(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
07 December 2017 (07.12.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/208003 A1

(51) International Patent Classification:
F03G 7/06 (2006.01) *G06F 3/01* (2006.01)

(21) International Application Number:
PCT/GB2017/051577

(22) International Filing Date:
01 June 2017 (01.06.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

1609750.3	03 June 2016 (03.06.2016)	GB
1610613.0	17 June 2016 (17.06.2016)	GB
1613596.4	08 August 2016 (08.08.2016)	GB
1703242.6	28 February 2017 (28.02.2017)	GB

(71) Applicant: **CAMBRIDGE MECHATRONICS LIMITED** [GB/GB]; St John's Innovation Centre, Cowley Road, Cambridge Cambridgeshire CB4 0WS (GB).

(72) Inventors: **HOWARTH, James**; c/o Cambridge Mechatronics Limited, St John's Innovation Centre, Cowley Road, Cambridge CB4 0WS (GB). **BROWN, Andrew Benjamin David**; c/o Cambridge Mechatronics Limited, St John's Innovation Centre, Cowley Road, Cambridge CB4 0WS (GB). **HUNTING, Stephen Matthew**; c/o Cambridge Mechatronics Limited, St John's Innovation Centre, Cowley Road, Cambridge CB4 0WS (GB). **WEBBER, Dominic George**; 124 Blinco Drive Cambridge, Cambridge CB1 7TT (GB). **CHOQUETTE, Julian**; Cambridge Mechatronics Limited, St John's Innovation Centre, Cowley Road, Cambridge CB4 0WS (GB).

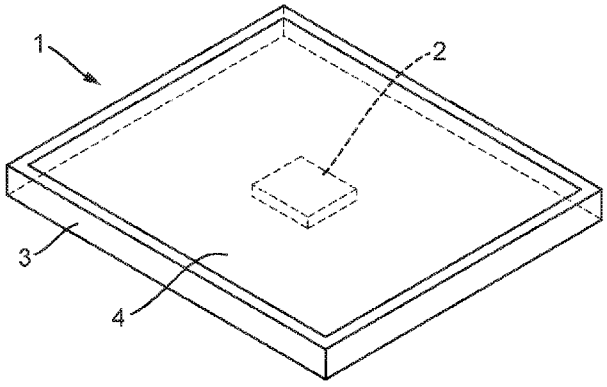
(74) Agent: **MERRYWEATHER, Colin Henry**; J A Kemp, 14 South Square, Gray's Inn, London Greater London WC1R 5JJ (GB).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,

(54) Title: SHAPE MEMORY ALLOY ASSEMBLY

Fig. 1



(57) Abstract: A haptic assembly comprises a chassis, a mass movably supported on the chassis; and at least one SMA actuator wire arranged, on contraction, to move the mass relative to the chassis. SMA provides actuation with a relatively large force which provides an improved haptic effect. A trigger element releases a retention element holding the mass against a resilient element loaded by the SMA. Drive signal powers may be controlled using resistance-based closed-loop control to allow shaping of the haptic waveform. Alternatively, the degree of movement may be increased by using a drive signal having sufficient power during an initial period that the mass achieves a sufficient velocity to cause the SMA actuator wire to go slack. A secondary actuator arrangement may be mounted on said mass to additionally generate vibrational movement.

WO 2017/208003 A1

[Continued on next page]

TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

SHAPE MEMORY ALLOY ASSEMBLY

The present invention relates to an assembly in which an SMA (shape memory alloy) actuator wire is used to move a mass relative to a chassis. In some aspects, the assembly is a haptic assembly in which the purpose of moving the mass relative to a chassis is to provide a haptic effect.

Haptic assemblies are used in mobile phones and handheld controllers to provide a haptic effect by creating an acceleration which is perceptible to the user holding the device, for example a click or a vibration.

Current types of haptic assembly include an Eccentric Rotating Mass (ERM) actuator where a mass is mounted offset on a Voice Coil Motor (VCM) to provide a vibration. Another type of haptic assembly is a Linear Resonance Actuator (LRA) which drives a mass spring assembly at resonance along a linear axis, again using a VCM. In use, the haptic assembly is mounted to the chassis of the handheld device to transmit the force sensation to the hand of the user.

Such current haptic assemblies are limited by the requirement for the VCM drive to increase the speed of the mass until it is moving fast enough for the acceleration of the mass to be felt. This reduces the clarity of the feedback sensation. The ERM actuator additionally generates forces in all directions in the plane perpendicular to the axis of rotation, which may be undesirable in some applications.

The first aspect of the present invention is concerned with provision of a single distinct sensation. Such an assembly may be used to provide a haptic effect that would improve certain applications, such as touch typing.

According to a first aspect of the present invention, there is provided an assembly comprising: a chassis; a mass movably supported on the chassis; a resilient element arranged, when loaded, to bias movement of the mass relative to the chassis; at least one SMA actuator wire arranged, on contraction, to move the mass to load the resilient element; and a retention element arranged to hold the mass with the resilient element in a loaded state; and a trigger element operable to release the retention element when holding the resilient element.

Such an assembly provides a solution which delivers a single distinct force. In particular, this is achieved by using at least one SMA actuator to load the resilient element, the retention element storing the force to deliver a fast response when triggered by the

trigger element. Release of the retention element therefore provides a single distinct force as perceived by a user.

The SMA actuator wire may be arranged, on contraction, both to operate the trigger element and to load the resilient element, preferably by operating the trigger element on initial contraction, and loading the resilient element on further contraction.

The assembly may be a haptic assembly. Alternatively, the assembly may be used in other applications where it is desired to achieve a similar benefits of using a trigger-released mass loaded against a resilient element by SMA actuator wire.

The second aspect of the present invention is concerned with provision of an improved haptic assembly.

According to a second aspect of the present invention, there is provided a haptic assembly comprising: a chassis; a mass movably supported on the chassis; and at least one SMA actuator wire connected between the chassis and the mass and arranged, on contraction, to move the mass relative to the chassis.

The use of SMA actuator wire provides actuation with a relatively large force, that allows an improved haptic effect to be provided.

The haptic assembly may further comprise a control circuit arranged to supply drive signals to the at least one SMA actuator wire.

Advantageously, the control circuit may comprise: a drive circuit operative to supply the drive signals to the at least one SMA actuator wire; a detection circuit arranged to detect a measure of the resistance of the at least one SMA actuator wire; and a control circuit configured to control the powers of the drive signals supplied by the drive circuit on the basis of the measure of resistance using closed-loop control, for example to follow a target waveform that may be shaped to provide a haptic effect, for example a click.

Use of closed-loop control of an SMA actuator allows the haptic effect delivered by the haptic assembly to be improved compared to the use of a VCM as an actuator.

Alternatively, the control circuit may be arranged to supply a drive signal through the at least one SMA actuator wire that drives contraction during an initial period and then to cease to supply the drive signal, the drive signal during the initial period having sufficient power that the mass is accelerated to a sufficient velocity that the momentum of the mass causes the at least one SMA actuator wire to go slack.

Such a type of control increases the range of accelerations that may be achieved

and also allows the mass to be moved a greater distance. In general terms, the change in length of an individual SMA actuator wire is limited, which in turn limits the stroke and acceleration that can be achieved. Typically, the maximum stroke that an individual SMA actuator can provide is around 2% to 4%, depending on the mechanical design, for example the load, material and fatigue behaviour.

In addition, if an SMA actuator wire is required to operate at elevated temperatures then a return force is required to return the wire to its long state even at those elevated environmental temperatures. This limits the range of accelerations that the actuator can apply to the moving mass. The maximum positive acceleration (SMA contracting) is the acceleration resulting from the moving mass and the difference between the maximum force that the wire can sustain without suffering from fatigue and the return force, e.g. from a resilient element. Similarly, the maximum negative acceleration (SMA extending) is the acceleration resulting from the return force and the force required to extend the wire.

However, an improvement is achieved by supplying a drive signal during an initial period having sufficient power that the mass is accelerated to a sufficient velocity that when the drive signal ceases the momentum of the mass moves the mass to a position in which the at least one SMA actuator wire goes slack. Thus, the range of acceleration is substantially larger than that in a traditional SMA actuator since the maximum positive acceleration (SMA contracting) is still given by the acceleration resulting from the moving mass and the difference between the maximum force that the wire can sustain without suffering from fatigue and the return force from the spring. However, the maximum negative acceleration (SMA extending) is the acceleration resulting from the return force and the residual tension in the wire at the maximum position reached.

The control circuit may be configured to cease to supply the drive signal before the at least one SMA actuator wire is fully transformed into an Austenite phase.

The control circuit may cease to supply the drive signal at a timing based on the measure of resistance detected by a detection circuit and/or ambient temperature detected by a temperature sensor.

Advantageously, in the haptic assembly the at least one SMA actuator wire may comprise an even number of SMA actuator wires, each being mechanically connected in parallel to the chassis and to the mass, the SMA actuator wires being electrically connected in series.

Haptic assemblies employing a VCM are limited by a requirement for the electromagnetic drive to increase the speed of the mass until it is moving fast enough for the acceleration of the mass to be felt. This introduces a delay and reduces the clarity of the feedback sensation. However, by using an even number of SMA actuator wires, each being mechanically connected in parallel to the chassis and to the mass, the overall force may be increased, which therefore allows for delivery of a haptic effect in an improved manner compared to using a VCM.

In many applications, for example in a handheld device such as a mobile phone, the drive power comes from a battery, for which efficient drive depends on matching the load to the drive circuit, and to this end it is advantageous for the load to have relatively high resistance. Thus, by electrically connecting the SMA actuator wires in series so that the resistance to the drive signal is increased, the matching of the drive circuit may be improved.

Advantageously, the mass may have a cuboid shape including four parallel edges alongside which four SMA actuator wires are respectively arranged. This provides the advantages of increasing the number of SMA actuator wires, but in an arrangement that is compact and provides balanced application of force to the mass.

The SMA actuator wires may be mechanically connected to the chassis and to the mass by crimp portions, and the haptic assembly further comprises jumper components that electrically connect crimp portions and through which the SMA actuator wires are electrically connected in series.

Advantageously, the mass may be made of a material having a density of at least $8.5kg/m^3$, for example tungsten.

Using a material with such a high density material for the moving mass is advantageous when driving the movement by an SMA actuator wire to provide a haptic effect. The moving mass is desired to move with a given motion, e.g. frequency. To achieve the required acceleration, there is a trade-off between mass and stroke. An SMA wire configured to pull the mass in the simplest layout is limited on stroke so a higher mass improves the response. This may be achieved by choosing a material having a density of at least $8.5kg/m^3$, which also reduces the package size of the assembly.

The third aspect of the present invention is concerned with an assembly where a biasing element allows a mass to vibrate. Typical haptic assemblies employing a VCM are

limited by the requirement for the VCM drive to increase the speed of the mass until it is moving fast enough for the acceleration of the mass to be felt.

According to a third aspect of the present invention, there is provided an assembly comprising: a mass; one or more biasing elements, e.g. springs; means for compressing the spring; a retention component arranged to hold the mass with the spring in a loaded, e.g. compressed ,state; a trigger which releases the spring and mass; and a latch which stops the mass after a partial, single or multiple number of oscillations.

Such an assembly is similar to a Linear Resonant Actuator in the sense that a mass and two springs are combined to act as a harmonic oscillator. However, instead of applying force to the mass during the actuation, as in the known LRA device, the driving force is applied to a spring before the actuation. The device is primed by compressing one of the two springs and then triggered to set the mass in motion along the axis at its resonant frequency. The reset mechanism is needed to return the mass to its primed start position, as energy will have been lost during operation. The rest position will depend critically on damping, which will depend on how the mobile device is being held. A reset is also required in the case of an impact, for example a drop event.

During such events, the mass-spring combination resonates and the mass eventually comes to rest at some position, which may or may not be at the centre of its stroke. Typically, the start position will be at the centre of the stroke. Preferably the reset mechanism is a ratchet mechanism.

The assembly may be a haptic assembly. Alternatively, the assembly may be used in other applications where it is desired to achieve a similar benefits of using a trigger-released mass loaded against a resilient element by SMA actuator wire.

The fourth aspect of the present invention is concerned with providing a haptic assembly that can deliver a range of haptic effects.

According to a fourth aspect of the present invention, there is provided a haptic assembly comprising: a chassis; a mass movably supported on the chassis; a primary actuator arrangement comprising at least one SMA actuator wire arranged, on contraction, to move the mass linearly relative to the chassis; and a secondary actuator arrangement mounted on said mass and arranged to generate a vibrational movement of the mass.

