



(51) International Patent Classification:
F03G 7/06 (2006.01)

(21) International Application Number:
PCT/GB2020/050161

(22) International Filing Date:
23 January 2020 (23.01.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
1900950.5 23 January 2019 (23.01.2019) GB

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(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, JO, 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, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, 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, 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,

(54) Title: SHAPE MEMORY ALLOY ACTUATOR

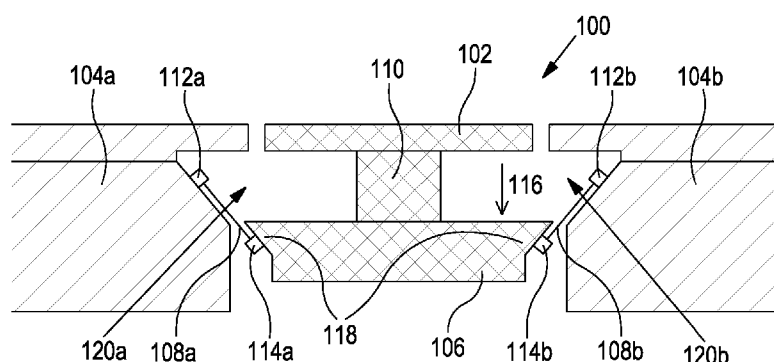


FIGURE 1

(57) Abstract: The present application relates to shape memory alloy actuators. We describe a shape memory alloy (SMA) actuator comprising a static element (104a, 104b); a moveable element (106) which is moveable relative to the static element; and a plurality of SMA wire sections (108a, 108b). Each of the plurality of SMA wire sections (108a, 108b) are coupled to the static element (104a, 104b) and the moveable element (106) and on contraction cause the moveable element to move in a direction of movement. An axis of each of the plurality of SMA wire sections is generally at an acute angle to the direction of movement of the moveable element which are connected to both the static element and the moveable element and which on contraction cause movement of the moveable element.

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 Actuator

The present techniques generally relate to shape memory alloy actuators.

5 Consumer electronics devices, such as laptops and smartphones, may employ different types of controls to give users of the devices some feedback indicating that they have successfully pressed a button on the device. This is generally known as haptic feedback, and haptic buttons or controls on a device may provide a tactile sensation to the user to confirm that they have
10 successfully pressed the button/control/switch. To generate a good haptic sensation, it is desired that the actuator moves with a high enough force to provide a sufficient displacement. It will be appreciated that there are other applications, for example latches or medical devices where a high force is also desired to achieve a relatively large displacement.

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The present applicant has identified the need for an improved shape memory alloy actuator.

According to a first approach of the present techniques, there is provided a
20 shape memory alloy (SMA) actuator comprising a static element; a moveable element which is moveable relative to the static element; a plurality of SMA wire sections each of which are coupled to the static element and the moveable element and which on contraction cause the moveable element to move in a direction of movement; and wherein an axis of each of the plurality of SMA wire sections is
25 generally at an acute angle to the direction of movement of the moveable element.

According to a second approach of the present techniques, there is provided a haptic assembly comprising a touchable component (e.g. a button) and the actuator described above, wherein when a user presses the touchable component,
30 the actuator assembly is activated to provide haptic feedback to the user by moving the touchable component using the moveable element.

According to a further approach of the present techniques, there is provided an apparatus comprising any of the SMA actuators described herein. The
35 apparatus may be: a smartphone, a protective cover or case for a smartphone, a

camera, a foldable smartphone, a foldable image capture device, a foldable smartphone camera, a foldable consumer electronics device, a camera with folded optics, an image capture device, an array camera, a 3D sensing device or system, a servomotor, a consumer electronic device (including domestic appliances such as vacuum cleaners, washing machines and lawnmowers), a mobile or portable computing device, a mobile or portable electronic device, a laptop, a tablet computing device, an e-reader (also known as an e-book reader or e-book device), a computing accessory or computing peripheral device (e.g. mouse, keyboard, headphones, earphones, earbuds, etc.), an audio device (e.g. headphones, headset, earphones, etc.), a security system, a gaming system, a gaming accessory (e.g. controller, headset, a wearable controller, joystick, etc.), a robot or robotics device, a medical device (e.g. an endoscope), an augmented reality system, an augmented reality device, a virtual reality system, a virtual reality device, a wearable device (e.g. a watch, a smartwatch, a fitness tracker, etc.), an autonomous vehicle (e.g. a driverless car), a vehicle, a tool, a surgical tool, a remote controller (e.g. for a drone or a consumer electronics device), clothing (e.g. a garment, shoes, etc.), a switch, dial or button (e.g. a light switch, a thermostat dial, etc.), a display screen, a touchscreen, and a wireless communication device (e.g. near-field communication (NFC) device). It will be understood that this is a non-exhaustive list of possible apparatus.

Preferred features are set out in the appended dependent claims.

