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- (71) **Applicant (for all designated States except US):**
**AGENCY FOR SCIENCE, TECHNOLOGY AND RE-
SEARCH** [SG/SG]; 1 Fusionopolis Way #20-10, Connex-
is, Singapore 138632 (SG).
- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only):** **FONG, Wee Teck**
[SG/SG]; c/o PKM, Institute for Infocomm Research, 1 Fu-
sionopolis Way, #21-01 Connexis South Tower, Singapore
138632 (SG). **CHER, Jingting** [SG/SG]; c/o PKM, Insti-

tute for Infocomm Research, 1 Fusionopolis Way, #21-01
Connexis South Tower, Singapore 138632 (SG).

- (74) **Agent:** **VIERING, JENTSCHURA & PARTNER LLP;**
P.O. Box 1088, Rochor Post Office, Rochor Road, Singa-
pore 911833 (SG).
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- (54) **Title:** A HAPTIC ACTUATOR, A METHOD OF FORMING THE HAPTIC ACTUATOR AND A METHOD OF CON-
TROLLING THE HAPTIC ACTUATOR, A HAPTIC DEVICE AND A METHOD OF FORMING THE HAPTIC DEVICE

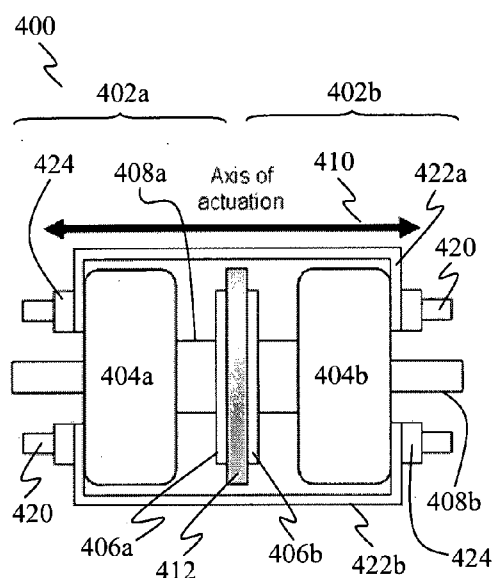


FIG. 4A

(57) **Abstract:** According to embodiments of the present in-
vention, a haptic actuator is provided. The haptic actuator in-
cludes a first solenoid comprising a first body and a first
base, and a second solenoid comprising a second body and a
second base, the first base and the second base being
coupled with each other and movable between the first body
and the second body, such that the first base and the second
base generate a first force on the first body when a first elec-
trical signal is applied to the first solenoid and generate a
second force on the second body when a second electrical
signal is applied to the second solenoid. Further embodi-
ments relate to a method of forming the haptic actuator, a
method of controlling the haptic actuator, a haptic device
comprising the haptic actuator and a method of forming the
haptic device.

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A HAPTIC ACTUATOR, A METHOD OF FORMING THE HAPTIC ACTUATOR
AND A METHOD OF CONTROLLING THE HAPTIC ACTUATOR, A HAPTIC
DEVICE AND A METHOD OF FORMING THE HAPTIC DEVICE

5 **Cross-Reference To Related Application**

[0001] This application claims the benefit of priority of Singapore patent application No. 201009241-9, filed 13 December 2010, the content of it being hereby incorporated by reference in its entirety for all purposes.

10 **Technical Field**

[0002] Various embodiments relate to a haptic actuator, a method of forming the haptic actuator and a method of controlling the haptic actuator. Further embodiments relate to a haptic device and a method of forming the haptic device.

Background

[0003] Haptics is the science of applying touch (tactile) sensation and control, which for example may be applied for interaction with computer applications. By using special input/output devices (e.g. joysticks, data gloves, or other similar devices), users can receive feedback from computer applications in the form of felt sensations in the hand or other parts of the body. In combination with a visual display, haptic technology can be used to train people for tasks requiring hand-eye coordination, such as surgery and space ship manoeuvres. It can also be used for games. For example, in a mixed reality tennis game where the player or user can see the moving ball, by using the haptic device (e.g. in the form of a tennis racket), position and swing of the tennis racket, the user can feel the impact of the ball.

[0004] Haptic sensory information falls into two categories: tactile and kinesthetic (or force feedback) information. The initial sense of contact is provided by the touch receptors in the skin, for example of a hand, which also provide information on the

contact surface geometry, the surface texture of an object, and slippage. When the hand applies more force, kinesthetic information comes into play, providing details about the position and motion of the hand and arm, and the forces acting on them, to give a sense of total contact forces, surface compliance, and weight if the hand is supporting an object in some way. In general, tactile and kinesthetic sensing occurs simultaneously.

[0005] Currently, the most common methods used for haptic feedback are based on electromagnetic motors, hydraulics, and pneumatic actuators. Some low-end haptic devices are already common in the form of game controllers, in particular, in the form of joysticks and steering wheels. Initially, such features and/or haptic devices were optional components for game consoles but have increasingly become part of the game consoles to enhance the users' sense of reality during gameplay. However, not many game controllers provide such haptic devices.

[0006] Some of the newer generation console controllers, joystick features and game controllers now have built-in haptic devices, for example such as that of Sony's Dualshock technology. The Wii wireless remote controller also provides feedback, but uses a simpler vibration mechanism for haptic feedback compared to Sony's remote controller. Another example of such game controller is the simulated automobile steering wheels that are programmed to provide a "feel" of the road. As the user makes a turn or accelerates, the steering wheel responds by resisting turns or slipping out of control.

[0007] The common approach for vibration-based haptic feedback is using DC-motors or piezo-actuators based approach. The main advantages of vibration-based haptic feedback are that it offers a low-cost and a tether-less approach. However, the perceived haptic feedback is far from being realistic.

[0008] One of the most popular methods in providing haptic force feedback is to use a series of cables attached to the user's body. Although such methods achieve realistic haptic feel, such tether solutions using cable systems restrict the user's movement and hence, they are not suitable for applications such as ball games (e.g. tennis).

Summary

[0009] According to an embodiment, a haptic actuator is provided. The haptic actuator may include a first solenoid including a first body and a first base, and a second solenoid including a second body and a second base, the first base and the second base being coupled with each other and movable between the first body and the second body, such that the first base and the second base generate a first force on the first body when a first electrical signal is applied to the first solenoid and generate a second force on the second body when a second electrical signal is applied to the second solenoid.

[0010] According to an embodiment, a method of forming a haptic actuator is provided. The method may include providing a first solenoid including a first body and a first base, providing a second solenoid including a second body and a second base, and coupling the first base and the second base with each other, wherein the first base and the second base are movable between the first body and the second body, such that the first base and the second base generate a first force on the first body when a first electrical signal is applied to the first solenoid and generate a second force on the second body when a second electrical signal is applied to the second solenoid.

[0011] According to an embodiment, a method of controlling a haptic actuator as described above is provided. The method may include applying a first electrical signal to the first solenoid such that the first base and the second base generate a first force on the first body.

[0012] According to an embodiment, a haptic device for ungrounded haptic feedback is provided. The haptic device may include at least one haptic actuator as described above, and a circuit electrically coupled to the at least one haptic actuator.

[0013] According to an embodiment, a method of forming a haptic device for ungrounded haptic feedback is provided. The method may include forming at least one haptic actuator as described above, and electrically coupling a circuit to the at least one haptic actuator.

Brief Description of the Drawings

[0014] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis
5 instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0015] FIG. 1A shows a schematic block diagram of a haptic actuator, according to various embodiments.

10 [0016] FIG. 1B shows a schematic block diagram of a haptic actuator, according to various embodiments.

[0017] FIG. 1C shows a schematic block diagram of a haptic device, according to various embodiments.

15 [0018] FIG. 1D shows a schematic block diagram of a haptic device, according to various embodiments.

[0019] FIG. 2A shows a flow chart illustrating a method of forming a haptic actuator, according to various embodiments.

[0020] FIG. 2B shows a flow chart illustrating a method of controlling a haptic actuator, according to various embodiments.

20 [0021] FIG. 2C shows a flow chart illustrating a method of forming a haptic device, according to various embodiments.

[0022] FIGS. 3A and 3B respectively show a schematic side view and a perspective view of a solenoid, according to various embodiments.

25 [0023] FIGS. 4A and 4B respectively shows a schematic side view and a perspective view of a haptic actuator, according to various embodiments.

[0024] FIG. 4C shows a perspective view of a haptic actuator, according to various embodiments.

30 [0025] FIGS. 5A and 5B show schematic side views of the haptic actuator of the embodiments of FIG. 4A and 4B in an operational configuration, according to various embodiments.

[0026] FIG. 6A shows a schematic representation of a haptic actuator and a circuit for controlling the haptic actuator, according to various embodiments.

[0027] FIGS. 6B and 6C show respectively different electrical signals for controlling a haptic actuator, according to various embodiments.

5 [0028] FIG. 7 shows a schematic block diagram of a haptic actuator and a circuit for controlling the haptic actuator, according to various embodiments.

[0029] FIG. 8 shows details of the components of the embodiment of FIG. 7.

[0030] FIG. 9A shows a schematic view of a haptic device, according to various embodiments.

10 [0031] FIG. 9B shows a schematic view of a haptic device, according to various embodiments.

[0032] FIG. 10 shows photographs of the haptic device of the embodiment of FIG. 9B.

[0033] FIG. 11A shows a plot of acceleration measurement for a haptic actuator of the haptic device of the embodiment of FIG. 9B.

15 [0034] FIG. 11B shows a plot of acceleration measurement for the haptic device of the embodiment of FIG. 9B.

Detailed Description

20 [0035] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope
25 of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0036] Embodiments described in the context of one of the methods or devices are analogously valid for the other method or device. Similarly, embodiments described in
30 the context of a method are analogously valid for a device, and vice versa.

[0037] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a variance of +/- 5% thereof. As an example and not limitations, “A is at least substantially same as B” may encompass embodiments where A is exactly the same as B, or where A may be within a variance of +/- 5%, for example of a value, of B, or vice versa.

[0038] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a variance of +/- 5% of the value.

[0039] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0040] Various embodiments provide a tether-less (untethered) haptic approach that provides realistic haptic sensations and feedback force, for example reactive forces and impulsive forces, in a mixed reality environment, without or with reduced at least some of the associated disadvantages of conventional systems and approaches.

[0041] Various embodiments may provide an ungrounded mobile haptic actuator for single-axis high force tactile feedback, and a haptic device employing the haptic actuator.

[0042] Various embodiments may provide a haptic actuator having a pair of solenoids (e.g. a pair of lightweight, low impedance solenoids), coupled or arranged back-to-back, to provide high force ungrounded haptic feedback. Various embodiments may further provide a haptic device including at least one haptic actuator of various embodiments.

[0043] In various embodiments, attaching the pair of solenoids back-to-back allows the shaft of each solenoid to actuate back and forth, bi-directionally, as well as to hold as a magnetic clutch. This eliminates the need for a mechanical structure such as a spring, while allowing the pair of solenoids to be held securely when no actuation is carried out.

In various embodiments, when powered by a power supply (e.g. a battery, e.g. a high capacity battery with milli-ohm internal resistance), the energized solenoids may be able to produce high forces without sacrificing mobility. Furthermore, by varying the power or current through the solenoids, the strength of the actuation may be controlled, resulting in various degrees of tactile feedback.

[0044] In various embodiments, the haptic device incorporates a tether-less approach. In other words, the haptic device may employ a wireless approach for communication

between a remote terminal such as a processing device (e.g. a computer) and the haptic actuator or haptic device, for example for use in a haptic system, without any wire or cable connections that may limit the freedom of movement of the user(s).

[0045] Various embodiments provide an ungrounded haptic interface. In other words, the haptic actuator and haptic device of various embodiments are ungrounded, configured to provide ungrounded haptic feedback. The term “ungrounded” as applied to a haptic actuator and a haptic device, means that the haptic actuator and haptic device need not be attached to a static object (e.g. a table) or affixed to part of the user’s body, for leverage, to generate the intended interaction loads. Such an approach allows portability, and correspondingly enable use of the ungrounded haptic actuator and device in a large workspace.

[0046] Various embodiments may provide a haptic device configured to simulate an impact or a collision caused by a virtual object incident on a surface (i.e. a surface impact) of a device, for example at an impact point. In addition, various embodiments may provide a haptic device configured to provide force feedback (e.g. impulsive force feedback and/or torque feedback) in one axis, two axes, three axes or multiple axes or provide force feedback in one direction, two directions, three directions or multiple directions.

[0047] Various embodiments may provide a haptic device including one or more haptic actuators of various embodiments arranged on the haptic device. The one or more haptic actuators may be actuated or driven to generate a physical sensation and haptic feedback, such as impulsive force feedback and torque feedback, to a user using the haptic device. In various embodiments, each haptic actuator includes a pair of solenoids arranged back-to-back. Each solenoid in the haptic actuator may be actuated by an electrical signal (e.g. a current), where the electrical signal may be generated and/or controlled by, for example a microcontroller. In various embodiments where a plurality of haptic actuators are provided, the plurality of haptic actuators may be arranged in any particular spatial pattern on the haptic device, and may be actuated selectively, consecutively or simultaneously in accordance with the haptic feedback to be generated.

[0048] The haptic actuator and haptic device of various embodiments may be employed in a mixed reality environment, for example mixed reality game simulations, where a user

in the mixed reality environment interacts with a virtual object or objects using a physical device. The haptic actuator and device may be employed for mixed reality games, virtual sports simulations or human-computer interaction games. For example, in a mixed reality game or virtual sports simulation, for example a tennis, squash or table tennis game simulation, the physical device may be a racket or racquet held by a user (human player), and the virtual object is a virtual ball. Furthermore, the virtual sports simulation may include the game of badminton, where the virtual object is a virtual shuttlecock. In addition, the virtual sports simulation is not limited to racquet sports simulations and the haptic actuator and haptic device of various embodiments may be configured to be used with or on other sports equipment such as a bat for sports simulations of cricket, baseball, etc. The haptic actuator and device of various embodiments may also be adapted to be used with or on a sword or a striking weapon in mixed reality martial art games. In various embodiments, the haptic actuator and haptic device may provide realistic feedback force that imparts a physical sensation and a reactive force sensation corresponding to the interaction with the virtual object or objects.