The primary actuator arrangement may provide a first haptic effect by moving the mass linearly relative to the chassis, driven by an SMA actuator wire. Haptic assemblies

driven by a VCM are limited by the requirement for the VCM to increase the speed of the mass until it is moving fast enough for the acceleration of the mass to be felt. This reduces the clarity of the haptic sensation. However, an SMA actuator provides a relatively high force, allowing the form of the haptic effect to be improved compared to using a VCM. By way of example, the primary actuator arrangement may be arranged, on operation, to create a feel of click. For example, the primary actuator arrangement may comprises an assembly in accordance with the first aspect of the present invention.

The secondary actuator arrangement may provide a second haptic effect that is a vibration, which may be perceived by the user as a buzzer. By way of example, secondary actuator arrangement may be arranged, on operation, to create a vibratory feel. For example, the secondary actuator arrangement may be a VCM driven eccentric rotating mass actuator arrangement.

A haptic assembly in accordance with any of the aspects of the present invention may be to provide, on mounting of the haptic assembly in a handheld electronic device, a haptic effect perceptible to a user holding the handheld electronic device on movement of the mass relative to the chassis.

Such a haptic assembly may be provided in a handheld electronic device, for example a mobile telephone. In that case, the handheld electronic device may comprise a housing and the haptic assembly may be disposed internally of the housing.

Embodiments of the present invention will now be described in detail by way of non-limitative example with reference to the accompanying drawings, in which:

Fig. 1 is a schematic view of a handheld electronic device including a haptic assembly;

Fig. 2 is a perspective view of a first arrangement of the haptic assembly;

Fig. 3 is a perspective view of a modified form of the first arrangement of the haptic assembly;

Fig. 4 is a diagram of a control circuit of the haptic assembly;

Fig. 4 is a diagram of the control circuit arranged to apply resistance-based closed-loop control;

Fig. 6 is a graph of acceleration against time for a typical computer mouse click;

Fig. 7 is a graph of acceleration against time for the SMA haptic assembly and for a VCM actuated haptic assembly;

Fig. 8 is a graph of force against time when a particular type of control is applied to the haptic assembly;

Fig. 9 is schematic view of a modified form of the haptic assembly;

Fig. 10 is a graph of force against time when the particular type of control is applied to the modified form of the haptic assembly shown in Fig. 9;

Fig. 11 is schematic view of a modified form of the haptic assembly;

Fig. 12 is a graph of force against time when the particular type of control is applied to the modified form of the haptic assembly shown in Fig. 11;

Fig. 13 is a side view of a second arrangement of the haptic assembly;

Fig. 14 is a perspective view of the SMA actuator wires in the second arrangement of the haptic assembly of Fig. 13;

Figs. 15 and 16 are cross-sectional views of a third arrangement of the haptic assembly;

Fig. 17 is a side view of a fourth arrangement of the haptic assembly.

Figs. 18 to 28 are side views of a fifth arrangement of the haptic assembly; and

Figs. 29 and 30 are graphs of position against time during two different operations of the fifth arrangement of the haptic assembly.

Fig. 1 illustrates a handheld electronic device 1 in which a haptic assembly 2 is mounted. The handheld electronic device 1 may be any type of electronic device, for example a mobile telephone. The handheld electronic device 1 has a housing 3 including a display 4. The haptic assembly 2 is disposed internally of the housing 3, behind the display 4.

The haptic assembly 2 provides a haptic effect that is perceptible to a user holding the handheld electronic device 1. The haptic effect may be an acceleration of the portable electronic device 1. For some applications, for example as feedback for typing on the display 4, the haptic effect may be an acceleration perpendicular to the extent of the display 4.

Haptic effects may be expressed as a frequency and acceleration on a test mass, typically 100g. The frequency is specified to ensure the feel is within the sensitive range of touch nerves in the skin. The acceleration defines the strength of the sensation.

The haptic assembly 2 is described in more detail below, but includes a chassis 11 and a mass 12 that is moved relative to the chassis 11. The chassis 11 is fixed to the

handheld electronic device 1. The mass of the mass 12 is sufficiently small relative to the mass of the chassis 11 and other components of the handheld electronic device 1 that the chassis 11 and other components of the handheld electronic device 1 may be considered as a static portion. Typically the mass 12 has a mass that is less that is at most 5% of the mass of the chassis 11 and other components of the handheld electronic device 1. For example, in haptic assembly 2 applied to a handheld electronic device 1 that is a mobile telephone, the chassis 11 and other components of the handheld electronic device 1 may have a mass of around 100g or more, and the mass 12 may have a mass of around 3g.

There will now be described various alternative arrangements for the haptic assembly 2, any of which may be applied to the handheld electronic device 1 shown in Fig. 1.

A first arrangement for the haptic assembly 2 is shown in Fig. 2 and arranged as follows.

The haptic assembly 2 comprises a chassis 11 and a mass 12 which is movably supported on the chassis 11 by a spring 13. The spring 13 permits the mass 12 to move along a predetermined movement direction which is vertical in Fig. 2.

The chassis 11 may be injection moulded.

The mass 12 comprises a block 17 of material and a stamped metal sheet 15 is fixed to one surface thereof. The block 17 may be injection moulded or die cast. The sheet 15 is of low mass compared to the block 17 and has the function of acting as an element that connects the SMA actuator wires 16 for moving the mass 12 as described below.

Two SMA actuator wires 16 are connected between the chassis 11 and the mass 12 as follows. Each SMA actuator wire 16 is connected to the chassis 11 by crimp components 14 that crimp the ends of the SMA actuator wire 16. Each SMA actuator wire 16 is shaped as two straight portions 18, that extend from the crimp components 14 on either side of a bend 19 that is hooked over the sheet 15 so as to connect the SMA actuator wires 16 to the mass 12. Thus, the SMA actuator wires 16 have a V shape, in which the two straight portions 18 extend in a plane that is parallel to the movement direction of the mass 12.

On contraction, the SMA actuator wires 16 drive movement of the mass 12 relative to the chassis 11 along its movement direction. The spring 13 acts as a resilient biasing element that provides a biasing force acting against the SMA actuator wires 16. In this

manner, the movements of the mass 12 driven by the SMA actuator wires 16 and spring 13 apply forces to the chassis 11 which provide the haptic effect perceptible to a user holding the handheld electronic device 1.

In general, the haptic assembly 2 could be adapted to include any number of one or more SMA actuator wires 16.

Similarly, a different type of resilient biasing element could be used instead of the spring 13, for example a flexure. Alternatively, SMA actuator wires 16 could be arranged in opposition to drive the movement in opposite ways along the movement direction.

In the first arrangement of the haptic assembly 2 shown in Fig. 2, the force generated by the SMA actuator wires 16 is limited by the constraints of the geometrical arrangement in which the two straight portions 18 extend in a plane that is parallel to the movement direction on one side of the mass 12. Fig. 3 shows a modified form of the first arrangement of the haptic assembly 2 in which the two straight portions 18 on either side of the bend 19 extend in a plane that is inclined with respect to the movement direction. That allows the bend 19 to be arranged in a corner of the mass 12 with the two straight portions 18 extending on adjacent sides of the mass 12, thereby increasing the length of the SMA actuator wires 16 within the constraints of the geometrical arrangement. This increases the force that can be generated by the SMA actuator wires 16, compared to Fig. 2.

Fig. 4 shows a control circuit 20 which is connected to the SMA actuator wires 16 and supplies drive signals to them. The drive signals heat the SMA actuator wires 16 causing them to contract against the resilient biasing force. The drive signals are selected to control the form of the haptic effect that is generated. Such a control circuit 20 may be applied to any of the arrangements of the haptic assembly 2 described herein.

In a first type of control, the drive signals may be supplied under open loop control. In another type of control, the drive signals may be supplied under closed-loop control, which may be resistance-based. In order to apply resistance-based closed-loop control, the control circuit 20 may be arranged as shown in Fig. 5, as will now be described.

In this example, the control circuit 20 comprises a drive circuit 21, a controller 22 and a detection circuit 23, which operate as follows.

The drive circuit 21 is connected to the SMA actuator wires 16. The drive circuit 21 generates the drive signals and supplies them to the SMA actuator wires 16.

The controller 21 controls the powers of the drive signals. In one example, pulse-width modulation may be applied. In this case, the drive signals have a pulsed form and the controller 21 varies the width of the pulses to vary the power.

The detection circuit 23 is connected to the SMA actuator wires 16 and detects a measure of the resistance thereof. Any suitable resistance measurement technique may be used. For example, in the case that drive circuit 21 supplies drive signals having a constant current, the detection circuit 23 may measure the voltages across the SMA actuator wires 16 as a measure of resistance.

The measures of the resistance detected by the detection circuit 23 are supplied to the controller 21. The controller 21 controls the powers of the drive signals supplied by the drive circuit 21 on the basis of the measures of resistance using closed-loop control to follow a target waveform. Any suitable closed-loop control algorithm may be applied. Typically, the controller 21 derives an error between the measures of resistance and the target waveform, and controls the powers of the drive signals to minimise the error.

The closed-loop control may be applied as described in any of WO-2009/071898, WO-2010/049689, or WO-2014/076463, albeit that the movable element and target waveform are different.

The target waveform is shaped to provide a haptic effect, for example a click.

The benefit of such resistance-based closed-loop control of the SMA actuator wires 16 as applied to generate a haptic effect is that it improves the resulting haptic sensation and allows variations in the output as required. Haptics depend on human perception and so small changes in the waveform of the resultant acceleration or impulse can have a large effect on how compelling the haptic sensation feels. It is therefore desirable to be able to fine-tune the waveform of the actuator with a degree of control that is available using resistance-based closed-loop control. This may be thought of as the SMA control being able to provide a quicker start and stop than a VCM actuator. The haptic assembly 2 can thus be configured to deliver a range of responses at different frequencies and amplitudes. The haptic waveform may be finely tuned to provide the most desirable haptic effect, or indeed a range of different haptic effects.

By way of comparison, the performance of the control circuit 20 operating in open loop may be prone to variations due to minor differences in the actuator build, the thermal and mechanical history of the SMA wire, the ambient temperature and other environmental

conditions. Thus the use of resistance-based closed-loop control improves repeatability and reliability.

To illustrate this, reference is made to Figs. 6 and 7 to compare haptic assemblies to a computer mouse click. A computer mouse produces a click that is "satisfying" to the user by mechanical means, and so is a type of haptic effect which it is desired to emulate in some applications.

Fig. 6 is a graph of acceleration against time for a typical computer mouse click, showing a short rise-time, high peak-to-peak acceleration and rapid decline of the waveform.

Fig. 7 is a graph of acceleration against time for the haptic assembly (thick line 25) using closed-loop control and a suitable target waveform and a top-end VCM haptic actuator (thin line 26). As can be seen, the VCM actuator waveform builds up to its peak over about 10ms or one and a half cycles, and then dies away gradually over several cycles, due to resonances in the system. Such a waveform will give an indistinct haptic sensation, with a perceptible delay and a buzz feel. In comparison, the SMA actuator waveform reaches its peak in its first cycle in about 1ms to 2ms and dies away immediately. The SMA waveform is therefore very much closer to that of the computer mouse click of Fig. 6, and will give a distinct sharp haptic sensation. The characteristic achieved by the SMA actuator wire 16 as shown in Fig. 7 may be achieved by careful control of the power supplied to the SMA wire.

In a particular type of control, the haptic waveform is designed to give a sufficient response from only the heating part of the first cycle. Haptic actuators are typically required to deliver frequencies above 50Hz in the region where the skin is most sensitive. SMA actuators typically work at lower frequencies. To achieve this the SMA actuator wires 16 may be used only in the heating direction where the bandwidth of operation can be much higher. The haptic effect is delivered by heating the SMA actuator wires 16 fast so that the mass 12 compresses the spring 13. The SMA actuator wires 16 are then allowed to cool slowly to return the mass 12 to its start position.

In a second type of control, the drive signal is controlled to drive contraction during an initial period and then to cease. In this case, during the initial period the drive signal may be provided with sufficient power that the mass 12 is accelerated to a sufficient velocity that the momentum of the mass 12 causes the SMA actuator wires 16 to go slack.

This allows the generated acceleration to be increased.

This type of control is illustrated in Fig. 8 which is a graph of force against time that result from this type of control. Fig. 8 illustrates the force in the SMA actuator wire 16 (line 27), the force in the spring 13 (line 28) and the resultant force acting on the chassis 11 (line 29). Fig. 8 relates in particular to an example using a mass 12 of 3.3g and a single SMA actuator wire 16 having a diameter of 100 micron diameter such that the force from the spring 13 when the SMA actuator wire 16 is unheated is 4N to provide a tension of 2N in each portion 18 of the SMA actuator wire 16.

