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(54) **MINIATURIZED ELECTROMAGNETIC ROTARY ACTUATOR**

(57) Miniaturized electromagnetic rotary actuator for use in body medical applications comprising a stator layer (12) with electromagnetic actuation coils (3) spaced axially around a rotation axis of a rotor (8), each coil (3) being oriented in the thickness direction; a stacked magnetic flux modulator layer (4) fixed to form a stacked stator assembly and provided with teeth (5) arranged axially around the rotor axis, the rotor (8) being aligned with the stator layer (12), being stacked on the stacked stator assembly and comprising a permanent magnet layer with alternating multipolar magnetizations arranged axially around the rotor axis, the rotor (8) being also configured to rotate relative to the stacked stator assembly.

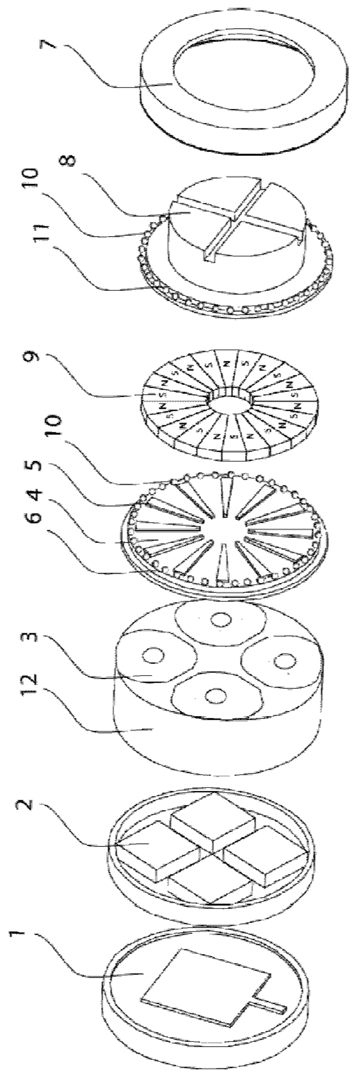

Fig. 2

Description

TECHNICAL FIELD

[0001] The present invention relates generally to rotary actuators, and more particularly to miniaturized electromagnetic rotary actuators.

BACKGROUND OF THE INVENTION

[0002] During surgery and catheters interventions, the smaller is the access to patients' body, the faster is the recovery time and the fewer are the complications that appear. Millimeter tools such as scissors or forceps have been widely used and developed and used during the last decades worldwide. However, still a larger number of medical invasive interventions may reduce their risk if proper miniaturized tools existed. For example, mitral regurgitation, rotational atherectomies, arrhythmia ablations, brain tumors resections or intracranial angioplasties constitute risky interventions that produce large collateral damages due to the use of too big tools that have to be externally actuated through large catheters.

[0003] Furthermore, health non-invasive inside body treatments based on mechanical or thermal intervention could in some cases replace chemical treatments when treating issues like cancer or tissue reparation. Devices like endoscopic capsules, pacemakers or insulin pumps have demonstrated for years their benefits. However, mechanical interventions are currently limited by the large size of the devices and by their mobility capacity.

[0004] What would be desirable is to have strong mechanical tools with smaller dimensions that can be used in treating patients, and in particular, a miniaturized electromagnet rotary actuator that can be used in treating patients. Several interesting electromagnetic miniaturized motors and actuators can be found in literature. In this field, there can be found two typologies: On-Printed-Circuit-Board (On-PCB) and bulk, or separable, micro-actuators. On-PCB miniaturized electromagnetic actuator refers to those devices having torque and rotation capacity but whose stator part is constructed over a PCB like presented by (Koser and Lang 2006; Waldschik and Buttgenbach 2010). They present very efficient motors, claiming for diameters close to 1 mm in the rotary elements but as they are forced to be attached to a PCB the real size will be always larger than the nominal diameter preventing its utilization in catheters and or minimally invasive health tools.

[0005] Separable, or bulk, miniaturized motors can be found in literature as for example the 1 mm diameter micromotor commercialized by Kinetron company described in patent NL9002624A and in article (Wang et al. 2014). This motor is elegant, simple and very efficient since it can operate at very high speeds. However, its torque and specific torque capacity is very reduced because it does not include iron-cores in the stator actuation coils. Similar coreless radial flux micromotors can be found in patent application JP2009247191A with similar reduced torque capacity. Another example of coreless motor is found in patent JP2009247191A. In this patent, they claim for a coreless permanent magnet miniaturized motor connected to a gearhead to increase the total output torque. Although, the gearhead provides larger torque within the same diameter, it requires much larger length, complicating its application in meandering paths through in body vessels. In addition, it may suffer from jamming because gearhead frictions may be too large for a low torque motor actuation.

[0006] The absence of iron cores in miniaturized electromagnetic motors, lower than 1 mm diameter, can be explained by the cogging torque. This cogging torque has to be overcome by the consecutive actuation coil at each motor step. At macroscale, this is easily achieved since magnetic induction of the iron cores can be obtained with a reasonable number of coil wire turns. However, when decreasing the scale, current densities in the wires have to be much larger to achieve similar induction level, generating excessive heat and related issues. On the contrary, magnetic forces acting between iron and magnets are constant with the scale as they depend with the volume of the magnetic materials. This implies that a DC miniaturized electromagnetic permanent magnet motor would need extremely large current densities in the wires to overcome cogging torque and to make the rotor rotate into the next step position. This issue can be overcome by special electromagnetic motor topology called Vernier motor type. Vernier motors have high torque producing capability that exceeds that of a conventional electrical machine by 2-3 times (Wu and El-Refaie 2019). But the most interesting feature is that cogging torque of a Vernier motor is fairly small because it includes a flux modulator part between actuation coils and rotor magnets. The modulated stator flux and the PM flux interacts in the airgap so that the proposed machine works. This working principle is similar to the one of coaxial magnetic gears (Diez-Jimenez, Sanchez-Montero, and Martinez-Muñoz 2017).

[0007] There are two main types of Vernier electric motors radial and axial flux. For a stack construction of the motor, as proposed in this invention, the most relevant type is axial configuration. There can be found several axial flux Vernier motors in literature as for example in (Rallabandi et al. 2017; Zhang et al. 2016; Zou et al. 2017) and in patents KR920020811A, CN110676985A, CN109104059A or CN103178667A. They all present very high torque density due to the gearing effect but none of them has been developed in layers stack, which simplifies the miniaturized assembly process and none of them has such a reduced size as intended in this invention.

[0008] Powering electromagnetic motors and actuator using wireless power transfer system has been considered in previous developments for macroscale applications. For example, it has been proposed wireless induction powering of robotic arms actuators in patents

US2019372341A1, JP2016129479A, CN106560981A or wireless power transfer for water pumps in patent KR102026289B1. Moreover, it has been proposed to power car electric motors as shown in CN106451818A or in article (Fujimoto and Sato 2016) and for general applications electric motors like in CN203225631U or in article (Multiple-frequency et al. 2019).