[0049] Various embodiments may provide untethered high-g haptic actuators and impact devices (haptic devices) for virtual reality and gaming applications (e.g. sports simulation such as tennis, golf, baseball and hockey, weapons simulation and games). The haptic actuators of various embodiments may also be used to replace vibration motors in the current game controllers to produce impacts rather than rumbles. In the context of various embodiments, the term "high-g" may mean a force output of accelerations of 10-g or more (i.e. $\geq 10\text{-g}$), in other words, 10 times or more that of the Earth's gravity.

[0050] The untethered haptic actuator and the untethered haptic device including one or more haptic actuators may be lightweight, have small dimensions and capable of generating high-g impacts that may be required in virtual reality and games to simulate impacts, such as weapon recoil and hitting the ball by a racket. The haptic actuator incorporates a solenoid-based approach that uses a current pulse that delivers more than 100 watts of power in an instant, where the haptic actuator, and therefore the haptic device may generate a high force output, of accelerations in excess of 25-g, in other words, more than 25 times that of the Earth's gravity, for high-g impacts. This allows a sharp impact to be created or generated, in contrast to rumbling of a vibration motor,

which is the commonly deployed solution for untethered force feedback. The haptic device may be easily held in a user's hand, and the user may pick up the haptic device and use it with no complicated set-up necessary. Furthermore, the untethered haptic device allows the user to move freely, without restraints of cables or mechanical structures.

[0051] In various embodiments, the haptic actuator employs a springless and bi-directional push-pull configuration based on a pair of solenoids, where the pair of solenoids may be coupled back-to-back. Such a configuration allows actuation in two directions such that impacts may be generated in two directions, and magnetic latching of a solenoid in the haptic actuator at maximum stroke length for maximum impact force, while avoiding the use of returning springs, which reduce the actuator force output. The haptic actuator of various embodiments may weigh about 100 grams or less (i.e. ≤ 100 g)

[0052] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

[0053] FIG. 1A shows a schematic block diagram of a haptic actuator 100, according to various embodiments. The haptic actuator 100 includes a first solenoid 102 including a first body 104 and a first base 106, and a second solenoid 108 including a second body 110 and a second base 112, the first base 106 and the second base 112 being coupled with each other and movable between the first body 104 and the second body 110, such that the first base 106 and the second base 112 generate a first force on the first body 104 when a first electrical signal is applied to the first solenoid 102 and generate a second force on the second body 110 when a second electrical signal is applied to the second solenoid 108. The line represented as 114 is illustrated to show the relationship between the first solenoid 102 and the second solenoid 108, which includes mechanical coupling.

[0054] The first force may be generated, for example, when the first base 106 and the second base 112 impact or collide with the first body 104 of the first solenoid 102, for example by contacting the first body 104. The second force may be generated, for example, when the first base 106 and the second base 112 impact or collide with the second body 110 of the second solenoid 108, for example by contacting the second

body 110. In the context of various embodiments, the first force that is generated may or may not be equal to the second force that is generated.

[0055] The phrase “generate a force”, as used herein, may be interchangeably used with the phrases “create a force”, “produce a force”, “generate an impact” or “produce an impact”, for simulating haptic/tactile feedback. The force that is generated may be an impact force, a collision force or an actuation force.

[0056] FIG. 1B shows a schematic block diagram of a haptic actuator 120, according to various embodiments. The haptic actuator 120 includes a first solenoid 102 comprising a first body 104 and a first base 106, and a second solenoid 108 comprising a second body 110 and a second base 112, which may be similar to the embodiment as described in the context of FIG. 1A.

[0057] The haptic actuator 120 may further include a first shaft 122 coupled to the first base 106, the first shaft 122 being received in a first bore defined through the first body 104. The haptic actuator 120 may further include a second shaft 124 coupled to the second base 112, the second shaft 124 being received in a second bore defined through the second body 110.

[0058] The haptic actuator 120 may further include a plate 126 coupled between the first base 106 and the second base 112. The plate 126 may have a cross-sectional dimension that is larger than respective cross-sectional dimensions of the first base 106 and the second base 112.

[0059] The haptic actuator 120 may further include a mounting structure 128 configured to hold the first solenoid 102 and the second solenoid 108. The mounting structure 128 may include or may be a pair of brackets.

[0060] The line represented as 130 is illustrated to show the relationship between the different components, which includes mechanical coupling.

[0061] FIG. 1C shows a schematic block diagram of a haptic device 150, according to various embodiments. The haptic device 150 includes at least one haptic actuator (e.g. the haptic actuator 100 of FIG. 1A or the haptic actuator 120 of FIG. 1B), and a circuit (e.g. a control circuit) 152 electrically coupled to the at least one haptic actuator. The line represented as 154 is illustrated to show the relationship between the different components, which may include electrical coupling and/or mechanical coupling.

[0062] FIG. 1D shows a schematic block diagram of a haptic device 160, according to various embodiments. The haptic device 160 includes at least one haptic actuator (e.g. the haptic actuator 100 of FIG. 1A or the haptic actuator 120 of FIG. 1B), and a circuit 152, which may be similar to the embodiment as described in the context of FIG. 1C. In the context of various embodiments, the haptic device 160 may include a plurality of haptic actuators.

[0063] In the haptic device 160, the circuit 152 may include a first transistor 162 electrically coupled to the first solenoid 102, and a second transistor 164 electrically coupled to the second solenoid 108. The circuit 152 may further include a microcontroller 166 electrically coupled to the first transistor 162 and the second transistor 164.

[0064] The circuit 152 may further include a power supply 168. The circuit 152 may further include a buck-boost regulator (e.g. a DC-DC buck-boost regulator) 170 configured to regulate an output voltage of the power supply 168. The circuit 152 may further include a wireless transceiver 172 configured to communicate with a remote terminal (e.g. a computer).

[0065] The circuit 152 may further include an inertial measurement circuit 174 configured to determine a direction of the haptic device 160.

[0066] The line represented as 176 is illustrated to show the relationship between the different components, which which may include electrical coupling and/or mechanical coupling.

[0067] FIG. 2A shows a flow chart 200 illustrating a method of forming a haptic actuator, according to various embodiments.

[0068] At 202, a first solenoid including a first body and a first base is provided.

[0069] At 204, a second solenoid including a second body and a second base is provided.

[0070] At 206, the first base and the second base are coupled with each other, wherein the first base and the second base are movable between the first body and the second body, such that the first base and the second base generate a first force on the first body when a first electrical signal is applied to the first solenoid and generate a second force on the second body when a second electrical signal is applied to the second solenoid.

[0071] The first force may be generated, for example, when the first base and the second base impact or collide with the first body of the first solenoid, for example by contacting the first body. The second force may be generated, for example, when the first base and the second base impact or collide with the second body of the second solenoid, for example by contacting the second body. In the context of various embodiments, the first force that is generated may or may not be equal to the second force that is generated.

[0072] The phrase “generate a force”, as used herein, may be interchangeably used with the phrases “create a force”, “produce a force”, “generate an impact” or “produce an impact”, for simulating haptic/tactile feedback. The force that is generated may be an impact force, a collision force or an actuation force.

[0073] The method may further include coupling a first shaft to the first body, and receiving the first shaft in a first bore defined through the first body. The method may further include coupling a second shaft to the second base, and receiving the second shaft in a second bore defined through the second body.

[0074] The method may further include coupling a plate between the first base and the second base. The plate may have a cross-sectional dimension that is larger than respective cross-sectional dimensions of the first base and the second base.

[0075] The method may further include providing a mounting structure configured to hold the first solenoid and the second solenoid. The mounting structure may include or may be a pair of brackets.

[0076] FIG. 2B shows a flow chart 220 illustrating a method of controlling a haptic actuator, according to various embodiments. The haptic actuator may be of the embodiment of the haptic actuator 100 of FIG. 1A or the haptic actuator 120 of FIG. 1B.

[0077] At 222, a first electrical signal (e.g. a pulse width modulation signal) is applied to the first solenoid such that the first base and the second base generate a first force on the first body. The first force may be generated, for example, when the first base and the second base impact or collide with the first body of the first solenoid, for example by contacting the first body. The phrase “generate a force”, as used herein, may be interchangeably used with the phrases “create a force”, “produce a force”, “generate an impact” or “produce an impact”, for simulating haptic/tactile feedback. The force that is generated may be an impact force, a collision force or an actuation force.

[0078] The method may further include applying a second electrical signal (e.g. a low duty or low duty ratio pulse width modulation signal) to the second solenoid to move the first base and the second base proximal to the second body, wherein the second electrical signal has a power that is lower than a power of the first electrical signal. The second electrical signal may be continuously applied to the second solenoid. In other words, the second electrical signal may be applied prior to applying the first electrical signal, and continuously applied even after the first electrical signal has been applied.

[0079] In various embodiments, the first electrical signal (e.g. current) may include or may be an electrical pulse (i.e. a single electrical pulse), in order to create a single strong impact. The electrical pulse may have a duration of between about 1 ms and about 20 ms, e.g. between about 1 ms and about 10 ms or between about 5 ms and about 10 ms, e.g. about 5 ms, about 10 ms or about 20 ms. In various embodiments, as an example and not limitation, the duration of the electrical pulse, with maximum current input, may be within about 5 ms or less than about 5 ms for the base of a solenoid to move through the maximum stroke length of the solenoid (e.g. where the motion range of the solenoid has run out). Therefore, the duration of the electrical pulse applied may depend on the maximum stroke length of a solenoid and/or the amplitude of the electrical pulse. In various embodiments with a lower duty cycle, the movement of the base may be slowed down, resulting in a lower impact or force that is generated, by applying a pulse of increased duration, e.g. about 20 ms. In addition, the amplitude of the pulse may be decreased to reduce the force.

[0080] In various embodiments, the first electrical signal (e.g. current) may include or may be a plurality of electrical pulses, for creating any impact force less than the maximum force. Each electrical pulse of the plurality of electrical pulses may have a duration of between about 10 μ s and about 100 μ s, e.g. between about 20 μ s and about 80 μ s or between about 20 μ s and about 50 μ s. For example, instead of applying a single electrical pulse having a duration, T , a plurality of pulses may be applied to the first solenoid during the duration, T .

[0081] The plurality of electrical pulses may have a period of less than about 1 ms (or a frequency of more than about 1 kHz). It should be appreciated that the period may be, for

example, less than about 0.8 ms, less than about 0.5 ms, less than about 0.1 ms or less than about 0.05 ms, e.g. about 0.01 ms (i.e. 10 μ s; i.e. a frequency of about 100 kHz).

[0082] In various embodiments, multiple pulses may be applied alternately to the first solenoid and the second solenoid in order to maximize the stroke length of each cycle of the haptic actuator and achieve a stronger force or impact output. Each cycle of the actuator refers to the actuation by the first solenoid and the actuation by the second solenoid. Each pulse may have a duration of between about 1 ms and about 20 ms, e.g. between about 1 ms and about 10 ms or between about 5 ms and about 10 ms, e.g. about 5 ms, about 10 ms or about 20 ms.

[0083] FIG. 2C shows a flow chart 240 illustrating a method of forming a haptic device, according to various embodiments.

[0084] At 242, at least one haptic actuator is formed. The at least one haptic actuator may be of the embodiment of the haptic actuator 100 of FIG. 1A or the haptic actuator 120 of FIG. 1B.

[0085] At 244, a circuit (e.g. a control circuit) is electrically coupled to the at least one haptic actuator.

[0086] The method may further include arranging a first transistor and a second transistor in the circuit, electrically coupling the first transistor to the first solenoid, and electrically coupling the second transistor to the second solenoid.

[0087] The method may further include arranging a microcontroller in the circuit, and electrically coupling the microcontroller to the first transistor and the second transistor.

[0088] The method may further include arranging a power supply in the circuit.

[0089] The method may further include arranging a buck-boost regulator in the circuit, the buck-boost regulator being configured to regulate an output voltage of the power supply.

[0090] The method may further include arranging a wireless transceiver in the circuit, the wireless transceiver being configured to communicate with a remote terminal.

[0091] The method may further include arranging an inertial measurement circuit in the circuit, the inertial measurement circuit being configured to determine a direction of the haptic device.

[0092] In the context of various embodiments, the haptic device (e.g. 150, 160) may be or may include a sports racquet with a racquet head. In various embodiments, the at least one actuator (e.g. 100, 120) may be arranged at a sweet spot of the racquet head.

5 [0093] In the context of various embodiments, the haptic device (e.g. 150, 160) may include three haptic actuators. In various embodiments, the haptic device (e.g. 150, 160) may be at least substantially Y-shaped, and wherein each of the three haptic actuators may be arranged at a respective end of the Y-shaped device.

[0094] In the context of various embodiments, the first solenoid and the second solenoid may be interchangeable, for example depending on the configuration of the haptic
10 actuator and use of the haptic actuator.

[0095] In the context of various embodiments, the term “solenoid” includes an electromechanical solenoid. The term “solenoid” includes a linear solenoid. Each solenoid may provide an impulsive force feedback and/or a torque feedback. In contrast, components such as vibrators, motors (e.g. DC motors) and piezo-actuators generate a
15 trembling sensation. In addition, motors and rotary actuators use rotary motions to generate vibrations which are not concentrated along a single axis.

