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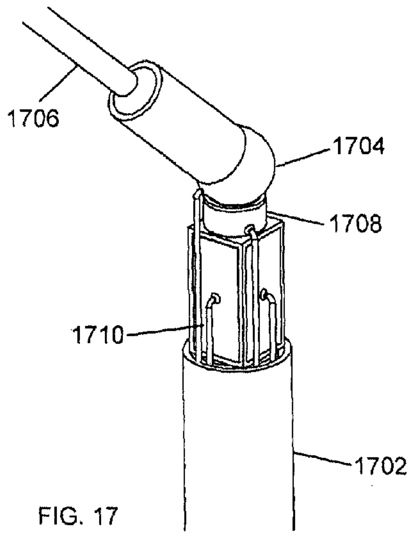

FIG. 17

(57) **Abstract**: An actuator includes an actuator member and a drive member. The drive member is configured to selectively apply drive forces to the actuator member via a frictional coupling therebetween, and to thereby drive corresponding linear and/or rotary motion of the actuator member. One or more friction control components are configured to electromechanically and selectively control or modify the frictional coupling between the drive member and the actuator member. The actuator can be miniaturised with micrometre or millimetre scale dimensions.

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ACTUATOR WITH ELECTROMECHANICAL FRICTION CONTROL

Technical Field

The present invention relates to an actuator with electromechanical friction control, and in particular to miniaturised actuators with micrometre or millimetre scale dimensions.

Background

Miniaturised actuators having dimensions on the order of millimetres or less are useful for many applications, including microsurgical applications. However, such miniaturised actuators are typically difficult to control. It is desired to provide an actuator that alleviates one or more difficulties of the prior art, or at least provides a useful alternative.

Summary

In accordance with the present invention, there is provided an actuator, including:

an actuator member; and

a drive member configured to selectively apply drive forces to the actuator member via a frictional coupling therebetween, and to thereby drive corresponding linear and/or rotary motion of the actuator member; and

one or more friction control components configured to electromechanically and selectively control or modify the frictional coupling between the drive member and the actuator member.

In some embodiments, the one or more friction control components electromechanically control at least one further force that determines the frictional coupling between the drive member and the actuator member.

In some embodiments, the drive forces are substantially orthogonal to the at least one further force.

In some embodiments, the one or more friction control components are configured to electromechanically control and/or modify the frictional coupling between the drive member and the actuator member such that the linear and/or rotary motion of the actuator member can be selectively modified, prevented and/or allowed.

In some embodiments, the one or more friction control components are configured to selectively lock the actuator member relative to the drive member.

In some embodiments, the one or more friction control components are configured to selectively lock the actuator member relative to the drive member, but allow movement of the actuator member relative to the drive member when the actuator member is subjected to a force or torque exceeding a selected force or torque determined by the friction control components.

In some embodiments, the drive member is configured to drive the actuator member by periodically pressing against the actuator member to provide or increase the frictional coupling therebetween while moving in a direction substantially transverse to said pressing.

In some embodiments, one or more of the friction control components are configured to electromechanically modify the frictional coupling between the drive member and the actuator member as a function of time.

In some embodiments, one or more of the friction control components modify the frictional coupling as a function of time based on a corresponding alternating current (AC) electrical signal.

In some embodiments, the modification of the frictional coupling is controlled by a direct current (DC) electrical signal applied to one or more of the friction control components.

The frictional coupling may be controlled to increase the operability, functionality, performance and/or efficiency of the actuator.

In some embodiments, the one or more friction control components are configured to electromechanically control the frictional coupling between the drive member and the actuator member by controlling non-contact forces of attraction and/or repulsion between the actuator member and at least one other component of the actuator.

In some embodiments, the at least one other component of the actuator includes the drive member. In some embodiments, the at least one other component of the actuator includes one or more friction control members spaced from the actuator member and the drive member.

In some embodiments, the non-contact forces of attraction and/or repulsion include non-contact forces generated by one or more electric fields. In some embodiments, the one or more electric fields are generated by electric charges on the actuator member and the at least one other component of the actuator, at least a first part of the actuator member and at least a first part of the at least one other component of the actuator being electrically conductive and mutually insulated by at least one electrically insulating or dielectric material.

In some embodiments, the one or more electric fields are generated by electric charges on the actuator member and the at least one other component of the actuator, at least one of the actuator member and the at least one other component of the actuator being composed of at least one electrically insulating or dielectric material.

In some embodiments, the one or more electrically insulating or dielectric materials have high dielectric permittivities and/or high dielectric breakdown strengths. In some embodiments, the one or more electrically insulating or dielectric materials include one or more thin films.

In some embodiments, the actuator further includes one or more chargeable elements configured to screen the one or more electric fields from other components of the actuator.

In some embodiments, the non-contact forces of attraction and/or repulsion include non-contact forces generated by at least one magnetic field.

In some embodiments, the one or more friction control components are configured to electromechanically control the frictional coupling between the drive member and the actuator member by physically pressing the actuator member against the drive member.

In some embodiments, the drive member is configured to vibrate longitudinally and/or transversely to frictionally drive the actuator member.

In some embodiments, the actuator is part of a surgical device. In some embodiments, the actuator is part of a guidewire or catheter device for use in interventional cardiology, neuroradiology and/or other minimally invasive medical procedures.

In some embodiments, the dimensions of the actuator member are millimetre scale dimensions. In some embodiments, the dimensions of the actuator member are micrometre scale dimensions.

