In a related approach of the present techniques, there is provided an apparatus comprising an actuator assembly as described herein. The apparatus may be any one of: a smartphone, a camera, a foldable smartphone, a foldable image capture device, a foldable smartphone camera, an image capture device, a servomotor, a consumer electronic device, a mobile computing device, a laptop, a tablet computing device, a security system, a gaming system, an augmented reality system, an augmented reality device, a virtual reality system, a virtual reality device, a miniature pump, a medical device, a microfluidics device, a wearable device, a drone (aerial, water, underwater, etc.), an aircraft, a spacecraft, a submersible vessel, a vehicle, and an autonomous vehicle. It will be understood that this is a non-exhaustive list of example apparatus.

Preferred features are set out in the appended dependent claims.

Implementations of the present techniques will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 shows a schematic diagram of an actuator assembly for directly driving a drive spindle of a motor;

Figure 2 shows a schematic diagram of another actuator assembly for directly driving a drive spindle of a motor;

Figure 3 shows a schematic diagram of another actuator assembly for directly driving a drive spindle of a motor;

Figure 4 shows a schematic diagram of an actuator assembly for indirectly driving a motor using magnetism;

Figure 5 shows a schematic diagram of an actuator assembly for indirectly driving a drive spindle of a motor;

Figures 6A to 6C show components of another actuator assembly for indirectly driving a drive spindle of a motor;

Figure 7 shows a schematic diagram of another actuator assembly for indirectly driving a drive spindle of a motor;

Figures 8A and B show further embodiments of the actuator assembly, comprising V-shaped SMA wires;

Figures 9A and B show a further embodiment of the actuator assembly; and

Figures 10A and B show further embodiments of the actuator assembly, comprising lever arms for amplifying SMA wire stroke.

Broadly speaking, the present techniques provide continuous drive motors that are driven by shape memory alloy (SMA) actuator wires. The present techniques use SMA actuator wires to rotate or control the position of a drive spindle, which can in turn cause a rotor or other component of a motor to rotate. The present techniques may advantageously enable fine control of the velocity of the rotation of the rotor/motor and/or the position of the rotor/motor, and may enable the motor to be driven continuously. The present techniques may be used to actuate a motor used to drive a pop-up camera in a smartphone, a panning camera in a drone, a miniature pump (e.g. for a medical device), a camera shutter or iris shutter, haptic devices/mechanisms, and medical devices. It will be understood that this is a non-exhaustive and non-limiting list of example applications/uses of the actuator assemblies described herein.

The SMA actuator wires may be used to directly move or rotate the drive spindle, and thereby cause the rotor to rotate. This may be considered 'direct SMA drive'. Alternatively, the SMA actuator wires may be used to drive movement of a further component, where movement of the further component causes a drive spindle or a rotor to rotate. This may be considered 'indirect SMA drive'. Both types of drive are described in more detail below with respect to the Figures.

Figure 1 shows a schematic diagram of a first actuator assembly 100 for directly driving a drive spindle of a motor. The actuator assembly 100 comprises a first component (not shown) and a second component 108 that is rotatable relative to the first component. The second component 108 has a central axis of rotation 110 about which the second component 108 rotates. The second component may be a rotor or rotor disc of a motor. The actuator assembly 100 comprises a drive spindle 104. The drive spindle 104 is coupled to the second component 108 at a position away from the central axis of rotation 110 of the second component 108. The actuator assembly 100 comprises at least two shape memory alloy (SMA) actuator wires 106. In the example shown in Figure 1, the actuator assembly comprises three SMA actuator wires 106, but Figure 2 shows an example comprising two SMA actuator wires. The at least two SMA actuator wires 106 are each coupled at a first end to the first component via crimps or connection components 102. The SMA actuator wires 106 are arranged to apply, upon contraction, a force to the drive spindle 104 to thereby drive rotation of the second component 108.

The drive spindle 104 may be able to rotate relative to the second component 108, so that the SMA wire exit angle does not vary as the second component 108 rotates. Thus, the drive spindle 104 may be a pin or rod that moves as a sliding bearing within a hole in the second component 108. The drive spindle 104 must be able to transfer the force applied by the SMA actuator wires 106 on the drive spindle to a torque applied to the second component 108.

In actuator assembly 100, the two SMA actuator wires 106 are directly coupled to the drive spindle 104. Specifically, a second end of each SMA actuator wire 106 is coupled to the drive spindle 104. The second end of each SMA actuator wire 106 may be coupled to the drive spindle 104 by a crimp or connection component (not shown).

When the SMA actuator wires 106 are electrically driven, the resultant force on the drive spindle 104 acts as a moment that causes rotation of the drive spindle 104. The moment may be controlled to cause rotation of the drive spindle in any direction (i.e. clockwise or anti-clockwise). Each SMA actuator wire 106 may be driven independently to control the position of the drive spindle 104, and thereby the position of the second component/rotor 108. If the SMA actuator wires 106 are driven such that there is no resultant force or such that the resultant force does not create a moment, then the drive spindle 104 will be stationary.

The actuator assembly 100 may comprise a bearing (not shown) to constrain motion of the second component to rotation only. The bearing may be provided between the second component 108 and the first component.

In the example actuator assembly 100 of Figure 1, the first end of each SMA actuator wire 106 is spaced from the other two SMA actuator wires. Preferably, the first end of each SMA actuator wire 106 may be equidistantly spaced from the other two SMA actuator wires. However, equidistant spacing is not essential for the operation of the actuator assembly 100, as other techniques may be used to compensate for non-equidistant spacing (e.g. by applying a different drive voltage to each SMA actuator wire).

Figure 2 shows a schematic diagram of another actuator assembly 100 for directly driving a drive spindle of a motor. The actuator assembly 100 of Figure 2 is similar to actuator assembly 100 described in relation to Figure 1and therefore, for the sake of conciseness, only the differences are described.

As mentioned above, actuator assembly 100 comprises only two SMA actuator wires instead of the three actuator wires shown in Figure 1. The actuator assembly 100 comprises a resilient component or spring 112 in place of the third SMA actuator wire of Figure 1. Thus, actuator assembly 100 comprises two SMA actuator wires 106 and a spring 112. A first end of spring 112 is coupled to the first component (not shown) via a crimp or connection component 102. A second end of the spring 112 may be coupled to either the second component 108 or the drive spindle 104. The spring 112 applies a return force to the drive spindle 104 or the second component 108, which causes the drive spindle or second component 108 to move into a particular position. Thus, the spring 112 performs the same function as the third SMA actuator wire 106 of assembly 100. The resilient component/spring 112 may take any suitable form, such as a coil spring.

The first end of the two SMA actuator wires 106 and the first end of spring 112 are spaced from each other. Preferably, the first end of the two SMA actuator wires 106 and the first end of spring 112 may be equidistantly spaced from each other. However, equidistant spacing is not essential for the operation of the actuator assembly 100, as other techniques may be used to compensate for non-equidistant spacing.

Figure 3 shows a schematic diagram of another actuator assembly 100 for directly driving a drive spindle of a motor. The actuator assembly 100 is similar to actuator assembly 100 described in relation to Figure 1 and therefore, for the sake of conciseness, only the differences are described.

The actuator assembly 100 comprises at least two shape memory alloy (SMA) actuator wires 106. In the example shown in Figure 3, the actuator assembly 100 comprises three SMA actuator wires 106a, 106b and 106c that are directly coupled to the drive spindle 104. The three SMA actuator wires 106a-c are each coupled at a first end to the first component via crimps or connection components 102. The three SMA actuator wires 106a-c are each coupled at a second end to the first component via crimps or connection components 102. The three SMA actuator wires 106a-c are each coupled at a point along their length to the drive spindle 104. The drive spindle 104 may comprise one or more holes along its length, and the SMA actuator wires 106a-c pass through the hole(s) to couple to the drive spindle 104. Thus, each SMA actuator wire 106a-c may be slidably coupled at a point along its length to the drive spindle 104.

The first ends of the SMA actuator wires 106a-c may be equidistantly spaced from each other, and the second ends of the SMA actuator wires 106a-c may be equidistantly spaced from each other.

An advantage of actuator assembly 100 relative to assembly 100 may be increased stroke. This is because the length of each SMA actuator wire 106a-c in assembly 100 is longer than that of SMA actuator wires 106 in assembly 100, and longer SMA actuator wires result in greater stroke. Furthermore, the wires 106a-c are angled, which provides a mechanical advantage that leads to increased stroke. The increased stroke may be achieved without increasing the overall footprint or size of the actuator assembly 100 relative to that of assembly 100.

A further advantage of the actuator assembly 100 relative to assembly 100 is smoother torque or changes in torque, i.e. the variation in torque at different stages of the rotation of the second component 108 is smaller. This is because in assembly 100, each SMA actuator wire 106 may only be able to exert a force in one direction when the drive spindle 104 is on the circular loci it moves along. However, in assembly 100, each SMA actuator wire 106a-c may be able to apply a force in two (opposite) directions, depending on what half of the circular loci the rotor is in. In other words, each SMA actuator wire 106a-c could be considered two wires that are able to apply a force in opposite directions to the drive spindle 104. In assembly 100, the second component 108 is caused to rotate by 120° by each SMA actuator wire 106, but in assembly 100, the second component 108 is caused to rotate by 60° by each SMA actuator wire 106a-c (such that it appears that there are six actuator wires controlling the movement of the drive spindle 104 and second component 108).