[0096] In the context of various embodiments, the haptic actuator includes a pair of solenoids coupled back-to-back. In various embodiments, one or more haptic actuators (e.g. two, three, four or five haptic actuators) may be used, for example on a haptic
20 device, to simulate and provide realistic impact sensations, for example a collision with a virtual object in a mixed reality environment such as a racquet game simulation.

[0097] In the context of various embodiments, the first base and the second base being coupled with each other may include direct coupling (e.g. the first base and the second base directly in contact with each other) and indirect coupling, with an intervening
25 structure (e.g. a plate), in between the first base and the second base.

[0098] In the context of various embodiments, the term “base” may include any portion of the solenoid which may be movable relative to the solenoid body along an axis of actuation, and may generate a force (e.g. an impact force or an actuation force) on the solenoid body to provide the haptic feedback. As examples and not limitations, the force
30 may be generated when the base impacts or collides with the solenoid body, for example by contacting the solenoid body.

[0099] In the context of various embodiments, “electrically coupled” may be achieved by, for example electrical interconnections (e.g. wire or bus).

[0100] In the context of various embodiments, the terms “racket” and “racquet” may be used interchangeably.

5 [0101] FIGS. 3A and 3B respectively shows a schematic side view (profile view) and a perspective view (3-D view) of a solenoid 300, according to various embodiments. The solenoid may be employed in the haptic actuator of various embodiments. The solenoid 300 includes a body 302 having a bore 304 defined through the body 302, and an opening 305 defined on a surface 306 of the body 302. The solenoid 300 further
10 includes a base 308 and a shaft 310 coupled or connected to the base 308. The shaft 310 is received in the bore 304 and passes through the opening 305 and an opposed opening (not shown) defined on a surface 307 of the body 302. The body 302 may have a diameter of about 20 mm.

[0102] The base 308 and the shaft 310 are movable relative to the body 302 and may
15 move bi-directionally, back and forth, through the bore 304 along an axis of actuation, as represented by the double-headed arrow 314.

[0103] As shown in FIG. 3A, the shaft 310 may include an upper portion 312a and a lower portion 312b. The upper portion 312a and the lower portion 312b may be a single continuous structure.

20 [0104] In various embodiments, the base 308 has a diameter that is larger than the diameter of the bore 304, thereby preventing further movement of the base 308 when the base 308 comes into contact with the body 302 (i.e. when the base contacts the surface 307 of the body). This also produces an impact force when the base 308 contacts the body 302.

25 [0105] In various embodiments, the bore 304 has a diameter that is at least the diameter of the lower portion 312b. The opening 305 has a diameter at least substantially similar to the diameter of the upper portion 312a, thereby preventing further movement of the shaft 310 and the base 308 when the lower portion 312b comes into contact with the surface 320 of the body 302, in addition to the base 308 contacting the body 302.
30 However, it should be appreciated that the opening 305 may have a diameter that is larger

than the diameter of the upper portion 312a, for example a diameter that is at least the diameter of the lower portion 312b.

[0106] Furthermore, it should be appreciated that the shaft 310 may be a single continuous structure with an at least substantially constant diameter along the length of the shaft 310. In such embodiments, the opening 305 has a diameter that is at least the diameter of the shaft 310.

[0107] The solenoid 300 further includes one or more wires 316 for electrical connection between the solenoid 300 and, for example, a microcontroller (not shown).

[0108] The solenoid 300 may further include protrusions or screws 318 for attachment to a mounting structure (not shown in FIGS. 3A and 3B) when forming the haptic actuator of various embodiments.

[0109] While the body 302, the base 308 and the shaft 310 are shown in FIGS. 3A and 3B to have circular shapes, it should be appreciated that the body 302, the base 308 and the shaft 310 may have other shapes, for example square, rectangular or oval shape. Accordingly, the bore 304 and/or the opening 305 may have a corresponding shape other than circular. The respective cross-sectional dimensions of the body 302, the bore 304, the opening 305, the base 308 and/or the shaft 310 relative to each other may be as described above in relation to the diameter of the respective feature or structure.

[0110] In various embodiments, the solenoid 300 may be a Ledex™ low profile lightweight solenoid (model 0EC) with an internal impedance of about 2.4 Ω and a current rating of about 4 A at about 9.9 V, and which is designed for a holding force of about 9.3 N at about 10% duty cycle and about 0.15 cm of stroke length. A maximum impact force may be generated by passing short pulses of electrical signal (e.g. current) through the solenoid 300, for example, using a high capacity, low internal impedance battery. Although the solenoid 300 may be capable of generating a high force output, the solenoid 300 may be relatively light, weighing about 25 grams, therefore being suitable for applications requiring high mobility.

[0111] FIGS. 4A and 4B respectively shows a schematic side view (profile view) and a perspective view (3-D view) of a haptic actuator 400, according to various embodiments, for example in a non-operational configuration when no actuation is carried out. The haptic actuator 400 includes a pair of solenoids including a first solenoid 402a and a

second solenoid 402b coupled back-to-back. Each of the first solenoid 402a and the second solenoid 402b may be of the embodiment as described in the context of solenoid 300 (FIGS. 3A and 3B).

[0112] The first solenoid 402a includes a first body 404a and a first base 406a movable relative to the first body 404a along an axis of actuation, as represented by the double-headed arrow 410. The first base 406a may be coupled or connected to a first shaft 408a, which is movable relative to the first body 404a along the axis of actuation 410. Similarly, the second solenoid 402b includes a second body 404b and a second base 406b movable relative to the second body 404b along the axis of actuation 410. The second base 406b may be coupled or connected to a second shaft 408b, which is movable relative to the second body 404b along the axis of actuation 410.

[0113] The haptic actuator 400 further includes a plate 412 arranged or coupled in between the first base 406a and the second base 406b when the first base 406a and the second base 406b are coupled with each other. The first base 406a and the second base 406b are coupled with each other and movable between the first body 404a and the second body 404b, bi-directionally back and forth along the axis of actuation 410, relative to the first body 404a and the second body 404b.

[0114] The first base 406a and the second base 406b may be coupled or attached to a point where tactile feedback is to be observed (i.e. point of impact). The point of impact may be on or within the plate 412. As shown in FIG. 4B, the plate 412 has a cross-sectional dimension that is larger than each of the cross-sectional dimension of the first base 406a and the second base 406b. In various embodiments, the plate 412 may be a rigid and/or metal plate, for example an aluminium plate. The dimensions of the plate 412 may depend on the configuration and size of the haptic actuator 400. In one embodiment, and in order to have the smallest package, the plate 412 may have a length of about 30 mm. Each of the first body 404a and the second body 404b may have a diameter of about 20 mm. Therefore, about 5 mm of the plate 412 may extend out from opposed sides of each of the first solenoid 402a and the second solenoid 402b. The plate 412 may have a width of about 10 mm and a thickness of about 2 mm.

[0115] However, it should be appreciated that the plate 412 may have a cross-sectional dimension that is at least substantially similar to each of the cross-sectional dimension of

the first base 406a and the second base 406b. In addition, it should be appreciated that the first base 406a and the second base 406b may also be coupled with each other without the plate 412 therebetween and the point of tactile feedback may be within the coupled first base 406a and second base 406b.

5 [0116] Each of the first solenoid 402a and the second solenoid 402b may include a number of screws (e.g. 2 screws) 420 for securing a mounting structure. As shown in FIGS. 4A and 4B, the mounting structure may be a pair of brackets (e.g. extremely lightweight aluminium brackets) 422a, 422b. Each of the pair of brackets 422a, 422b, may be secured to the screws 420 by the use of nuts 424, to hold and secure the first
10 solenoid 402a and the second solenoid 402b to form the haptic actuator 400.

[0117] While not shown in FIGS. 4A and 4B, each of the first solenoid 402a and the second solenoid 402b further includes one or more wires for electrical connection with, for example, a microcontroller (not shown).

[0118] FIG. 4C shows a perspective view of a haptic actuator 450, according to various
15 embodiments, for example in a non-operational configuration when no actuation is carried out. The haptic actuator 450 includes a first solenoid 402a and a second solenoid 402b similar to the embodiment as described in the context of the haptic actuator 400 (FIGS. 4A and 4B). Features or components of the haptic actuator 450 that are similarly present in the haptic actuator 400 may be as described in the context of the
20 haptic actuator 400.

[0119] For the haptic actuator 450, the first solenoid 402a and the second solenoid 402b are held and secured with a mounting structure including a housing 452 and a pair of plates or slabs 454a, 454b. The first slab 454a may be secured to the first solenoid 402a via screws 420 and nuts 424. Similarly, the second slab 454b may be secured to the
25 second solenoid 402b via screws 420 and nuts 424. The housing 452 includes a number of slots 456, where each of the first slab 454a and the second slab 454b may at least partially pass through a respective slot 456 and be secured in position so as to hold and secure the first solenoid 402a and the second solenoid 402b respectively.

[0120] The housing 452 further includes openings 458 on opposed sides of the
30 housing 452 through which the plate 412 may partially extend out.

[0121] As shown in FIG. 4C, the first solenoid 402a includes a pair of wires 460a and the second solenoid 402b includes a pair of wires 460b, for electrical connection with, for example, a microcontroller (not shown).

[0122] FIGS. 5A and 5B show schematic side views of the haptic actuator 400 of the embodiments of FIG. 4A and 4B in an operational configuration, according to various embodiments.

[0123] In FIG. 5A, the second solenoid 402b is energised (i.e. an electrical signal is applied to the second solenoid 402b, for example a low duty pulse width modulation signal) to move the first base 406a, the second base 406b and the plate 412, which are coupled with each other, towards the energised second solenoid 402b, proximal to the energised second solenoid 402b. The first base 406a, the second base 406b and the plate 412 may be in contact with and against the second body 404b of the energised second solenoid 402b. Therefore, the second solenoid 402b has an at least substantially zero stroke length. In this configuration, the first solenoid 402a is in a state ready for actuation with a maximum stroke length, as indicated by the double-headed arrow 500.

[0124] Subsequently where an electrical signal is applied to the first solenoid 402a, having a higher power and/or higher duty ratio than the electrical signal initially applied to the second solenoid 402b, the first base 406a, second base 406b and plate 412 may move/accelerate in the direction of impact, as indicated by the arrow 502, towards the energised first solenoid 402a. This creates or generates a force or impact force on the first body 404a of the energised first solenoid 402a, for haptic feedback, for example when the first base 406a and the second base 406b, coupled with each other, collide with or contact the first body 404a of the energised first solenoid 402a.

[0125] In various embodiments, the electrical signal applied to the second solenoid 402b is continuously applied or maintained, even during actuation when the first solenoid 402a is energised and after actuation, such that the first base 406a, the second base 406b and the plate 412 may move back towards the energised second solenoid 402b, and maintain the coupled first base 406a, second base 406b and plate 412 proximal to or in contact against the second body 404b of the energised second solenoid 402b, so that the first solenoid 402a is in a state with a maximum stroke length 500 for the next actuation. Accordingly, in between actuations, the second solenoid 402b is continuously energised

at a low power setting so that the first solenoid 402a is at maximum stroke length 500 and ready for actuation.

[0126] In FIG. 5B, the first solenoid 402a is energised (i.e. an electrical signal is applied to the first solenoid 402a, for example a low duty pulse width modulation signal) to move the first base 406a, the second base 406b and the plate 412, which are coupled with each other, towards the energised first solenoid 402a, proximal to the energised first solenoid 402a. The first base 406a, the second base 406b and the plate 412 may be in contact with and against the first body 404a of the energised first solenoid 402a. Therefore, the first solenoid 402a has an at least substantially zero stroke length. In this configuration, the second solenoid 402b is in a state ready for actuation with a maximum stroke length, as indicated by the double-headed arrow 504.

[0127] Subsequently where an electrical signal is applied to the second solenoid 402b, having a higher power and/or higher duty ratio than the electrical signal initially applied to the first solenoid 402a, the first base 406a, the second base 406b and the plate 412 may move/accelerate in the direction of impact, as indicated by the arrow 506, towards the energised second solenoid 402b. This creates or generates a force or impact force on the second body 404b of the energised second solenoid 402b, for haptic feedback, for example when the first base 406a and the second base 406b, coupled with each other, collide with or contact the second body 404b of the energised second solenoid 402b.

[0128] In various embodiments, the electrical signal applied to the first solenoid 402a is continuously applied or maintained, even during actuation when the second solenoid 402b is energised and after actuation, such that the first base 406a, the second base 406b and the plate 412 may move back towards the energised first solenoid 402a, and maintain the coupled first base 406a, second base 406b and plate 412 proximal to or in contact against the first body 404a of the energised first solenoid 402a, so that the second solenoid 402b is in a state with a maximum stroke length 504 for the next actuation. Accordingly, in between actuations, the first solenoid 402a is continuously energised at a low power setting so that the second solenoid 402b is at maximum stroke length 504 and ready for actuation.

[0129] The first solenoid 402a and the second solenoid 402b may be secured by the pair of brackets 422a, 422b, to affix the relative position of the first solenoid 402a and the

second solenoid 402b such that when one solenoid is energized and its stroke length is at least substantially zero, the other solenoid is at its maximum stroke length ready for actuation.

[0130] Such a method of actuation enables one solenoid to be at a position of maximum stroke length where the solenoid is ready to exert maximum force once energized by an electrical signal, e.g. a short current pulse. In addition, this methodology allows each solenoid (or the first base 406a, the second base 406b and the plate 412) to return to the position prior to actuation, after the actuation process, so as to be in a state ready for the subsequent actuation, thereby eliminating the need for a mechanical spring for such a purpose.

[0131] Furthermore, it should be appreciated that, for example, the first solenoid 402a may be energised such that the first base 406a, the second base 406b and the plate 412 may move/accelerate along the axis of actuation 410 towards the energised first solenoid 402a, with a stroke length less than the maximum stroke length, to create or generate a force on the energised first solenoid 402a, for haptic feedback. This may mean that the second solenoid 402b is not initially energised to maintain a zero stroke length. This similarly applies to the second solenoid 402b being energised to generate an impact force on the energised second solenoid 402b when the stroke length of the second solenoid 402b is not at maximum stroke length.