[0009] Wireless power transfer has been also considered for in body applications like for example in patent CN209593110U, where an induction coil is used to power an endoscopic capsule. Patent KR101749586B1 includes a helical coil antenna attached to a catheter. They do not claim for any rotary actuation system attached to this antenna but only uses a catheter to include a coil antenna and a simple linear magnetic coin motor.

[0010] More related to the present invention is patent application CN103083049A. In said document, invertors claim a system including wireless connected to rotary DC motor for controlling the inflation of a gastric balloon for weight-losing treatments. This patent does combine wireless with electric motor, but the whole system has an external diameter of several millimeters and a length which is several times its diameter, far from the objective of present invention. No information is given about the rotary DC electric motor topology. Besides the size itself, the main constructive difference with the present invention is that the device in constructed by connecting each different element (rotary motor, wireless power transfer, leadscrew, piston, etc...) to a large cylindrical frame getting benefit of a better structural support. The conceptual difference is that in the present invention the elements themselves conform the structure by stacking them which simplifies and reduces the construction, thus enabling miniaturization to diameter smaller than 1 mm.

[0011] Another relevant development affecting the present invention is the article (Gao and Yan 2019). This interesting and detailed article describes the construction and test of a motor-driven capsule robot for exploring the intestinal tract. The whole device measures 14 mm diameter x 46.8 mm and includes a front facing camera, an electric motor, a telemetry circuit, and a solid-cylinder three-dimensional receiving coil for wireless power induction. This device has the same type of elements than the present invention, but its construction is based on a large rigid frame where different elements are attached. This can be done since elements are millimetric scale, so it is not comparable with the claimed lay-out and size of present invention.

[0012] To sum up, according to the previous background selected, it has not been found any development nor commercial device with the characteristics and advantages effects claimed in this invention. The main novelty is the use of an axial flux Vernier type electric motor having magnetic flux gearing effect, with the option for wireless powering, and conditioning system in a single miniaturized device. Its small and constant diameter, considered smaller than 1 mm, enables the access through narrow holes and space for minimally invasive in body interventions. The construction of the device as a set of modules or layers with constant diameter stacked permits its miniaturization. The inclusion of magnetic flux modulator layer, as in any Vernier type motor, allows a much higher output torque of the actuator, providing larger capacity for actuation than previous ironless micromotors or actuators in microscale. Moreover, being capable of wireless powering widens significantly the applicability because it does not require direct physical link with the operator as in non-invasive interventions. Besides, the diameter of the catheter could be reduced since no wires have to be embedded on the catheter. As far as concerned, no similar concept has been found in literature and therefore, and as a conclusion, the novelty, inventive step and industrial application of this invention is demonstrated.

SUMMARY OF THE INVENTION

[0013] The present disclosure describes a miniaturized electromagnet rotary actuator that can be used in treating patients and other applications.

[0014] In one example, a rotary electromagnetic actuator includes a stator layer extending in a thickness direction between a top side and an opposing bottom side. In this example, the stator layer is configured to include a plurality of electromagnetic actuation coils spaced axially around an axis of rotation of a rotor with each oriented in the thickness direction. A magnetic flux modulator layer is provided with a plurality of flux modulator teeth arranged axially around the axis of rotation of the rotor. In this example, the magnetic flux modulator layer is stacked with and fixed relative to the stator layer to form a stacked stator assembly. The rotor is aligned with the stator layer. The rotor includes a permanent magnet layer with alternating multipolar magnetizations arranged axially around the axis of rotation of the rotor. The rotor is stacked on the stacked stator assembly and configured to rotate relative to the stacked stator assembly. In some cases, the stacked stator assembly and rotor are housed by an external frame.

[0015] In some examples, the electromagnetic actuation coils are encapsulated in an epoxy filler to form the stator layer. While not required, each of the electromagnetic actuation coils may include a ferromagnetic inner core and a conductive winding about the corresponding ferromagnetic inner core. When so provided, the efficiency of each conductive winding may be improved. Alternatively, and in another example, the electromagnetic actuation coils may be formed using conventional integrated circuit fabrication processing techniques. For example, each of the plurality of electromagnetic actuation coils of the stator layer may include a plurality of stacked planar conductive loops each formed on a separate deposited insulating layer and interconnected to at least one adjacent conductive loop through one or more VIAS formed through an intervening insulating layer(s).

[0016] In some cases, the rotary electromagnetic actuator includes control electronic operatively coupled to the plurality of electromagnetic actuation coils. At least some of the control electronics may be formed on a semiconductor layer that is processed as part of the integrated circuit fabrication process, but this is not required. For example, parts or all of the control electronics may be formed on an integrated circuit die that is then mounted (e.g. stacked) to the stacked stator assembly. In some cases, the control electronics may be provided in a circuit module that is stacked with the stacked stator assembly.

[0017] In some cases, the rotary electromagnetic actuator may be powered wirelessly. When so provided, the rotary electromagnetic actuator includes one or more power receiving antennas for wirelessly receiving power from an external power source for powering the rotary electromagnetic actuator. The one or more power receiving antennas may include, for example, an induction coil, a plurality of patch microwave antenna arrays, a double helical antenna, and/or any other suitable power receiving antenna(s) as desired. In some cases, the rotary electromagnetic actuator may be powered via a wired connection.

[0018] In some instances, the rotary electromagnetic actuator includes a first bearing situated between the stacked stator assembly and the rotor. The first bearing can include one or more ball bearings aligned in a bearing track, roller bearings, a jewel bearing, a fluid bearing, a magnetic bearing, and/or any other suitable bearing. A second bearing may be situated between the rotor and the external frame.

[0019] In some examples, the permanent magnet layer of the rotor is magnetized in alternating north-south pole pairs, and the difference of the number of pole pairs of the permanent magnet layer and a number of flux modulator teeth of the magnetic flux modulator layer corresponds to a number of electromagnetic actuation coil pole-pairs. In other examples, the permanent magnet layer of the rotor is magnetized in single direction pole pairs with the pole pair made by one permanent magnet pole and one ferromagnetic pole-piece.

[0020] The preceding summary is provided to facilitate an understanding of some of the innovative features unique to the present disclosure and is not intended to be a full description. A full appreciation of the disclosure can be gained by taking the entire specification, claims, figures, and abstract as a whole.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021]

Fig. 1 is a cross section of a first preferred embodiment of the present invention showing the different elements in their stack lay-out.

Fig 2 is an exploded perspective view of the first preferred embodiment of the present invention showing the different elements separately and in the corresponding assembly order.

Fig 3 is an isometric view of the first preferred embodiment of the present invention with the alternative options for the receiver antenna: array of patch antennas arranged in the cylindrical outer surface (Fig 3a), array of patch antennas in stack configuration (Fig 3b), ferromagnetic coil winding (Fig 3c) as inductive link element and double helical coil antenna (Fig 3d).

Fig 4 shows two constructions methods for actuation coils, first shown in Fig 4 - a shows typical multilayers coil winding method and Fig 4 - b shows the construction using epitaxial growth methods in axial magnetization direction.

Fig 5 shows a second preferred embodiment of the present invention where wireless powering system is replaced by direct tethering.

Fig 6 represents the coils activation schemed steps for the rotation of the magnetic field in the 2-phases actuation coils layer.