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

Figure 1 is a schematic cross-sectional view of a first haptic assembly;

Figure 2a is a schematic block diagram of the haptic assembly of Figure 1;

Figure 2b is a graph of the minimum wire resistance (Ohms) against wire angle (degrees) which achieves a target force and target stroke;

Figure 2c plots wire angle (degrees) against wire length (mm) and shows the boundaries for suitable solutions which achieve a target force and target stroke;

5 Figure 2d plots number of wires against wire length (mm) and shows the boundaries for suitable solutions which achieve a target force and target stroke;

Figure 3a is a schematic perspective view showing a variation of attachment of SMA wire sections which can be used in the haptic assembly of Figure 1;

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Figure 3b is a schematic block diagram of the electrical connections for the SMA wire sections in the assembly of Figure 3a;

Figure 4 is a schematic perspective view showing a variation of attachment of SMA wire sections which can be used in the haptic assembly of Figure 1;

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Figures 5a and 5b are schematic cross-sectional views of variations of the first haptic assembly;

20 Figure 6 is a schematic cross-sectional view of another haptic assembly;

Figure 7 is a schematic top view of another haptic assembly with the button removed for clarity;

25 Figure 8 is a schematic cross-sectional view of another haptic assembly;

Figures 9a and 9b are schematic perspective views showing further variations of attachment of SMA wire sections which can be used in the haptic assembly of Figure 1; and

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Figure 10 is a schematic cross-sectional view of another haptic assembly.

The embodiments described below illustrate a shape memory alloy (SMA) actuator. Such an SMA actuator may be any type of device that comprises a static part (or element – the words may be used interchangeably) and a moveable part

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which is moveable with respect to the static part. The moveable part is moved by a plurality of SMA wire sections which are coupled (or connected – the words may be used interchangeably) between the static part and the moveable part. Embodiments of the present techniques describe haptic assemblies which may be arranged to move the button perpendicularly with respect to the edge of the device (i.e. vertically). Other examples of actuators which generate vertical movement are described in GB1803084.1 and GB1813008.8 to the present applicant. Embodiments of the present techniques describe haptic assemblies that may be arranged to move the button laterally along the edge of the device, helically around an axis perpendicular to the edge of the device or in any other suitable direction, e.g. in plane rotation parallel to the edge of the device or perpendicular to the device. Examples of actuators which move the button in a lateral direction with respect to the contact by the user are described for example in WO2018/046937 and GB2551657.

As shown in more detail below, the plurality of SMA wire sections may be electrically connected to form at least one electrical path wherein each path comprises at least two SMA wire sections which are electrically connected in series. All the plurality of SMA wire sections may be connected in series. The plurality of SMA wire sections may be electrically connected to form at least two electrical paths each of which comprises at least one SMA wire section with each path connected in parallel to the at least one other path. All of the plurality of SMA wire sections may be in an individual electrical path of only one SMA wire section so that there are the same number of paths as SMA wire sections which are all connected in parallel. Between the two extremes of all connected in parallel and all connected in series, there may be a mixture of parallel and series electrical connections ranging between one path having all SMA wire sections connected in series and all SMA wire sections connected in parallel. It will be appreciated that changing the number of SMA wire sections which are connected in parallel or series changes the resistance of the system and thus the number of SMA wire sections which are electrically connected in series and the number of SMA wire sections which are electrically connected in parallel may be selected to generate a predetermined (i.e. target) resistance. The target resistance may be determined from the power and voltage available from the drive circuitry. A series connection

may be achieved by forming the SMA wire sections from the same wire or by connecting individual SMA wire sections with appropriate electrical connections.

Other parameters of the system may be selected to achieve desired results.

5 For example, at least one parameter of the plurality of SMA wire sections may be selected so that when the plurality of SMA wire sections contract a minimum force in the direction of movement of the moveable element is generated, and the moveable element moves a minimum distance. The at least one parameter may be selected from the group comprising the acute angle between the axis of each
10 of the plurality of SMA wire sections, the diameter of each of the plurality of SMA wire sections, the length of each of the plurality of SMA wire sections, and the number of SMA wire sections. Merely as examples, each of the plurality of SMA wire sections may be less than 3mm in length, for example between 1mm and 2.5mm in length, the acute angle may be less than 70 degrees, there may be
15 between 12 and 30 SMA wire sections and the wire diameter may be less than 40µm with 25µm and 36µm being commonly available wire gauges. It will be appreciated that changing one parameter may affect the suitable ranges for other parameters. Each of the SMA wire sections may be uniform, i.e. same length, same diameter, and set at the same acute angle.

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One end of each of the plurality of SMA wire sections may be coupled to one edge of the moveable element and the opposed end of each of the plurality of SMA wire sections may be coupled to an adjacent edge of the static element. In such an arrangement, all the SMA wire sections may thus be located on one
25 side and the SMA actuator may be considered to be a single sided drive. The adjacent edge of the static element may comprise a recess having an angled slope and each of the plurality of SMA wire sections may extend along the angled slope. The angled slope may thus define the angle of each SMA wire section. Within the angled recess, there may also be a restoring element (e.g. a compression spring,
30 flexure or similar suitable mechanism) which is connected between the moveable element and the static element to restore the moveable element to its original position after the SMA wire sections have contracted.