The SMA actuator wires 106a-c run across the second component and may form shallow angles with the drive spindle 104. The SMA actuator wires 106a-c may be powered in turn. For example, when the actuator assembly 100, and specifically the second component 108, is in the position shown in Figure 3, SMA actuator wire 106a may be powered the most (or may be the only powered wire), while SMA actuator wire 106b is stretched. To cause rotation of the second component, SMA actuator wire 106c may be powered next, followed by SMA actuator wire 106b.

Figure 4 shows a schematic diagram of an actuator assembly 100 for indirectly driving a motor using magnetism. Here, actuator assembly 100 comprises a first magnet 116. The SMA actuator wires 106 are coupled at one end to the first component and at another end to first magnet 116. The first magnet 116 may be mounted on a plate or disc, or may simply be held in position by the SMA actuator wires. The actuator assembly comprises a second magnet 118 provided on the second component 108 at a position away from a central axis of rotation of the second component 108. As described above, the SMA actuator wires 106 are driven to cause rotation/movement of the first magnet 116. Movement of the first magnet 116 relative to the second magnet 118 drives rotation of the second component 108 (because the second magnet 118 is attracted towards or repelled from the first magnet 116).

In each of the embodiments shown in Figures 1 to 4, the at least two SMA actuator wires 106 have electrical connections that allow each SMA actuator wire 106 to receive an independent drive signal.

In some cases, the drive spindle 104 may be connected to an electrical ground. Thus, the end of each SMA actuator wire 106 that is connected to the drive spindle 104 is connected to ground, and the end of each SMA actuator wire 106 that is connected to the first component via crimps 102 may be driven individually. This may provide the greatest control over the motion of the drive spindle 104, but requires a common connection to drive spindle 104 or the second component 108 (which is a moving part). The common connection could be made to the second component 108 by providing at least one electric brush (not shown) on the second component 108. Alternatively, the end of each SMA actuator wire 106 that is connected to the first component via crimps 102 may be connected to an electrical ground, and the drive spindle 104/second component 108 may be driven (again via one or more brush contacts). It may be possible to use a simple DC drive and control the motor by regions on the second component 108 connecting to different SMA actuator wires 106.

In some cases, the assembly comprises three SMA actuator wires connected together using a star connection or a three-phase connection system. The voltage applied to each of the crimps 102 may be controlled to control the length of each SMA actuator wire 106. Resistance measurement between the three pairs of crimps may enable the resistance of each individual wire (and therefore its length) to be determined.

In cases where an SMA actuator is replaced by a spring 112, the spring may be electrically connected to an electrical ground. This may advantageously remove the need for the electrical common to be provided on the moving second component 108.

It will be understood that the continuous rotary motion of the second component 108 may be combined with mechanisms that are typically used to convert rotary motion to linear motion (such as rack and pinions, or worm gears).

Figures 5 to 7 show further examples of indirect SMA drive actuator assemblies. In each of these example, the actuator assembly comprises a first component (also referred to as a support structure herein); a second component (also referred to as a rotating part) rotatable relative to the first component; a third component (which may be a drive spindle or cam, also referred to as an eccentric portion herein) coupled to the second component at a position away from a central axis of rotation of the second component; and at least two shape memory alloy (SMA) actuator wires, each coupled at a first end to the first component and arranged to apply, upon contraction, a force to the third component, thereby driving rotation of the second component. The actuator assemblies further comprise a fourth component (also referred to as a movable component herein) moveable relative to the first component, wherein the at least two SMA actuator wires are each coupled to the fourth component, and wherein the third component is coupled to the fourth component and to the second component. Each of the SMA actuator wires may be coupled at a second end to the fourth component, or each SMA wire may be coupled to the fourth component at a point along the length of the SMA wire.

Figure 5 shows a schematic diagram of an actuator assembly 100 for indirectly driving a drive spindle of a motor. The actuator assembly 100 is able to actuate movement of a movable component 122 (an example of the fourth component 122) in two dimensions perpendicular to a primary axis as per the actuator assemblies described in International Patent Publications WO2013/175197 and WO2014/083318. Movement of the movable component 122 drives rotation of a rotating part 108 (an example of the second component 108)

These actuator assemblies comprise four SMA actuator wires connected between a moveable component 122 and a support structure 101 (an example of the first component). Each wire 106 is connected at one of its ends (via crimps/connectors 120) to the moveable component 122 and at its other end (via crimps 102) to the support structure 101. A bearing arrangement (not shown) supports the movable component 122 on the support structure and allows movement of the movable component 122 relative to the support structure 101.

In addition to the features mentioned above, the actuator assembly 100 comprises a support structure that comprises or corresponds to the first component. The movable component 122 is supported on the support structure in a manner allowing movement of the fourth component 122 relative to the support structure in two orthogonal directions perpendicular to a notional primary axis extending through the third component 122. The second component 108 (rotating part 108) is rotatably arranged relative to support structure around 1 rotation axis R. The at least two SMA actuator wires 106 are arranged to, upon contraction, move the movable component 122 and thereby drive rotation of the second component 108.

So, the actuator assembly 100 comprises a total of four SMA wires 30. Each SMA wire 106 is connected between the support structure and the movable component.

Each SMA wire 106 is held in tension, thereby applying a force between the movable component 122 and the support structure in a direction perpendicular to the rotation axis R about which the second component is rotatable. In operation, the SMA wires 106 move the movable component 122 relative to the support structure in two orthogonal directions perpendicular to the rotation axis R, i.e. in the x-y plane, as described further below.

The SMA wires 106 may each extend perpendicular to the rotation axis R. In some embodiments, the SMA wires 106 extend in a common plane which is advantageous in minimising the size of the SMA actuator assembly 1 along the rotation axis R. This arrangement also minimises the force on the movable component 122 (and any bearing arrangement supporting the movable component 122) in a direction parallel to the rotation axis R.

Alternatively, the SMA wires 102 may be arranged inclined at a non-zero angle to the orthogonal directions perpendicular to the rotation axis R, which angle is preferably small. In this case, the SMA wires 106 in operation generate a component of force along the rotation axis R that may tend to tilt or to move the movable component 122 in a direction parallel to the rotation axis R. Such a component of force may be resisted by the bearing arrangement to provide movement in the orthogonal directions perpendicular to the rotation axis R. Conversely, the degree of inclination of the SMA wires 106 that provides acceptably small tilting or movement in a direction along the rotation axis R may be dependent on the stiffness of the bearing arrangement along the rotation axis R. Thus, relatively high inclinations are permissible in the case of the bearing arrangement having a high stiffness along the rotation axis R, for example when comprising a plain bearing or ball bearings.

In the case where the bearing arrangement comprises a plain bearing or ball bearings, it may even be desirable for the SMA wires 106 to be inclined with a significant component in a direction parallel to the rotation axis R such that the tension in the SMA wires 106 pushes the movable component 20 onto the plain bearing or onto the ball bearings.

Irrespective of whether the SMA wires 106 are perpendicular to the rotation axis R or inclined at a small angle to the plane perpendicular to the rotation axis R, the actuator assembly 1 can be made very compact, particularly in the direction along the rotation axis R. The SMA wires 106 are themselves very thin, typically of the order of 25μm in diameter, to ensure rapid heating and cooling. The arrangement of SMA wires 106 barely adds to the footprint of the actuator assembly 1 and may be made very thin in the direction along the rotation axis R, since the SMA wires 106 are laid essentially in a plane perpendicular to the rotation axis R in which they remain in operation. The height along the rotation axis R then depends on the thickness of the other components such as the connection elements described below and the height necessary to allow manufacture.

As shown in Figure 5, the SMA wires 106 may have an arrangement around the rotation axis R as follows.

Each of the SMA wires 106 is arranged along one side of the movable component 122. Thus, the SMA wires 106 are arranged in a loop at different angular positions around the rotation axis R. Thus, the four SMA wires 106 consist of a first pair of SMA wires arranged on opposite sides of the rotation axis R and a second pair of SMA wires arranged on opposite sides of the rotation axis R. The first pair of SMA wires is capable on selective driving to move the movable component 122 relative to the support structure in a first direction in said plane, and the second pair of SMA wires is capable on selective driving to move the movable component 122 relative to the support structure in a second direction in said plane transverse to the first direction. Movement in directions other than parallel to the SMA wires 106 may be driven by a combination of actuation of these pairs of the SMA wires 106 to provide a linear combination of movement in the transverse directions. Another way to view this movement is that simultaneous contraction of any pair of the SMA wires 106 that are adjacent each other in the loop will drive movement of the movable component 122 in a direction bisecting those two of the SMA wires 106 (diagonally in figure 1).

As a result, the SMA wires 106 are capable of being selectively driven to move movable component 122 relative to the support structure to any position in a range of movement in two orthogonal directions perpendicular to the rotation axis R. The magnitude of the range of movement depends on the geometry and the range of contraction of the SMA wires 106 within their normal operating parameters.