[0022] While the disclosure is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the disclosure to the particular examples described. On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure.

DESCRIPTION

[0023] On one example, a technical problem is to provide high torque and rotation control capacity in a small and constant diameter actuator, as macroscopic robotic joints or rotary actuators, in combination with wireless powering capacity. Having a miniature rotary actuator with similar behavior to macroscopic actuators could lead to a large number of robotic arms applications, being especially useful in potential applications in health minimally invasive interventions.

[0024] A robotic joint or rotary actuator is typically made by a motor-reducer which is, in the macroscale, an electromechanical device composed of an electric motor (AC or DC) that provides power to a gearhead. The speed provided by the electric motor can be very high (> 100.000 rpm). The output torque of an electric motor is not usually high, thus it is needed to use a gearhead stage to multiply torque and reach useful mechanical performance. In the macro-scale there are many examples of motor-reducers, but not so much in the micro-scale. The smallest electric motor found in literature is a 1 mm diameter system, which is still large and does not contain any gearhead. This absence of any previous micro-robotic joint developments is explained since there are many critical physical and technological issues like assembly, structure, multipolar magnetization and micro-integration that inhibit their creation using conventional methods.

[0025] On the other hand, integrated circuit fabrication processing has shown excellent results in the microelectronics industry, which in a general sense stacks various layers to produce a desired device. It has been found that a "layer stacking" approach may be useful to construct a miniaturized rotary actuator.

[0026] In one example, a miniaturized rotary actuator may include a stator element, one or more high-frequency power receiving antennas, a rectifier and power conditioning circuit, a plurality of actuation coils, a magnetic flux modulator, and a rotary element (e.g. rotor) including a shaft, permanent magnet with multipolar axial magnetization, and bearing balls and corresponding bearing tracks. The construction of this example actuator is oriented to assure and maintain a constant outer diameter while keeping a high torque and efficiency. Assembling this example miniaturized rotary actuator includes stacking different layers with different functions to produce the desired miniaturized rotary actuator. The term "layer" can include a plurality of different sub-components. For example, the plurality of actuation coils (3) may be encapsulated in an epoxy filler, collectively forming a stator "layer" (12). Likewise, the rectifier and power conditioning circuit can be provided in a circuit module forming a "layer", which is then stacked with the stator layer and/or one or more intervening "layers" as desired. These are just examples.

[0027] Wireless powering of the example actuator is done through a radiative link using high-frequency receiver antennas. The antenna is energized by using another larger antenna controlled externally. Both are tuned to resonate in the same frequency range, so the efficiency of the link is maximized. Different receiver antennas can be considered including, for example, a single unbalanced patch antenna, as shown in figure 1, an array of patch antennas arranged in on a cylindrical outer surface (e.g. on external frame (7)), and/or an array of patch antennas in stack configuration. In some cases, an inductive link may be used by adding a ferromagnetic coil winding instead of or in addition to the patch antenna. These alternative antennas options are shown in figure 3.

[0028] The type of antenna depends on the selected resonant frequency. Patch antennas of this small size are most useful in the range of 1 to 10 GHz, while an inductive link antenna may operate most efficiently in the range between 0.1 and 1000 MHz. In some cases, the optimal selection of the antenna will depend on the expected depth and/or location of the intended use of the example actuator in body application since different frequencies are absorbed differently by the body tissue.

[0029] Electromagnetic absorption is a significant issue when miniaturizing wireless power transfer systems for in-body applications. Size of the receiver antenna often directly effects the working resonant frequency of the antenna. Typically, the smaller the receiver antenna, the higher the resonant frequency must be to produce a high efficiency power link. However, the absorption of the electromagnetic energy varies with the frequency and the affected tissue. For the intended working frequency ranges, absorption may be almost negligible between 0.1 to about 500 MHz having penetration depths of tens of cm. Penetration depths start to decrease with frequency, and with a frequency at about 1 GHz the penetration depth may be only about 1 mm. With a frequency of about 10 GHz, the penetration depth may be reduced to practically zero.

[0030] Because of this limitation and depending on the selected antenna, two different wireless energy reception schemes are preferred: continuous high power reception or accumulative low power reception. In continuous high-power reception, the energy is directly and continuously used to power to the actuation coils of the actuator through rectifier and control microelectronic circuit. Although not required, the rectifier and control microelectronic circuit may be fabricated on an integrated circuit die that is mounted (e.g. stacked) to a stacked stator assembly. In the continuous high power reception mode, the example actuator can operate continuously and so it can have both high torque and high speed, therefore high power. In the accumulative low power reception mode, the energy received by the antenna is rectified to a DC signal which is then used to charge a relatively high capacity capacitor. The energy accumulated in the capacitor is released, such as once it is fully charged, to power the actuator. In one example, the periods of charging and discharging the capacitor are controlled by two different microelectronic circuits allowing a slower charge mode and a faster discharging mode. In this way, the example actuator may have an available high-power level for its motion but only during a reduced time. For small-angle controlled actuations, there may be no need of continuous high speed, so even in cases where the efficiency link is relatively low, the actuator can still be useful.

[0031] The energy available from the antenna, in continuous or accumulative mode, is conditioned and transformed in order to create a rotational inducing magnetic field in the actuation coils. The actuation coils must be activated with a certain delay between them depending on the number of phases of the rotary electromagnetic actuator. For a first preferred embodiment, there are 4 axial arranged actuation coils connected in 2 phases scheme. Thus, the activation of the actuation coils is done with a 90 degrees delay (or phase shift) if a sinusoidal activation signal is considered, or in steps if a multiple-on-off-step synchronized activation signal is considered as usual in stepper or brushless DC permanent magnet motors.

[0032] In some cases, the actuation coils include high saturation ferromagnetic cores to increase the total and the specific torque capacity of the electromagnetic actuator. Such coils may need higher inducing currents to overcome cogging torque. Cogging torque of electrical motors is the torque due to the interaction between the permanent magnets of the rotor and the stator. This cogging torque has to be overcome by the consecutive actuation coil at each motor step. At macroscale, this is easily achieved since magnetic induction of the iron cores of the stator can be obtained with a reasonable number of coil wire turns and a large current density in the wires where proper heat removal elements can be considered. However, when decreasing the scale of the motor, current densities in the wires would need to be much larger to achieve similar induction level, generating excessive heat and related issues. Magnetic forces acting between iron and magnets are constant with the scale as they depend on the volume of the magnetic materials. This implies that a simple miniaturized electromagnetic permanent magnet motor would need extremely large current densities in the wires to overcome cogging torque and to make the rotor rotate into the next step position.

[0033] In a preferred embodiment, a Vernier motors design is used to help overcome some of these cogging torque issues. Vernier type motors have high torque producing capability that exceeds that of a conventional electrical machine by 2-3 times. But the most interesting feature is that cogging torque of a Vernier motor is fairly small because it includes a flux modulator part between the actuation coils of the stator and the rotor magnets. The flux modulators give the motor a gearing effect that increases the torque and permits the motor to overcome the cogging torque with lower current densities in the actuation coils.