The drive signal is applied in an initial period from times 31 to 32, being 2 amps with an initial period of between 2ms and 10ms in this example. This drive signal accelerates the mass 12. At time 32, drive signal ceases. The mass is moving at a velocity such that it continues to move against the spring 13 due to its momentum until the SMA actuator wire 16 goes slack as illustrated at time 33 in Fig. 8. The spring 13 continues to decelerate the mass 12 from time 33 to time 34 in Fig. 8, at which point the SMA actuator wire 16 starts to tighten again. Thereafter, the force in the SMA actuator wire 16 increases until it matches the force applied by the spring 13 at time 35.

As can be seen in Fig. 8, in this example the resultant force when the SMA actuator wire is slack between times 33 and 34 is significantly greater than when the SMA actuator wire 16 is driven during the initial period between times 31 and 32. Thus, this type of control increases the range of accelerations that may be achieved and also allows the mass to be moved a greater distance.

If the SMA actuator wires 16 are required to operate at elevated temperatures then a return force is required to return the wire to its long state even at those elevated environmental temperatures. This limits the range of accelerations that the SMA actuator wire 16 can apply to the mass 12. The maximum positive acceleration (SMA contracting) is the acceleration resulting from the mass 12 and the difference between the maximum force that the SMA actuator wires 16 can sustain without suffering from fatigue and the return force from the spring 13. Similarly, the maximum negative acceleration (SMA extending) is the acceleration resulting from the return force and the force required to extend the SMA actuator wires 16.

However, the present method increases the range of acceleration since the maximum positive acceleration (SMA contracting) is still given by the acceleration

resulting from the mass 12 and the difference between the maximum force that the SMA actuator wires 16 can sustain without suffering from fatigue and the return force from the spring 13. However, the maximum negative acceleration (SMA extending) is the acceleration resulting from the return force from the spring 13 and the residual tension in the SMA actuator wires 16 at the maximum position reached.

When this type of control is applied, advantageously, the drive signal ceases to be applied before the SMA actuator wires 16 are fully transformed into an Austenite phase.

The timing when the drive signal ceases to be applied is controlled by the control circuit 20. This timing may be predetermined, but advantageously may be selected based on (a) a measure of the resistance of the SMA actuator wires 16, which may be detected by a detection circuit 23 as shown in Fig. 5, and/or (b) the ambient temperature detected by a temperature sensor 24.

Optional modifications that may be applied to advantage with this type of control will now be described.

At point 34 in Fig. 8, the SMA actuator wires 16 may receive a sudden shock as the spring 13 returns the mass 12 and the SMA actuator wires 16 become taut. This may cause lifetime reliability issues.

Two potential solutions to reduce this impact are described below and illustrated in Figs. 9 and 11, in which the SMA actuator wires 16 are shown schematically for clarity.

A first solution shown in Fig. 9 is to introduce a second spring 36 between the mass 12 and the chassis 11, in this example located on the opposite side of the mass 12 to the first spring 13. In this case, the second spring 36 acts as a coupling that can be configured to allow the full force of the SMA actuator wires 16 to drive the mass 12 in the compression stroke but will allow deceleration on the return stroke to reduce the shock loading. This reduces the resultant forces as shown in Fig. 10.

A second solution shown in Fig. 11 is to decouple the SMA actuator wires 16 from the mass 12 at the end of the drive stroke (at time 32), for example by a latch which releases the mass 12 from the wire SMA actuator wires 16 at the appropriate point. The mass 12 may then complete a full return stroke without being restricted by the cooling speed of the SMA actuator wires 16. The SMA actuator wires 16 may be returned with a separate return spring 37, illustrated in Fig. 11. This reduces the resultant forces as shown in Fig. 12.

Advantageously, the mass 12 may be made of a material having a density of at least 8.5kg/m^3, for example tungsten which has a density of 19.25 kg m^{-3} . Using a material with such a high density is advantageous when driving the movement by the SMA actuator wires 16 to provide a haptic effect. The moving mass is desired to move with a given motion, e.g. frequency. To achieve the required acceleration, there is a trade-off between mass and stroke. An SMA actuator 16 wire configured to pull the mass 12 in the simplest layout is limited on stroke so a higher mass improves the response.

Some further arrangements for the haptic assembly 2 will now be described. Each of these further arrangements is a modified form of the first arrangement. Common elements have common reference numerals. For brevity and clarity, only the modifications will be described, and otherwise the arrangements of the haptic assembly 2 are the same as described above.

A second arrangement for the haptic assembly 2 is shown in Fig. 13 and arranged as follows.

In the second arrangement, the haptic assembly 2 employs four SMA actuator wires 16 in an arrangement shown in greater detail in Fig. 14, wherein the mass 12 is omitted for clarity. In particular, the mass 12 has a cuboid shape including four parallel edges 40. The four SMA actuator wires 16 are respectively arranged alongside those edges 40 of the mass 12. This is a convenient and compact arrangement that balances the forces applied by the SMA actuator wires 16. The SMA actuator wires 16 are mechanically connected in parallel to the chassis 11 and to the mass 12 by crimp components 41, but are electrically connected in series, through jumper components 42 provided on the chassis 11 and on the mass 12.

As a result of the SMA actuator wires 16 being mechanically connected in parallel and electrically connected in series, the forces applied by the SMA actuator wires 16 are combined and similarly the resistances are combined. This allows the overall applied force to be increased, or similarly for the overall resistance to be increased.

In the case of SMA actuator wires 16, the force that can be generated from them is proportional to the cross-sectional area. This force is then converted into an acceleration of the mass 12. A given level of acceleration may be maintained when increasing the number of SMA actuator wires 16 by reducing the diameter of each SMA actuator wire proportionally to maintain the same cross section area, but the amount of surface area in

contact with air increases which has an effect of increasing the thermal losses into the air. In general, a balance is made between the series resistance of the SMA actuator wires 16 and the thermal losses.

A third arrangement for the haptic assembly 2 is shown in Figs. 15 and 16, and arranged as follows. Each of Figs. 15 and 16 show one half of the haptic assembly 2 in cross-section, the features being mirrored around the centre line on the left side of the drawings.

In the third arrangement, the overall configuration of the mass 12 and the SMA actuator wires 16 are the same as in the first arrangement, but instead of the SMA actuator wires 16 being connected directly to the mass 12, the SMA actuator wires 16 are connected indirectly to the mass 12 and the operation uses a trigger mechanism to release movement of the mass 12, as follows.

The haptic assembly 2 comprises a chassis 11 and a mass 12 which is movably supported on the chassis 11 by a spring 13. The spring 13 is fixed to the chassis 11 by a heat stake 40. The chassis 11 may be injection moulded. The mass 12 comprises a block of material and may be injection moulded or die cast, but the stamped metal sheet 15 of the first arrangement is omitted.

The spring 13 permits the mass 12 to move along a predetermined movement direction which is vertical in Figs. 15 and 16. The spring 13 acts as a resilient element and, when loaded in a compressed state, biases movement of the mass 12 relative to the chassis 11. In Fig. 16, the spring 13 is shown in its loaded state and biases movement upwardly.

The haptic assembly 2 further comprises a retention flexure 41 which includes a catch portion 42 formed by its end being bent over. The mass 12 has a keeper portion 43 formed thereon and with which the catch portion 42 engages when the spring 13 is in a loaded state as shown in Fig. 16. In this manner, the retention flexure 41 acts a retention element to hold the mass 12 with the spring 13 in a loaded state.

On flexing of the retention flexure 41 to the position shown in dotted outline in Fig. 16, the catch portion 42 disengages the keeper portion 43, so that the retention flexure 41 is released. This permits the mass 12 to move under the biasing from the spring 13. As shown in Fig. 15, the mass 12 moves upwardly until, at the position shown dotted outline, the catch portion 42 engages an end-stop 44 formed on the mass 12 behind the keeper portion 43. The movement distance may typically be of in the range from 100 to 200 microns.

Fig. 16 shows an arrangement by which the SMA actuator wires 16 load the spring 13 and trigger its release, as follows. Each of the SMA actuator wires 16 is connected in the manner shown in Fig. 16.

The haptic assembly 2 comprises two SMA actuator wires 16 connected between the chassis 11 and the mass 12 in the same overall position as in the first arrangement using crimp components 14 in the manner shown in Fig. 2. That is, each SMA actuator wire 16 is shaped as two straight portions 18 on either side of a bend 19 so that the SMA actuator wires 16 have a V shape, in which the two straight portions 18 extend in a plane that is parallel to the movement direction of the mass 12.

The SMA actuator wires 16 are hooked over a trigger flexure 45, by which they are connected indirectly to the mass 12 as described below. Fig. 16 illustrates the loaded state of the spring 13, in which state the trigger flexure 45 is separated from the mass 12. The trigger flexure 45 and has a step feature 46 which engages with a catch feature 47 formed on the retention flexure 41, as shown in Fig. 16. By means of this engagement, the trigger flexure 45 acts as a trigger element and releases the retention flexure 41 from holding the spring 13, driven by contraction of the SMA actuator wires 16, as will now be described.

When the SMA actuator wires 16 contract, they move the trigger element 16 downwardly in Fig. 16. Through the engagement between the step feature 46 and the catch feature 47, this motion flexes the retention flexure 41 to the position shown in dotted outline in Figs. 15 and 16, thereby releasing the spring 13 from its loaded state and allowing it to bias movement of the mass 12, as described above. In Fig. 16, the position at which the mass 12 stops moving when it engages the end stop 44 is shown in dotted outline.

The motion of the mass 12 under the biasing of the spring 12, both at the point of release of the spring 13 from its loaded state and at the point of engagement with the end stop 44 applies a force to the chassis 11, and hence to the handheld electronic device 1. The motion and hence the forces occur along the movement direction, as described above.

On further contraction, the SMA actuator wires 16 move the mass 12 to load the spring 13 and reset the trigger flexure 45, as follows.

The mass 12 is now at the position shown in dotted outline in Fig. 16. The trigger flexure 45 has been moved down, typically by a distance in the range from 50 to 100 microns, into contact with the mass 12 at a curved surface 48 formed on the mass 12. The

curved surface 48 has a sufficiently large radius of curvature to reduce the degree of bending in the SMA actuator wires, for example of the order of 0.5mm.

As the SMA actuator wires 16 continue to contract, the mass 12 is moved downwards back towards its initial position. This loads the spring 13. Therefore the contraction of the SMA actuator wires 16 operates the trigger flexure 45, on the initial contraction, and loads the spring 13, on further contraction.

For resetting the trigger mechanism, the chassis 11 is formed with a reset feature 49 in the form of a ramp, and the trigger flexure 45 is formed with a lip 50 at its end. The reset feature 49 and the lip 50 are configured so that the reset feature 49 engages the lip 50 after the spring 13 has been loaded. On further contraction of the SMA actuator wires 16, this engagement lifts the trigger flexure 45, as shown in dotted outline, thereby causing disengagement of the step feature 46 and the catch feature 47. That in turn releases the retention flexure 41 causing it to spring back and re-engage with the keeper portion 43 on the mass 12 which has now been moved by the SMA actuator wires 16 sufficiently far to allow that re-engagement to occur. The retention flexure 41 is therefore now reset and ready for the next actuation cycle. Accordingly, the driving of the SMA actuator wires 16 is ceased, allowing the SMA actuator wires 16 to cool. The trigger flexure 45 springs back into its original shape, thereby extending the SMA actuator wires 16 back to their original length and allows the step feature 46 to re-engage the catch feature 47. The reset cycle is completed and the haptic assembly 2 has been returned to its initial condition.

The third arrangement of the haptic assembly 2 therefore delivers a single distinct force due to the retention flexure 41 storing the force to deliver a fast response when triggered by the trigger flexure 45. Release of the retention flexure 41 therefore provides a single distinct force as perceived by a user.

Optionally, any of the first arrangement for the haptic assembly 2 shown in Fig. 2, the second arrangement for the haptic assembly 2 shown in Fig. 13, or the third arrangement for the haptic assembly 2 shown in Figs. 15 and 16 may be modified to include a secondary actuator arrangement 60 mounted on said mass 12. The secondary actuator arrangement 60 generates a vibrational movement of the mass 12. In this case, the SMA actuator wires 16 are considered to be a primary actuator arrangement that move the mass 12 linearly relative to the chassis 11 as described above.

A fourth arrangement for the haptic assembly 2 that includes primary and

secondary actuator arrangements is shown in Fig. 17, and arranged as follows.

In this arrangement, the mass 12 is movably supported on the chassis 11 by a pair of springs 13. The SMA actuator wires 16 are connected between the mass 12 and the chassis 11 and provide a primary actuator arrangement that moves the mass 12 relative to the chassis 11 in a linear direction which is horizontal in Fig. 17

In addition, a secondary actuator arrangement 60 is mounted on the mass 12. The secondary actuator arrangement 60 generates a vibrational movement of the mass 12. In any of these arrangements, the provision of primary and secondary actuator arrangements allows multiple different haptic effects to be provided. For example, the primary actuator arrangement may provide a first haptic effect by moving the mass linearly relative to the chassis, driven by SMA actuator wires 16, as described above, for example a feel of a click, whereas the secondary actuator arrangement 60 may provide a second haptic effect that is a vibratory feel, which may be perceived by the user as a buzzer.