Brief Description of the Drawings

By way of example only, some embodiments of the present invention are hereinafter described, with reference to the accompanying drawings, in which:

Figures 1 and 2 are schematic and cross-sectional side views of a frictionally driven actuator with an actuator member in the form of a spherical rotor and electrostatic friction control components configured to control the frictional coupling between the rotor and the drive member by controlling electrostatic forces of attraction and/or repulsion therebetween;

Figure 3 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, but where the drive member has a surface shape complementary to that of the rotor to increase the frictional coupling therebetween;

Figure 4 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, but where the actuator member is in the form of a planar slider element or plate;

Figure 5 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, but where the dielectric layer insulating the rotor from the drive member is on the rotor rather than the drive member;

Figures 6 to 9 show the embodiment of Figures 1 and 2, illustrating various different electric charge configurations that all produce compressive interbody contact forces at the interface between the actuator member and the drive member;

Figure 10 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, where the rotor is electrically conductive and is charged by conductive brushes that contact the rotor;

Figure 11 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, including three chargeable elements and two dielectric elements, wherein the dielectric elements are air layers and compressive interbody contact forces at the interface between the actuator member and the drive member are generated using the charge configuration shown;

Figure 12 is similar to Figure 11, but where the drive member is also charged to increase the compressive interbody contact force, thus making four chargeable elements in total, and three dielectric elements;

Figure 13 is a cross-sectional side view of an actuator similar to that of Figures 1 and 2, but also including a screening element or electrode to shield a piezoelectric element from the electric fields generated by the charges placed upon the actuator member, the drive member and/or any other chargeable friction control components;

Figure 14 is a cross-sectional side view of an actuator similar to that of Figure 3, but where an electromagnet is used to generate magnetic forces to control the frictional coupling between the rotor and the drive member;

Figures 15 and 16 are cross-sectional side views of actuators wherein the frictional coupling between the rotor and the drive member is modified by pressing the rotor against the drive member; and

Figure 17 is a schematic diagram of a steerable guidewire device for use in minimally invasive surgery, the device including an actuator with electrostatic friction control components.

Detailed Description

Embodiments of the present invention include actuators. Each actuator includes an actuator member and at least one drive member configured to apply drive forces to the actuator member to drive the motion of the actuator member. The motion may be linear and/or rotary motion. The motion may (but need not) be continuous; the actuator may be a motor. Where the motion is linear, the actuator member is typically (but need not be) in the form of a planar slider element or member. Where the motion is rotary, the actuator member is typically (but need not be) in the form of a rotor. The rotor may be cylindrical or spherical.

Some embodiments of the present invention are hereinafter described in the context of a micrometre or millimetre scale actuator in which the actuator member is or includes a spherical rotor member that is frictionally driven with up to three degrees-of-freedom by the vibrating tip of a drive member mounted to a piezoelectric crystal, as described in G. Rogers, *Journal of Micromechanics and Microengineering* 20, 2010 ("Rogers"). However, it will be apparent to those skilled in the art that other embodiments of the present invention may involve other forms of actuators and actuator drive mechanisms.

The actuator described in Rogers is only one form of actuator that relies on friction coupling between at least one drive member and the actuator member. Such actuators transfer the mechanical energy of the drive member to the actuator member via a frictional coupling or 'joint' force that is proportional to the product of the friction coefficient and the normal contact force between (either directly or indirectly) the actuator member and the drive member(s). Furthermore, such actuators/motors may operate via a stick-slip type of relationship, whereby a relatively high normal force is selectively applied to cause the actuator member to engage with or 'stick' to the drive member(s), and conversely a relatively low normal force is selectively applied to allow these members to mutually disengage or at least 'slip' relative to one another. In such actuators, selective control or modification of the normal contact force between the actuator member and the drive member(s) allows the stick-slip forces and hence the actuator linear and/or rotational motion to be controlled.

In the described embodiments of the present invention, each actuator further includes one or more friction control components configured to electromechanically selectively modify the frictional coupling between the drive member and the actuator member, and to thereby modify, prevent and/or allow the linear and/or rotary motion of the actuator member.

The friction control components described herein greatly improve the ability to control the motion of the actuator member, and in particular are amenable to miniaturisation to millimetre or micrometre or even nanometre scale dimensions. As described below, in some embodiments, a remotely controlled actuator for minimally invasive surgical applications is provided.

Figure 1 is a computer-generated image of a portion of a microscale actuator 100 of the general form described in Rogers, having an actuator member in the form of a spherical rotor 102 and a drive member 104 in the form of a hollow tube 104, of which only the tip is shown. As described in Rogers, the tube 104 is driven by an associated piezoelectric crystal (not shown) to cause the tube 104 to simultaneously vibrate or oscillate in flexural (transverse) and/or longitudinal (axial) motions or modes. These motions or modes can be independently controlled so that their combination causes the tip 104 to move along a generally and approximately elliptical or circular path.

In one part of the periodic cycle for one type of motion, the tube 104 longitudinally extends and presses against the actuator member 102 to provide or increase the normal force (and hence the frictional coupling) between the tip 104 and the spherical rotor 102 so that they 'stick' or become mutually engaged. The transverse motion of the tip 104 while in this extended or 'stick' state thus drives the spherical rotor 102, effecting a form of rim drive. Subsequently, in another part of the cycle, the tube 104 longitudinally compresses, thereby decreasing (or removing) the normal force (and consequently the degree of engagement or frictional coupling) between the tip 104 and the spherical rotor 102, allowing the tip 104 to return transversely without driving the rotor 102, or at least driving it to a lesser extent than the other half-cycle. As described in Rogers, the result of this general arrangement is that the spherical rotor can be caused to move as desired, with up to three degrees-of-freedom, depending on the applied drive signals.

As indicated above, the described embodiments of the present invention further provide friction control components that allow the motion of the actuator member to be further controlled by modifying the frictional coupling between the actuator member 102 and the drive member(s) 104; for example, and in the above context, by modifying the contact forces between the spherical rotor 102 and the tip of the tube 104.

In most of the embodiments described herein, the one or more friction control components are configured to electromechanically control the frictional coupling between the drive member 104 and the actuator member 102 by controlling non-contact forces of attraction and/or repulsion between the actuator member 102 and at least one other component of the actuator. In some of these embodiments, the at least one other component of the actuator includes the drive member 104.

In some embodiments, the non-contact forces of attraction and/or repulsion include non-contact forces generated by an electric field. For example, in some embodiments, the frictional coupling between the actuator member 102 and the drive member(s) 104 is modified by introducing and controlling electrostatic forces of attraction and/or repulsion between the spherical rotor 102 and the tube 104. In these embodiments, electric charges on the spherical rotor 102 and the tube 104 are maintained by providing an electrically insulating or dielectric layer or component to prevent the flow of electrical charge between the actuator member 102 and the drive member(s) 104. For example, in the embodiment of Figure 1, a layer of an electrically insulating material 106 is provided on the tip of the tube 104, and the spherical rotor 102 and at least the tip of the tube 104 are composed of one or more electrically chargeable materials. Figure 2 is a corresponding cross-sectional side view, showing the electrically insulating material 106 as an annular disk at the tip of the hollow tube 104.