The arrangement of the SMA wires 106 along respective sides of the movable component 122 assists in providing a compact arrangement since each of the SMA wires 106 fits largely or entirely within the profile of the movable component 122 as viewed from that side, unlike for example an arrangement in which wires extend radially of the rotation axis R, which would increase the footprint of the SMA actuator assembly. However as a result of not being radial, each SMA wire 106 individually applies a torque to the movable component 122 in the plane of the two orthogonal directions around the rotation axis R. Such torques may potentially increase the requirements any bearing arrangement which needs to resist any net torque, whilst permitting movement in that plane.

However, since none of the wires are collinear, they can be arranged to apply cancelling torques when operated together. Successive SMA wires 106 around the rotation axis R are connected to apply a force to the movable component 122 in alternate senses around the rotation axis R. That is, as viewed outwardly of the rotation axis R, one SMA wire 106 is connected at its left end to the support structure and its right end to the movable component 122, but the next SMA wire 106 is connected at its left end to the movable component 122 and its right end to the support structure, and so on. As a result, successive SMA wires 106 around the rotation axis R also apply a torque in alternate senses around the rotation axis R. That is, one SMA wire 106 applies a force to the movable component 122 in an anticlockwise sense, but the next SMA wire 106 applies a force to the movable component 122 in a clockwise sense, and so on.

This means that the first pair of SMA wires 106 generates a net torque to the movable component 122 in said plane around the rotation axis R in a first sense (e.g. anti-clockwise), and the second pair of SMA wires 106 generate a net torque to the movable component 122 in said plane around the rotation axis R that is in an opposite sense (e.g. clockwise). As a result, for an arbitrary degree of heating in each SMA wire 106, the torques tend to cancel.

Moreover, with this arrangement movement to any position in the range of movement may in principle be achieved without applying any net torque to the movable component 122 in the plane of the two orthogonal directions around the rotation axis R. To appreciate this, one can consider the first pair of SMA wires 106 separately from the second pair of SMA wires 106. For movement to any given position in two dimensions, the movement derived from the first pair of SMA wires 106 may be obtained with a range of stresses in the first pair of SMA wires 106, and hence with a range of torques in the first sense. Similarly the movement derived from the second pair of SMA wires 106 may be obtained with a range of stresses in the second pair of SMA wires 106, and hence with a range of torques in the second sense. This means the torques can be balanced by appropriate selection of the stresses in each SMA wire 106, based on a simply geometrical calculation relating the desired position and the arrangement of SMA wires 106. In contrast, if all the SMA wires 106 were connected to apply a force to the movable component 122 in the same sense around the rotation axis R then they would always generate a net torque around the rotation axis R irrespective of how they were driven.

When moving the movable component 122 in other directions that are a linear combination of movement in directions X and Y, some degree of balancing is a natural effect of the arrangement, and indeed by appropriate selection of the forces generated in each one of the SMA wires 106, it is possible to cause the SMA wires 106 to generate no net torque around the rotation axis R. Furthermore, the SMA wires 106 may be controlled to cancel any torque on the movable component 122 that is due to contact of the movable component 122 with the rotating part 40. As such, the torque acting on the movable component 122 (due to forces from the SMA wires 106 and forces due to contact with the rotating part 40) during operation of the SMA actuator assembly 1 may be zero.

This reduction of torque around the rotation axis R reduces the tendency for the movable component 122 to rotate around the rotation axis R. The reduction or balancing of torques around the rotation axis R reduces the constraints on the bearing arrangement. In fact, in some embodiments, the constraints may be reduced to the extent that no bearing arrangement is needed, and the movable component 122 is instead supported by the SMA wires 106 themselves.

It is noted in particular that these benefits can be achieved in this actuator arrangement 10 employing just a single set of four SMA wires 106, which provides for a very simple and compact arrangement.

In this SMA actuator assembly 1, the SMA wires 106 extend in a common plane which is advantageous in minimising the size of the actuator assembly 1 along the rotation axis R. Alternatively, the SMA wires 106 could be offset from each other along the rotation axis R and still obtain the benefits described above, if they meet the more general requirement that projections of the four SMA wires 106 onto a notional plane perpendicular to the rotation axis R have the arrangement shown in figure 5 when viewed in that direction.

In the example of Figure 5, the drive spindle 126 may be part of the movable component 122, and may extend through a hole 124 in the second component 108 located at a position away from a central axis of rotation of the second component 108 (where the position away from the central axis corresponds to the third component, or eccentric portion). Alternatively, the drive spindle 126 may be part of the second component 108 (rotating component 108) so as to correspond to the third component or eccentric portion, and may extend through a hole 124 in the movable component 122 located at a position away from a central axis of rotation of the second component 108.

Assembly 100 of Figure 5 may advantageously provide a larger stroke actuator relative to the examples shown in Figures 1, 2 and 4, within the same footprint.

Figures 6A to 6C show components of an actuator assembly 100 for indirectly driving a drive spindle of a motor. Assembly 100 comprises a movable component 122 which is driven by two SMA actuator wires 106 in one dimension only (e.g. left and right or side-to-side). The movable component 122 comprises a slot 132, and a portion of drive spindle 128 extends through slot 132. The width of slot 132 is slightly bigger than the diameter of drive spindle 128, such that the drive spindle is able to move/run smoothly within the slot 132.

The assembly 100 may comprise a drive cylinder 130 that is coupled to the drive spindle 128 such that a central axis of rotation 130a of the drive cylinder 130 is at a position away from a central axis 128a of the drive spindle 128. When the SMA actuator wires 106 are actuated to move the movable component 122 in one direction, an edge of the slot 132 exerts a force on drive spindle 128, which, causes the drive cylinder 130 to rotate.

The assembly 100 may comprise a cam 136 coupled to the drive spindle 128. The drive torque on the drive spindle 128 and drive cylinder 130 may drop to zero when the cam 136 is perpendicular to a length of the slot 132. This means that the motor drive may be reliant on rotational inertia to keep rotating. The assembly 100 may comprise resilient components 134 arranged to apply a return force on the cam 136 before the drive spindle 128 rotates into a zero torque position. The resilient components 134 may prevent the cam 136 from stopping and becoming jammed when in the zero torque position. The resilient components 134 may be leaf springs, which push the cam 136 way from the zero torque position.

Figure 7 shows a schematic diagram of another actuator assembly 100 for indirectly driving a drive spindle of a motor. Here, in addition to the features described above, the actuator assembly 100 comprises a first magnet 142 provided on the drive spindle 138, and a second magnet 140 provided on the movable component 122 at a position away from a central axis of rotation of the movable component 122. Movement of the movable component 122 is achieved using two, three or four SMA actuator wires, and causes movement of the second magnet 140 relative to the first magnet, which in turn drives rotation of the drive spindle 138.

Figure 8 to 10 show schematic diagrams of further actuator assemblies 100 according to aspect of the present invention. The actuator assemblies 100 comprise a support structure 101, a rotating part 108 and a movable component

122. The rotating part 108 is rotatable relative to the support structure 101 about a rotation axis R. The rotating part 108 comprising an eccentric portion 128, which may be a cam or drive spindle, for example.

The movable component 122 is movable relative to the support structure along a movement axis that is orthogonal to the rotation axis R. Movement of the movable component 122 in directions other than along the movement axis may be constrained, for example by a suitable bearing arrangement. Although not shown in Figures 8-10, however, the movable component 122 may in some embodiments move in a plane orthogonal to the rotation axis R.

The actuator assemblies 100 thus in essence correspond to the actuator assembly 100 already described with reference to Figure 6B. In Figure 6B, the SMA wires 106 are connected between the movable component 122 and the support structure 101. So, one end of the SMA wires 106 is connected to the support structure 101 and the other end of the SMA wires 106 is connected to the movable part 122. This arrangement of SMA wires 106 is different in Figures 8-10, as described below.

In the embodiment of Figures 8A and 8B, the SMA wires 106 are V-shaped SMA wires 106. In particular, the SMA wires 106 are connected at both ends to the support structure 101. The SMA wires 106 bend around the movable component 122, thereby forming two lengths that are angled relative to one another. The angle between the lengths of SMA wires 106 may in general be greater than 0 degrees. Preferably, the angle between the lengths of SMA wires 106 is greater than 90 degrees, further preferably greater than 120 degrees.

Although not depicted, the SMA wires 106 may equally be connected at both ends to the movable component 122 and bend around the support structure 101.

The actuator assembly 100 comprises opposing SMA wires 106. So, the SMA wires 106 move the movable part 122 in opposing directions along the movement axis. With reference to Figure 8A, for example, selective contraction of the SMA wires 106 may move the movable component 122 up and down.

In some embodiments, the rotating part 108 comprises a second eccentric portion 128b (e.g. a second cam). The second eccentric portion may be different from the eccentric portion 128, in that the second eccentric portion is angularly offset about the rotation axis R from the eccentric portion angular direction. For example, as shown in Figure 8A, the second eccentric portion 128b may be angularly offset from the eccentric portion by about 90 degrees, for example in the range from 45 to 135 degrees.

Although not shown in the Figures, the actuator assembly 100 may further comprise a second movable component that is movable relative to the support structure. The second movable part may be movable in the same manner as the movable part 122 (e.g. along the movement axis or in the movement plane) relative to the support structure 101.