Compared to two separate haptic assemblies, the integrated actuator of the invention saves weight, as the entire secondary actuator arrangement 60 serves as the part of the mass 12 of the primary actuator arrangement. It therefore provides a compact, low weight and potentially low cost solution to providing a varied haptic experience in the handheld electronic device 1.

The secondary actuator arrangement 60 may be of any suitable type. The secondary actuator arrangement 60 may itself employ SMA actuator wires, but may equally employ actuators that are not SMA.

In one non-limitative example illustrated in Fig. 17, the secondary actuator arrangement 60 may be a Eccentric Rotating Mass (ERM) actuator arrangement integrated within the mass 12 and comprising an eccentric mass 61 rotatably mounted on the mass 12, and a motor 62, which may be a VCM, arranged to rotate the eccentric mass 61. This may be an off-the-shelf VCM ERM device of suitable size to fit within the mass 12.

A fifth arrangement for the haptic assembly 2 in which the SMA actuator wire 16 is connected indirectly to the mass 12 is shown in Figs. 18 to 28, and arranged as follows.

The fifth arrangement for the haptic assembly 2 is illustrated in Fig. 18 and its operation explained in Figs. 19 to 26.

The haptic assembly 2 comprises a moving mass 102 suspended on two springs 103 and 104, which are connected to a support structure (the support structure is shown

throughout as ground, a solid line backed by hashed lines). A first SMA wire 105, the trigger wire, is connected at one end to the support structure and at its other end to one end of a trigger pawl component 106.

A first bias spring 107 connects the pawl component 6 to the support structure. The pawl component 106 is pivoted about a pivot 108 and has at its far end a pawl tooth 109. When the SMA wire 105 contracts, it causes the pawl 106 to rotate about its pivot 108 and lift the pawl tooth 109 out of a recess 110 in a ratchet 111 located on the moving mass 102.

Also present is a second pawl, the reset pawl 112, which is connected to a second SMA wire, the SMA reset wire 113, and a second bias spring 114. Contraction of the SMA reset wire 113 causes the reset pawl 112 to rotate about its pivot 115 and lower the tooth 116 at its far end into recess 117 on ratchet 111.

The operation of the haptic assembly 2 and reset mechanism is described in Figs. 19 to 26, in which similar numbers denote similar components as in Fig. 18. Fig. 19 shows the haptic assembly 2 at the start of its cycle, in the primed position. The first spring 103 (on the right of Fig. 19) is in the compressed state.

In Fig. 20, the first SMA wire 105 is heated electrically through an electrical circuit (not shown) such that it contracts. This causes the pawl 106 to rotate (clockwise) and the pawl tooth 109 to be released. The mass 102 then accelerates in the direction of the arrow (to the left in Fig. 19) under the action of the spring 103 expanding and releasing its potential energy. As the mass moves to the left, it compresses the second spring 104 on the left.

In Fig. 21, the mass 102 is accelerating back to the right as the left-hand spring 104 expands. This causes the right-hand spring 103 to be compressed. Meanwhile, the SMA trigger wire 105 is no longer being heated, and as it cools it is extended under the action of the bias spring 107, causing the pawl 106 to rotate back (anti-clockwise).

In Fig. 22, the SMA trigger wire 105 is cool and the pawl 106 has dropped its tooth 109 into recess 20 on the ratchet 111. Compared to its original position shown in Fig. 19, the mass has moved along one recess to the right. The tooth and ratchet prevent the mass moving any further.

In Fig. 23, the second SMA wire, reset wire 113, is heated to contract causing the second pawl 112 to rotate and drop its tooth 116 into recess 121 on the ratchet 111.

In Fig. 24, the reset wire 113 continues to be heated, contracting further and pulling

the entire reset pawl 112 to the right, driving the mass 102 to the right, thereby further compressing spring 103 and dislodging pawl tooth 109 and allowing it to drop into the next recess to the left. Thus, the spring 103 is compressed in a series of small motions using the ratchet 111 and pawl 106. Alternatively, a piezoelectric inchworm motor could be used as the means for compressing the spring 103.

In Fig. 25, the reset wire 113 is cooling, causing the pawl 112 to rotate back and lift its tooth 116 out of the recess 121 on the ratchet 111.

In Fig. 26, the reset wire 113 is reset, ready for the next ratchet event if required. As drawn, Fig. 26 and Fig. 19 are identical, that is, one operation of the ratchet mechanism has been sufficient to fully prime the haptic assembly 2 for the next haptic event. In other circumstances, for instance high damping of the resonance or following a drop event, further ratchet operations may be required until the haptic assembly 2 is fully primed for haptic operation.

Fig. 27 illustrates schematically modification to the fifth arrangement of the haptic assembly 2. A third pawl 128 is pivoted about a pivot 122 and has at its far end a pawl tooth 123. A third SMA wire 24 is attached to the third pawl 128. Also present is a third bias spring 125 which connects the third pawl 128 to the support structure. Fig. 27 shows the haptic assembly 2 at the start of its cycle, in the primed position. Mass 102 is held in place by trigger pawl 106 and the first spring 103 (on the right of Fig. 27) is in the compressed state. Thus, the trigger pawl 106 acts as a latch.

In Fig. 28, the mass 102 has moved to the left after being released by the trigger pawl 106 (according to the sequence described in Fig. 20) and is now held in place by the pawl tooth 123 positioned in a recess 126 of raised feature 127 located on the moving mass 102. To release the mass 102 again, the SMA wire 24 contracts, this causes the pawl 128 to rotate counter-clockwise about its pivot 122 and lifts the pawl tooth 123 out of the recess 126. The mass 102 accelerates back to the right as the left-handspring 104 expands and is caught by pawl 106 as described in Figs. 21 and 22.

Fig. 29 plots the movement of the mass 102 in the context of the fifth arrangement of the haptic assembly 2 shown in Figs. 18 to 26. The reference position “zero” is defined as the centre of the stroke. It can be seen from Fig. 29 that the initial position is at the highest position (or furthest to the right when looking at Fig. 18) and that the final position is slightly below the initial position (this is due to the energy loss).

Fig. 30 plots the movement of the mass 102 in the context of the modification to the fifth arrangement of the haptic assembly 2 shown in Figs. 27 and 28. The reference position "zero" is defined as the centre of the stroke. It can be seen from Fig. 30 that the initial position is at the highest position (or furthest to the right when looking at Fig. 27) and that the final position is at the lowest position (or furthest to the left when looking at Fig. 28).

In this modification, the haptic assembly 2 may be arranged to provide a single short force feedback when operated. On triggering, the mass is released and moves in a single direction, completing a partial cycle before being stopped by the third pawl 23. This is achieved by powering the trigger SMA wire 105 briefly. The gives a fast sharp 'click' feeling to the user. To reset, the SMA wire 24 is powered briefly and the mass 102 is stopped by the trigger pawl tooth 109.

Similarly, in this modification the haptic assembly 2 may be arranged to give a sharp force feedback when operated. That is, on triggering, the mass is released and moves back and forth, completing a single cycle before being stopped by re-engagement of the trigger pawl tooth 109. In fact, there is always energy loss, such that the mass completes a little less than a full cycle. Such a single cycle is achieved by powering the trigger SMA wire 105 only briefly. This also gives a sharp 'click' feeling to the user.

Alternatively, the haptic assembly 2 may be arranged to resonate, in which the mass is allowed to move back and forth at resonance, giving a buzz feel. This is achieved by powering the trigger SMA wire 105 for longer. The oscillation may occur at a set frequency.

The mass may be 102 may be reset and released multiple times to produce a series of force impulses.

Resistance control of the SMA wires may be applied to provide more complicated waveforms or improve the performance of the device.

Claims

1. An assembly comprising:

a chassis;

a mass movably supported on the chassis;

a resilient element arranged, when loaded, to bias movement of the mass relative to the chassis;

at least one SMA actuator wire arranged, on contraction, to move the mass to load the resilient element; and

a retention element arranged to hold the mass with the resilient element in a loaded state; and

a trigger element operable to release the retention element when holding the resilient element.

2. An assembly according to claim 1, wherein the SMA actuator wire is arranged to have two straight portions on either side of a bend.

3. An assembly according to claim 2, wherein the two straight portions are connected to the chassis and the bend is hooked over an element which is arranged to move the mass relative to the chassis on contraction of at least one SMA actuator wire.

4. An assembly according to claim 3, wherein the element over which the bend is hooked is the trigger element.

5. An assembly according to any one of the preceding claims, wherein the at least one SMA actuator wire comprises plural SMA actuator wires.

6. An assembly according to any one of the preceding claims, wherein said loaded state of the resilient element is a compressed state.

7. An assembly according to any one of the preceding claims, wherein the at least one SMA actuator wire is arranged, on contraction, both to operate the trigger element and to

load the resilient element.

8. An assembly according to claim 7, wherein the at least one SMA actuator wire is arranged, on initial contraction, to operate the trigger element and on further contraction to load the resilient element.

9. An assembly according to any one of the preceding claims, wherein
the mass comprises a keeper portion, and
the retention element is a flexure comprising a catch portion which is arranged to engage the keeper portion so as to hold the mass with the resilient element in the loaded state, and is arranged, on flexing of the retention element to disengage the keeper portion so as to release the retention element, the trigger element being operable to engage the flexure and cause said flexing.

10 . An assembly according to claim 9, further comprising a reset feature arranged to engage the trigger element after loading of the resilient element by the SMA actuator wire so as to disengage the retention element and permit release of the retention element to re-engage the keeper portion.

11. An assembly according to any one of the preceding claims, being a haptic assembly.

12. A haptic assembly according to claim 11, wherein the haptic assembly is arranged to provide, on mounting of the haptic assembly in a handheld electronic device, a haptic effect perceptible to a user holding the handheld electronic device on movement of the mass relative to the chassis.

13. A handheld electronic device comprising a haptic assembly according to any one of claim 11 or 12.

14. A handheld electronic device according to claim 13, wherein the handheld electronic device comprises a housing and the haptic assembly is disposed internally of the

housing.

15. A haptic assembly comprising:

a chassis;

a mass movably supported on the chassis; and

at least one SMA actuator wire connected between the chassis and the mass and arranged, on contraction, to move the mass relative to the chassis.

16. A haptic assembly according to claim 15, further comprising a control circuit arranged to supply drive signals to the at least one SMA actuator wire.

17. A haptic assembly according to claim 16, wherein the control circuit comprises:

a drive circuit operative to supply the drive signals to the at least one SMA actuator wire;

a detection circuit arranged to detect a measure of the resistance of the at least one SMA actuator wire; and

a controller configured to control the powers of the drive signals supplied by the drive circuit on the basis of the measure of resistance using closed-loop control.

18. A haptic assembly according to claim 17, wherein the closed-loop control is configured to drive the measure of resistance to follow a target waveform.

19. A haptic assembly according to claim 18, wherein the target waveform is shaped to provide a haptic effect.

20. A haptic assembly according to claim 19, wherein the haptic effect is a click.

21. A haptic assembly according to claim 16, wherein the control circuit is arranged to supply a drive signal through the at least one SMA actuator wire that drives contraction during an initial period and then to cease to supply the drive signal, the drive signal during the initial period having sufficient power that the mass is accelerated to a sufficient velocity that the momentum of the mass causes the at least one SMA actuator wire to go

slack.

22. A haptic assembly according to claim 20, wherein the control circuit is configured to cease to supply the drive signal before the at least one SMA actuator wire is fully transformed into an Austenite phase.

23. A haptic assembly according to claim 21 or 22, wherein the control circuit includes a detection circuit arranged to detect a measure of the resistance of the at least one SMA actuator wire, and is configured to cease to supply the drive signal at a timing based on the detected measure of resistance.

24. A haptic assembly according to any one of claims 21 to 23, wherein the control circuit includes a temperature sensor arranged to detect an ambient temperature, and is configured to cease to supply the drive signal at a timing based on the detected ambient temperature.

25. A haptic assembly according to any one of claims 15 to 24, wherein the SMA actuator wire is arranged to have two straight portions on either side of a bend.

26. A haptic assembly according to claim 25, wherein the at least one SMA actuator wire is arranged, on contraction, to move the mass relative to the chassis in a predetermined direction, and the two straight portions of SMA on either side of the bend extend in a plane that is inclined with respect to the predetermined direction.

27. A haptic assembly according to claim 25 or 26, wherein the two straight portions are connected to the chassis and the bend is hooked over an element which is arranged to move the mass relative to the chassis on contraction of the at least one SMA actuator wire.

28. A haptic assembly according to any one of claims 15 to 27, wherein the at least one SMA actuator wire comprises plural SMA actuator wires.