An electrostatic force is produced when two objects, each carrying a net charge, are sufficiently close that their electric fields interact. In the simplest form, two point charges will produce an electrostatic force according to Coulomb's Law. By definition, if the two charges have the same polarity, then the resulting electrostatic force is repulsive and will act to separate them, and conversely if the two charges have different polarities, then the resulting electrostatic force is attractive and will act to draw them together.

As an extension of Coulomb's Law, the electrostatic force between two charged, extended objects can be approximated by the following equation for the force between two capacitor plates:

$$F = \frac{1}{2} \varepsilon A V^2/d^2 \quad \ldots. (1)$$

In Eq. (1), ε is the electric permittivity of the medium separating the objects; A is the surface area upon which the electrostatic force acts; V is the electric potential (voltage) difference between the two objects; and d is the separation distance (gap) between the two objects. According to Eq. (1), by increasing ε, A and V, and/or by decreasing d, it is possible to increase the magnitude of the electrostatic force.

Although the drive member 104 shown in Figures 1 and 2 is a hollow cylindrical tube, in other embodiments it can take other forms, including solid-cylindrical, solid-rectangular and hollow-rectangular configurations, for example. Furthermore, while the drive member 104 is depicted in Figures 1 and 2 as having a straight-cut endface, in other embodiments it may have a different shape, including, for example, tapered, filleted, convex, concave or cupped configurations. For example, Figure 3 is a cross-sectional side view of an actuator having a solid-cylindrical drive member 304 with a part-spherical concave endface and the insulating layer or member 306 is in the form of a part-spherical shell.

As described above, although the embodiments described herein are predominantly rotational actuators that provide rotational movement of an actuator member, other embodiments include linear actuators that provide linear movement of an actuator member, which may be in the form of a slider plate or planar member 402, as shown in Figure 4, which may be mounted at the end of the hollow tube 104 described above, or another form of drive member.

As described above, in some embodiments, the frictional coupling between the actuator member 102 and the drive member(s) 104 is modified by controlling electrostatic forces of attraction and/or repulsion between the actuator member 102 and at least one drive member 104. This requires at least part of the actuator member 102 and at least one other member or component of the actuator to be electrically chargeable. For convenience, such members or components of the actuator are collectively referred to herein as "chargeable elements."

Each of these chargeable elements may be composed of one or more electrically conductive materials or one or more non-electrically conductive (*i.e.*, electrically insulating or dielectric) materials. Examples of suitable electrically conductive materials include, *inter alia*, carbon steel, stainless steel, titanium, copper, brass, platinum, gold and silver. Examples of suitable electrically insulating materials include, *inter alia*, polymers or ceramics. In some embodiments, the chargeable elements are electrically conductive electrodes, wherein the charge stored in the electrodes is controlled via an electrical power source.

For the electrically insulating (*i.e.*, dielectric) layer(s) or component(s) 106, examples of suitable materials include polymers, ceramics, or even a fluid – air, for example. In some embodiments, the dielectric elements are composed of one or more materials having high permittivities (*e.g.*, $\varepsilon_r > 10$) and high dielectric breakdown strengths (*e.g.*, >50 MV/m). In some embodiments, the dielectric elements are in the form of thin films or layers (*e.g.*, with thicknesses <2 μm). Where the dielectric elements are applied or deposited over another structure or component, they may be applied or deposited on one or more drive member(s) (as depicted in Figures 1 to 4) and/or to one or more actuator members (*e.g.*, rotor or slider members). For example, Figure 5 is a cross-sectional side view of an actuator in which the actuator member 502 is a spherical rotor consisting of a dielectric outer layer or shell 506 deposited on a spherical core 508 of different composition.

The dielectric elements or layers can be deposited uniformly, for example via plasma coating or atomic layer deposition. In this instance, suitable materials include, for example, parylene, polyvinylidene fluoride (PVDF), aluminium oxide (Al_2O_3), hafnium oxide (HfO_2), titanium dioxide (TiO_2), strontium titanate ($SrTiO_2$), lanthanum oxide (La_2O_3), lanthanum aluminate ($LaAlO_3$), zirconium dioxide (ZrO_2), tantalum oxide

(Ta_2O_5), barium titanate ($BaTiO_3$) and lead zirconate titanate (PZT). Many other suitable dielectric materials will be apparent to those skilled in the art.

In general, the electrostatic forces between the actuator member and the at least one drive member(s) may be attractive, repulsive, or both (*e.g.*, alternating between attractive and repulsive over time), as determined by the respective signs of the electric charges on these respective members at any given time.

Figures 6 to 9 illustrate how compressive contact forces at the interface(s) between an actuator member and at least one drive member (in the depicted embodiments being the (chargeable) spherical rotor 102 and the (chargeable) hollow tube 104) can be generated by providing electrical charges of opposite polarities on these respective components. In Figure 6, the rotor 102 is given a positive electric charge, and the hollow tube 104 is given a negative electric charge, the resulting attractive force providing a compressive interbody contact force at the interface between these members.

As will be apparent to those skilled in the art, a compressive force between the rotor 102 and the drive member (tube) 104 can alternatively be generated by providing:

- a positive charge to the drive member (tube) 104 and a negative charge to the rotor 102, as depicted in Figure 7; or
- a positive or negative charge to the drive member (tube) 104 and electrically grounding the rotor 102, as depicted in Figure 8; or
- a positive or negative charge to the rotor 102 and electrically grounding the drive member (tube) 104, as depicted in Figure 9.

There are many ways in which electrical charges can be applied to or injected into a chargeable member. For example, where a chargeable member is electrically conductive, electrical charges can be provided by connecting the conductive member to a power source via an electrically conductive wire or brush 1002, as depicted in Figure 10. A yet further way to apply electrical charges to a chargeable member is via electrostatic charge, for example wherein the chargeable member is an electrically insulating material. Electrostatic charges can be applied to an electrically insulating member in many ways, including by plasma charging prior to assembly or use, for example.