In alternative embodiments, the second eccentric portion 128b may be the same as the eccentric portion 128, i.e. the eccentric portions may be formed by the same component or at least have the same eccentricity. The second movable component may be movable relative to the support structure in a manner different to the movement of the movable component 122, for example in a direction orthogonal to the movement axis and to the rotation axis R.

In general, the movable component 128 and the second movable component may be stacked or offset relative to each other along the rotation axis R.

The SMA wires are configured alternately (or successively) to move the movable part and the second movable part. This may improve continuous rotation of the rotating part, especially in embodiments in which the movable parts are movable along a single axis only.

In Figure 8A, the movable component 122 is constrained to move along the movement axis by a bearing arrangement comprising a plain bearing 151. The movable component 122 this may slide relative to the support structure 101, and may be referred to as a slider. In Figure 8B, the bearing arrangement comprises a flexure bearing 152. The flexure bearing 152 comprises four flexures that are arranged to allow movement along the movement axis. In either case, the movable part is constrained from rotating about the rotation axis R relative to the support structure 101 by the bearing arrangement. In general, any bearing arrangement (e.g. also a rolling bearing) may be used instead.

Figure 9A and B depict schematic plan and side views of another actuator assembly 100. The actuator assembly 100 of Figures 9A and B in essence corresponds to that of Figure 8. However, as shown, the movable component 122 is formed as two separate elements, movement of which is separately driven by a respective SMA wires 106. Furthermore, the movable component 122 is formed integrally with one of the connection components for connecting an end of the SMA wire 106 to the support structure 101. The movable component 122 may be made of sheet material, such as sheet metal for example. Such a construction may be particularly compact. The movable component 122 may be urged towards the rotating part, so as to remain in sliding contact with the rotating part, by a resilient element that is integral with the sheet metal component.

Figure 9B shows the stack of two movable parts that may be alternately moved by the SMA wires to drive continuous rotation of the rotating part.

In Figures 8 and 9, the stroke of the SMA wires 106 (i.e. the amount of contraction of the SMA wires 106) is amplified into larger movement of the movable component. So, a relatively small stroke of the SMA wire 106 may achieve a relatively larger movement of the movable component 122. In Figures 8 and 9, this stroke amplification is achieved by the V-shape of the SMA wires. So, in general terms, the actuator assemblies 100 of Figures 8 and 9 comprise an amplifying mechanism for amplifying the stroke of the SMA wires 106 into greater movement of the movable part 122.

Figures 10A and 10B schematically depict plan and side views of another SMA actuator assembly 100. The SMA actuator assembly 100 also comprises an amplifying mechanism for amplifying the stroke of the SMA wires 106 into greater movement of the movable part 122. In the embodiment of Figure 10, the amplifying mechanism is comprised by the movable component 122. In particular, the movable component 122 comprises a lever arm. The lever arm is arranged to pivot about a pivot point 160. The SMA wire 106 is connected to the lever arm at a location that is closer to the pivot point 160 than the contact of the lever arm with the eccentric portion of the rotating part 108. As such, the stroke of the SMA wire 106 is amplified into greater movement for driving rotation of the rotating part.

In general, a flexure arm may replace the lever arm of Figure 10, i.e. instead of providing a lever arm that pivots about a pivot point, the flexure arm may be fixedly connected at one end to the support structure 101 and at the other to the movable component 122. The SMA wire 106 may drive bending of the flexure arm about the connection point to the support structure 101 so as to move the movable component 122.

Each of the actuator assemblies described herein may further comprise: control circuitry electrically connected to the SMA actuator wires and arranged to: measure a resistance of each SMA actuator wire; and supply drive signals to each SMA actuator wire.

Each of the actuator assemblies described herein may further comprise: a bearing to constrain motion of the second component (rotating part) to rotation.

Those skilled in the art will appreciate that while the foregoing has described what is considered to be the best mode and where appropriate other modes of performing present techniques, the present techniques should not be limited to the specific configurations and methods disclosed in this description of the preferred embodiment. Those skilled in the art will recognise that present techniques have a broad range of applications, and that the embodiments may take a wide range of modifications without departing from any inventive concept as defined in the appended claims.

CLAIMS

1. An actuator assembly comprising:

a first component;

a second component rotatable relative to the first component;

a third component coupled to the second component at a position away from a central axis of rotation of the second component; and

at least two shape memory alloy (SMA) actuator wires, each coupled at a first end to the first component and arranged to apply, upon contraction, a force to the third component, thereby driving rotation of the second component.

2. The actuator assembly as claimed in claim 1 wherein the third component is a drive spindle rotatable relative to the second component.

3. The actuator assembly as claimed in claim 1 or 2 wherein the third component is a drive spindle and the at least two SMA actuator wires are each directly coupled to the drive spindle.

4. The actuator assembly as claimed in claim 3 wherein a second end of each SMA actuator wire is coupled to the drive spindle.

5. The actuator assembly as claimed in claim 4 wherein the assembly comprises three SMA actuator wires, the first end of each SMA actuator wire being spaced from the other two SMA actuator wires.

6. The actuator assembly as claimed in claim 4 wherein the assembly comprises two SMA actuator wires and further comprises a spring having a first end coupled to the first component and a second end coupled to one of the drive spindle or the second component, wherein the first end of the two SMA actuator wires and spring are spaced from each other.

7. The actuator assembly as claimed in claim 3 wherein a second end of each SMA actuator wire is coupled to the first component and wherein each SMA actuator wire is coupled at a point along its length to the drive spindle.

8. The actuator assembly as claimed in claim 7 wherein first end of each SMA actuator wire is equidistantly-spaced from each other, and wherein the second end of each SMA actuator wire is equidistantly-spaced from each other.

9. The actuator assembly as claimed in claim 7 or 8 wherein each SMA actuator wire is slidably coupled at a point along its length to the drive spindle.

10. The actuator assembly as claimed in any of claims 3 to 9 wherein the at least two SMA actuator wires have electrical connections that allow each SMA actuator wire to receive an independent drive signal.

11. The actuator assembly as claimed in claim 10 wherein the drive spindle is connected to an electrical ground.

12. The actuator assembly as claimed in claim 11 further comprising:

at least one electric brush attached to the second component and electrically connected to the electrical ground.

13. The actuator assembly as claimed in claim 10 wherein the at least two SMA actuator wires are connected to an electrical ground at the first component.

14. The actuator assembly as claimed in any of claims 3 to 6 wherein the assembly comprises three SMA actuator wires connected together using a star connection or a three-phase connection system.

15. The actuator assembly as claimed in claim 6 wherein the spring is electrically connected to an electrical ground.

16. The actuator assembly as claimed in claim 1 wherein the third component is a first magnet and the at least two SMA actuator wires are each directly coupled to the first magnet, and wherein the actuator assembly further comprises:

a second magnet provided on the second component at a position away from a central axis of rotation of the second component, wherein the third component is magnetically coupled to the second component;

wherein movement of the first magnet drives rotation of the second component.

17. The actuator assembly as claimed in claim 1 or 2 further comprising a fourth component moveable relative to the first component, wherein the at least two SMA actuator wires are each coupled to the fourth component, and wherein the third component is coupled to the fourth component and to the second component.

18. The actuator assembly as claimed in claim 17 wherein the at least two SMA actuator wires are each coupled at a second end to the fourth component.

19. The actuator assembly as claimed in claim 17 or 18 further comprising:

a support structure comprising the first component;

wherein the fourth component is supported on the support structure in a manner allowing movement of the fourth component relative to the support structure in two orthogonal directions perpendicular to a notional primary axis extending through the fourth component; and

wherein the at least two SMA actuator wires are arranged to, upon contraction, move the fourth component and thereby drive rotation of the second component.

20. The actuator assembly as claimed in claim 19 wherein the third component is part of the fourth component, and extends through a hole in the second component located at a position away from a central axis of rotation of the second component.

21. The actuator assembly as claimed in claim 17 or 18 wherein the third component extends through a slot in the fourth component, and the actuator assembly further comprises:

a drive cylinder that is coupled to the third component such that a central axis of rotation of the drive cylinder is at a position away from a central axis of the third component;

a cam coupled to the third component; and

resilient components arranged to apply a return force on the cam before the third component rotates into a zero torque position.

22. The actuator assembly as claimed in claim 17, 18 or 19 further comprising:

a first magnet provided on the third component; and

a second magnet provided on the fourth component at a position away from a central axis of rotation of the fourth component,

wherein movement of the fourth component moves the second magnet relative to the first magnet and drives rotation of the third component.

23. The actuator assembly as claimed in any preceding claim further comprising:

control circuitry electrically connected to the SMA actuator wires and arranged to:

measure a resistance of each SMA actuator wire; and

supply drive signals to each SMA actuator wire.

24. The actuator assembly as claimed in any preceding claim further comprising:

a bearing to constrain motion of the second component to rotation.

25. An actuator assembly comprising:

a support structure;

a rotating part that is rotatable relative to the support structure about a rotation axis, the rotating part comprising an eccentric portion;

a movable component that is movable relative to the support structure along at least one movement axis that is orthogonal to the rotation axis; and

at least two SMA wires arranged to move the movable component relative to the support structure along the at least one movement axis, to thereby drive movement of the eccentric portion and continuous rotation of the rotating part relative to the support structure.