29. A haptic assembly according to any one of claims 15 to 28, further comprising a

resilient biasing element connected between the chassis and the mass and arranged to provide a biasing force acting against the at least one SMA actuator wire.

30. A haptic assembly according to any one of claims 15 to 29, wherein the at least one SMA actuator wire comprises an even number of SMA actuator wires, each being mechanically connected in parallel to the chassis and to the mass, the SMA actuator wires being electrically connected in series.

31. A haptic assembly according to claim 30, wherein the even number of SMA actuator wires is four, the mass has a cuboid shape including four parallel edges alongside which the SMA actuator wires are respectively arranged.

32. A haptic assembly according to claim 30 or 31, wherein the SMA actuator wires are mechanically connected to the chassis and to the mass by crimp portions, and the haptic assembly further comprises jumper components that electrically connect crimp portions and through which the SMA actuator wires are electrically connected in series.

33. A haptic assembly according to any one of claims 15 to 32, wherein the mass is made of a material having a density of at least 8.5kg/m^3.

34. A haptic assembly according to claim 33, wherein the material comprises tungsten.

35. A haptic assembly according to any one of claims 15 to 34, wherein the haptic assembly is arranged to provide, on mounting of the haptic assembly in a handheld electronic device, a haptic effect perceptible to a user holding the handheld electronic device on movement of the mass relative to the chassis.

36. A handheld electronic device comprising a haptic assembly according to any one of claims 15 to 35 mounted therein.

37. A handheld electronic device according to claim 36, wherein the handheld electronic device comprises a housing and the haptic assembly is mounted internally of the

housing.

38. An assembly comprising:

a mass;

one or more biasing elements, e.g. springs;

means for compressing the spring;

a retention component arranged to hold the mass with the spring in a loaded, e.g. compressed ,state;

a trigger which releases the spring and mass; and

a latch which stops the mass after a partial, single or multiple number of oscillations.

39. An assembly according to claim 38 wherein the means for compressing the spring comprises at least one SMA actuator wire.

40. An assembly according to claim 39, further comprising a bias spring arranged to extend the at least one SMA actuator wire during cooling.

41. An assembly according to any one of claims 38 to 40, wherein the spring is arranged to be compressed in a series of small motions.

42. An assembly according to any one of claims 38 to 42, wherein the means for compressing the spring includes a ratchet and pawl.

43. An assembly according to any one of claims 38 to 42, wherein the means for compressing the spring includes a piezoelectric inchworm motor.

44. An assembly according to any one of claims 38 to 43, wherein the trigger is operated by one or more SMA actuator wires.

45. An assembly according to any one of claims 38 to 44, wherein the latch and trigger are the same component.

46. An assembly according to any one of claims 38 to 45, wherein the mass and spring is configured to oscillate at a set frequency.

47. An assembly according to any one of claims 38 to 46, wherein the mass is reset and released multiple times to produce a series of force impulses.

48. An assembly according to any one of claims 38 to 47, wherein the at least one SMA wire is powered under resistance control.

49. An assembly according to any one of claims 38 to 48, being a haptic assembly.

50. A haptic assembly according to claim 49, wherein the haptic assembly is arranged to provide, on mounting of the haptic assembly in a handheld electronic device, a haptic effect perceptible to a user holding the handheld electronic device on movement of the mass relative to the chassis.

51. A handheld electronic device comprising a haptic assembly according to any one of claim 49 to 50.

52. A haptic assembly comprising:

a chassis;

a mass movably supported on the chassis;

a primary actuator arrangement comprising at least one SMA actuator wire arranged, on contraction, to move the mass linearly relative to the chassis; and

a secondary actuator arrangement mounted on said mass and arranged to generate a vibrational movement of the mass.

53. A haptic assembly according to claim 52, wherein the primary actuator arrangement comprises an assembly as defined in any one of claims 1 to 52.

54. A haptic assembly according to claim 52 or 53, wherein the secondary actuator

arrangement is an eccentric rotating mass actuator arrangement.

55. A haptic assembly according to any one of claims 52 to 54, wherein the primary actuator arrangement is arranged, on operation, to create a feel of a click.

56. A haptic assembly according to any one of claims 52 to 55, wherein secondary actuator arrangement is arranged, on operation, to create a vibratory feel.

57. A haptic assembly according to any one of claims 52 to 56, wherein the haptic assembly is arranged to provide, on mounting of the haptic assembly in a handheld electronic device, a haptic effect perceptible to a user holding the handheld electronic device on movement of the mass relative to the chassis.

58. A handheld electronic device comprising a haptic assembly according to any one of claims 52 to 57.

59. A handheld electronic device according to claim 58, wherein the handheld electronic device comprises a housing and the haptic assembly is disposed internally of the housing.

Fig. 1

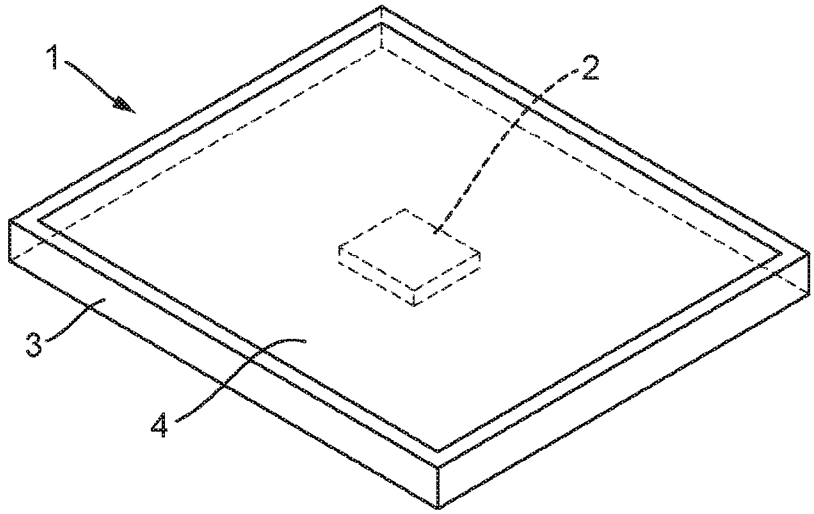


Fig. 2

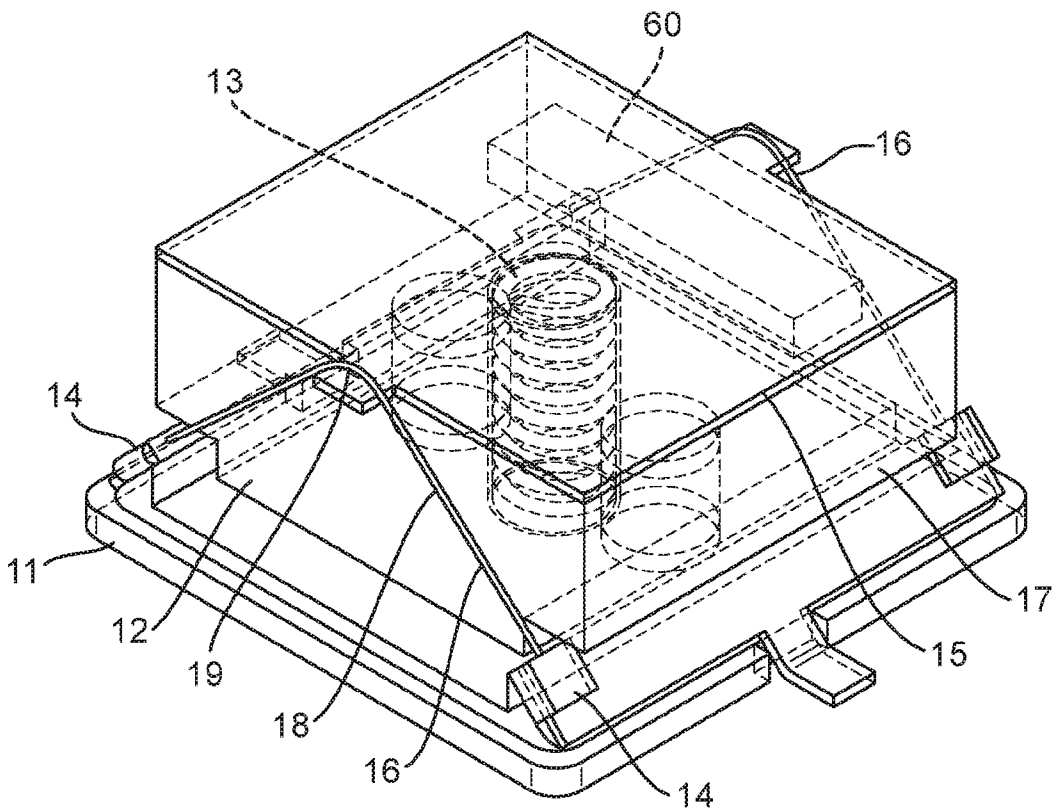


Fig. 3

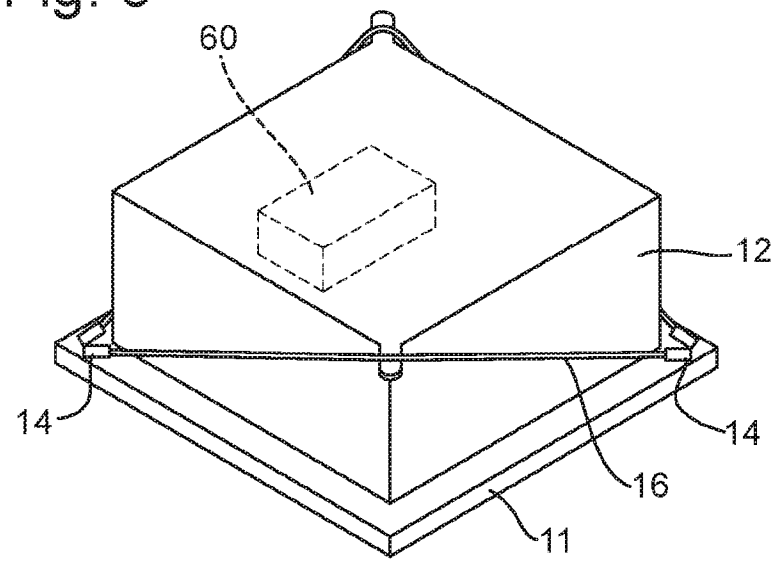


Fig. 4

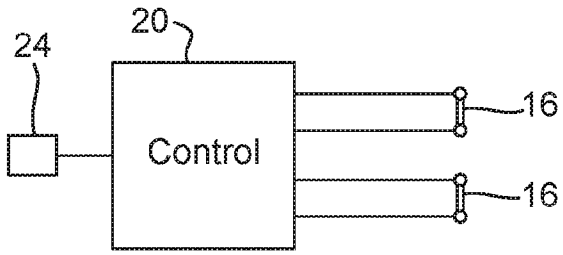


Fig. 5

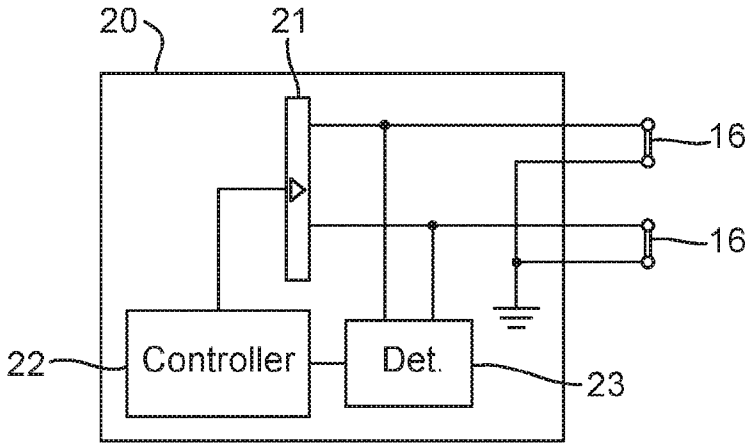


Fig. 6

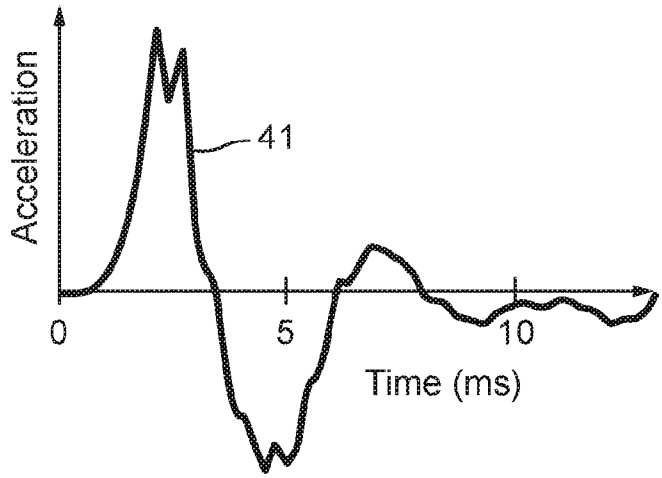

Acceleration
41
0
5
10
Time (ms)