In general, the electrical charge applied to a chargeable member can take on any magnitude and/or polarity, and may be equal to or differ from the charge applied to one or more other chargeable members, and may either be constant over time or vary as a function of time. Where the charge applied to a chargeable member is constant over time, it may, for example, be applied via a direct current (DC) electrical signal. Where the charge applied to a chargeable member varies over time, it may, for example, be applied via an alternating current (AC) electrical signal.

In the embodiments described above and shown in Figures 1 to 10, the actuator member 102 and the drive member 104 are both chargeable elements, and are the only chargeable elements. However, this need not be the case in other embodiments. For example, Figure 11 depicts an actuator having three conductive chargeable elements 102, 1102 and two dielectric elements 1104. In the illustrated embodiment, these three chargeable and conductive elements are the spherical rotor 102 and two part-spherical concave auxiliary or control electrodes 1102 arranged about the spherical rotor 102 and electrically insulated therefrom by respective air-filled gaps 1104. The two dielectric elements are thus the two air gaps 1104. More generally, however, the control electrodes 1102 may be insulated from the rotor 102 by dielectric elements or layers composed of air, another dielectric material (either a solid or fluid) or a combination of one or more layers of air and/or one or more other dielectric materials (either solids or fluids).

In any case, the interbody contact force between the drive member 104 and the actuator member (rotor) 102 can be controlled or modified by controlling the electrical charges on the electrodes 1102 and the rotor 102. The magnitudes and signs of these charges can be controlled as desired to increase or decrease (or both, varying with time) the contact force between the rotor 102 and the drive member 104.

For example, Figure 11 shows one possible arrangement of electric charges, wherein the rotor 102 and the control electrodes 1102 are all positively charged, such that there is an electrostatic force of repulsion between the control electrodes 1102 and the rotor 102, thereby repelling the rotor 102 into the drive member 104 and thus increasing the frictional coupling therebetween. Equivalently, the same effect can be produced by applying negative charges to the control electrodes 1102 and the rotor 102.

Similarly, Figure 12 depicts yet a further embodiment in which the drive member 104 is also chargeable and charged, providing a fourth chargeable element. In one possible arrangement of charges, as shown, positive charges are applied to the rotor 102 and the control electrodes 1102, generating electrostatic forces of mutual repulsion, and a negative charge is applied to the drive member 104, generating a force of attraction between it and the rotor 102. In this way, all of the electrostatic forces contribute to the compressive interbody contact force between the rotor 102 and the drive member 104. Alternatively, the drive member 104 may be electrically grounded to achieve the same result.

It will be apparent that the interbody contact forces between the actuator member 102 and the drive member 104 can be controlled or modified by changing the magnitude and/or polarity of the electrical charges on one or more of the control electrodes 1102, the actuator member 102, and/or the drive member(s) 104. For example, if the charges on the control electrodes 1102 and the drive member(s) 104 are changed in polarity while leaving the charge on the actuator member 102 unchanged, then the resulting electrostatic forces all act to decrease the interbody contact forces between the actuator member 102 and the drive member 104, and may even separate the actuator member 102 from the drive member 104, thereby disengaging the actuator member 102 so that it is no longer driven by the drive member 104.

Many other configurations are possible. For example, in some embodiments, motion of the actuator member 102 may be normally prevented (for example, by a physical stop) until the friction control components are electrically activated to move the actuator member 102 away from the stop or vice versa, thereby freeing the actuator member 102 and allowing it to be driven by the drive member 104.

Conversely, where the friction control components act to increase the interbody contact forces (and hence the frictional coupling) between the actuator member 102 and the drive member 104, a variety of different outcomes can be produced. For example, where the drive member 104 periodically drives the actuator member through a periodic or cyclic frictional coupling, as in the actuator described in Rogers, for example, the magnitude of the interbody contact force can be increased so that the actuator member 102 and the drive member 104 remain fully mutually engaged (*i.e.*, in the 'stick' mode) throughout the drive cycle; *i.e.*, irrespective of the position of the drive member 104. When the drive member 104 is driven in this fully engaged state, this results in the actuator member 102 remaining fully coupled or engaged with the drive member 104 throughout its drive cycle, so that the actuator member 102 oscillates about its current position and/or orientation, corresponding to the oscillatory motion of the drive member 104, with no net movement of the actuator member 102 per cycle. If the contact force is increased further, the vibration of the drive member 104 can be reduced or even suppressed entirely, so that the position and/or orientation of the drive member 104 remains in a fixed position and orientation.

Similarly if the drive member 104 is not driven while the actuator member 102 remains fully engaged to it, the actuator member 102 is effectively locked in its current position and/or orientation. By selectively driving and engaging the actuator member 102 in this way, the actuator member (*e.g.*, a rotor 102 or slider 402) can be driven to a desired position and/or orientation and then locked in that position and/or orientation by increasing the interbody contact forces between the actuator member 102 and the drive member(s) 104 to a level sufficient for the friction therebetween to be able to withstand any forces/torques applied to the actuator member 102. Accordingly, where one or more dielectric elements or layers 106, 306 are used to separate the actuator member 102 from the drive member(s) 104, they can be configured in such a way as to provide a relatively high coefficient of friction for the interface or joint.

Moreover, the ability to control the interbody contact force allows the actuator member 102 to 'stick' or lock in a desired position and/or orientation, but only when subjected to forces/torques up to a selected threshold force/torque value. When the actuator member 102 is subjected to forces/torques exceeding the predetermined threshold value, the actuator member 102 can then disengage or slip relative to the drive member 104. This ability to selectively lock up to a predetermined force/torque can be important in some applications; for example, to prevent harm to a patient during surgery (such as to prevent the tip of a steerable guidewire from perforating the wall of an artery if too much pressure is applied to the proximal end).

In embodiments where the drive member(s) 104 are driven by a piezoelectric element, there may be some risk that the electric fields associated with the friction control components may affect the operation of the piezoelectric element. In order to address this potential difficulty, some embodiments include least one shield or screen electrode to shield or screen the piezoelectric element from the electric fields associated with the friction control components.