26. The actuator assembly of claim 25, wherein the movable component is movable relative to the support structure only along the movement axis.

27. The actuator assembly of claim 25, wherein the movable component is movable relative to the support structure in a plane orthogonal to the rotation

axis, wherein the at least two SMA wires are arranged to move the movable component in the plane.

28. The actuator assembly of claim 27, wherein the at least two SMA wires comprise a total of four SMA wires in an arrangement wherein none of the forces applied by the SMA wires are collinear, and wherein the SMA wires are capable of being selectively driven to move the movable part relative to the support structure to any position within a plane orthogonal to the rotation axis without rotating the movable part.

29. The actuator assembly of claim 28, wherein two of the SMA wires are arranged to apply a torque to the movable part in said plane in a first sense around the rotation axis and the other two SMA wires are arranged to apply a torque to the movable part in said plane in a second, opposite sense around the rotation axis.

30. The actuator assembly of claim 28 or 29, wherein the four SMA actuator wires are arranged in a loop at different angular positions around the rotation axis, successive SMA wires around the rotation axis being connected to apply a force to the movable element in alternate senses around the rotation axis.

31. The actuator assembly of any one of claims 25 to 27, wherein the at least two SMA wires are coupled at both ends to one of the support structure and movable component and bend around the other of the support structure and movable component, thereby forming two lengths that are angled relative to one another.

32. The actuator assembly of any one of claims 25 to 27, comprising an amplifying mechanism that is configured to amplify the stroke of the SMA wires into movement of the movable component for driving rotation of the rotating part.

33. The actuator assembly of claim 31, wherein the movable component comprises a lever arm or a flexure arm for amplifying the stroke of the SMA wires.

34. The actuator assembly of any one of claims 25 to 27 and 31 to 33, wherein the rotating part comprising a second eccentric portion, and

further comprising a second movable part that is movable relative to the support structure along at least one movement axis that is orthogonal to the rotation axis and at least two SMA wires arranged to move the second movable component relative to the support structure along the movement axis, to thereby drive movement of the second eccentric portion and continuous rotation of the rotating part relative to the support structure,

wherein SMA wires are configured alternately to move the movable part and the second movable part.

Fig. 1

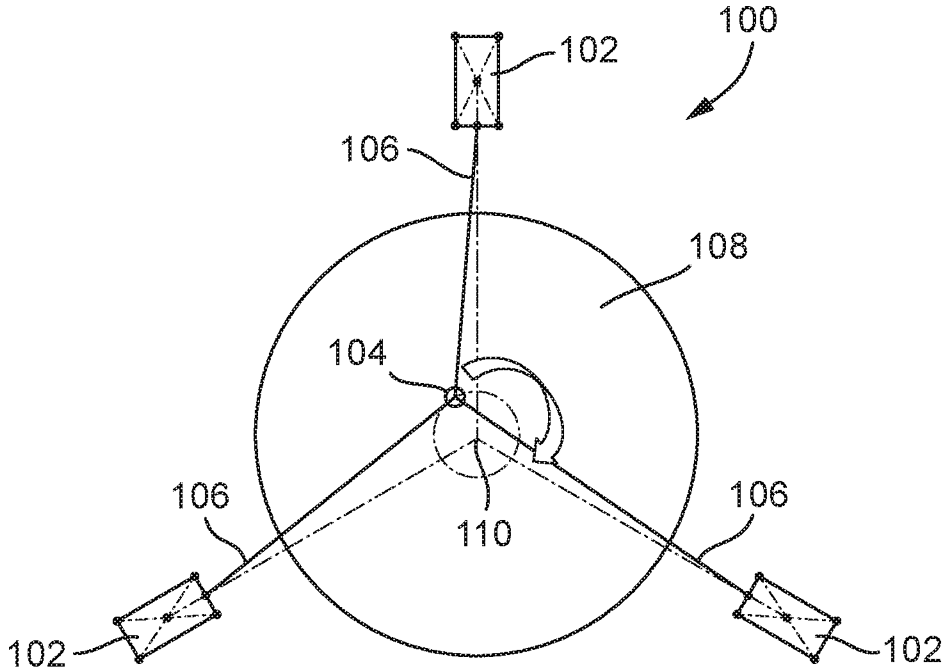
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Fig. 2

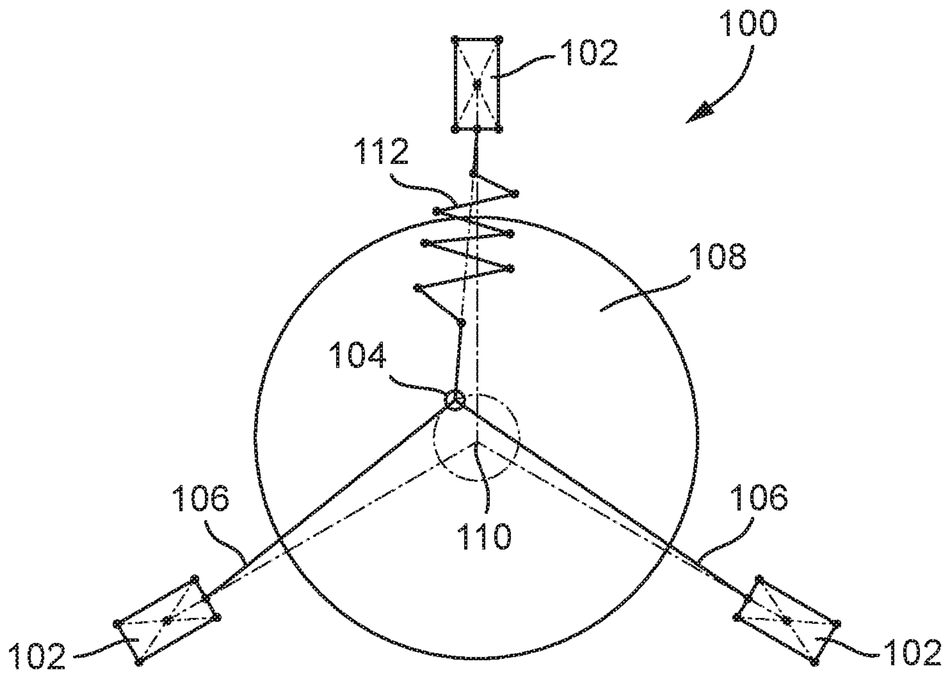
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Fig. 3

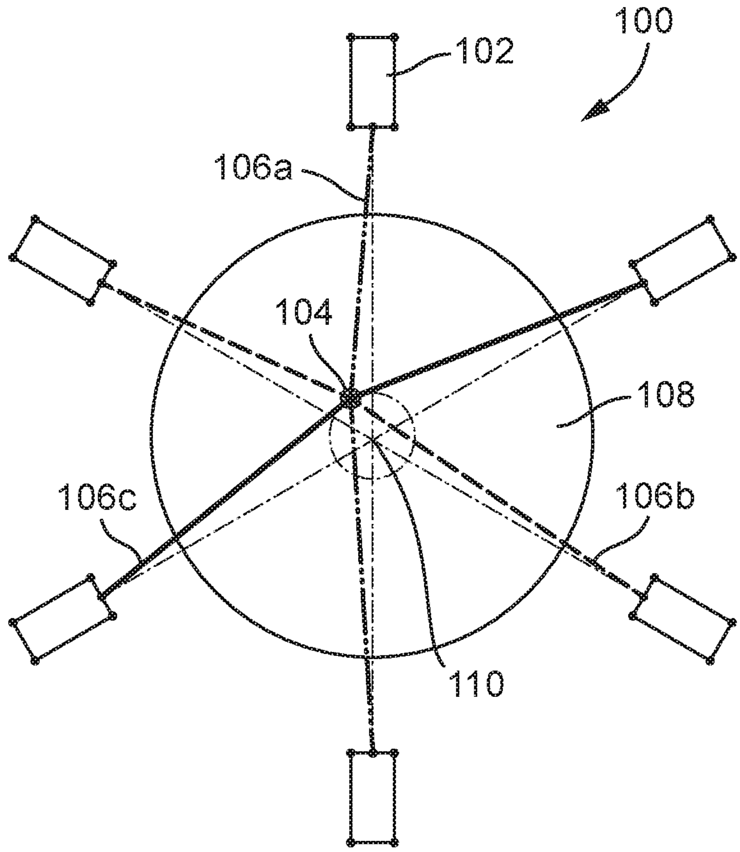
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Fig. 4