Fig. 7

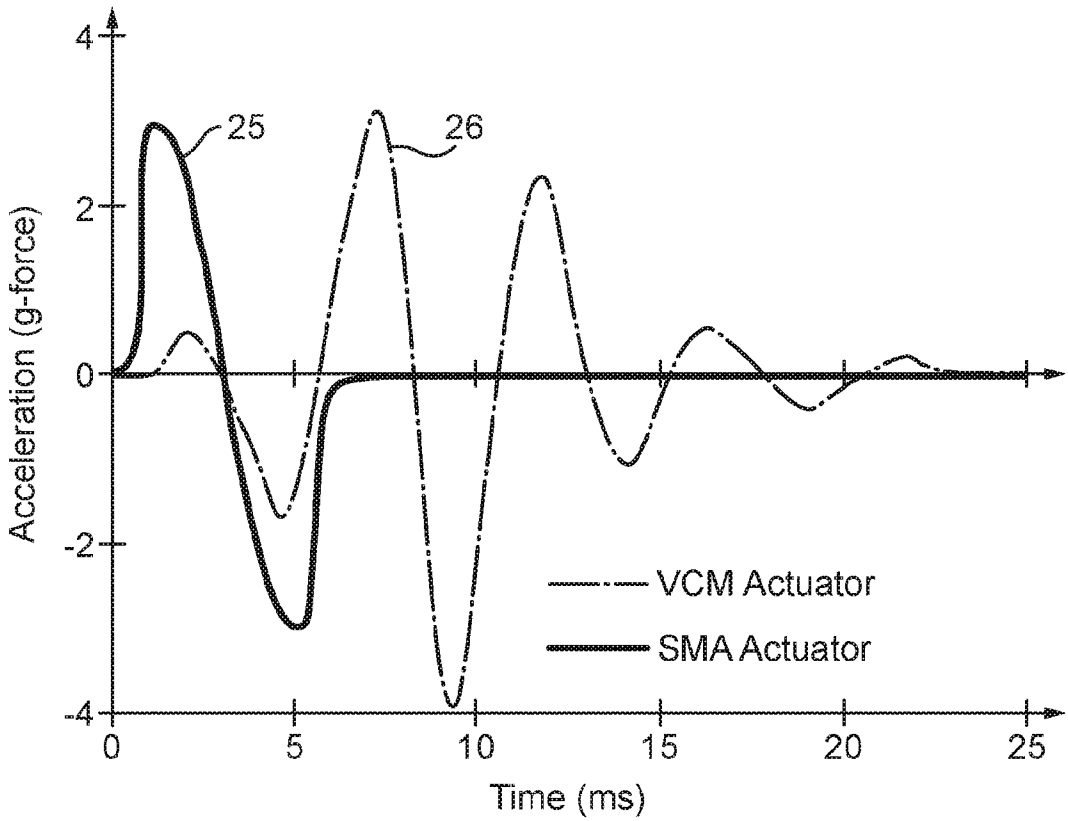

4
2
0
-2
-4
25
26
Acceleration (g-force)
VCM Actuator
SMA Actuator
0
5
10
15
20
25
Time (ms)

Fig. 8

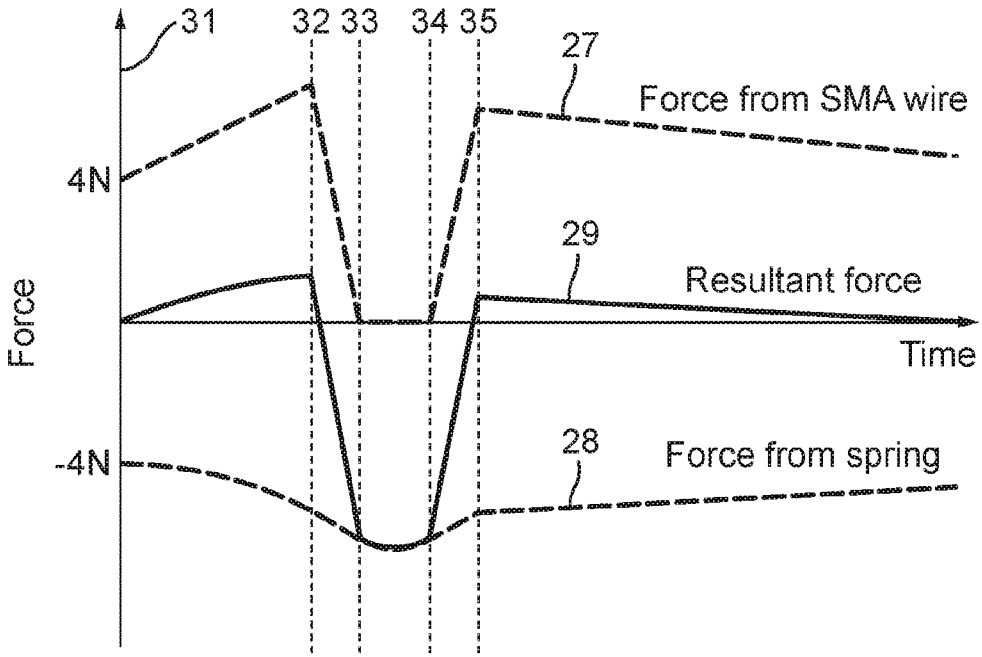

31
32 33
34 35
27
Force from SMA wire
4N
29
Resultant force
Force
Time
-4N
28
Force from spring