[0034] The magnetic flux is modulated between the actuation coils and rotor magnets pole-pairs. In the example actuator, a stator layer extends in a thickness direction between a top side and an opposing bottom side. The stator layer is configured to include the plurality of electromagnetic actuation coils spaced axially around an axis of rotation of a rotor with each oriented in the thickness direction. A magnetic flux modulator layer with a plurality of flux modulator teeth is arranged axially around the axis of rotation of the rotor. The magnetic flux modulator layer is stacked with and fixed relative to the stator layer to form a stacked stator assembly. The rotor is aligned with the stator layer, and includes a permanent magnet layer with alternating multipolar magnetizations arranged axially around the axis of rotation of the rotor. In this example, the rotor is stacked on the stacked stator assembly and configured to rotate relative to the stacked stator assembly.

[0035] The actuation coils of the stacked stator assembly produce a number of pole-pairs (ps). The pole pairs are modulated by a certain number of stator teeth (ns) included in the magnetic flux modulator layer of the stacked stator assembly. The difference (ps - ns) of the pole-pairs harmonic becomes the main flux component, which is set to equal the rotor pole-pairs number (pr) of the permanent magnet layer of the rotor.

[0036] The modulated stator flux and the permanent magnet flux interact in the intervening airgap to turn the rotor. There is a gearing effect between rotation of the rotor and rotation of the magnetic field in the actuation coils, typically reducing the speed and hence, multiplying torque in a reduction ratio factor Gr. This reduction ratio can be calculated as $Gr = (ns - pr) / pr$. In the first preferred embodiment these numbers are $ns = 12$, $pr = 11$ and $ps = 1$.

[0037] The Rotor in the example actuator includes a permanent magnet layer/disc with multipolar axial magnetization. The aspect ratio of diameter to thickness of the disc is selected as a trade-off of having enough thickness to provide magnetic forces and being thin enough to be easily magnetizable in multipolar configuration. In addition, thickness is preferably in the same order of the flux modulator teeth of the magnetic flux modulator layer of the stacked stator assembly. A very thick permanent magnet layer of the rotor will tend to make negligible the flux modulation acting directly against the actuation coils, and not against the flux modulator teeth, and consequently increasing relative cogging torque. In a second example, the permanent magnet layer can be constructed by replacing those permanent magnets with north or south magnetization direction by ferromagnetic pole pieces. This simplifies the magnetization process since a pulsed single direction magnetization is enough to magnetize the permanent magnet layer.

[0038] The permanent magnet layer is attached (stacked) to the rotor. The rotor can be made of ferromagnetic material to act as a back yoke of permanent magnet pole-pairs, but it is suggested to use a mid or low magnetic saturation material to help reduce magnetic force imbalances. The rotor is held in position with respect to the flux modulator in a parallel and uniform way, reducing the airgap between the flux modulator teeth and the permanent magnet layer as much as possible.

[0039] In the first preferred embodiment referenced above, the rotor with the permanent magnet layer is sustained over the flux modulator teeth through precision balls and bearings tracks. The use of ball bearings makes the manufacturing and assembly process more complex. However, they provide a friction coefficient orders of magnitude lower than some other type of bearings used in miniature devices like jewel bearings or bushings used in precision watch mechanisms. A jewel bearing provides a friction coefficient of around 0.1-0.15 while ball bearings typically reduces it to 0.01-0.03, depending on the selected materials for the ball and bearings tracks. The magnetic configuration of the first preferred embodiment, made by a single stator and single rotor permanent magnet, generates relatively large axial attractive forces between the stator and the rotor, and so it is desirable to reduce the friction coefficient in the bearings in order to deliver an effective output torque. When using some jewel or other bearings with larger friction coefficients, the motor may rotate at very high speed, but the effective torque capacity would be reduced. While ball bearings are used in the first preferred embodiment, it is contemplated that any suitable bearing may be used including, a roller bearing, a jewel bearing, a fluid bearing, a magnetic bearing, and/or any other suitable bearing.

[0040] In the first preferred embodiment, the rotor assembly is covered by an external cylindrical frame that is configured to acts as a counter bearing tracks for axial and radial loads in opposite directions, but also as a sealing mechanism to help prevent entry of external particles and/or fluids.

[0041] The first preferred embodiment is shown in figures 1, cross section view, and 2, exploded view. The embodiment comprises two main components: a stacked stator assembly and a rotor. In some cases, the stacked stator assembly is built by stacking layers of different subsystems including a plurality of electromagnetic actuation coils spaced axially around an axis of rotation of a rotor each oriented in the thickness direction of the stator layer.

[0042] A first layer shown in Figures 1 and 2 is the patch antenna (1) that is used to gather energy for powering the actuator, sometime gathering energy at different frequencies. This antenna (1) can be constructed in any of a number of different topologies, some of which are shown in figure 3. As shown in Figure 3, the antenna (1) can include an array of patch antennas arranged in a cylindrical outer surface (13) of an external frame (see Figure 3(a)), an array of patch antennas in a stack configuration (14) (see Figure 3(b)), a ferromagnetic coil winding (15) arranged as an inductive link element (see Figure 3(c)), and a double helical coil antenna (16)(see Figure 3(d)). Depending on the expected depth of use in the body, one antenna may be selected against the others.

[0043] The second layer (2) in Figures 1 and 2 includes rectifier and power conditioning electronics circuit layer (2). This electronic layer has several functional blocks. A first block is a matching circuit, which in some cases includes an RLC circuit between the rectifier and the antenna in order to match the resonant frequency of the antenna with the resonant frequency of the rest of the circuit. A second block includes a rectifier circuit, which is typically done by diodes in half or full bridge configuration. Once the energy is available as a DC signal, the energy can be directly distributed to the actuation coils (continuous high power operation) or stored in a capacitor waiting to be released (accumulative low power). In continuous high-power operation, the energy is directly and continuously used to properly power to actuation coils (3) through a control microelectronic circuit using pulses or a sinusoidal inverter. In accumulative low power operation, the DC signal is used to charge a relatively large volume capacitor. The energy accumulated in the capacitor is released to operator the actuator, such as once the capacitor is fully charged. In some examples, the periods of charging and discharging the capacitor are controlled by two different microelectronics circuits allowing a slower charge mode and a faster discharging mode. Therefore, a third block of layer (2) may include control and distribution transistors and/or capacitors. In some cases, parts of or all the second layer (2) in Figures 1 and 2 may be formed on an integrated circuit die that is then mounted (e.g. stacked) to the stacked stator assembly.

[0044] Third element in Figures 1 and 2 includes a stator layer. The stator layer extending in a thickness direction between a top side (facing to the right in Figure 2) and an opposing bottom side (facing to the left in Figure 2). The stator layer is configured to include a plurality of electromagnetic actuation coils spaced axially around an axis of rotation of a rotor (8) with each oriented in the thickness direction. The electromagnetic actuation coils (3) may be encapsulated by an epoxy filler to makeup the stator layer (12). In this preferred embodiment, the stator layer includes four actuation coils connected in two phases. Opposite coils belong to the same phase. By using two phases, the total magnetic field generated by the four coils can be accurately controlled and rotated around the axis of rotation axis of the rotor, as shown in figure 6.