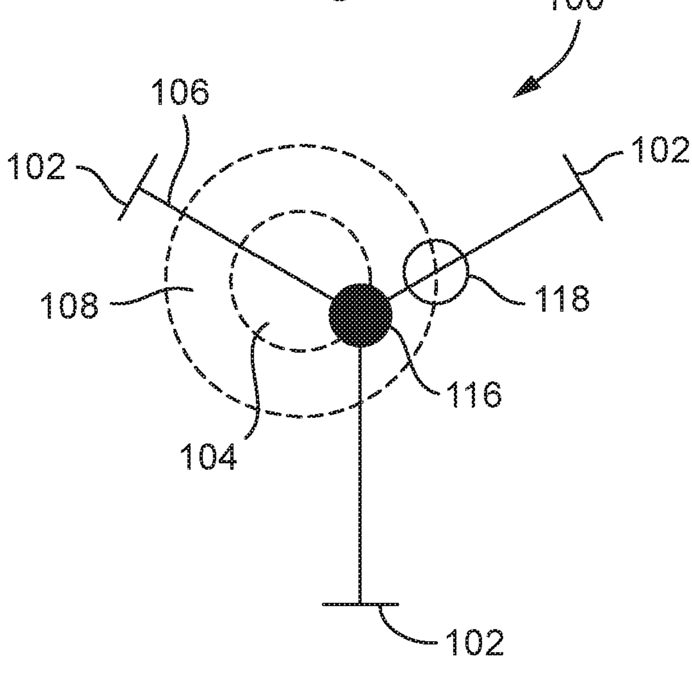
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Fig. 5