[0132] In various embodiments, the maximum stroke length, and also the generated force of force feedback, may be changed, for example by changing the length or distance through which the first base 406a, the second base 406b and the plate 412 may move relative to the first body 404a and the second body 404b. For example, changing the length of the first shaft 408a and/or the second shaft 408b may change the maximum stroke length. As a result, the length of each of the pair of brackets 422a, 422b, may be correspondingly changed.

[0133] While FIGS. 5A and 5B show a plate 412 coupled in between the first base 406a and the second base 406b, it should be appreciated that the first base 406a and the second base 406b may also be coupled with each other without the plate 412 therebetween and the descriptions in the context of FIGS. 5A and 5B are correspondingly applicable.

[0134] In various embodiments, a low duty (<1%) continuous pulse width modulation (PWM) signal may be applied to either of the first solenoid 402a or the second solenoid 402b to provide a sufficiently low current to sufficiently secure or hold the respective shaft, and therefore the respective base, in a static or stationary position when
5 no actuation is carried out, for example to maintain the first base 406a, the second base 406b and the plate 412 at zero stroke length with a respective solenoid, ready for actuation.

[0135] This overcomes the limitation of an actuator design involving the use of a spring, where a strong spring, while providing a secure maintaining or biasing force on the
10 solenoids and therefore the actuator, causes a significant reduction in the actuation force, while a weak spring causes less reduction in the actuation force, but is unable to provide sufficient maintaining or biasing force to hold the solenoids securely.

[0136] In addition, the use of a low duty continuous PWM signal may minimise or prevent overheating of the solenoids as well as reduce power consumption during periods
15 where no actuation occurs.

[0137] In various embodiments, the force output of the haptic actuators of various embodiments is bi-directional and controllable. The amount of force impacted (i.e. the actuation force) may be controlled by varying the signals applied to the respective solenoids.

[0138] FIG. 6A shows a schematic representation of a haptic actuator 600 and a circuit (e.g. a control circuit) for controlling the haptic actuator 600, according to various
20 embodiments. The haptic actuator 600 includes a first solenoid 602a and a second solenoid 602b. The haptic actuator 600 may be the haptic actuator 400 (FIGS. 4A and 4B) or the haptic actuator 450 (FIG. 4C).

[0139] The circuit includes a pair of transistors (e.g. power metal-oxide-semiconductor field-effect transistors or power MOSFETs) including a first transistor 604a electrically
25 coupled to the first solenoid 602a, and a second transistor 604b electrically coupled to the second solenoid 602b.

[0140] The circuit further includes a microcontroller (not shown) electrically coupled to
30 the first transistor 604a and the second transistor 604b. The first transistor 604a may

receive a first electrical signal, V1, from the microcontroller while the second transistor 604b may receive a second electrical signal, V2, from the microcontroller.

[0141] The circuit includes a power supply (e.g. battery source) 610 electrically coupled or in electrical communication with the haptic actuator 600 and the circuit.

5 [0142] The various components of the circuit may be electrically coupled to each other and to the haptic actuator 600 by interconnections (e.g. wires) 612.

[0143] In various embodiments, different electrical signals may be generated by the microcontroller, which then transmits pulse-width modulated (PWM) signals to the first transistor 604a and the second transistor 604b that control the voltage across the first
10 solenoid 602a and the second solenoid 602b respectively, thereby varying the power through the first solenoid 602a and the second solenoid 602b and resulting in various degrees of impact forces.

[0144] In various embodiments, in order to create a single strong impact, an electrical signal (e.g. current) in the form of a single electrical pulse 620 having a width or duration
15 of about 10 ms, as shown in FIG. 6B, may be generated by the microcontroller, which is sufficiently long to allow sufficient power from the power supply 610 to be transmitted to the first solenoid 602a or the second solenoid 602b of the haptic actuator 600 for a short instance, thus creating a full impact. However, it should be appreciated that the electrical pulse 620 may have any duration of between about 1 ms and about 20 ms, e.g. between
20 about 1 ms and about 10 ms or between about 5 ms and about 10 ms, e.g. about 5 ms, about 10 ms or about 20 ms. In various embodiments, the duration of the electrical pulse 620 may be sufficiently long to energise the first solenoid 602a or the second solenoid 602b such that the first base of the first solenoid 602a and the second base of the second solenoid 602b, which are coupled with each other, may move through the
25 maximum stroke length of the first solenoid 602a or the second solenoid 602b. As the power supply (e.g. battery) 610 may be able to provide a far higher burst current than the current rating of each of the first solenoid 602a and the second solenoid 602b of about 4 A, increasing the pulse width of the pulse 620 may lead to overheating of the first solenoid 602a and/or the second solenoid 602b.

30 [0145] In various embodiments, for any impact force less than the maximum force, an electrical signal (e.g. current) in the form of a series of electrical pulses (i.e. a plurality of

electrical pulses), as represented by 630 for two pulses, of shorter pulse widths, as shown in FIG. 6C, may be generated by the microcontroller to be transmitted to the first solenoid 602a or the second solenoid 602b of the haptic actuator 600. In various embodiments, each electrical pulse 630 may have a short duration such that the first base of the first solenoid 602a and the second base of the second solenoid 602b, which are coupled with each other, may move through a stroke length less than the maximum stroke length. For pulse width modulation (PWM), each pulse of the plurality of pulses 630 may have a width or duration, *Ton*, ranging from microseconds to a millisecond, for example between about 1 μ s and about 1 ms, e.g. between about 10 μ s and about 1 ms or between about 100 μ s and about 500 μ s. For example, instead of having a single electrical pulse as in FIG. 6B, having a duration, for example, of about 5 ms, a plurality of pulses 630 may be provided or applied to the first solenoid 602a or the second solenoid 602b during the duration of about 5 ms. As an example and not limitation, in order to supply approximately 80% of the maximum current, within the duration of 5 ms, 100 pulses (e.g. 630) each of about 40 μ s (fully on condition during each pulse), and with a duration of about 10 μ s where there is no current (fully off condition), in between adjacent pulses 630, may be applied. Therefore, each micro-pulse cycle is a total of about 50 μ s, where 100 cycles of micro-pulses may be continuously applied to one solenoid. Therefore, the amount of current supply may be controlled. Micro-pulses with smaller durations may provide a smoother operation, for example a duration as low as about 10 μ s. In various embodiments, the duration of each pulse 630 of the plurality of pulses may be between about 10 μ s and about 100 μ s, e.g. between about 20 μ s and about 80 μ s or between about 20 μ s and about 50 μ s.

[0146] The plurality of pulses 630 may have a constant width for each pulse 630 or different widths for different pulses 630. The plurality of pulses 630 may have a period, *Ttotal*, of less than about 1 ms (i.e. a frequency of more than about 1 kHz), for example less than about 0.8 ms, less than about 0.5 ms, less than about 0.1 ms or less than about 0.05 ms, e.g. about 0.01 ms (i.e. 10 μ s; i.e. a frequency of about 100 kHz).

[0147] By varying the duty or duty ratio (pulse width/period), the voltage across the first solenoid 602a and the second solenoid 602b may be varied correspondingly and the actuation force may therefore be controlled. For example, an electrical pulse may be

applied to the first solenoid 602a or the second solenoid 602b to allow the solenoid to complete its entire stroke distance in a few seconds instead of a split instance.

[0148] FIG. 7 shows a schematic block diagram of a haptic actuator and a circuit for controlling the haptic actuator, according to various embodiments. The haptic actuator includes a first solenoid (Ledex low profile OEC solenoid) 702a and a second solenoid (Ledex low profile OEC solenoid) 702b. The circuit (i.e. control circuit) electrically coupled to the haptic actuator for controlling the haptic actuator may be a wireless actuator controller setup including a microcontroller (Arduino Pro Mini 328) 704, a first high power MOSFET (NMOS FDD8796) 706a electrically coupled to the first solenoid 702a, a second high power MOSFET (NMOS FDD8796) 706b electrically coupled to the second solenoid 702b, a wireless transceiver with a chip antenna (nRF2401a) 708 and a DC-DC (direct current-direct current) buck-boost regulator (AnyVolt Micro) 710. The circuit is powered by a power supply (high capacity 350 mAh lithium polymer battery) 712, capable of up to 40 C (coulomb) burst discharge, (equivalent to up to 14 A) due to its extremely low internal resistance.

[0149] The DC-DC buck-boost regulator 710 is used to regulate the voltage from the 11.1 V battery 712 to a 3.3 V supply suitable for both the Arduino microcontroller 704 and the wireless transceiver 708. Current surge protection may be provided in the circuit to prevent damage to the DC-DC buck-boost regulator 710 as the battery 712 may be capable of very high current surges.

[0150] The nRF2401a transceiver 708 may be used to communicate with a remote terminal (e.g. a processing device, e.g. a computer), thereby enabling wireless control of the haptic actuator via the remote terminal. From the remote terminal, a user may set the type of control signals to be applied to the haptic actuator or the first solenoid 702a and/or the second solenoid 702b, thereby controlling the strength of actuation. In this way, ungrounded mobile haptic feedback is possible, enabling unlimited freedom in the workspace for the use of a haptic device including the haptic actuator.

[0151] As shown in FIG. 7, each of the first solenoid 702a, the second solenoid 702b, the microcontroller 704, the first high power MOSFET 706a, the second high power MOSFET 706b, the wireless transceiver 708, the DC-DC buck-boost regulator 710 and

the power supply 712 may be electrically coupled or in electrical communication with each other via electrical interconnections (e.g. wires) 720.

[0152] FIG. 8 shows details of the components of the embodiment of FIG. 7, illustrating the pins of the components.

5 [0153] In various embodiments, the circuitry for controlling the haptic actuator of various embodiments may be implemented on a single-sided printed circuit board (PCB) of dimensions of approximately 8 cm × 5 cm × 1 cm, and weighing less than about 20 g. Therefore, attaching the circuit in addition to a haptic actuator onto a haptic device of various embodiments, for haptic feedback, may not cause any significant burden to the
10 portability of the haptic device and the mobility of the user using the haptic device.

[0154] A haptic device including one or more haptic actuators (e.g. 400, 450) may be provided or implemented for applications that may require high force impulsive tactile feedback as well as high mobility. An example of such an application is in tennis simulation, where the haptic device may be a tennis racquet with the haptic actuator
15 attached or arranged to the tennis racquet at the sweet spot of the racquet head in order to maximize the impact felt when the user grips or holds the racquet at the handle. The term “sweet spot” as used herein may mean a spot or position which may result in a maximum response for a given amount of effort. For example, a given swing of the racquet may result in a more powerful hit if the ball strikes the racquet on the sweet spot.

20 [0155] FIG. 9A shows a schematic view of a haptic device 900, according to various embodiments. The haptic device 900 is a racquet, including a racquet head 902 with interleaving strings 904, and a handle 906. The haptic device 900 further includes a haptic actuator 908, which may be the haptic actuator 400 (FIGS. 4A and 4B) or the haptic actuator 450 (FIG. 4C). The haptic actuator 908 may not include the plate 412 of
25 the haptic actuator 400 or the haptic actuator 450.

[0156] The haptic actuator 908 may be arranged at a sweet spot of the racquet head 902, with the respective bases (collectively shown as 912) of the first solenoid 914a and the second solenoid 914b, of the haptic actuator 908 attached and secured by the interleaving nylon strings 904. While the sweet spot where the haptic actuator 908 is arranged is
30 shown in FIG. 9A as being located at least substantially centrally of the racquet head 902, the position of the sweet spot may vary and may be located at a position away from the

centre of the racquet head 902. In further embodiments, the haptic actuator 908 may be arranged at any spot other than the sweet spot.

[0157] The position indicated by 916 indicates the point of impact for simulating collision impact with a virtual object, for example a virtual ball in tennis simulation.

5 [0158] The haptic device 900 further includes a circuit for controlling the haptic actuator 908, in the form of a printed circuit board (PCB) 910, which is electrically coupled to the haptic actuator 908 by one or more wires 912.

[0159] The haptic device 900 may be lightweight, and capable of generating a high force output in excess of 25-g by the haptic actuator 908.

10 [0160] In various embodiments, the haptic device 900 may include a plurality of haptic actuators, in addition to or as alternative to the haptic actuator 908. These plurality of haptic actuators may be arranged at any locations, for example along a circumferential edge of the area defined by the interleaving strings 904 or throughout the area defined by the interleaving strings 904, in a uniform or a non-uniform pattern.

15 [0161] FIG. 9B shows a schematic view of a haptic device 930, according to various embodiments. The haptic device 930 is at least substantially Y-shaped, and includes a first haptic actuator 932a, a second haptic actuator 932b and a third haptic actuator 932c arranged at a respective first end 934a, second end 934b and third end 934c of the Y-shaped haptic device 930.

20 [0162] Each of the first haptic actuator 932a, second haptic actuator 932b and third haptic actuator 932c may be the haptic actuator 400 (FIGS. 4A and 4B) or the haptic actuator 450 (FIG. 4C). The haptic actuator 908 may or may not include the plate 412 of the haptic actuator 400 or the haptic actuator 450.

25 [0163] FIG. 10 shows a photograph 1000 of the haptic device 930, in partial disassembly (with the cover removed), to illustrate the internal assembly of the haptic device 930, as well as a photograph 1002 showing the haptic device 930 in use, held by a user, during a tennis simulation game.

30 [0164] As shown in the photograph 1000, the haptic device 930 includes two halves of a bottom portion 1010 and a top portion (cover) 1012. The bottom portion 1010 houses the first haptic actuator 932a and the second haptic actuator 932b (i.e. top solenoids), the

third haptic actuator 932c (i.e. bottom solenoid), a battery 1014 and a control circuit (arranged throughout the bottom portion 1010).