[0045] The windings of the actuation coils can be done using any usable approach. A first approach is to create a multilayer coil winding (17) using common winding machines customized for such small dimensions. The second approach is done using integrated circuit processing techniques, e.g. each of the plurality of electromagnetic actuation coils of the stator layer may include a plurality of stacked planar conductive loops (18) each formed on a separately deposited insulating layer and interconnected to at least one adjacent conductive loop through one or more VIAS formed through an intervening insulating layer.

[0046] In the example shown in Figure 2, the rotating magnetic flux from the actuation coils (3) is modulated using a magnetic flux modulator layer (4) with a plurality of flux modulator teeth (5) arranged axially around the axis of rotation of the rotor (8). The magnetic flux modulator layer (4) is stacked with and fixed relative to the stator layer (12) to form a stacked stator assembly.

[0047] The stacked stator assembly is made with a certain number of pole-pairs (ps), which is modulated by a certain number of stator teeth (ns) included in the magnetic flux modulator layer (4). The difference (ps - ns) in pole-pairs harmonic becomes the main flux component, which may equal the pole-pairs number (pr) of the permanent magnet layer (9) with alternating multipolar magnetizations of the rotor. There is a gearing effect between rotation of the rotor (8) and rotation of the magnetic field in the actuation coils (3), typically reducing the speed and hence, multiplying torque in a reduction ratio factor Gr. This reduction ratio can be calculated as $Gr = (ns - pr) / pr$. In the first preferred embodiment, these numbers are ns = 12, pr = 11 and ps = 1. The magnetic flux modulator layer (4) helps reduce the cogging torque occurring when the rotor (8) goes from one step angle to another.

[0048] The magnetic flux modulator layer (4) may include a rigid frame acting as a bearing track (6). The bearing track (6) may be coated with high hardness and low shear resistance materials reducing the friction coefficient between bearings ball (10) and the bearing track (6). An external cylindrical frame (7) may be used to close the bearing tracks laterally. There are two contact ball bearing tracks, one between bearing track (6) and rotor (8), closed laterally by the cylindrical frame (7). A second contact bearing track may be provided between the rotor and its bearing tracks (11), closed laterally and axially by the cylindrical frame (7). The bearing tracks (6) and (11) may be L-shape to simply manufacturing, and then closed by adjacent components to maintain the ball bearings within each track.

[0049] The first preferred embodiment also includes a rotor (8). The rotor (8) is aligned with the stator layer (12) and includes a permanent magnet layer (9) with alternating multipolar magnetizations arranged axially around the axis of rotation of the rotor (8). In a second example, the permanent magnet layer may include permanent magnets with single direction of magnetization with separating ferromagnetic pole pieces. During assembly, the rotor (8) is stacked on the stacked stator assembly and configured to rotate relative to the stacked stator assembly.

[0050] The permanent magnet layer (9) is polarized in order to have the number of pole-pairs necessary for the gearing effect, as described previously. In the first preferred embodiment, the number is pr = 11. The aspect ratio of the pole pitch with respect to the thickness of the permanent magnet layer (9) is preferably less than one (1) to help with proper magnetization of the pole-pairs of the permanent magnet layer (9). Thinner pole pairs may be more difficult to completely magnetize in alternative direction. For the second example, having single direction of magnetization, the magnetization process is much simpler and straightforward.

[0051] In the example shown, the bearings including bearing tracks with balls designed to simplify the assembly process. The bearing tracks (11) are shown manufactured in the rotor (8) as a simple perpendicular "L" shaped section. The counter tracks are not manufactured in the stator part, but they are simply made by the shape of the stator parts (6) and (7). The first bearing is inherently preloaded since there is an attractive force between permanent magnet layer (9) of the rotor and the magnetic flux modulator layer of the stator. Therefore, during the assembly process, the balls are placed over the external surface of stator part (6) precisely. Once the balls are in place, the rotor (8) is moved in a controlled way down to its final position. For the second bearing assembly, the balls are placed in the rotor (8) bearing tracks (11) and then the whole assembly is closed by external cylindrical frame (7).

[0052] A second preferred embodiment of the present invention is shown in figure 5. This second preferred embodiment includes similar layout of almost all the layers except the antenna layer. In this case, the antenna(s) is replaced by direct tethered powering of the actuator through two thin enameled copper wires (19). The main advantage of this second embodiment is that high, reliable, and continuous power flux can be provided to the actuator. However, this embodiment loses the wireless capacity, so this layout is best used when the actuator is attached to the end tip of a catheter externally manipulated.

[0053] Having thus described several illustrative embodiments of the present disclosure, those of skill in the art will readily appreciate that yet other embodiments may be made and used within the scope of the claims hereto attached. It will be understood, however, that this disclosure is, in many respects, only illustrative. Changes may be made in details, particularly in matters of shape, size, arrangement of parts, and exclusion and order of steps, without exceeding the scope of the disclosure. The disclosure's scope is, of course, defined in the language in which the appended claims are expressed.

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Claims

1. A rotary electromagnetic actuator comprising:

   a stator layer (12) extending in a thickness direction between a top side and an opposing bottom side, the stator layer (12) configured to include a plurality of electromagnetic actuation coils (3) spaced axially around an axis of rotation of a rotor (8) with each oriented in the thickness direction;

   a magnetic flux modulator layer (4) with a plurality of flux modulator teeth (5) arranged axially around the axis of rotation of the rotor, the magnetic flux modulator layer (4) is stacked with and fixed relative to the stator layer (12) to form a stacked stator assembly; and

   the rotor (8) is aligned with the stator layer (12), the rotor (8) comprising a permanent magnet layer (9) with alternating multipolar magnetizations arranged axially around the axis of rotation of the rotor (8), wherein the rotor (8) is stacked on the stacked stator assembly and configured to rotate relative to the stacked stator assembly.

2. The rotary electromagnetic actuator of claim 1, wherein the stator layer (12) includes the plurality of electromagnetic actuation coils (3) encapsulated in an epoxy filler.

3. The rotary electromagnetic actuator of claim 1, wherein each of the plurality of electromagnetic actuation coils (3) of the stator layer (12) comprises a plurality of stacked planar conductive loops (18) each formed on a separate insulating layer and interconnected to at least one adjacent conductive loop through one or more VIAS formed through an intervening insulating layer.

4. The rotary electromagnetic actuator of claim 3, wherein each of the plurality of electromagnetic actuation coils (3) is formed using an integrated circuit fabrication process.

5. The rotary electromagnetic actuator of claim 4, further comprising control electronic operatively coupled to the plurality of electromagnetic actuation coils (3), wherein at least some of the control electronics is formed on a semiconductor layer that is processed as part of the integrated circuit fabrication process.

6. The rotary electromagnetic actuator of any of claims 1-5, further comprising control electronics operatively coupled to the plurality of electromagnetic actuation coils (3), the control electronics provided in a circuit module that is stacked with the stacked stator assembly.

7. The rotary electromagnetic actuator of any of claims 1-6, further comprising one or more power receiving antennas (1) for wirelessly receiving power for powering the rotary electromagnetic actuator during use.