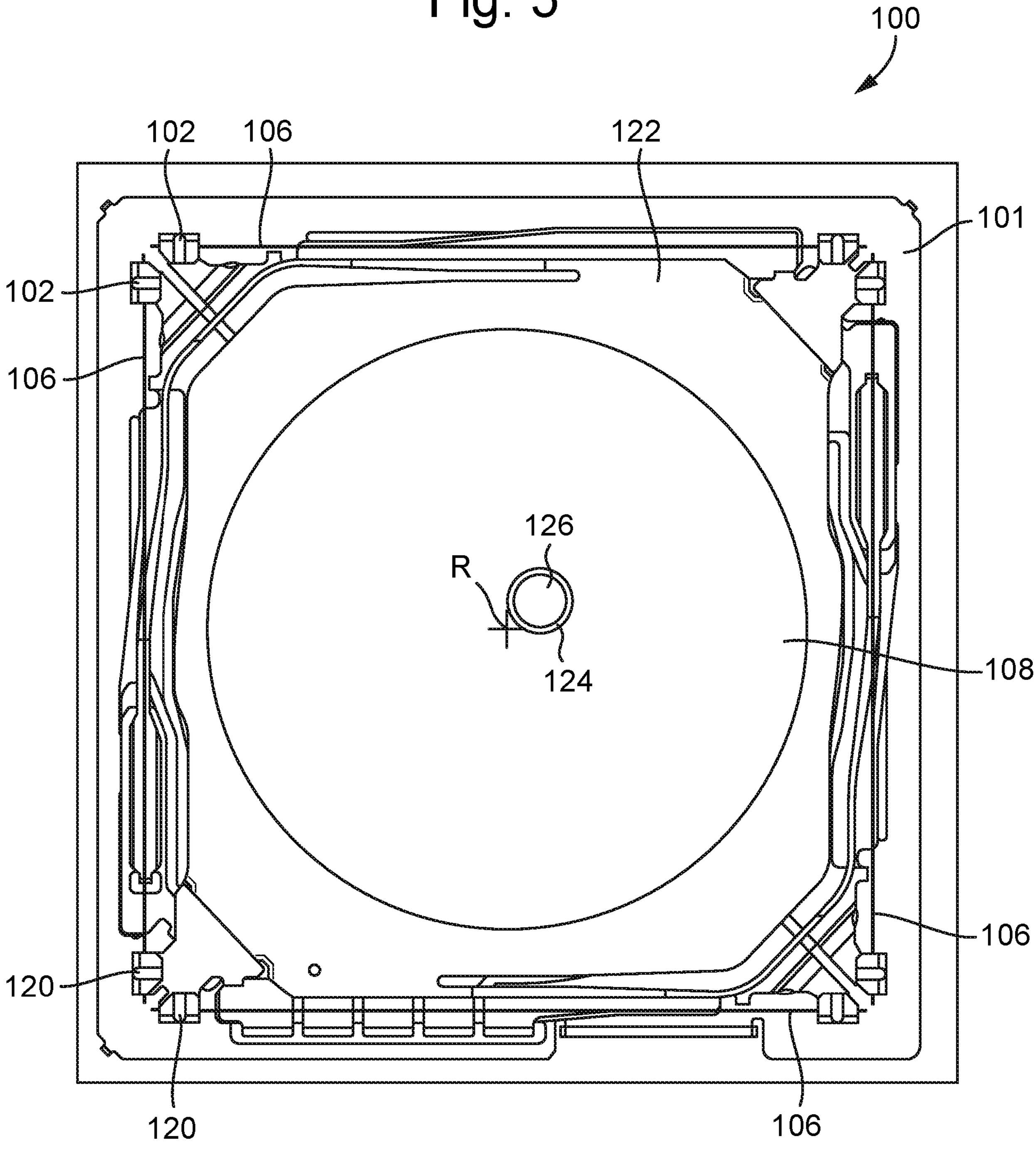


Fig. 6A

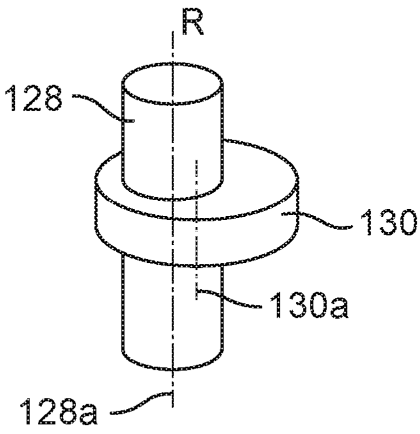


Fig. 6B

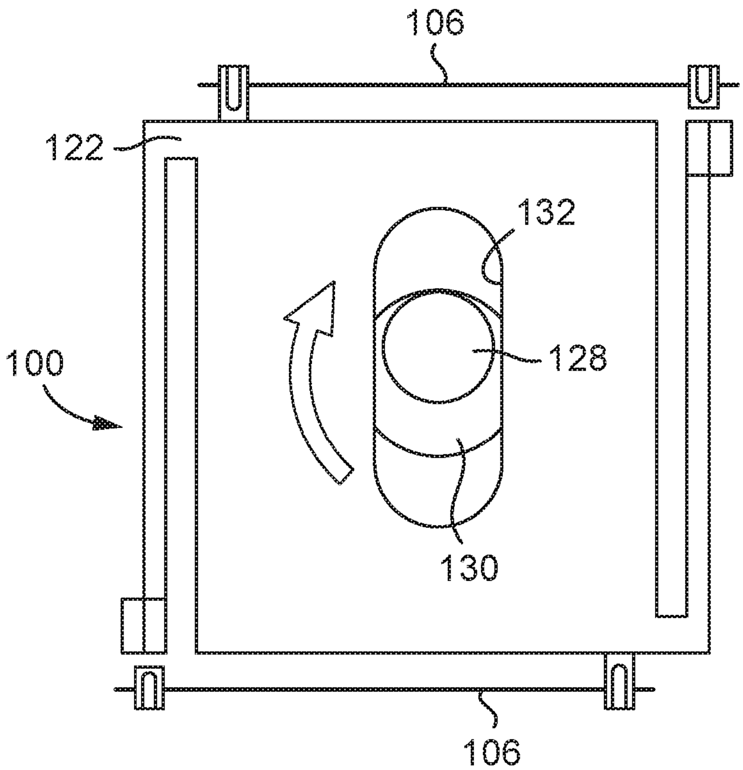


Fig. 6C

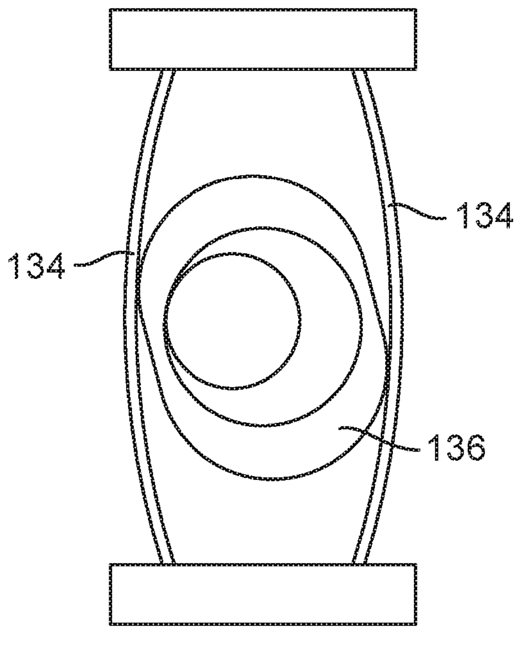


Fig. 7

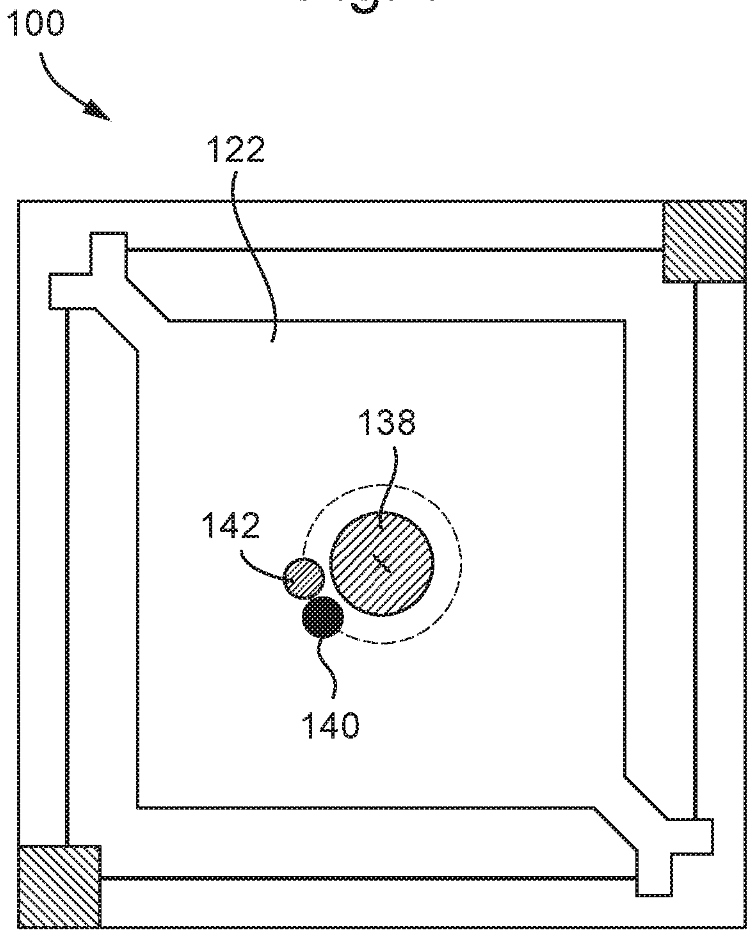
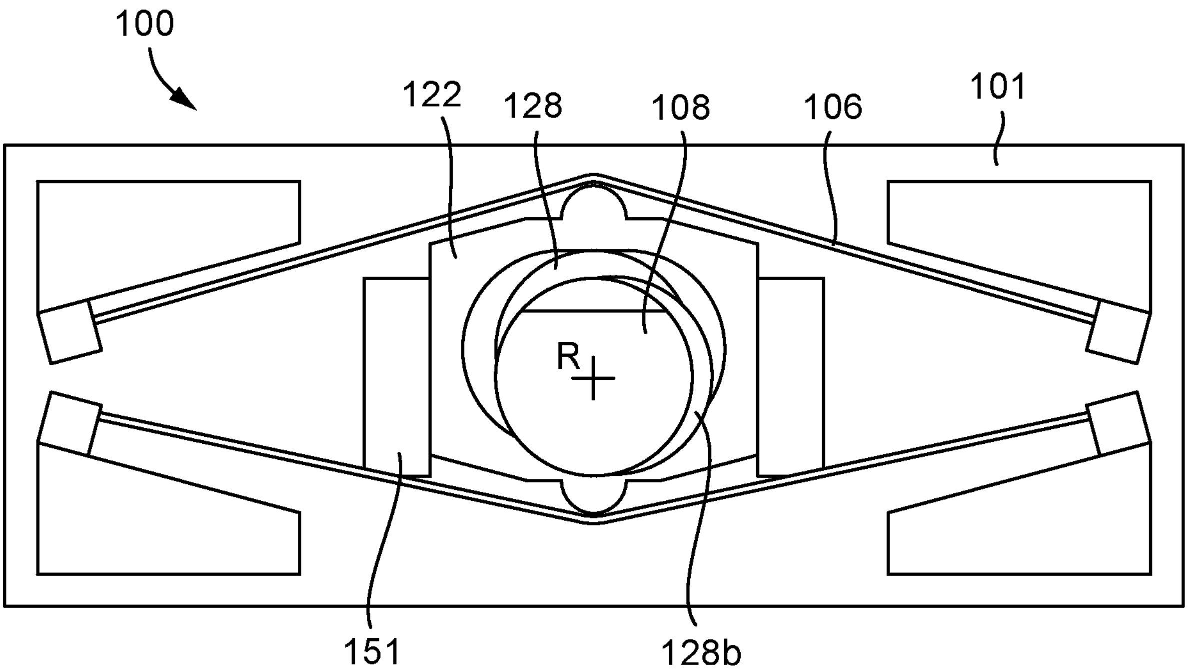


Fig. 8A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128b

Fig. 8B

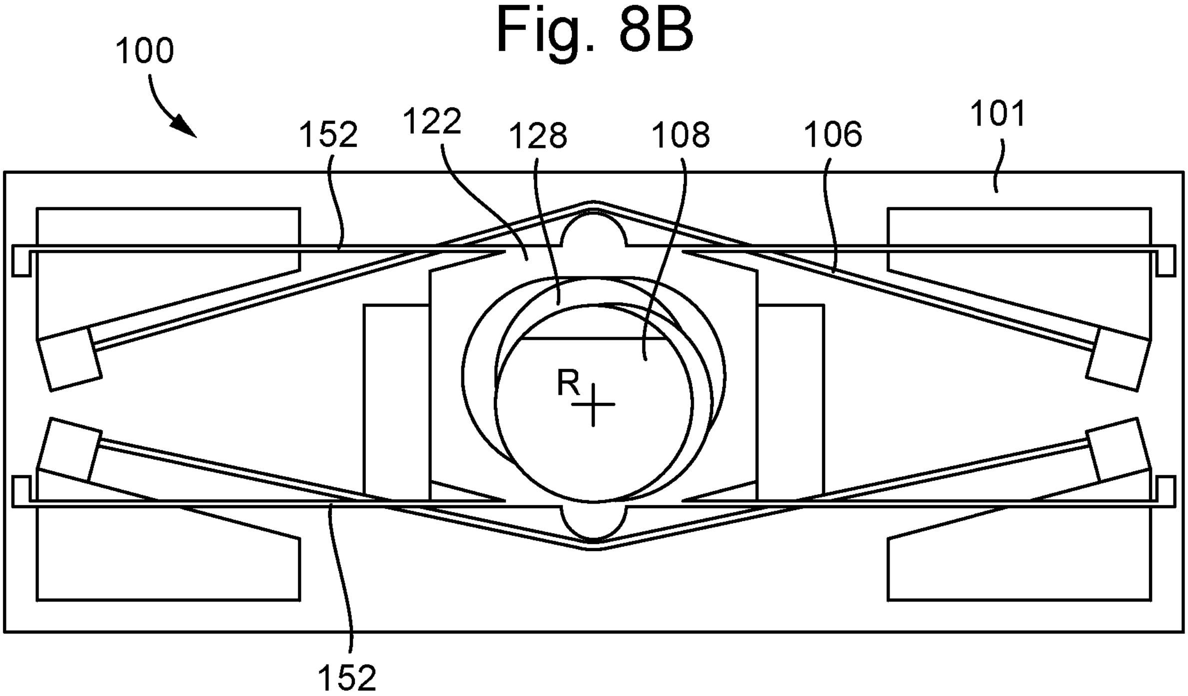
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Fig. 9A