[0165] The haptic device 930, while capable of generating a high force output in excess of 25-g for each of the first haptic actuator 932a, second haptic actuator 932b and third haptic actuator 932c, may be lightweight. For example, each of the first haptic actuator 932a, second haptic actuator 932b and third haptic actuator 932c may weigh less than about 100 g or less, while the battery and the control circuit may weigh less than about 100 g or less, in total. Therefore, the haptic device 930, including the structural frame of the haptic device 930, may weight about 428 g.

[0166] FIG. 11A shows a plot 1100 of acceleration measurement for a haptic actuator of the haptic device 930 of the embodiment of FIG. 9B. The acceleration was measured along a solenoid axis (i.e. axis of actuation) for one haptic actuator (e.g. 932a, 932b, 932c). The results of FIG. 11A shows that an acceleration in excess of 25-g was generated at the point of impact 1102. It should be appreciated that the results of FIG. 11A may relate to any haptic actuator of the various embodiments for use in any haptic device.

[0167] FIG. 11B shows a plot 1110 of acceleration measurement for the haptic device 930 of the embodiment of FIG. 9B, with the first haptic actuator 932a, the second haptic actuator 932b and the third haptic actuator 932c actuating simultaneously.

[0168] In various embodiments, the racquet 900 and the Y-shaped haptic device 930 are mobile and untethered to any external devices, thereby allowing the player or user to play the virtual game in complete freedom, similar to that in a real game. Therefore, each of the racquet 900 and Y-shaped haptic device 930 enables a realistic simulation of the tennis game.

[0169] In various embodiments, in a virtual simulation environment, the player or user is immersed in a virtual tennis court, for example displayed through a 3D display or a combination of 3D display and 3D glasses. When holding the haptic device (e.g. 900, 930) of various embodiments, the player may experience tactile feedback each time a virtual tennis ball hits the haptic device (e.g. 900, 930). The terminal or processing device (e.g. simulator) that generates the simulation environment may then control the degree of tactile feedback via wireless transmission, and via the control circuit, according to the

simulated impact of the collision between the virtual ball and the haptic device (e.g. 900, 930).

[0170] In between collisions or impacts, the solenoid of the haptic actuator opposite the direction of impact (i.e. opposite the impact point) may be continuously energized at a low power setting so that the solenoid where the impact is to occur is at a maximum stroke length and ready for actuation. Maintaining one solenoid energized continuously or at all times also ensures that the respective bases of the solenoids do not swing back and forth when the haptic device (e.g. 900, 930) is moved or swung during times when no impact is to be simulated (i.e. when no actuation occurs).

[0171] In various embodiments, the control circuit electrically coupled to the haptic actuator or actuators of the haptic device (e.g. 900, 930) may include an inertial measurement circuit configured to determine a direction of the haptic device (e.g. 900, 930). The inertial measurement circuit may allow the simulator to detect the side of the haptic device (e.g. 900, 930) that is facing and hitting the virtual ball. In particular, during a back swing, the player may flip the haptic device (e.g. 900, 930) over to execute a back swing, and where the simulator detects a flip of the haptic device (e.g. 900, 930), the simulator may switch the solenoid to be energised in order to correct the direction of impact, thereby providing a more accurate tactile/haptic feedback.

[0172] The term 'circuit', as applied to the inertial measurement circuit, may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, the 'circuit' may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g. a microprocessor (e.g. a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). The 'circuit' may also be a processor executing software, e.g. any kind of computer program, e.g. a computer program using a virtual machine code such as e.g. Java.

[0173] It should be appreciated that in embodiments where the haptic device includes a plurality of haptic actuators, one or more of the haptic actuators may be actuated, selectively, consecutively or simultaneously, depending for example on the haptic

feedback to be simulated, such as the strength of the impact and/or the position of the impact.

[0174] It should be appreciated that each haptic actuator of the plurality of haptic actuators may be actuated differently from another haptic actuator such that a physical
5 sensation or haptic feedback felt from a haptic actuator to another haptic actuator is different, depending on the location of the impact point so as to provide the user of the haptic device a sense of the location or position of the impact point caused by a virtual object on the haptic device.

[0175] The haptic actuator of various embodiments is configured in a way that the mass
10 asserted onto the impact zone is transferred to the energized solenoid of the actuator, thereby increasing the F (force) with less current. This allows the use of smaller batteries, and therefore less mass of the haptic device incorporating the haptic actuator.

[0176] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various
15 changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A haptic actuator comprising:
a first solenoid comprising a first body and a first base; and
5 a second solenoid comprising a second body and a second base, the first base and the second base being coupled with each other and movable between the first body and the second body, such that the first base and the second base generate a first force on the first body when a first electrical signal is applied to the first solenoid and generate a second force on the second body when a second electrical signal is applied to the second
10 solenoid.
2. The haptic actuator as claimed in claim 1, further comprising a first shaft coupled to the first base, the first shaft being received in a first bore defined through the first body.
15
3. The haptic actuator as claimed in claim 1 or 2, further comprising a second shaft coupled to the second base, the second shaft being received in a second bore defined through the second body.
- 20 4. The haptic actuator as claimed in any one of claims 1 to 3, further comprising a plate coupled between the first base and the second base.
5. The haptic actuator as claimed in claim 4, wherein the plate has a cross-sectional dimension that is larger than respective cross-sectional dimensions of the first base and
25 the second base.
6. The haptic actuator as claimed in any one of claims 1 to 5, further comprising a mounting structure configured to hold the first solenoid and the second solenoid.
- 30 7. The haptic actuator as claimed in claim 6, wherein the mounting structure comprises a pair of brackets.

8. A method of forming a haptic actuator, the method comprising:
providing a first solenoid comprising a first body and a first base;
providing a second solenoid comprising a second body and a second base; and
5 coupling the first base and the second base with each other, wherein the first base
and the second base are movable between the first body and the second body, such that
the first base and the second base generate a first force on the first body when a first
electrical signal is applied to the first solenoid and generate a second force on the second
body when a second electrical signal is applied to the second solenoid.

10 9. The method as claimed in claim 8, further comprising coupling a first shaft to the
first body, and receiving the first shaft in a first bore defined through the first body.

10. The method as claimed in claim 8 or 9, further comprising coupling a second shaft
15 to the second base, and receiving the second shaft in a second bore defined through the
second body.

11. The method as claimed in any one of claims 8 to 10, further comprising coupling
a plate between the first base and the second base.

20 12. The method as claimed in claim 11, wherein the plate has a cross-sectional
dimension that is larger than respective cross-sectional dimensions of the first base and
the second base.

25 13. The method as claimed in any one of claims 8 to 12, further comprising providing
a mounting structure configured to hold the first solenoid and the second solenoid.

14. The method as claimed in claim 13, wherein the mounting structure comprises a
pair of brackets.

15. A method of controlling the haptic actuator as claimed in any one of claims 1 to 7, the method comprising:

applying a first electrical signal to the first solenoid such that the first base and the second base generate a first force on the first body.

5

16. The method as claimed in claim 15, further comprising applying a second electrical signal to the second solenoid to move the first base and the second base proximal to the second body, wherein the second electrical signal has a power that is lower than a power of the first electrical signal.

10

17. The method as claimed in claim 16, wherein the second electrical signal is continuously applied to the second solenoid.

15

18. The method as claimed in any one of claims 15 to 17, wherein the first electrical signal comprises an electrical pulse.

19. The method as claimed in claim 18, wherein the electrical pulse has a duration of between about 1 ms and about 20 ms.

20

20. The method as claimed in any one of claims 15 to 17, wherein the first electrical signal comprises a plurality of electrical pulses.

21. The method as claimed in claim 20, wherein each electrical pulse of the plurality of electrical pulses has a duration of between about 10 μ s and about 100 μ s.

25

22. The method as claimed in claim 20 or 21, wherein the plurality of electrical pulses have a period of less than 1 ms.

30

23. A haptic device for ungrounded haptic feedback, the haptic device comprising:
at least one haptic actuator as claimed in any one of claims 1 to 7; and
a circuit electrically coupled to the at least one haptic actuator.

24. The haptic device as claimed in claim 23, wherein the circuit comprises:
a first transistor electrically coupled to the first solenoid; and
a second transistor electrically coupled to the second solenoid.

5

25. The haptic device as claimed in claim 24, wherein the circuit further comprises a microcontroller electrically coupled to the first transistor and the second transistor.

26. The haptic device as claimed in claims 23 to 25, wherein the circuit further
10 comprises a power supply.

27. The haptic device as claimed in 26, wherein the circuit further comprises a buck-boost regulator configured to regulate an output voltage of the power supply.

15 28. The haptic device as claimed in claims 23 to 27, wherein the circuit further comprises a wireless transceiver configured to communicate with a remote terminal.

29. The haptic device as claimed in claims 23 to 28, wherein the circuit further
comprises an inertial measurement circuit configured to determine a direction of the
20 haptic device.

30. The haptic device as claimed in any one of claims 23 to 29, wherein the haptic device comprises a sports racquet with a racquet head.

25 31. The haptic device as claimed in claim 30, and wherein the at least one actuator is arranged at a sweet spot of the racquet head.

32. The haptic device as claimed in any one of claims 23 to 30, comprising a plurality of haptic actuators.

33. The haptic device as claimed in any one of claims 23 to 30, comprising three haptic actuators.

34. The haptic device as claimed in claim 33, wherein the device is at least substantially Y-shaped, and wherein each of the three haptic actuators is arranged at a
5 respective end of the Y-shaped device.

35. A method of forming a haptic device for ungrounded haptic feedback, the method comprising:

10 forming at least one haptic actuator as claimed in any one of claims 1 to 7; and electrically coupling a circuit to the at least one haptic actuator.

36. The method as claimed in claim 35, further comprising:

arranging a first transistor and a second transistor in the circuit;
15 electrically coupling the first transistor to the first solenoid; and electrically coupling the second transistor to the second solenoid.

37. The method as claimed in claim 36, further comprising:

arranging a microcontroller in the circuit; and
20 electrically coupling the microcontroller to the first transistor and the second transistor.

38. The method as claimed in claims 35 to 37, further comprising arranging a power supply in the circuit.

25

39. The method as claimed in claim 38, further comprising arranging a buck-boost regulator in the circuit, the buck-boost regulator being configured to regulate an output voltage of the power supply.

40. The method as claimed in claims 35 to 39, further comprising arranging a wireless transceiver in the circuit, the wireless transceiver being configured to communicate with a remote terminal.

5 41. The method as claimed in claims 35 to 40, further comprising arranging an inertial measurement circuit in the circuit, the inertial measurement circuit being configured to determine a direction of the haptic device.

42. The method as claimed in any one of claims 35 to 41, wherein the haptic device
10 comprises a sports racquet with a racquet head.

43. The method as claimed in claim 42, further comprising arranging the at least one actuator at a sweet spot of the racquet head.

15 44. The method as claimed in any one of claims 35 to 42, comprising forming a plurality of haptic actuators.

45. The method as claimed in any one of claims 35 to 42, comprising forming three haptic actuators.

20

46. The method as claimed in claim 45, wherein the device is at least substantially Y-shaped, and the method further comprises arranging each of the three haptic actuators at a respective end of the Y-shaped device.