8. The rotary electromagnetic actuator of claim 7, wherein the one or more power receiving antennas (1) includes an induction coil (15).

9. The rotary electromagnetic actuator of claim 7, wherein the one or more power receiving antennas (1) includes a plurality of patch microwave antenna arrays.

10. The rotary electromagnetic actuator of claim 7, wherein the one or more power receiving antennas (1) includes a double helical antenna (16).

11. The rotary electromagnetic actuator of any of claims 1-10, further comprising a wired connection for receiving power for powering the rotary electromagnetic actuator during use.

12. The rotary electromagnetic actuator of any of claims 1-11 further comprising:

a first bearing situated between the stacked stator assembly and the rotor (8), wherein the first bearing includes one or more ball bearings;
an external frame and a second bearing situated between the rotor (8) and the external frame, wherein the second bearing includes one or more ball bearings.

13. The rotary electromagnetic actuator of any of claims 1-12, wherein the permanent magnet layer (9) of the rotor (8) is magnetized in alternating north-south pole pairs, and wherein the difference of the number of pole pairs of the permanent magnet layer (9) and a number of flux modulator teeth (5) of the magnetic flux modulator layer (4) corresponds to a number of electromagnetic actuation coil pole-pairs.

14. The rotary electromagnetic actuator of any of claims 1-12, wherein the permanent magnet layer (9) of the rotor (8) is magnetized in single direction pole pairs with the pole pair made by one permanent magnet pole and one ferromagnetic pole-piece, and wherein the difference of the number of pole pairs of the permanent magnet layer and a number of flux modulator teeth of the magnetic flux modulator layer corresponds to a number of electromagnetic actuation coil pole-pairs.

15. The rotary electromagnetic actuator of any of claims 1-14, wherein each of the electromagnetic actuation coils (3) comprises a ferromagnetic inner core and a conducive winding about the ferromagnetic inner core.

Amended claims in accordance with Rule 137(2) EPC.

1. A rotary electromagnetic actuator comprising:

a stator layer (12) extending in a thickness direction between a top side and an opposing bottom side, the stator layer (12) configured to include a plurality of electromagnetic actuation coils (3) spaced axially around an axis of rotation of a rotor (8) with each oriented in the thickness direction;
a magnetic flux modulator layer (4) with a plurality of flux modulator teeth (5) arranged axially around the axis of rotation of the rotor, the magnetic flux modulator layer (4) is stacked with and fixed relative to the stator layer (12) to form a stacked stator assembly; and
an external frame (7), inside which the stacked stator assembly and rotor (8) are housed;
the rotor (8) is aligned with the stator layer (12), the rotor (8) comprising a permanent magnet layer (9) with alternating multipolar magnetizations arranged axially around the axis of rotation of the rotor (8), wherein the rotor (8) is stacked on the stacked stator assembly and configured to rotate relative to the stacked stator assembly;
the actuator being **characterized in that** it also comprises:

a first bearing situated between the stacked stator assembly and the rotor (8), the first bearing including one or more balls disposed directly in contact between the external surface of stator (6) and a bearing track (11) provided in the rotor (8);
a second bearing situated between the rotor (8) and the external frame (7), the second bearing including one or more balls disposed directly in contact between a bearing track (11) provided in the rotor (8) and the external cylindrical frame (7);
a second layer (2) including rectifier and power conditioning electronic circuit layers;
one or more power receiving antennas (1) for wirelessly receiving power for powering the rotary electromagnetic actuator during use; and
being also **characterized in that** the external frame (7), the magnetic flux modulator layer (4), the stator layer (12), the second layer (2) and the power receiving antennas (1) all have the same constant outer diameter, said diameter being smaller than 1mm.

2. The rotary electromagnetic actuator of claim 1, wherein the stator layer (12) includes the plurality of electromagnetic actuation coils (3) encapsulated in an epoxy filler.

3. The rotary electromagnetic actuator of claim 1, wherein each of the plurality of electromagnetic actuation coils (3) of the stator layer (12) comprises a plurality of stacked planar conductive loops (18) each formed on a separate insulating layer and interconnected to at least one adjacent conductive loop through one or more VIAS formed through an intervening insulating layer.

4. The rotary electromagnetic actuator of claim 3, wherein each of the plurality of electromagnetic actuation coils (3) is formed using an integrated circuit fabrication process.

5. The rotary electromagnetic actuator of claim 4, further comprising control electronic operatively coupled to the plurality of electromagnetic actuation coils (3), wherein at least some of the control electronics is formed on a semiconductor layer that is processed as part of the integrated circuit fabrication process.

6. The rotary electromagnetic actuator of any of claims 1-5, further comprising control electronics operatively coupled to the plurality of electromagnetic actuation coils (3), the control electronics provided in a circuit module that is stacked with the stacked stator assembly.

7. The rotary electromagnetic actuator of claim 1, wherein the one or more power receiving antennas (1) includes an induction coil (15).

8. The rotary electromagnetic actuator of claim 1, wherein the one or more power receiving antennas (1) includes a plurality of patch microwave antenna arrays.

9. The rotary electromagnetic actuator of claim 1, wherein the one or more power receiving antennas (1) includes a double helical antenna (16).

10. The rotary electromagnetic actuator of any of claims 1-9, wherein the permanent magnet layer (9) of the rotor (8) is magnetized in alternating northsouth pole pairs, and wherein the difference of the number of pole pairs of the permanent magnet layer (9) and a number of flux modulator teeth (5) of the magnetic flux modulator layer (4) corresponds to a number of electromagnetic actuation coil pole-pairs.

11. The rotary electromagnetic actuator of any of claims 1-9, wherein the permanent magnet layer (9) of the rotor (8) is magnetized in single direction pole pairs with the pole pair made by one permanent magnet pole and one ferromagnetic pole-piece, and wherein the difference of the number of pole pairs of the permanent magnet layer and a number of flux modulator teeth of the magnetic flux modulator layer corresponds to a number of electromagnetic actuation coil pole-pairs.

12. The rotary electromagnetic actuator of any of claims 1-11, wherein each of the electromagnetic actuation coils (3) comprises a ferromagnetic inner core and a conducive winding about the ferromagnetic inner core.