For example, Figure 13 shows an actuator having electrostatic friction control components within a piezoelectric actuator or motor, wherein there are three chargeable elements 102, 104, 1302 and two dielectric elements or layers 106, 1306. In this configuration, the chargeable elements 102, 104, 1302 include the rotor 102 and a drive member 104 that are charged to generate a compressive electrostatic interbody contact force therebetween, while a third chargeable or screening element 1302 (insulated from the actuator drive component 104 by an intermediate dielectric layer 1306) is used to screen or shield a piezoelectric element 1304 from the electric field(s) generated by the electric charges on the other members. The rotor 102 and drive member 104 may have positive charge(s) or negative charge(s) applied to them, or may be electrically grounded, as described above. The screening element 1302 may have a positive charge or negative charge applied to it, or may be electrically grounded, but the magnitude and polarity of the charge are selected to reduce or cancel electric fields incident on the piezoelectric element 1304. The electrical charges applied to a given chargeable element can generally take on any value, magnitude and/or polarity, may be equal to or differ from one or more other chargeable elements, and may be either constant over time (*e.g.*, applied via a DC signal) or may vary over time (*e.g.*, applied via an AC signal).

The actuators described herein having friction control components that rely on non-contact forces generated by electric fields to control the frictional coupling can be fabricated in many ways, including those using standard fabrication methods known to those skilled in the art. For example, in some embodiments, either or both of the actuator member 102 and the drive member 104 are coated with a dielectric material. The dielectric material may be applied via one or more top-down and/or bottom-up methods, including, for example sputtering, chemical vapour deposition, plasma deposition, atomic layer deposition, cold or hot spraying, electro-plating, immersion and/or physical application (*e.g.*, painting). In some embodiments, two or more such dielectric application methods are used in a cumulative fashion.

In some embodiments, the chargeable elements include electrically conductive electrodes, wherein the charge carried by the electrodes is controlled using an electrical power source, such as via one or more electrical wires or brushes that are either permanently or non-permanently in electrical contact with the electrodes. In embodiments where both the actuator member 102 and the drive member 104 are chargeable, they will typically have opposite polarity charges applied to them so that they are electrostatically attracted to one another. In some embodiments, the thickness of the dielectric elements or layers is less than about one micrometre. In some embodiments, the dielectric elements or layers are composed of one or more materials with dielectric permittivities and breakdown strengths of about or greater than 30 and 100 MV/m, respectively. In some embodiments, the actuator member 102 and/or drive member(s) 104 are configured to increase the surface area upon which the electrostatic force acts. For example, in embodiments where the actuator member 102 is a spherical or cylindrical rotor, the drive member 104 may have a concave drive surface whose shape is complementary to that of the rotor 102, as shown in Figure 3, for example. This configuration improves the electrostatic force per unit electric potential (voltage) difference between two chargeable elements.

In the embodiments described above, the friction control components that control the force(s) applied to the actuator member 102 (and hence modify the frictional coupling between the actuator member 102 and the drive member(s) 104) achieve this by controlling one or more electrostatic forces of attraction and/or repulsion. However, in other embodiments, this control is achieved by controlling magnetic forces, rather than electrostatic forces.

A magnetic force is produced when an electrical current is passed through a conducting medium, such as an electrical wire or lead, which in turn generates a magnetic field that can act upon and impart force to a magnetic object. The current carrying conductor is commonly an electrical lead wound into a coil such that the magnetic field in the centre of the coil is linear and has a high strength. The strength of the magnetic field is a function of the number of turns in the coil, the cross-sectional area of the coil's core, and the amplitude of the current passing through the coil. Where an electromagnet is used to apply a magnetic force to a magnetic object, the strength of the magnetic force is also a function of the object.

Figure 14 is a schematic cross-sectional side view of an actuator of the general type described in Rogers, but having electromagnetic friction control components to modify, prevent and/or allow the rotary motion of a spherical (or cylindrical) actuator member or rotor 1402 composed of one or more magnetic materials. The interbody and interfacial contact force(s) between the rotor 1402 (or slider element in other embodiments) and a drive member 1404 is controlled by controlling the electrical current supplied to an electromagnetic coil 1406 disposed about the tip of the drive member 1404. By controlling the magnitude and direction of electric current flowing through the coil 1406, the interbody and interfacial contact forces between the rotor 1402 and the drive member 1404 can be increased, decreased and/or reversed, as desired. In general, in order to increase the generated magnetic field, the electromagnetic coil will have as many turns as practical.

In the embodiments described above, the friction control components operate by controlling one or more electric and/or magnetic fields that generate non-contact forces of attraction and/or repulsion between the actuator member 102, 1402 and at least one other component (*e.g.*, a drive member 104, 1404 or a control element co-located with the actuator member 102, 1402). That is, the frictional forces are directly controlled or modified by non-contact forces produced by electric and/or magnetic fields acting on the actuator member 102, 1402. However, this need not be the case in other embodiments, where the frictional forces are controlled and/or modified by directly applying forces to the actuator member 102, 1402 by physical contact and the direct application of pressure to a surface of the actuator member 102, 1402. For example, in some embodiments, the forces on the actuator member 102, 1402 are produced, at least in part, by physically pressing one or more electromechanically driven friction control components against the actuator member 102, 1402 itself; *i.e.*, by direct physical contact.

In some embodiments, an actuator includes one or more electromechanical latches, clamps or arms 1502 that physically contact and apply force(s) to an actuator member (*e.g.*, a rotor 102 or slider element 402), as shown in Figure 15. As with the non-contact embodiments described above, the contact forces control and/or modify the interbody forces between the rotor 102 and the drive member 104, thereby controlling the frictional coupling or mutual engagement between these components. The mechanical arms 1502 are themselves actuated or driven by an electromechanical actuation mechanism where, for example, the driving force is provided by a piezoelectric element(s) or by electric and/or magnetic fields. That is, the mechanical arms 1502 are part of a second electromechanical actuator used to control the frictional coupling between the drive member 104 and the actuator member 102 of the first actuator.

The contact arms 1502 shown in Figure 15 include spherical balls 1504 that are in physical contact with the rotor 102. The balls 1504 are disposed in a low friction coupling within the arms 1502 so that the balls can rotate freely. In contrast, Figure 16 shows a further embodiment in which the friction control components include arms 1602 having high friction pads 1604 that press against the rotor 102. In a further embodiment (not shown), an actuator includes at least one of the low friction arms 1502 of Figure 15 and at least one of the high friction arms 1602 of the type shown in Figure 16.