Fig. 9

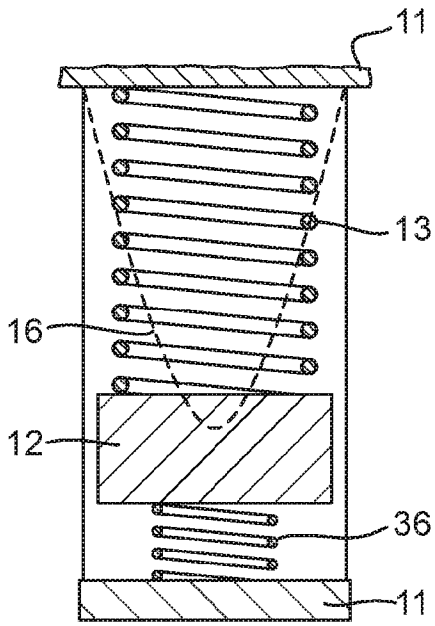

11
13
16
12
36
11

Fig. 10

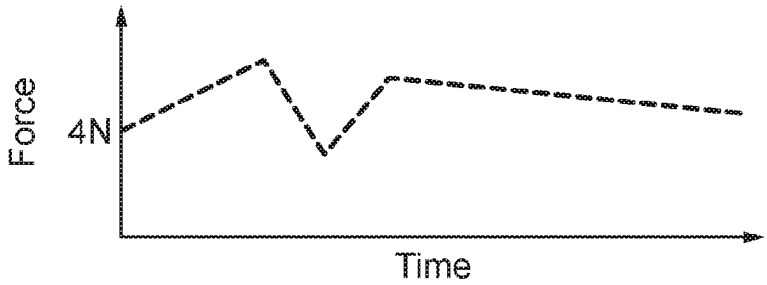


Fig. 11

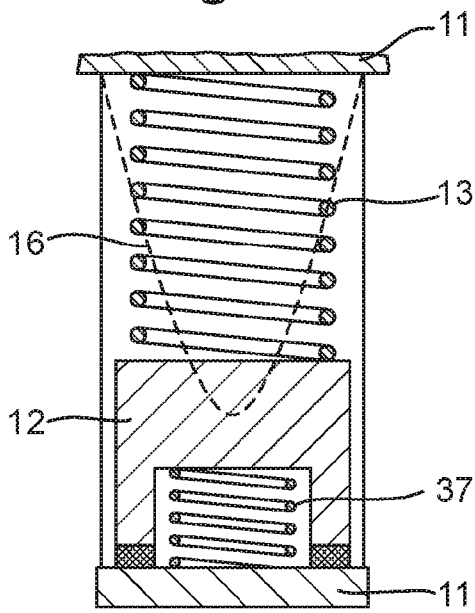


Fig. 12

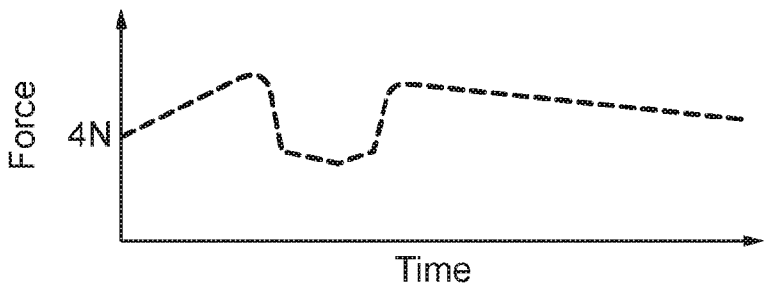


Fig. 13

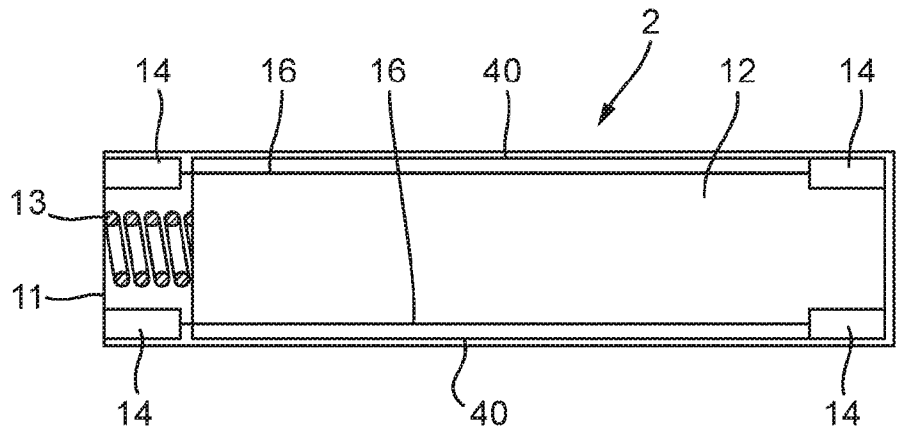

2
14
16
16
40
12
14
13
11
14
40
14

Fig. 14

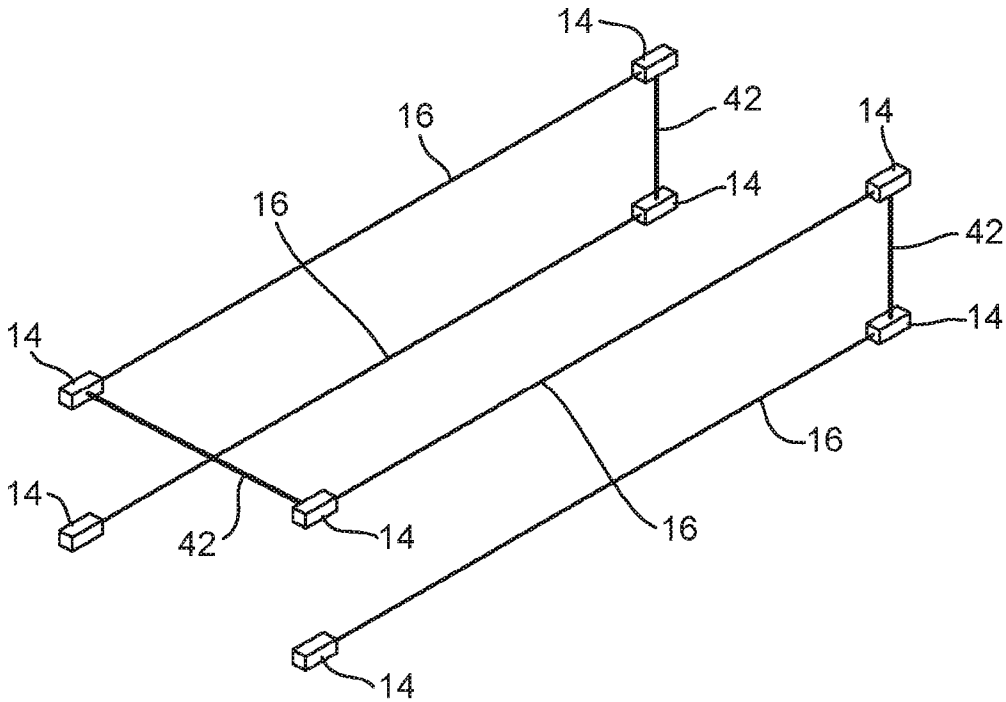

14
42
16
14
16
42
14
14
14
14
42
14
16
16
14

Fig. 15

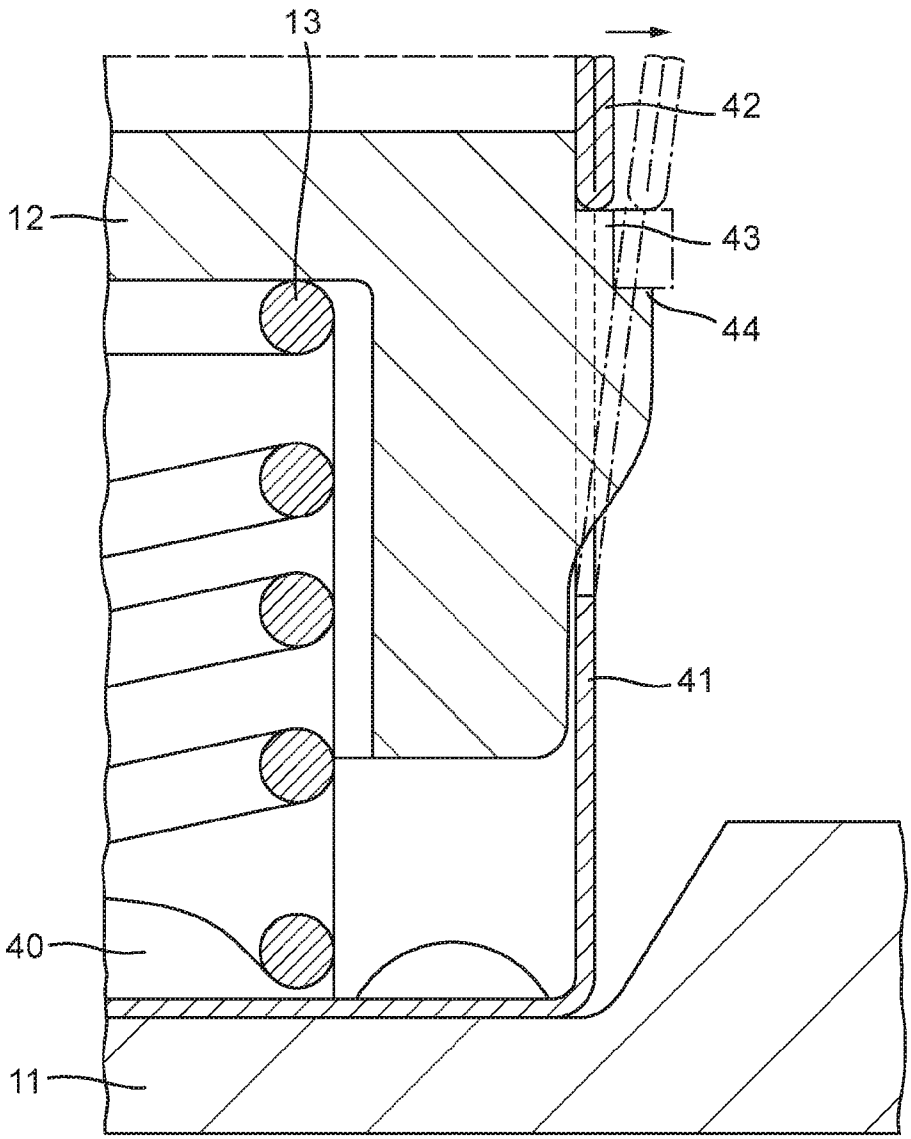


Fig. 16

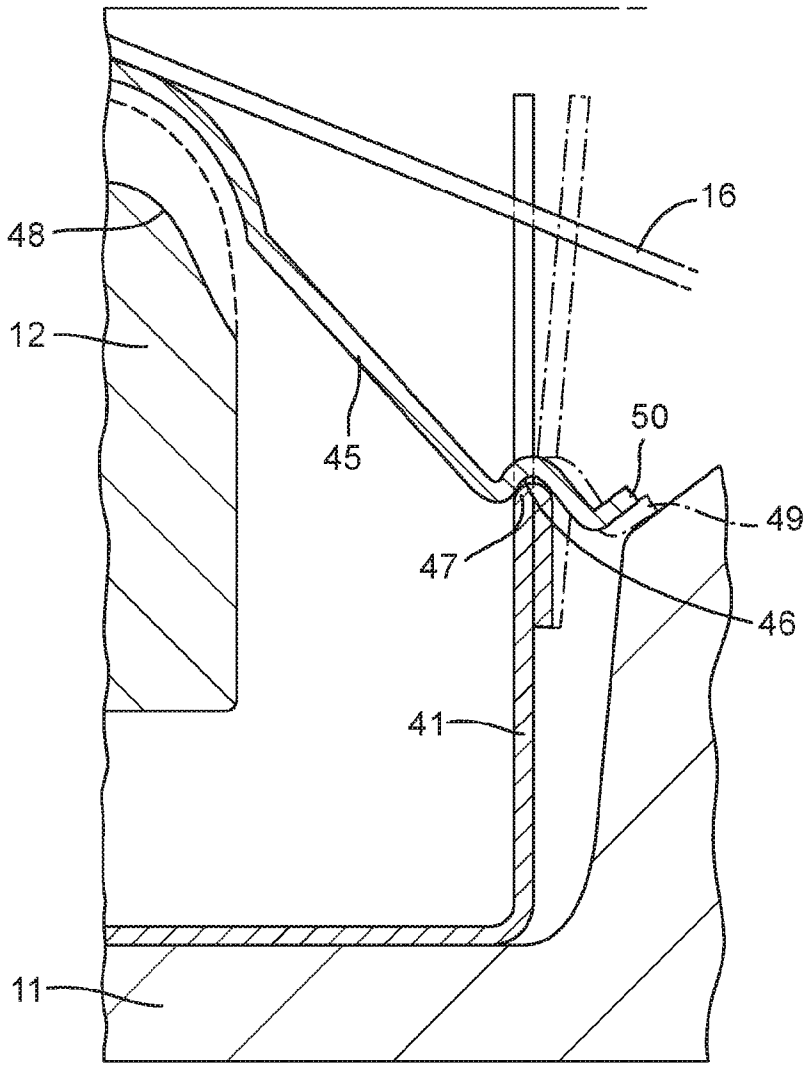


Fig. 17

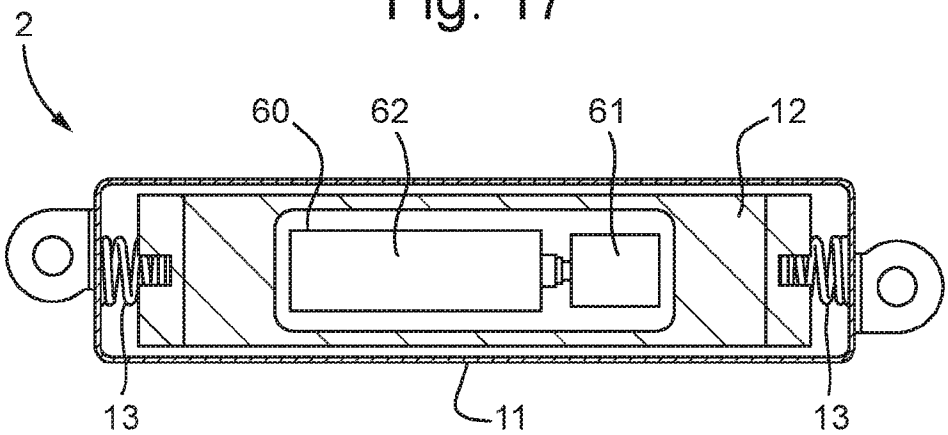


Fig. 18

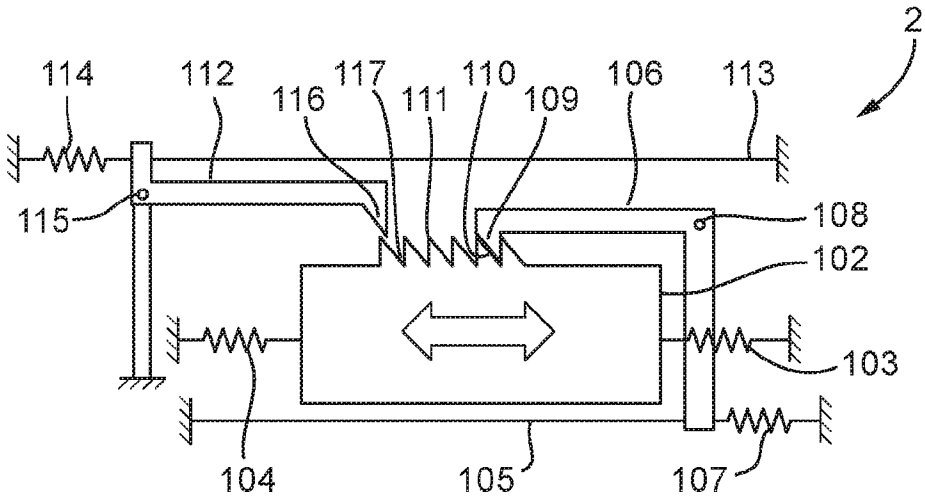


Fig. 19

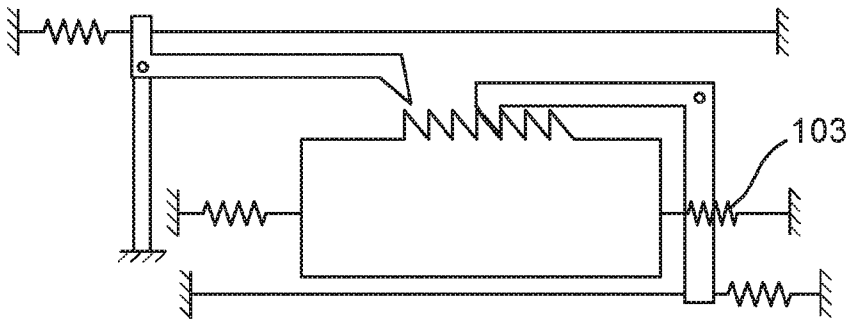


Fig. 20

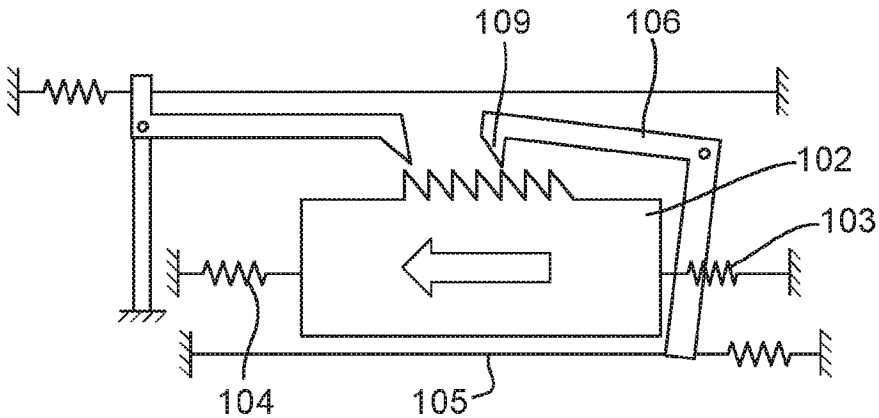


Fig. 21

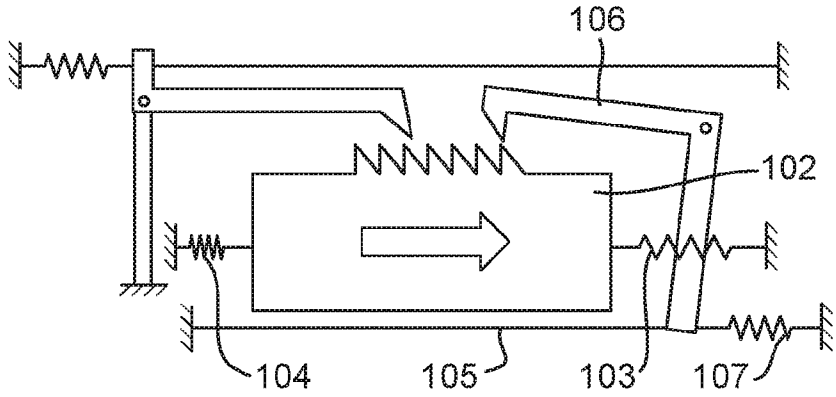


Fig. 22

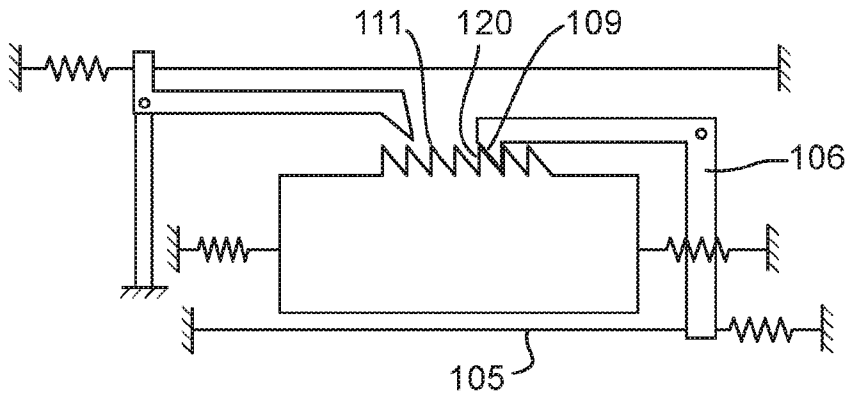


Fig. 23

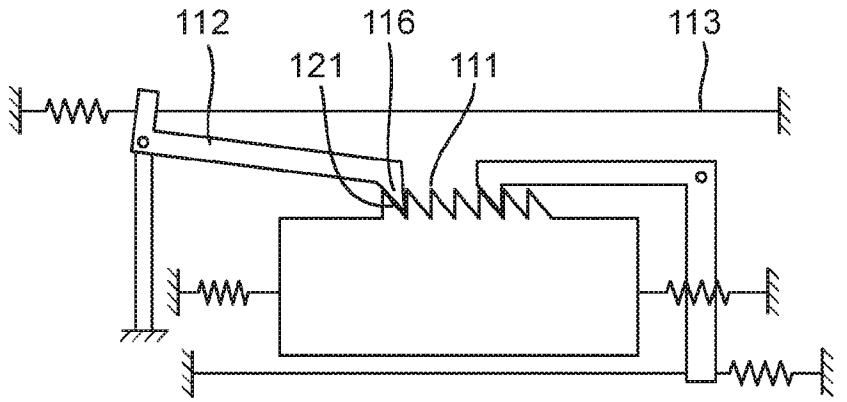


Fig. 24

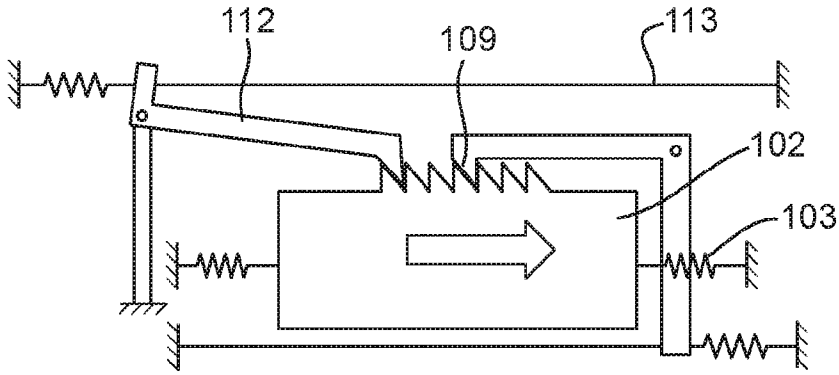


Fig. 25

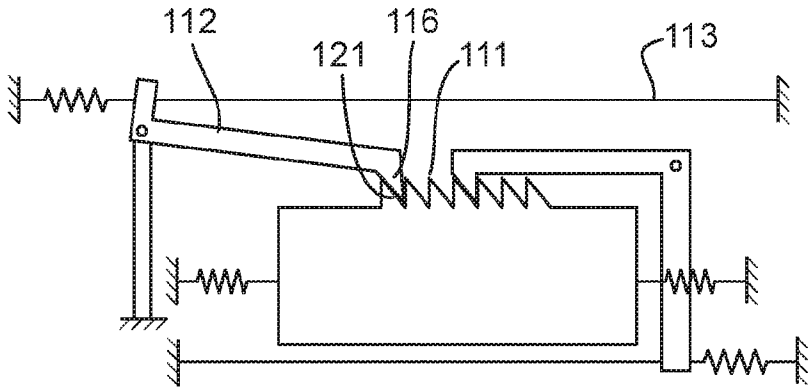


Fig. 26

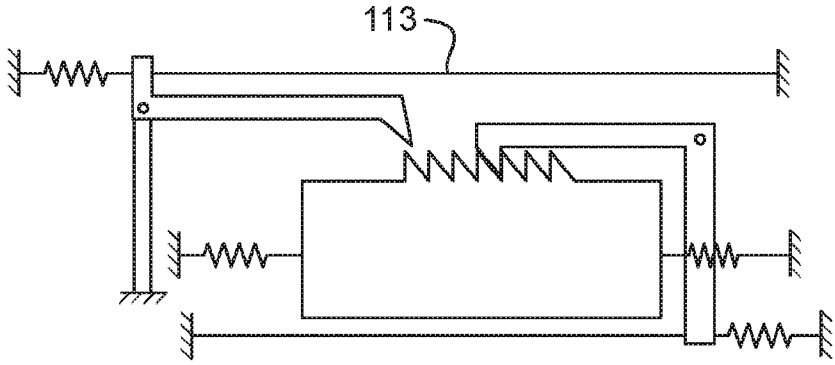


Fig. 27

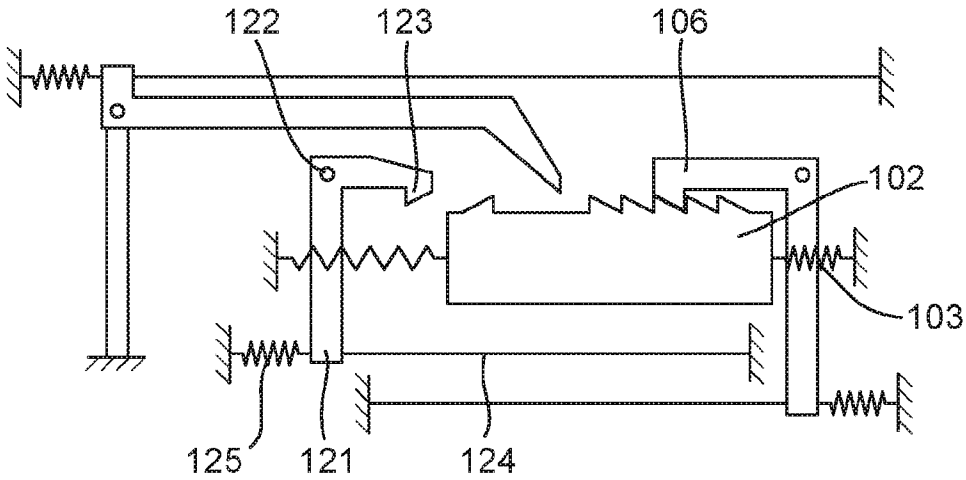

122
123
106
102
103
125
121
124

Fig. 28

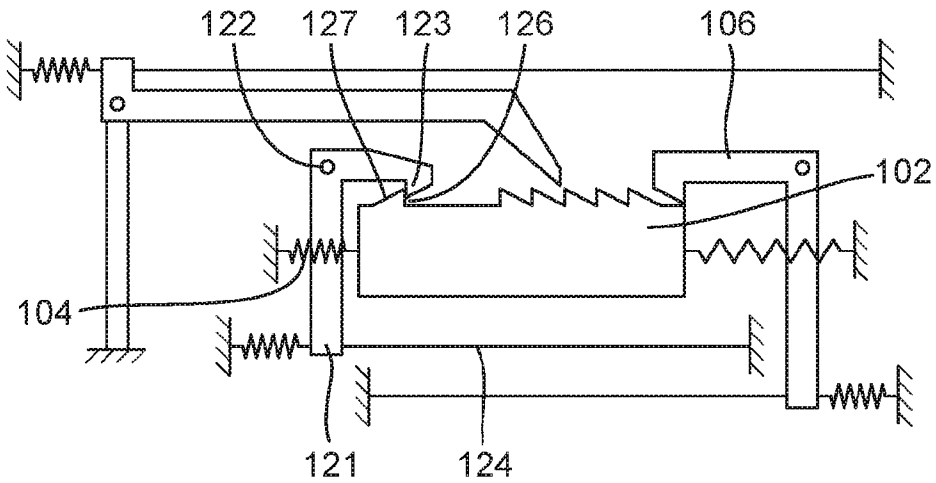

122
127
123
126
106
102
104
121
124

Fig. 29

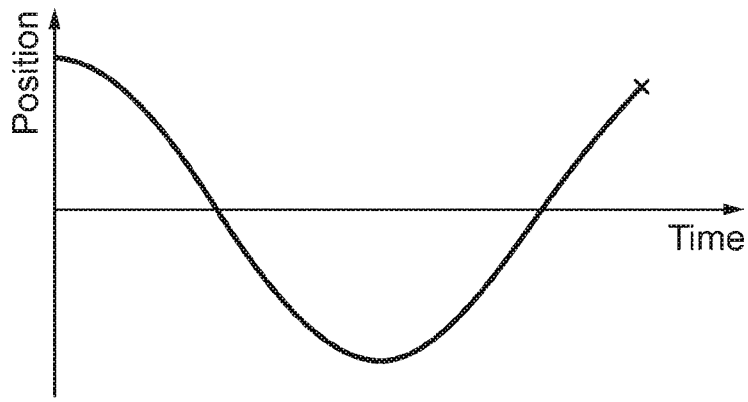
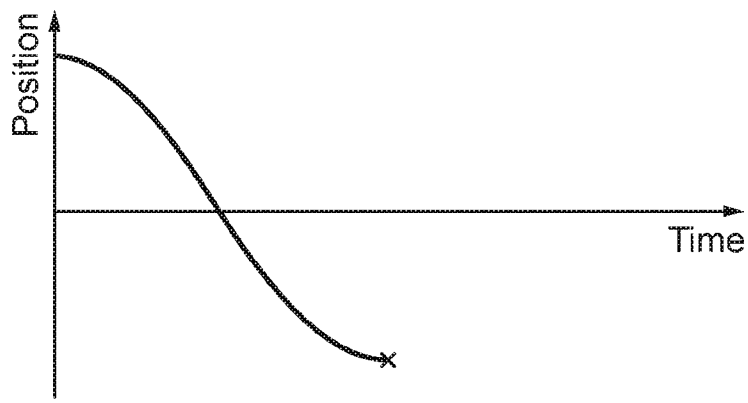


Fig. 30



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/051577

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03G7/06 G06F3/01
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03G G06F A61L H04M

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2014/077940 A1 (BROWNE ALAN L [US] ET AL) 20 March 2014 (2014-03-20) abstract figures 1,2 figure 8 paragraph [0036] paragraphs [0070], [0073] claim 4 -----	1-8, 11-59 9,10