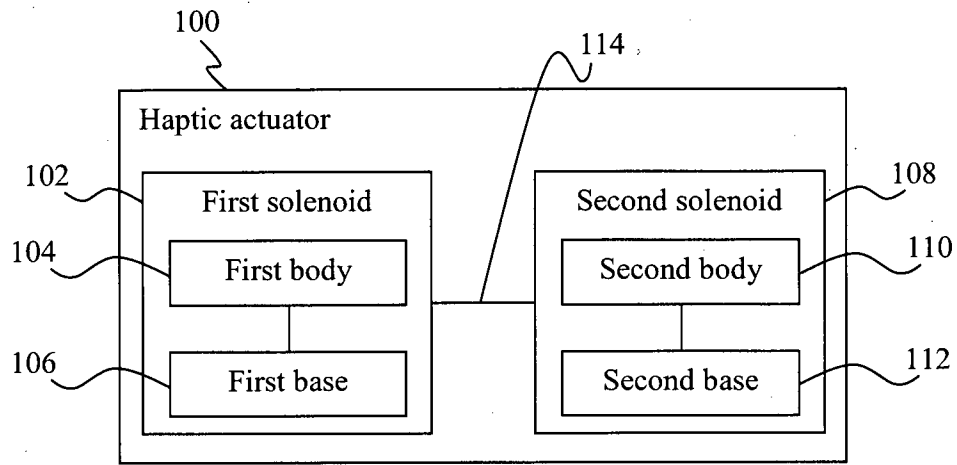


FIG. 1A

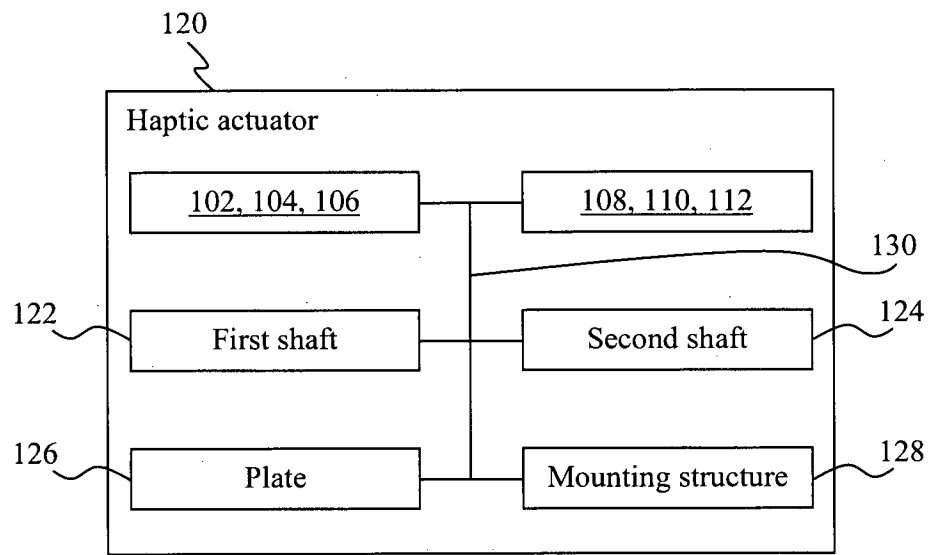


FIG. 1B

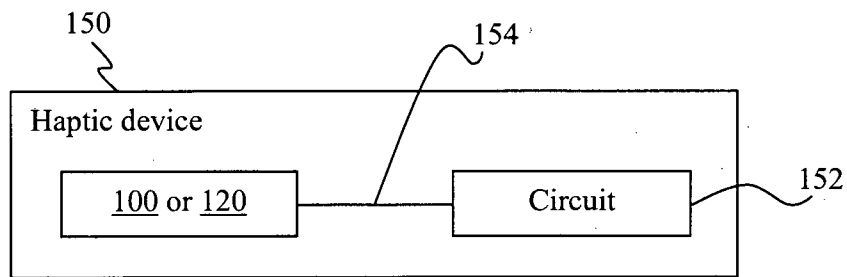


FIG. 1C

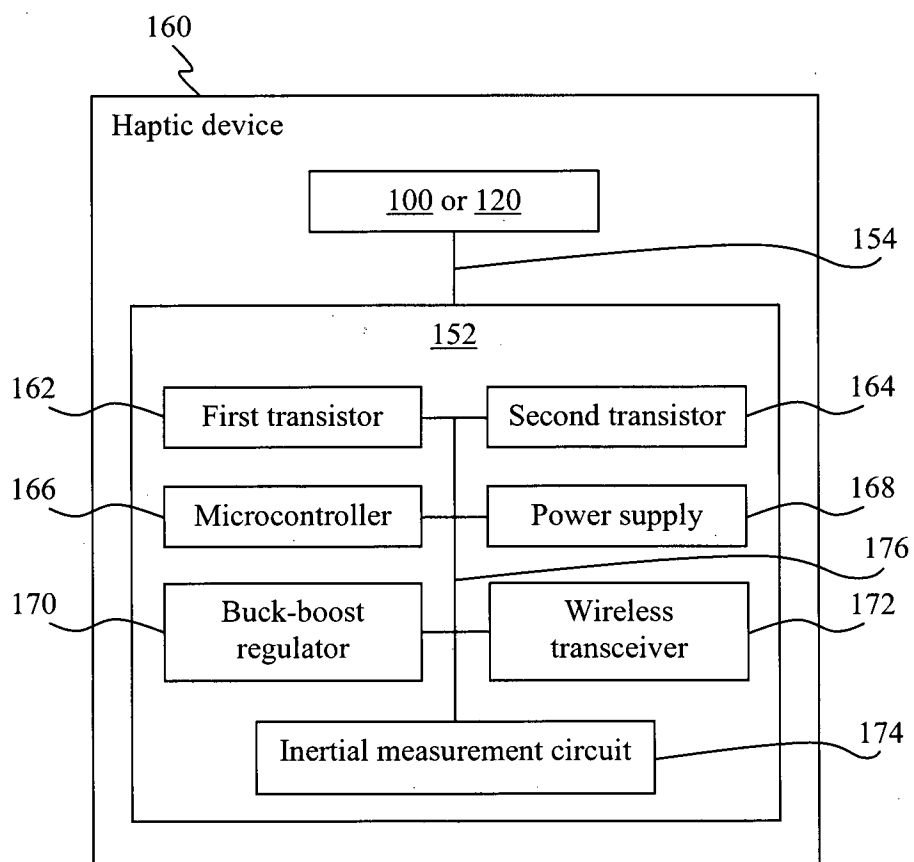


FIG. 1D

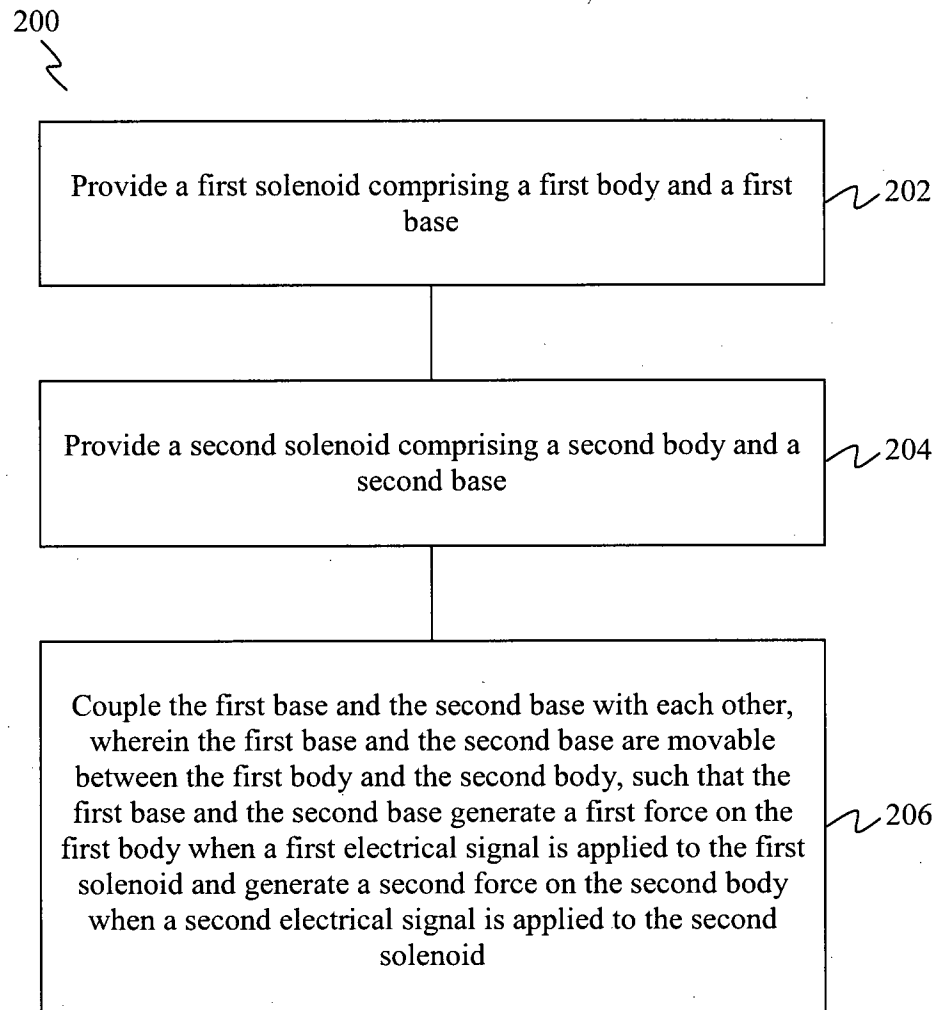


FIG. 2A

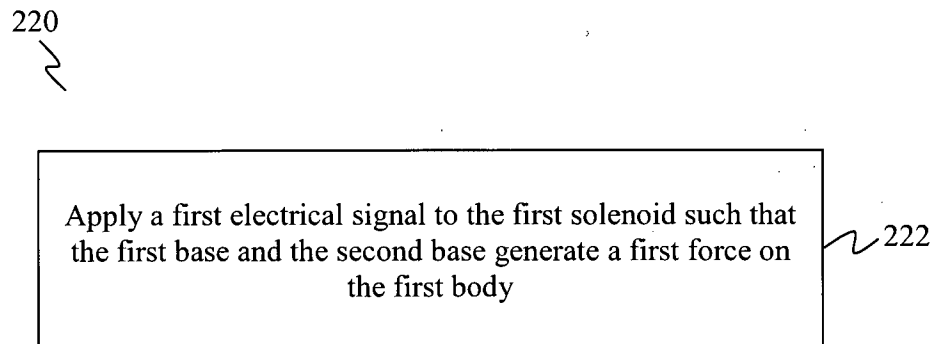


FIG. 2B

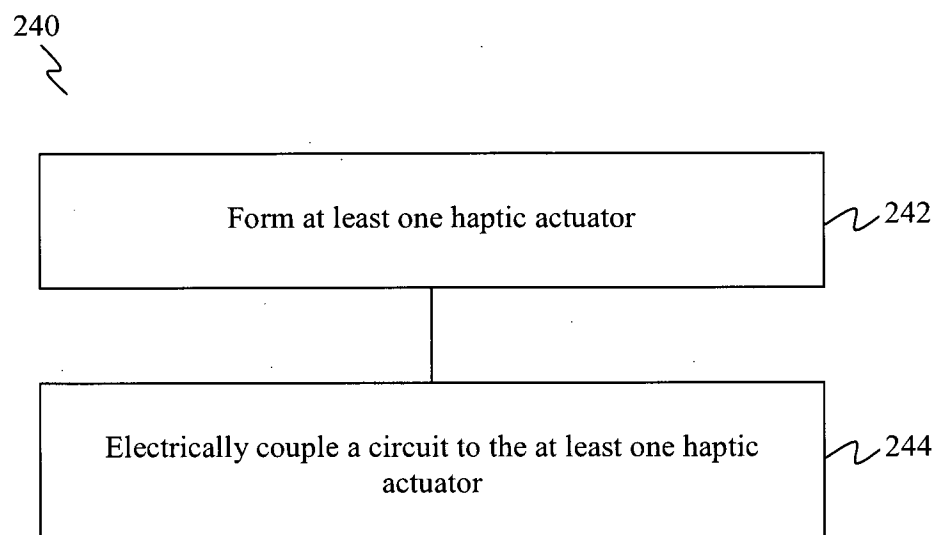


FIG. 2C

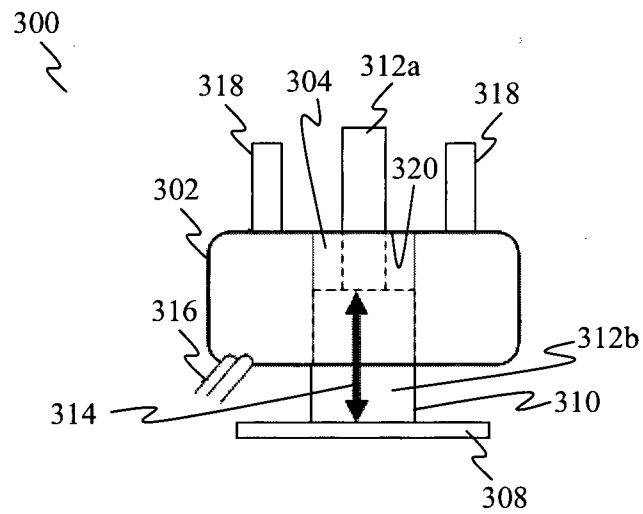


FIG. 3A

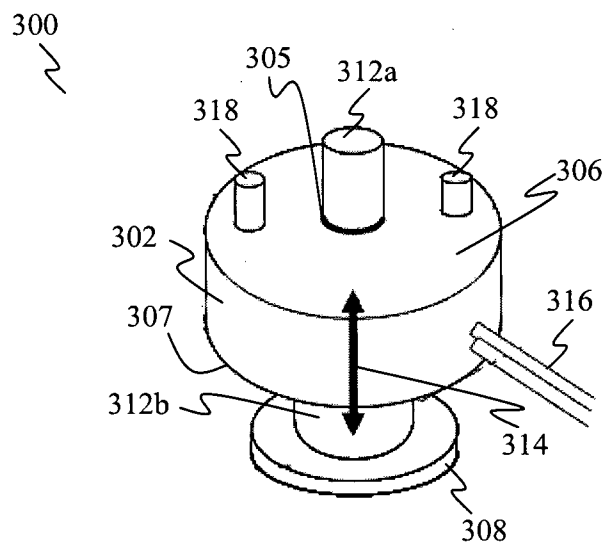


FIG. 3B

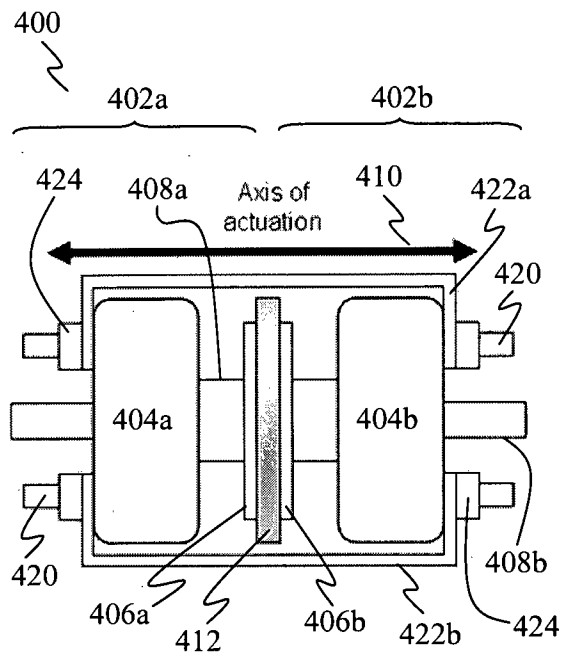


FIG. 4A

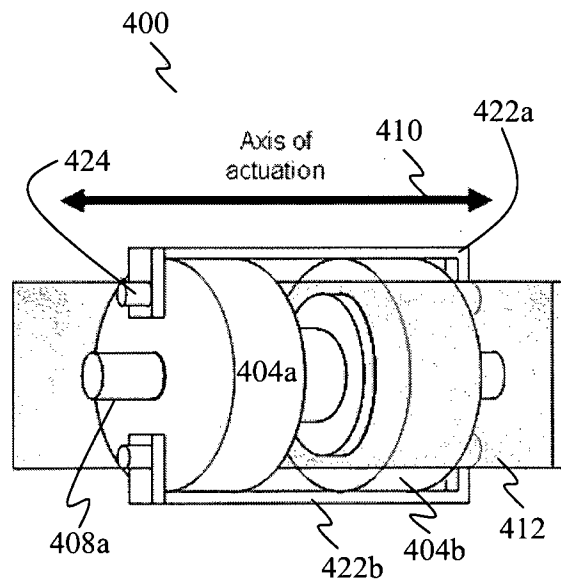


FIG. 4B

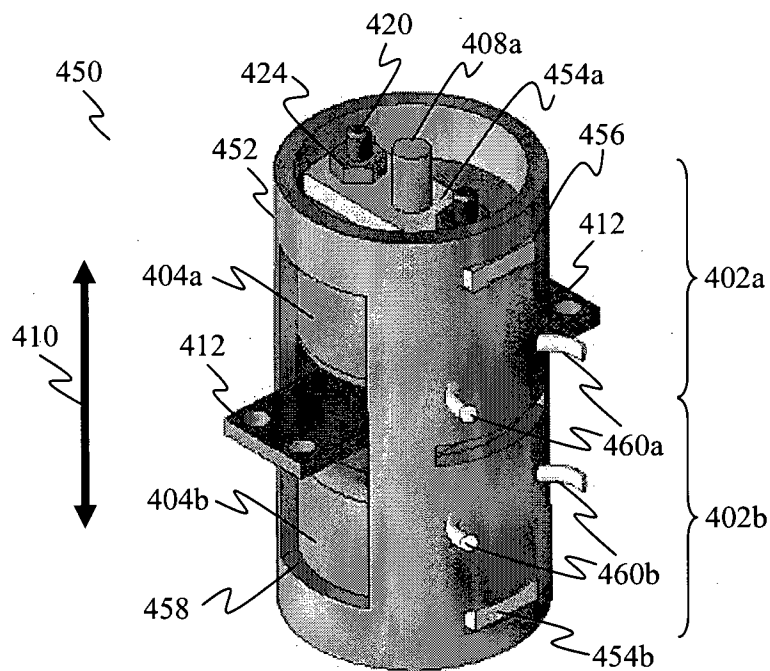


FIG. 4C

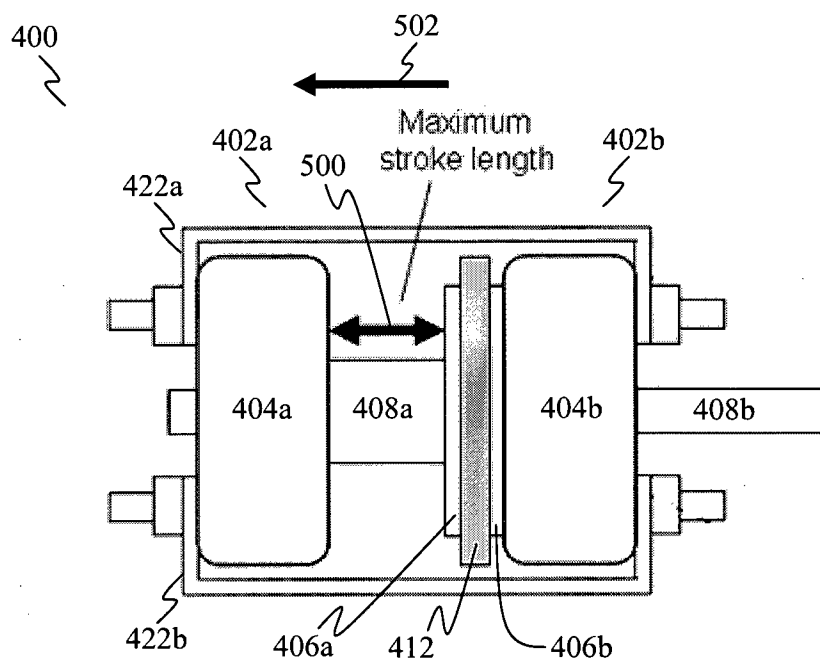


FIG. 5A

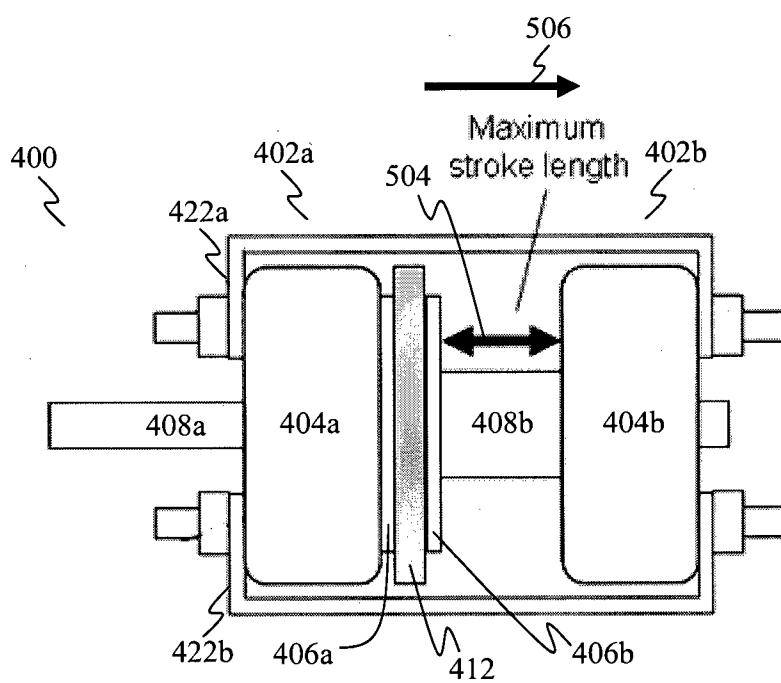


FIG. 5B

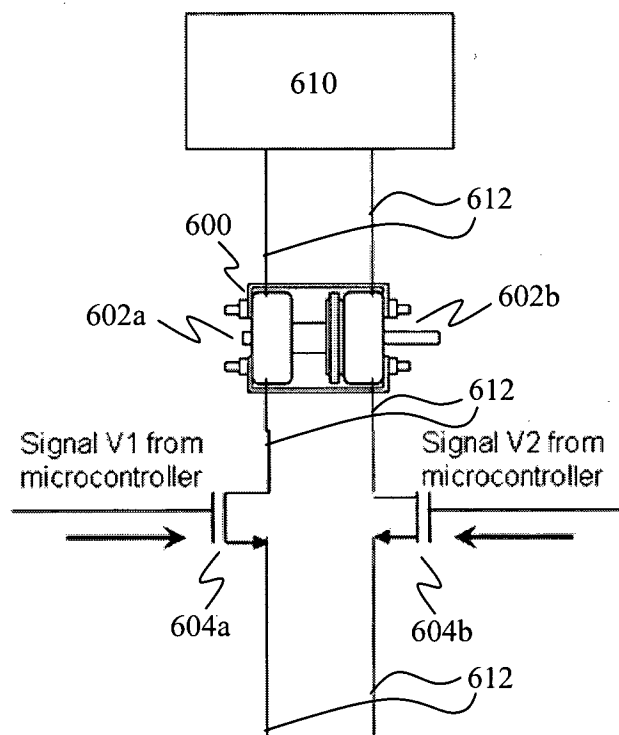


FIG. 6A

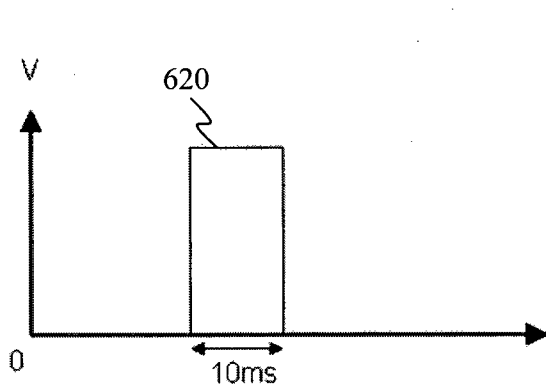


FIG. 6B

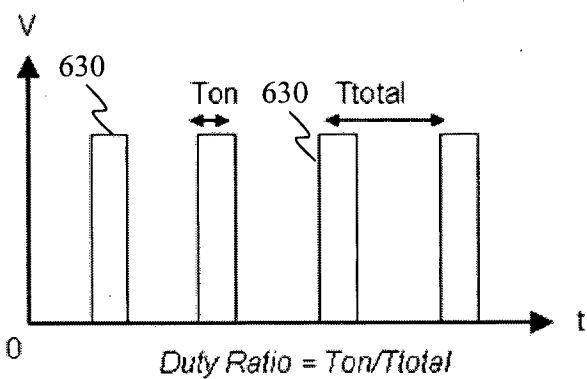


FIG. 6C

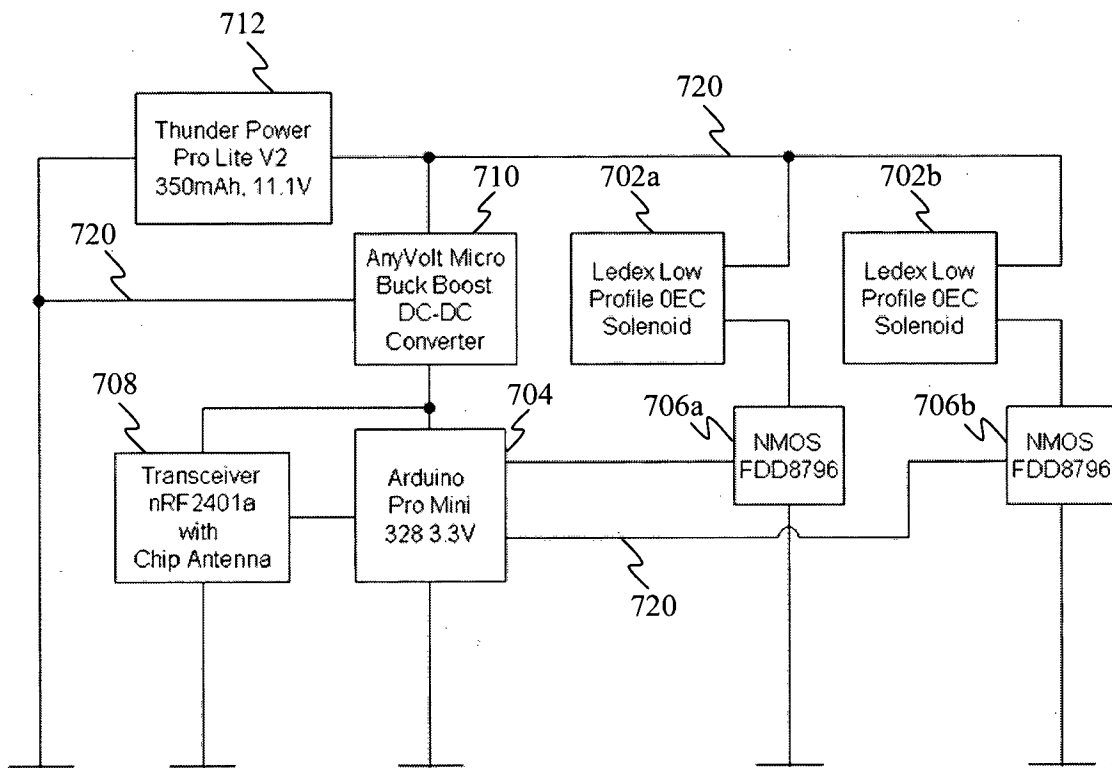


FIG. 7