In such embodiments, where two or more contact mechanisms are used, the different contact mechanisms can be used for different purposes. For example, in some embodiments, one contact mechanism is used to apply relatively small mechanical contact forces and another contact mechanism is used to apply relatively large mechanical contact forces. For example, the contact arms 1502 with rotatable spherical balls 1504 can be used to apply mechanical contact forces but not lock a rotor or slider element, and the arms 1602 having high friction pads 1604 can be used to lock the rotor or slider element in a desired position and/or orientation.

Irrespective of whether the forces on the actuator member 102 are provided by electric and/or magnetic fields and/or direct physical contact, the actuators described herein can be used to control the frictional coupling between the actuator member 102 and the drive member(s) 104 for the purpose of providing a preload to the actuator member 102, as necessary for many actuators (*e.g.*, piezoelectric motors) to operate correctly and efficiently. In this case, the interbody contact forces may be constant over time or may vary over time. Where the actuator is an oscillator (*i.e.*, operates via vibration), such as the piezoelectric motor in Rogers, the interbody contact forces can be controlled by one or more AC signals having the same period of oscillation (drive frequency) as the actuator or motor. This allows the interbody contact forces to be controlled in-cycle to provide optimal modulation of the friction coupling and dynamics.

The actuators described herein can be used for a wide variety of applications. For example, the actuators may be used in a piezoelectric micro-motor. The piezoelectric micro-motor may be a multi degree-of-freedom (DOF) micro-motor of the general type described in Rogers. Such a multi-DOF piezoelectric micro-motor can be used in minimally invasive surgery.

Figure 17 shows part of a steerable guidewire device for use in interventional cardiology, neuroradiology and other minimally invasive procedures. The device includes a piezoelectric micro-motor integrated with a standard guidewire 1702 to provide steering. The device includes a spherical rotor element 1704, to which is attached a rotor arm 1706 that can be used to steer the guidewire and engage arterial bends and/or lesions. The device includes electrostatic friction control components to control the frictional coupling between the rotor element 1704 and a drive member 1708, thereby allowing the friction coupling between these two members to be controlled in order to maximise the torque imparted to the rotor element 1704 by the drive member 1708.

The electrostatic friction control components can also be used to lock the rotor element 1704 of the micro-motor, for example to prevent the rotor element 1704 from rotating and/or translating while the guidewire is being pushed through an arterial bend and/or lesion. In this way, once the rotor element 1704 has been moved to the desired position, it can be locked in place. Electrical wires 1710 are used to control the frictional coupling between the rotor element 1704 and the drive member 1708, and/or to lock the rotor 1704.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

CLAIMS:

1. An actuator, including:

   an actuator member; and

   a drive member configured to selectively apply drive forces to the actuator member via a frictional coupling therebetween, and to thereby drive corresponding linear and/or rotary motion of the actuator member; and

   one or more friction control components configured to electromechanically and selectively control or modify the frictional coupling between the drive member and the actuator member.

2. The actuator of claim 1, wherein the one or more friction control components electromechanically control at least one further force that determines the frictional coupling between the drive member and the actuator member.

3. The actuator of claim 2, wherein the drive forces are substantially orthogonal to the at least one further force.

4. The actuator of any one of claims 1 to 3, wherein the one or more friction control components are configured to electromechanically control and/or modify the frictional coupling between the drive member and the actuator member such that the linear and/or rotary motion of the actuator member can be selectively modified, prevented and/or allowed.

5. The actuator of any one of claims 1 to 4, wherein the one or more friction control components are configured to selectively lock the actuator member relative to the drive member.

6. The actuator of any one of claims 1 to 4, wherein the one or more friction control components are configured to selectively lock the actuator member relative to the drive member, but allow movement of the actuator member relative to the drive

member when the actuator member is subjected to a force or torque exceeding a selected force or torque determined by the friction control components.

7. The actuator of any one of claims 1 to 6, wherein the drive member is configured to drive the actuator member by periodically pressing against the actuator member to provide or increase the frictional coupling therebetween while moving in a direction substantially transverse to said pressing.

8. The actuator of any one of claims 1 to 7, wherein one or more of the friction control components are configured to electromechanically modify the frictional coupling between the drive member and the actuator member as a function of time.

9. The actuator of claim 8, wherein one or more of the friction control components modify the frictional coupling as a function of time based on a corresponding alternating current (AC) electrical signal.

10. The actuator of any one of claims 1 to 9, wherein the modification of the frictional coupling is controlled by a direct current (DC) electrical signal applied to one or more of the friction control components.

11. The actuator of any one of claims 1 to 10, wherein the frictional coupling is controlled to increase the operability, functionality, performance or efficiency of the actuator.

12. The actuator of any one of claims 1 to 11, wherein the one or more friction control components are configured to electromechanically control the frictional coupling between the drive member and the actuator member by controlling non-contact forces of attraction and/or repulsion between the actuator member and at least one other component of the actuator.

13. The actuator of claim 12, wherein the at least one other component of the actuator includes the drive member.

14. The actuator of claim 12, wherein the at least one other component of the actuator includes one or more friction control members spaced from the actuator member and the drive member.

15. The actuator of any one of claims 12 to 14, wherein the non-contact forces of attraction and/or repulsion include non-contact forces generated by one or more electric fields.

16. The actuator of claim 15, wherein the one or more electric fields are generated by electric charges on the actuator member and the at least one other component of the actuator, at least a first part of the actuator member and at least a first part of the at least one other component of the actuator being electrically conductive and mutually insulated by at least one electrically insulating or dielectric material.

17. The actuator claim 15, wherein the one or more electric fields are generated by electric charges on the actuator member and the at least one other component of the actuator, at least one of the actuator member and the at least one other component of the actuator being composed of at least one electrically insulating or dielectric material.

18. The actuator of claim 16 or 17, wherein the one or more electrically insulating or dielectric materials have high dielectric permittivities and/or high dielectric breakdown strengths.

19. The actuator of any one of claims 16 to 18, wherein the one or more electrically insulating or dielectric materials include one or more thin films.

20. The actuator of any one of claims 15 to 19, further including one or more chargeable elements configured to screen the one or more electric fields from other components of the actuator.