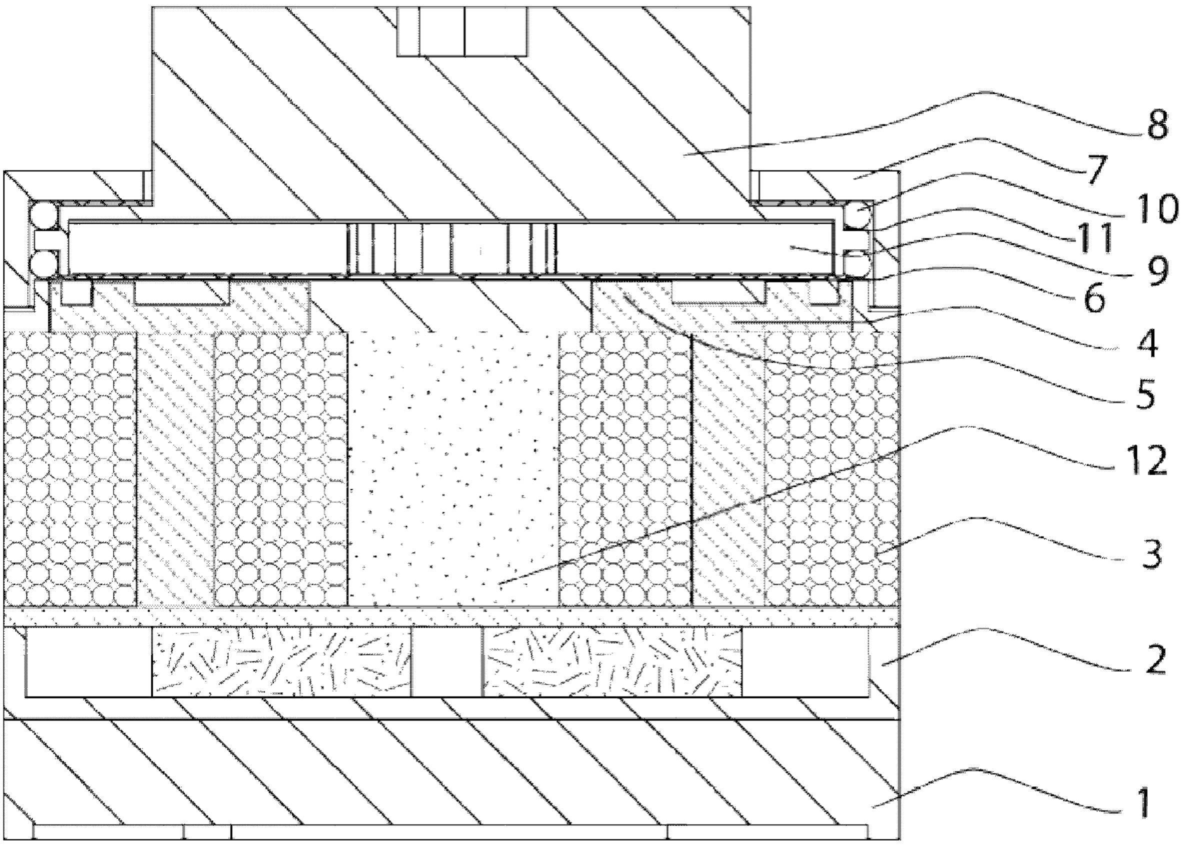

Fig.1

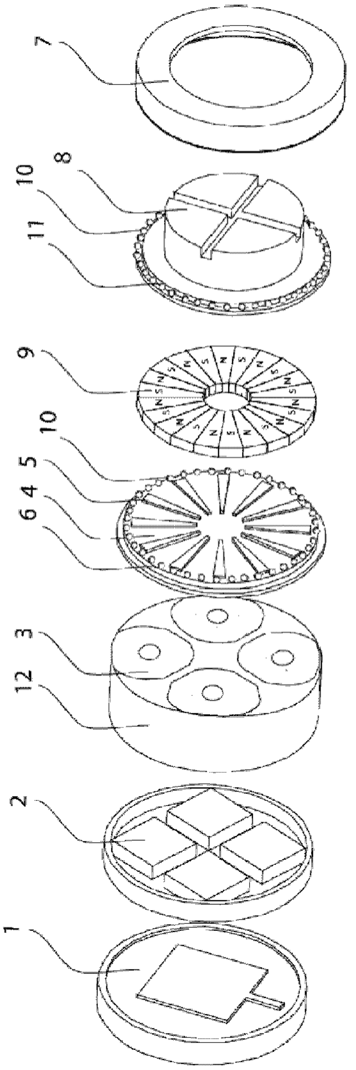

Fig. 2

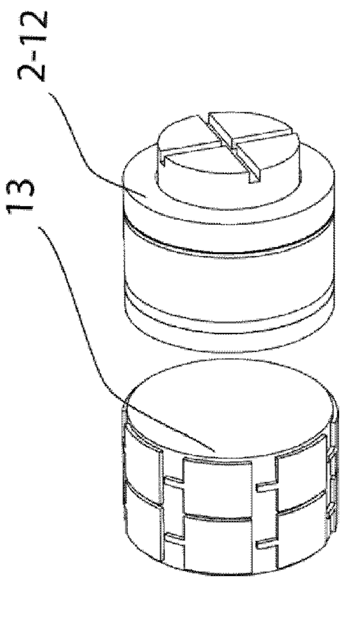

Fig. 3a

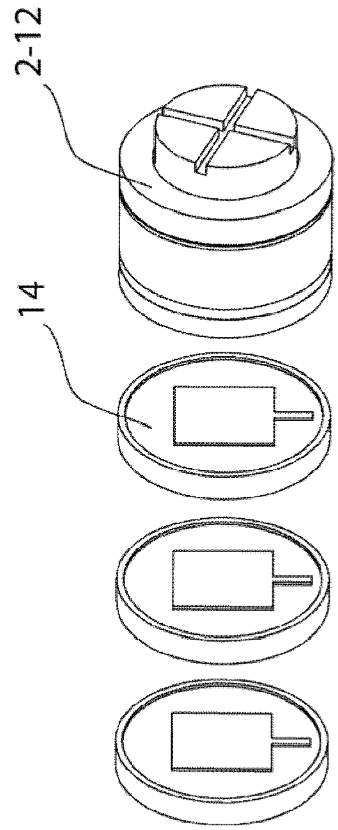

Fig. 3b

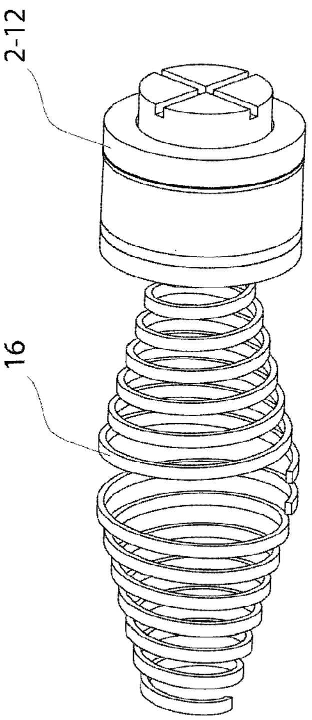

Fig. 3d

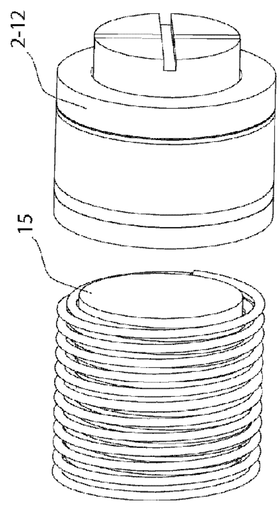

Fig. 3c

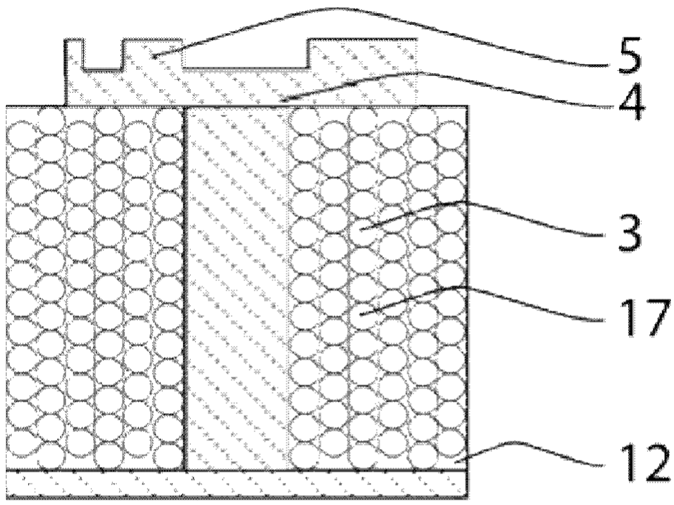

Fig. 4a

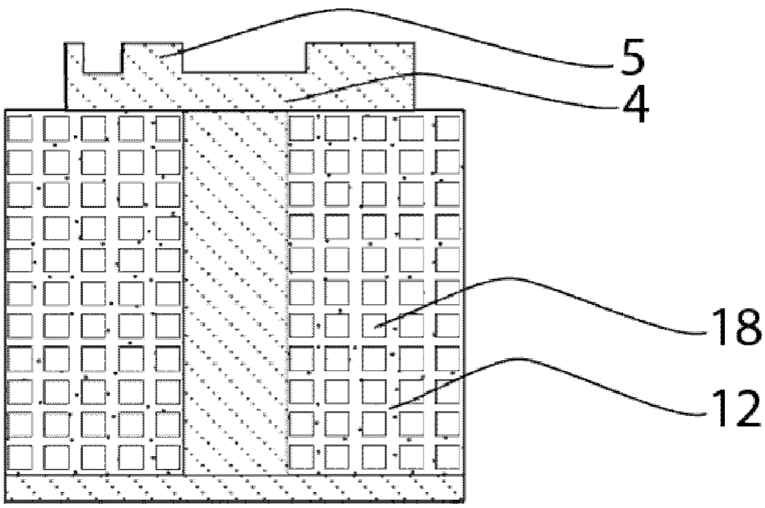

Fig. 4b