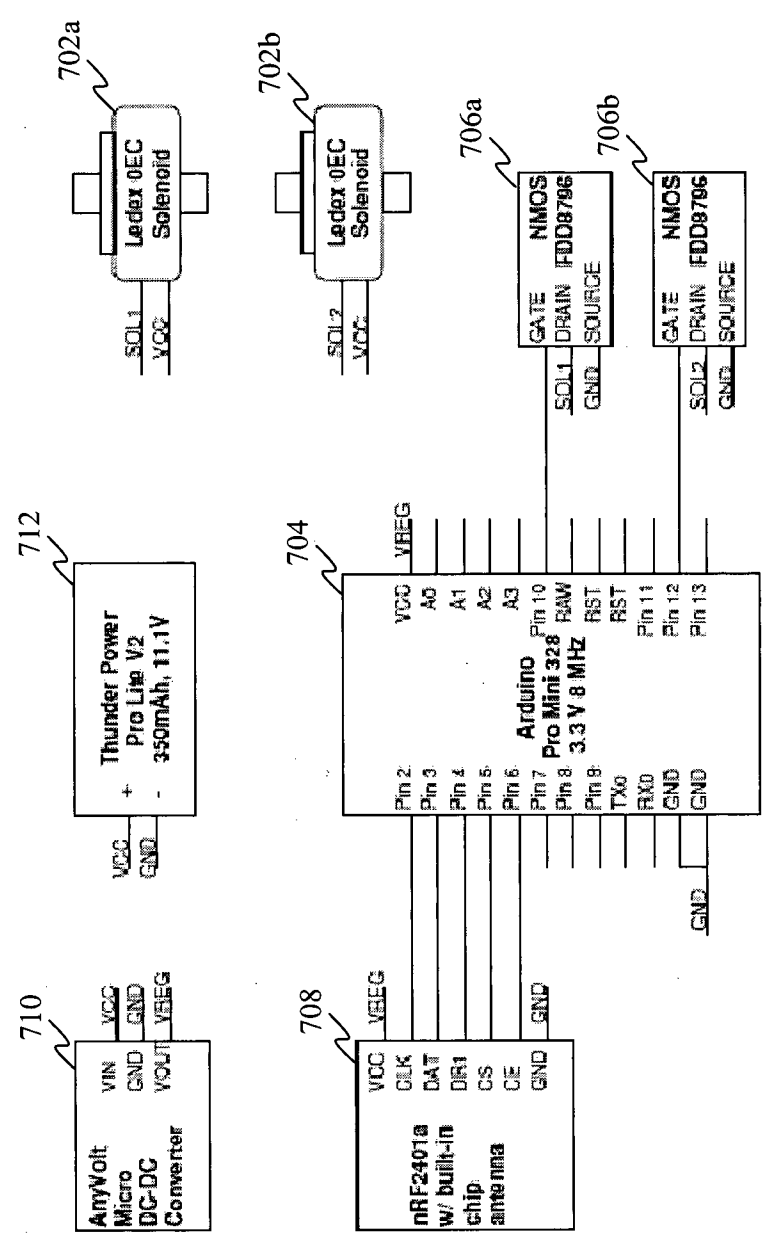
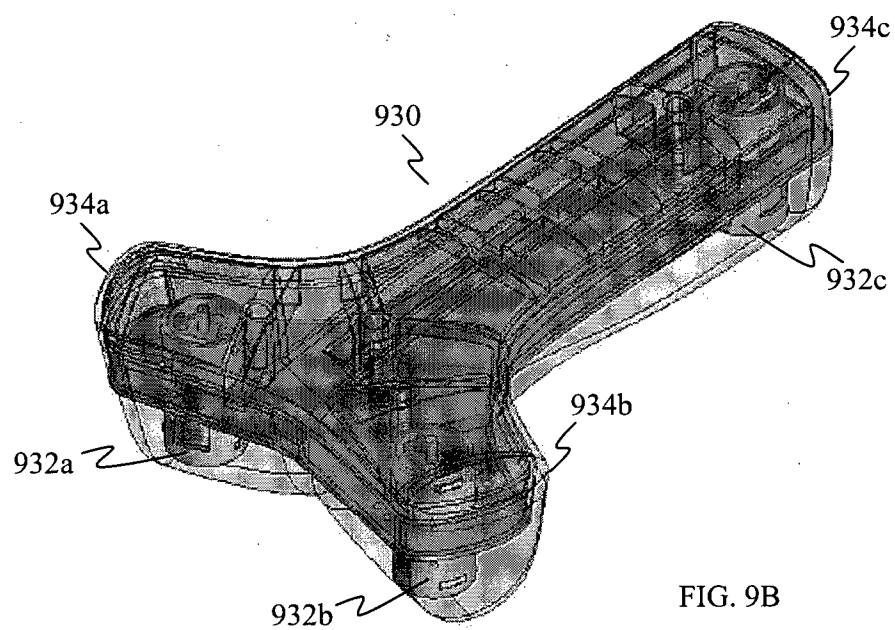
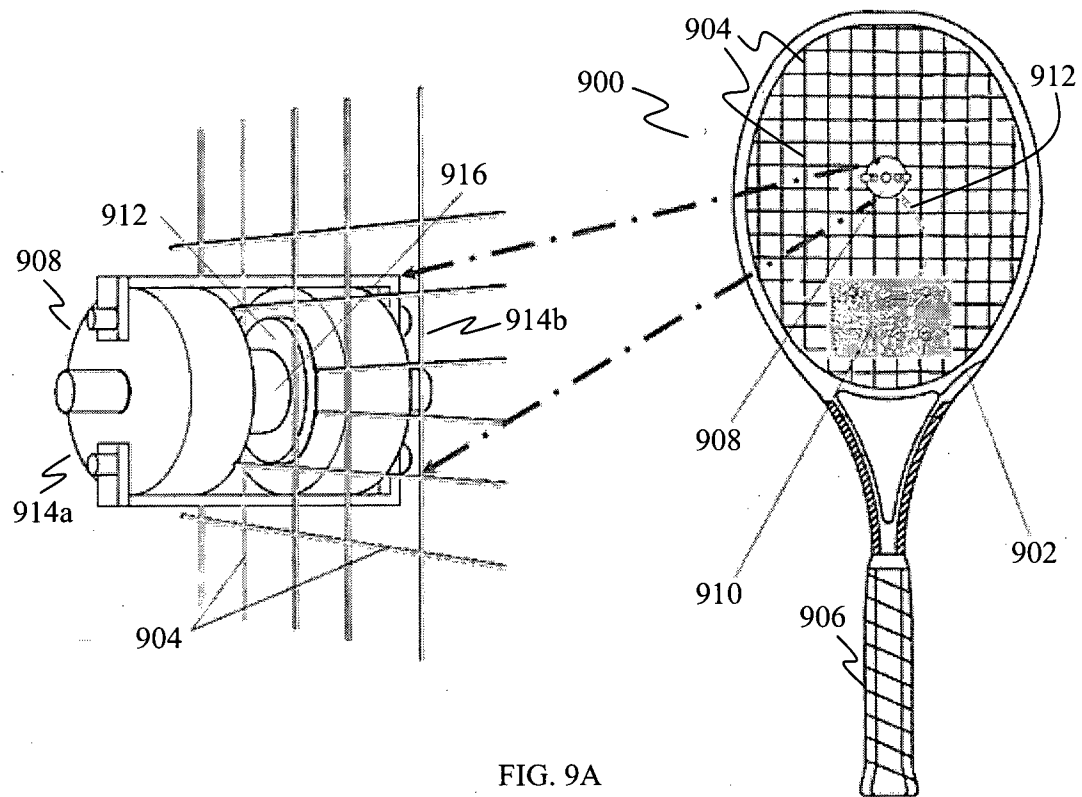
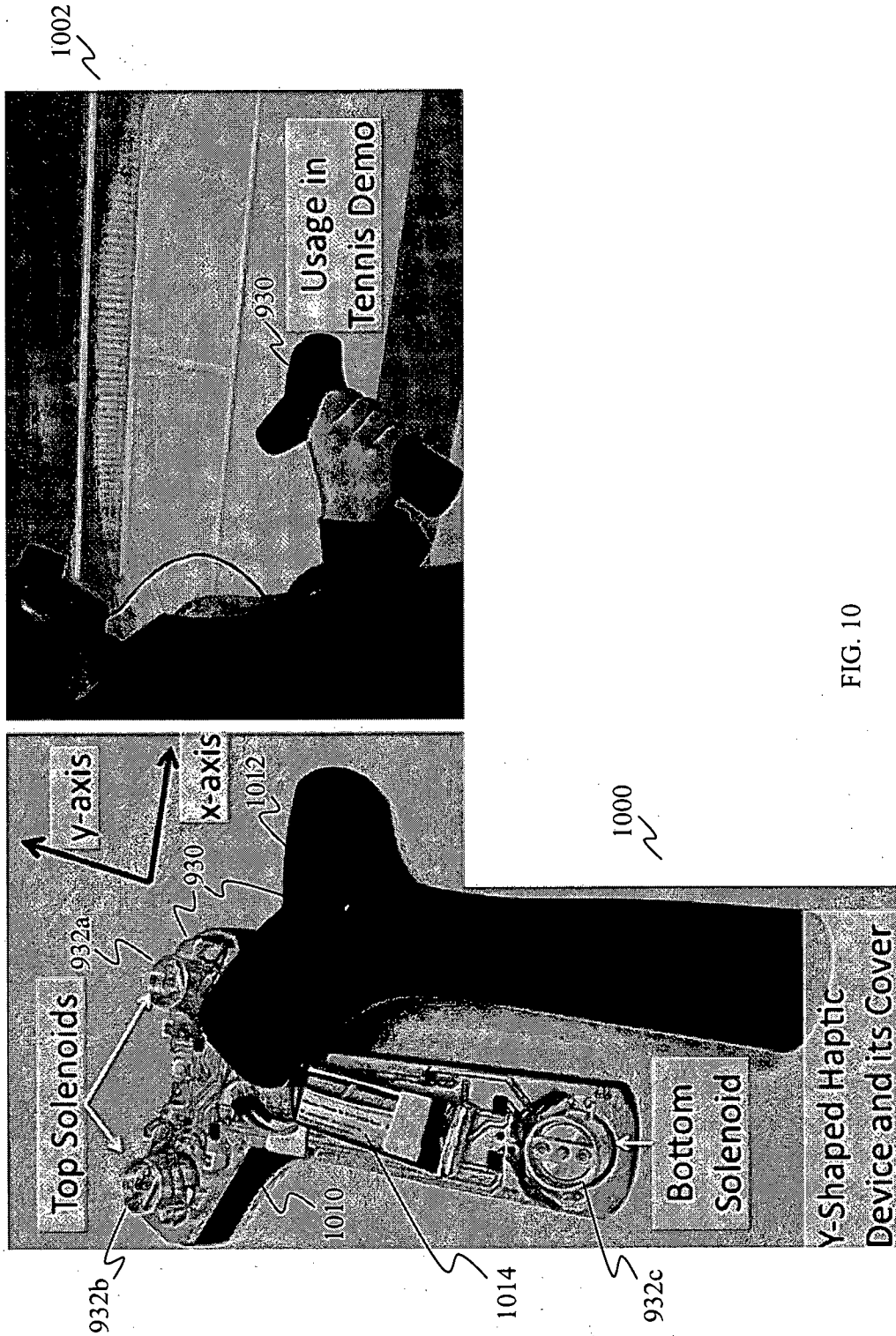


FIG. 8





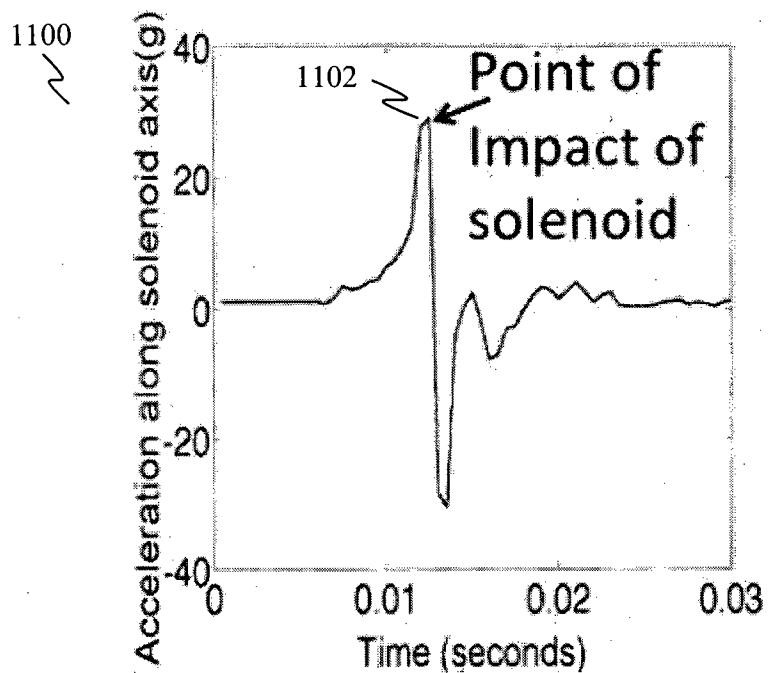


FIG. 11A

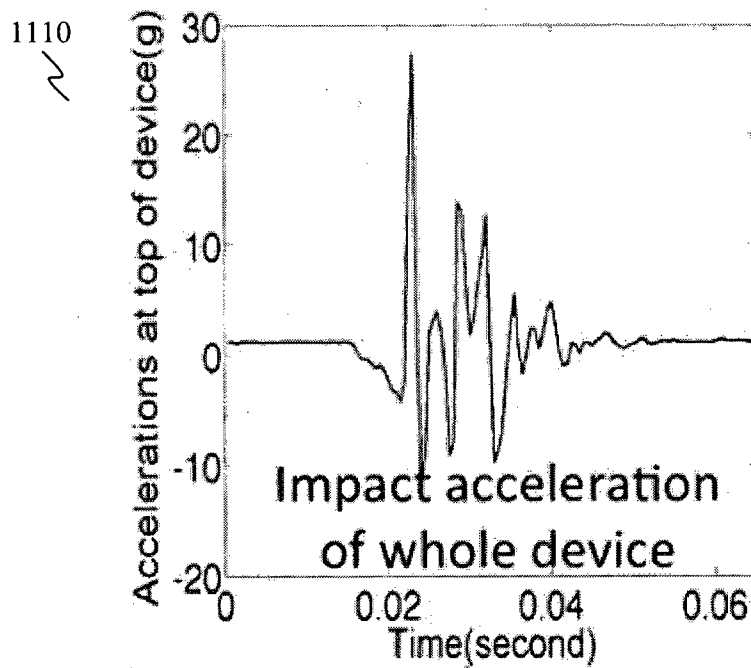


FIG. 11B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2011/000435

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G08B 6/00 (2006.01)*A63B 69/38* (2006.01)*G06F 3/01* (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)

WPI, espacenet, Patent Lens, Google Patent, Google "solenoid, haptic, tactile etc."

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5959230 A (FULFORD) 28 September 1999 Column 1 lines 39 to 42, column 2 lines 47 to 49, column 3 lines 44 to 58, column 3 line 60 to column 4 line 2, column 4 lines 20 to 34, column 4 line 55, column 5 line 2, column 5 lines 8 to 15, column 5 lines 5 to 23, column 5 lines 42 to 45, column 5 lines 52 to 55, figures 1, 2a, 3, 4, 5, 6 and 7 in particular.	1,4,6,7,8,11, 13-16,18,20, 23,24-28,32, 33,35-40,44, 45
P,A	WO 2011/119118 A1 (AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH) 29 September 2011	



Further documents are listed in the continuation of Box C



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 07 February 2012	Date of mailing of the international search report 10 February 2012
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustalia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer P. THONG AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2128

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2011/000435

This Annex lists the known "A" publication level 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 Cited in Search Report		Patent Family Member
US	5959230	NONE
WO	2011119118	NONE
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.		
END OF ANNEX		