21. The actuator of any one of claims 12 to 20, wherein the non-contact forces of attraction and/or repulsion include non-contact forces generated by at least one magnetic field.

22. The actuator of any one of claims 1 to 11, wherein the one or more friction control components are configured to electromechanically control the frictional coupling between the drive member and the actuator member by physically pressing the actuator member against the drive member.

23. The actuator of any one of claims 1 to 22, wherein the drive member is configured to vibrate longitudinally and/or transversely to frictionally drive the actuator member.

24. The actuator of any one of claims 1 to 23, wherein the actuator is part of a surgical device.

25. The actuator of any one of claims 1 to 24, wherein the actuator is part of a guidewire or catheter device for use in interventional cardiology, neuroradiology and/or other minimally invasive medical procedures.

26. The actuator of any one of claims 1 to 25, wherein the dimensions of the actuator member are millimetre scale dimensions.

27. The actuator of any one of claims 1 to 25, wherein the dimensions of the actuator member are micrometre scale dimensions.

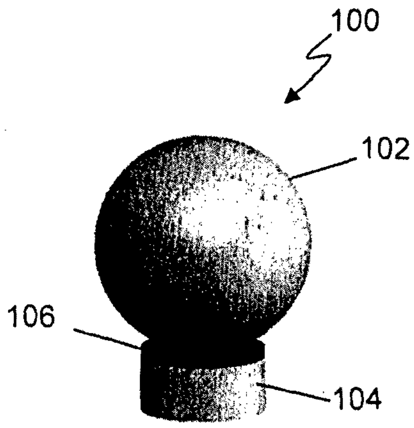

FIG. 1

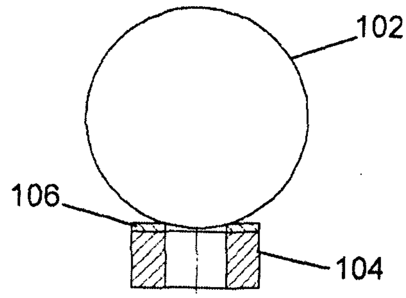

FIG. 2

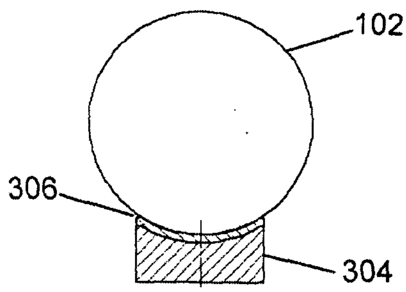

FIG. 3

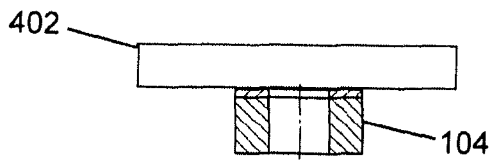

FIG. 4

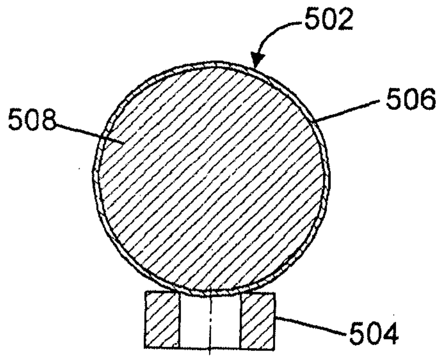

FIG. 5

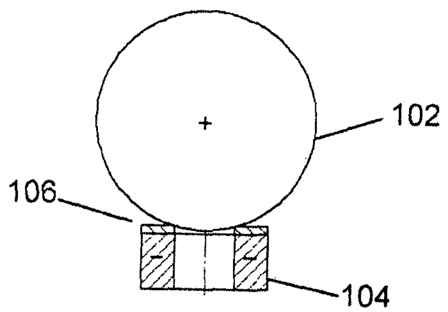

FIG. 6

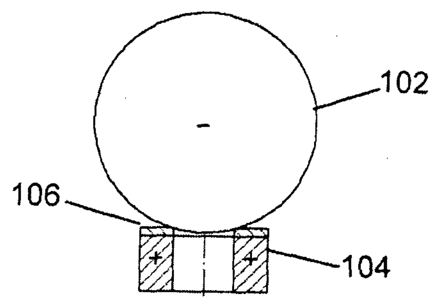

FIG. 7

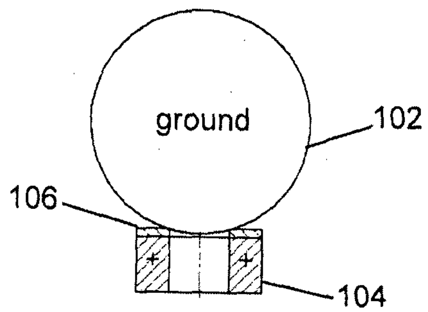

FIG. 8

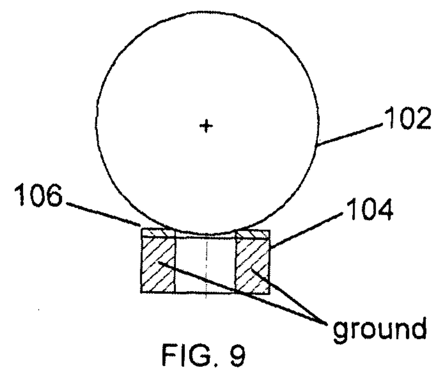

FIG. 9

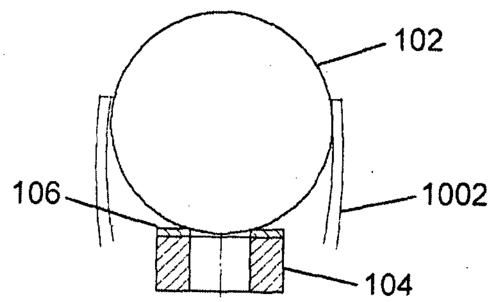

FIG. 10

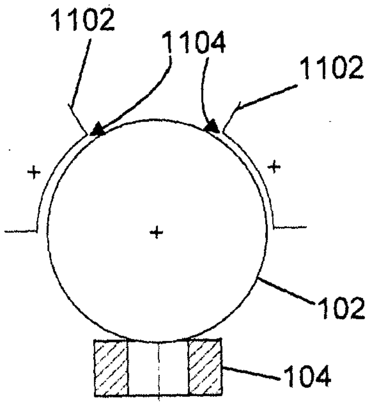

FIG. 11

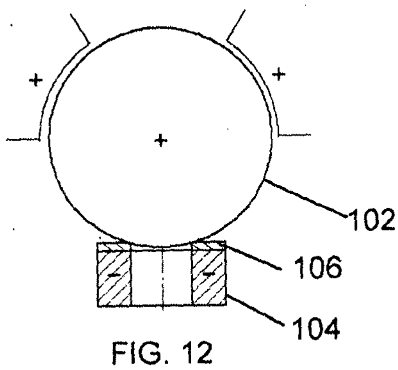

FIG. 12

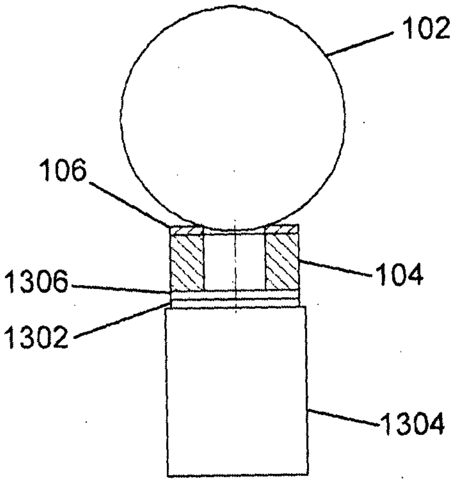

FIG. 13

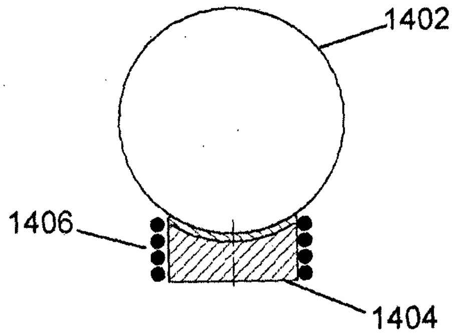

FIG. 14

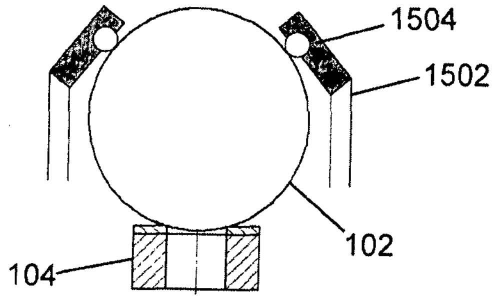

FIG. 15

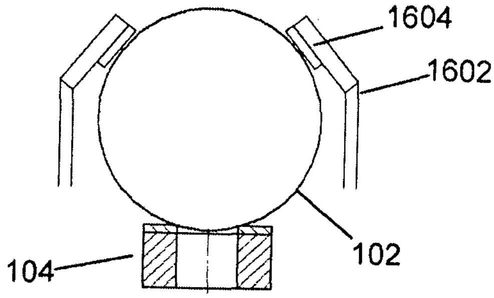

FIG. 16

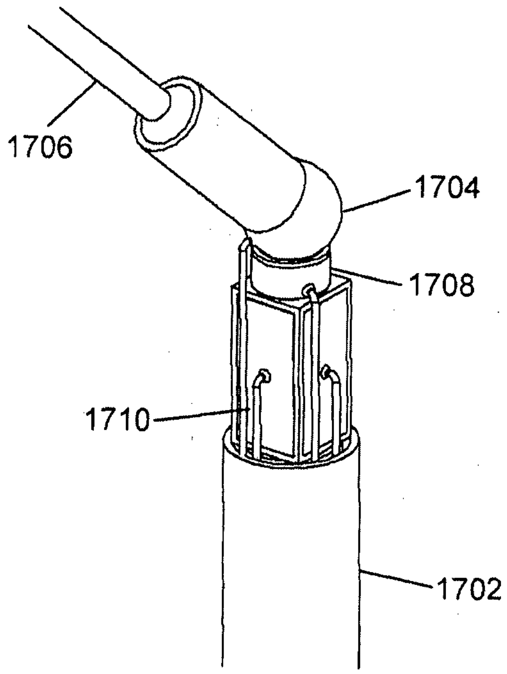

FIG. 17

INTERNATIONAL SEARCH REPORT	International application No. **PCT/AU2013/000954**

A. CLASSIFICATION OF SUBJECT MATTER