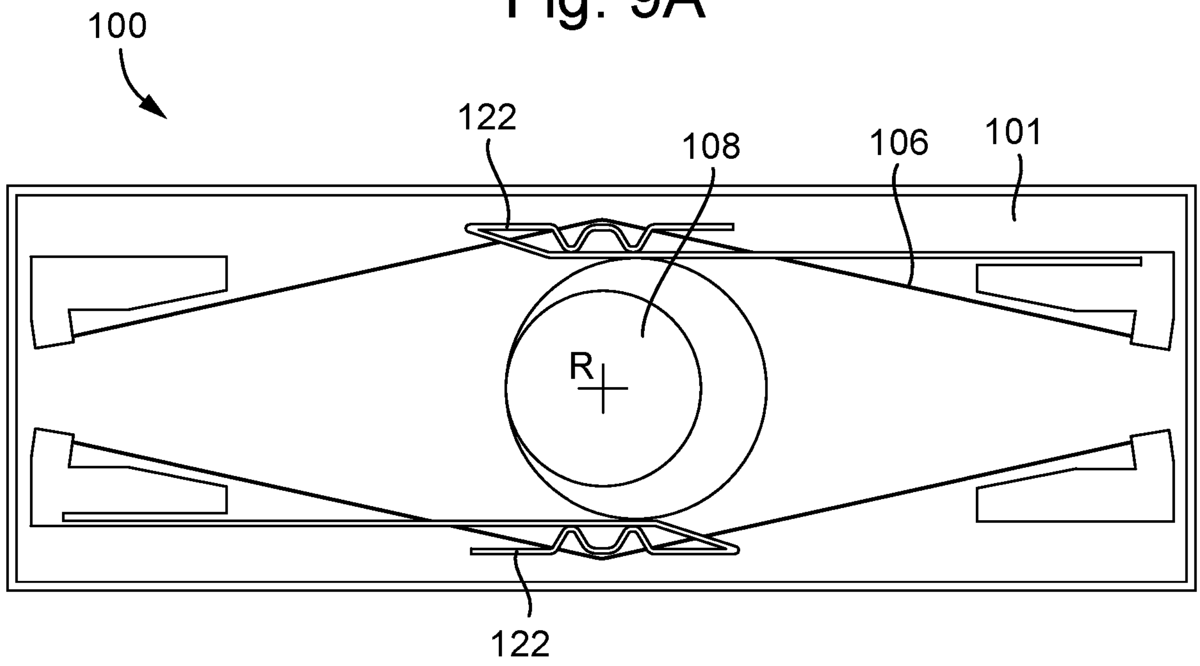


Fig. 9B

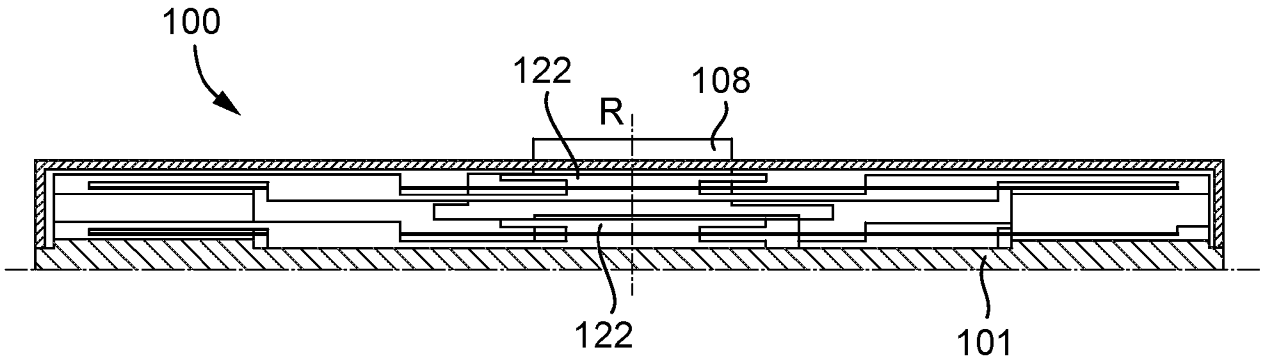


Fig. 10A

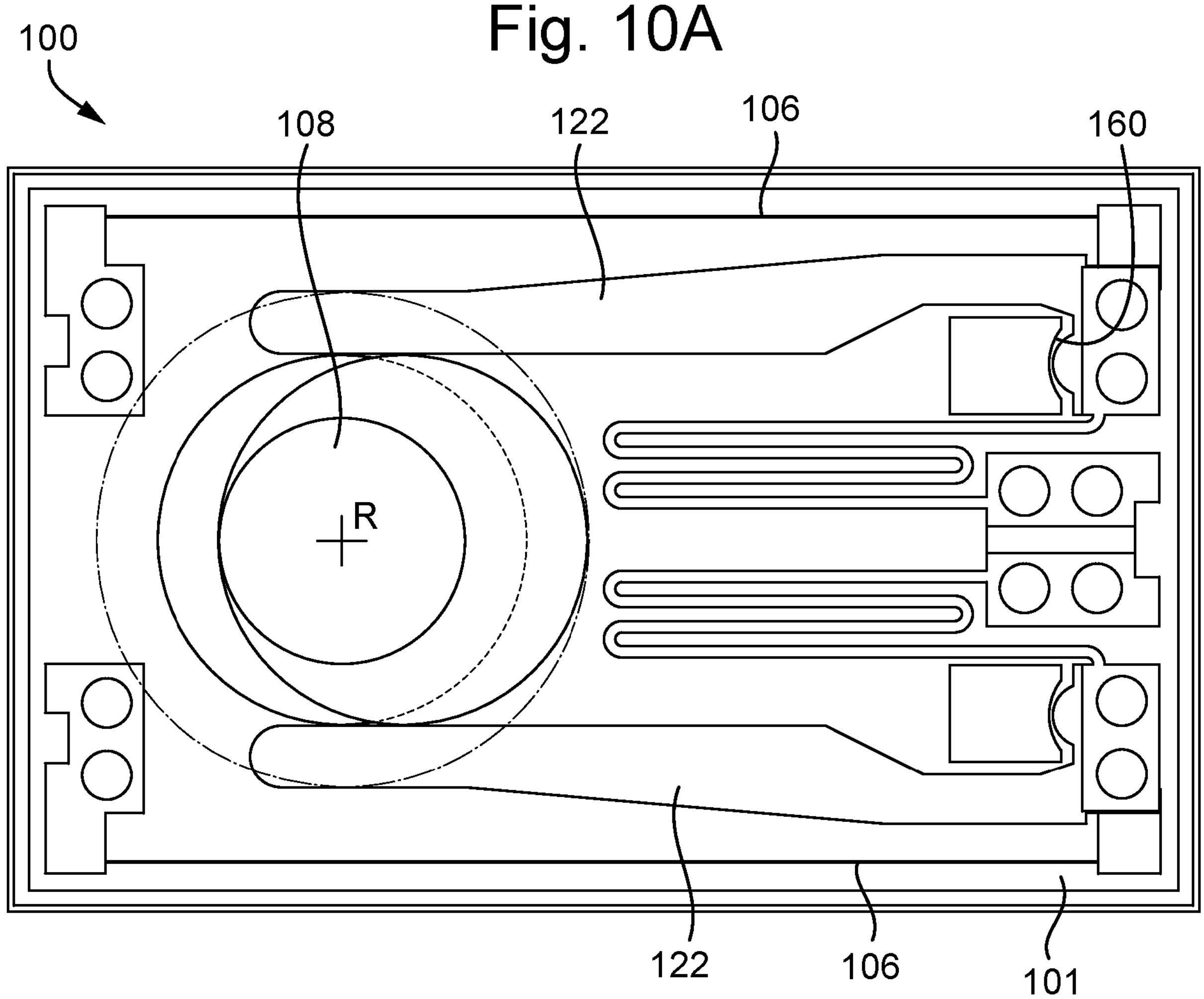
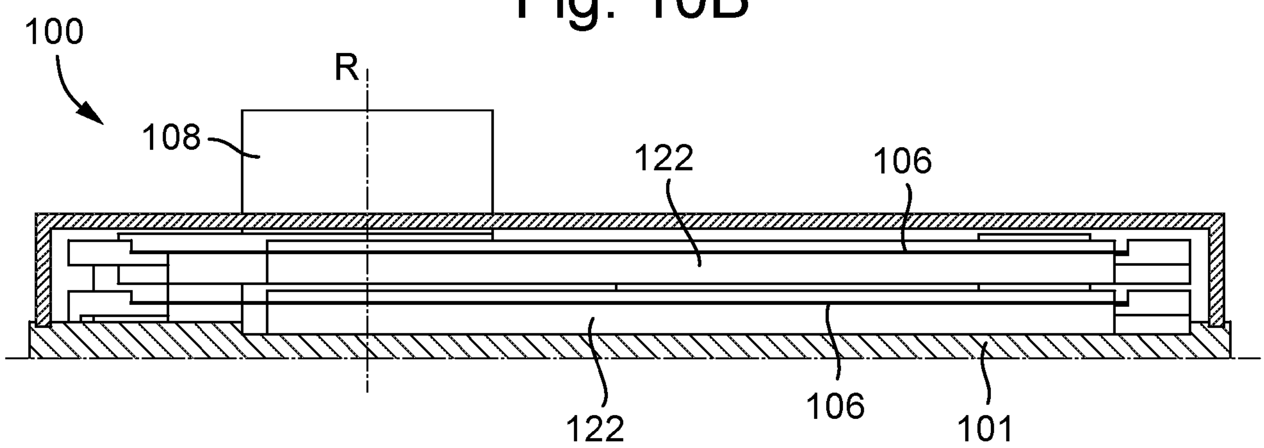


Fig. 10B



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2022/050056

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03G7/06
ADD.

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)
F03G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KATSUTOSHI KURIBAYASHI ED - INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS: "A NEW SERVO MOTOR USING SHAPE MEMORY ALLOY", PROCEEDINGS OF THE ANNUAL CONFERENCE OF THE INDUSTRIAL ELECTRONICS SOCIETY. (IECON). PHILADELPHIA, NOV. 6 - 10, 1989; [PROCEEDINGS OF THE ANNUAL CONFERENCE OF THE INDUSTRIAL ELECTRONICS SOCIETY. (IECON)], NEW YORK, IEEE, US, vol. 1 OF 04, 6 November 1989 (1989-11-06), pages 238-243, XP000130635, column 2, last paragraph - column 3, paragraph first; figure 2a -----	1-34
X	US 5 279 123 A (WECHSLER MONROE S [US] ET AL) 18 January 1994 (1994-01-18) column 3, lines 43-52,62-64; figure 1 -----	1-34
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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

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"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

Date of the actual completion of the international search	Date of mailing of the international search report
16 March 2022	30/03/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	de Martino, Marcello

1

International application No
PCT/GB2022/050056

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 683 721 A (SHIN MYUNG CHUL [KR] ET AL) 4 August 1987 (1987-08-04) column 1, lines 5-10; figure 3 -----	1,25

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2022/050056

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5279123	A	18-01-1994	NONE		
US 4683721	A	04-08-1987	JP S6260985	A	17-03-1987
			KR 870003306	A	16-04-1987
			US 4683721	A	04-08-1987