X	WO 2004/113679 A2 (NANOMUSCLE INC [US]; MACGREGOR RODERICK [US]; HEBENSTREIT JOSEPH J [US]) 29 December 2004 (2004-12-29) abstract figures 1-3 paragraph [0018] paragraph [0024] -----	1,38

-/--

[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

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 August 2017	29/08/2017

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

3

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/051577

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2015/073016 A1 (MASSACHUSETTS INST TECHNOLOGY [US]) 21 May 2015 (2015-05-21) abstract figure 6 paragraphs [0051] - [0052]	15,52
A	EP 1 079 105 A1 (SIEMENS BUILDING TECH AG [CH]) 28 February 2001 (2001-02-28) abstract paragraphs [0012] - [0014] figures 1,3	1-59
A	US 2008/178526 A1 (BROWNE ALAN L [US] ET AL) 31 July 2008 (2008-07-31) abstract figures 7,8	1-59
A	WO 2009/056822 A2 (CAMBRIDGE MECHATRONICS LTD [GB]; TOPLISS RICHARD [GB]; WEBBER DOMINIC) 7 May 2009 (2009-05-07) figures 1,6,7 abstract	1-59

3

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2017/051577

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014077940 A1	20-03-2014	NONE	
WO 2004113679 A2	29-12-2004	US 2005184533 A1	25-08-2005
		WO 2004113679 A2	29-12-2004
WO 2015073016 A1	21-05-2015	EP 3068914 A1	21-09-2016
		JP 2016540121 A	22-12-2016
		US 2016265089 A1	15-09-2016
		WO 2015073016 A1	21-05-2015
EP 1079105 A1	28-02-2001	NONE	
US 2008178526 A1	31-07-2008	DE 112008000323 T5	17-12-2009
		US 2008178526 A1	31-07-2008
		WO 2008094731 A2	07-08-2008
WO 2009056822 A2	07-05-2009	AT 508277 T	15-05-2011
		CN 101896719 A	24-11-2010
		EP 2215359 A2	11-08-2010
		JP 5296086 B2	25-09-2013
		JP 2011501245 A	06-01-2011
		KR 20100105547 A	29-09-2010
		US 2010283887 A1	11-11-2010
		WO 2009056822 A2	07-05-2009