H02N 2/12 (2006.01) H01L 41/04 (2006.01) H01L 41/047 (2006.01) H01L 41/09 (2006.01) B25J 7/00 (2006.01) B81B 5/00 (2006.01)

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)

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)

Searched Databases EPODOC, WPI with IPC marks H02N2/10/LOW, A61M and with keywords: "friction control", "electric field", electromechanically, "degrees of freedom", actuator, insulator, "minimally invasive surgery", and other similar terms.

Searched Google Patents and Google Scholar with keywords: actuator, "minimaly invasive, surgical, frictional coupling, magnetic, coil, charge, "multi DOF", spherical, electromechanical, guidewire, insulator, rotor and other similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C   [X] See patent family annex

* Special categories of cited documents:

"A"	document defining the general state of the art which is not considered to be of particular relevance	"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
"E"	earlier application or patent but published on or after the international filing date	"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
"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)	"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
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
14 October 2013	14 October 2013
Name and mailing address of the ISA/AU	**Authorised officer**
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au Facsimile No.: +61 2 6283 7999	Shuchin Taher AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832862

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	PCT/AU2013/000954

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/0320869 A1 (LI et al.) 23 December 2010 See the whole document, in particular, the abstract, fig. 1-7, para. 0019-0027.	1-27
A	US 5415633 A (LAZARUS et al.) 16 May 1995 See the whole document.	

INTERNATIONAL SEARCH REPORT	International application No.
Information on patent family members	PCT/AU2013/000954

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
US 2010/0320869 A1	23 Dec 2010	US 7973450 B2	05 Jul 2011
US 5415633 A	16 May 1995	EP 0712320 A1	22 May 1996
		US 5415633 A	16 May 1995
		WO 9504556 A2	16 Feb 1995

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.