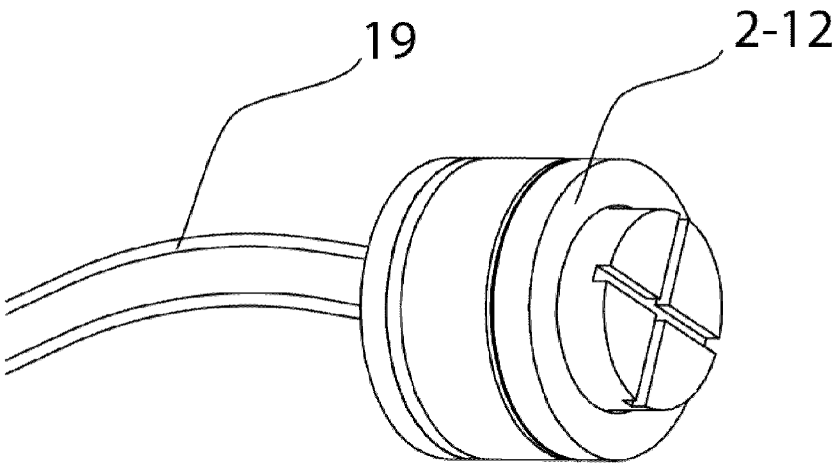

Fig. 5

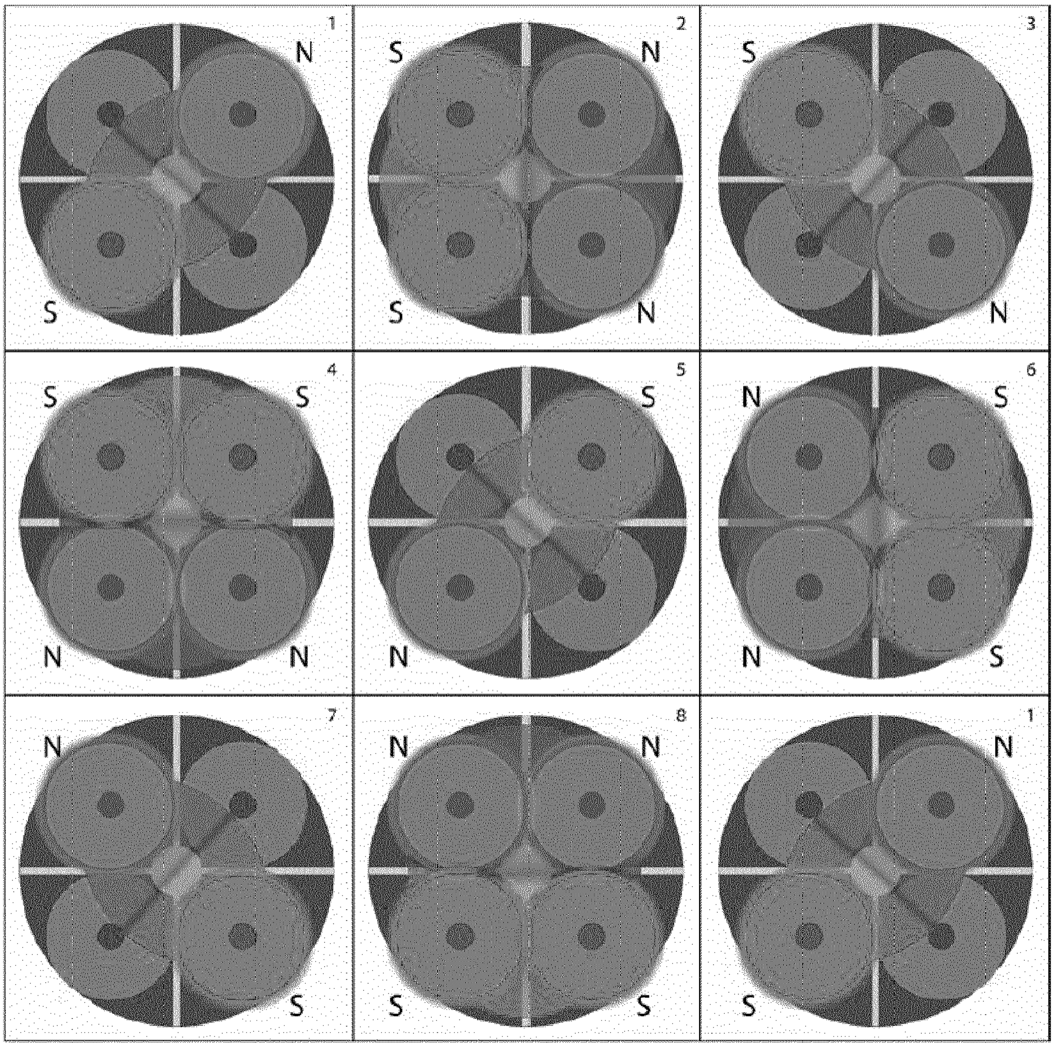

Fig. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 21 38 2782

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Place of search	Date of completion of the search	Examiner
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A : technological background
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