The moveable element may be located between first and second portions
35 of the static element, for example within a cavity or gap. The plurality of SMA

wire sections may comprise a plurality of pairs of SMA wire sections with a first SMA wire section in each pair having one end coupled to the first portion of the static element and the opposed end coupled to an adjacent edge of the moveable element and a second SMA wire section in each pair having one end coupled to the second portion of the static element and the opposed end coupled to an adjacent edge of the moveable element. By pairing the SMA wire sections, there are an even number on each side of the moveable element to provide a symmetric and balanced force and stroke. As explained in more detail below, the force from the SMA wire sections sums together in the direction of movement but is cancelled in the orthogonal direction.

As in the singled side drive arrangement, each of the first and second portions may comprise a recess having an angled slope and each of the plurality of SMA wire sections extends along the angled slope of the respective recess. In both arrangements, the moveable element may comprise an angled flange to which an end of each SMA wire section is attached. The angle of the flange may match the angle of the angled slope of the recess. Alternatively, there may be an angled recess in the moveable element.

A coupling element may be used to couple each of the plurality of SMA wire sections to at least one of the static part and the moveable part. At least one of the plurality of SMA wires sections may be coupled to at least one of the static element and the moveable element using a coupling element which is a fixed connector which provides a permanent (i.e. fixed) connection between an SMA wire section and the static element or the moveable element. Such a fixed connector may be in the form of a crimp connector, a welded component that is welded to the or each wire section to form a weld or other similar connectors. A crimp connector may hold multiple wire sections or may hold a single wire section. It will be appreciated that when there are multiple wire sections in a single crimp, a plurality of parallel paths will be formed.

The coupling element may alternatively comprise a connector which provides a non-fixed connection between an SMA section and the static element or the moveable element. Such a non-fixed connector may be in the form of a protruding element such as a hook, dowel pin or similar element around which an

SMA wire is looped to form a pair of SMA wire sections each extending at opposed angles either side of the non-fixed connector. Thus effectively, the end of an SMA wire section may be considered to be connected to the non-fixed connection.

5 Each coupling element may provide only a mechanical connection or both a mechanical and an electrical connection between the SMA wire section and the static element or the moveable element. For example, the non-fixed connector may provide only a mechanical connection with the electrical connection provided by using a continuous SMA wire to form the SMA wire sections.

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 The present techniques describe SMA actuators which are designed to deliver a high force in the direction of movement of the moveable element, e.g. between 1.2 to 3N, preferably between 1 to 5N, more preferably between 1.0 to 10N, whilst maintaining the strain in the wire within safe limits (e.g. 2-5%
15 reduction in length over original length). The force may be dependent on the application, for example the force may be dependent on the contact force that causes a haptic sensation to be triggered.

 The force generated by the SMA wire in a direction along the length of the
20 SMA wire may be proportional to the cross-sectional area of the wire. The SMA wire stroke may be dependent on the stress in the SMA wire at equilibrium (i.e. when the SMA wire is not being driven) and change in wire temperature as a result of a supplied drive signal. In the present techniques, the SMA wire sections are at an angle to the direction of movement of the button (i.e. are geared), and
25 therefore, the force and displacement at a surface of the button are different from the force and displacement generated by the SMA wire sections. The force generated at the surface of the button may therefore be controlled by the presence of a biasing element. Alternatively, if there is no biasing element present, the contact force may be used to determine the equilibrium stress in the SMA wire
30 sections – in this case, the force generated at the button surface may depend on the contact force. A plurality of relatively thin, short wire sections (e.g. approximately 25 μ m or 36 μ m in diameter) are used in combination to provide a desired force.

The SMA actuators may be incorporated in a haptic assembly to move a button or other touchable element which is contacted by a user (moveable element) relative to a casing or housing (static element) to deliver a haptic sensation to a user pressing on the button (or other touchable element).

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The present techniques may provide a local haptic sensation caused by a direct impulse, rather than through inertial effects. For example, smartphones with eccentric mass motors or linear resonance actuators comprise inertial haptic actuators – a significant mass is moved when a haptic effect is required. Movement of the mass causes the whole smartphone to shake or vibrate. Thus, the haptic effect is general and is not localised. The present techniques provide a localised haptic feedback. Further still, the haptic feedback provided by the present techniques may be customisable by a user by modifying software parameters. This allows different types of haptic feedback to be provided for different purposes or to suit different users.

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Each of the assemblies described herein may be incorporated into any device in which it may be useful to provide a user of the device with haptic feedback. For example, the haptic assemblies may be incorporated into any of the electronic devices or consumer electronics devices listed previously, including but not limited to a computer, laptop, portable computing device, smartphone, computer keyboard, gaming system, portable gaming device, gaming equipment/accessory (e.g. controllers, wearable controllers, etc.), medical device, user input device, etc. It will be understood that this is a non-limiting, non-exhaustive list of possible devices, which may incorporate any of the haptic assemblies described herein. The haptic assemblies described herein may be, for example, incorporated into or otherwise provided along an edge of a smartphone or on a surface of a smartphone.

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Various SMA actuators are now described with respect to the Figures. It will be understood that elements or features described with respect to one particular Figure may equally apply to any of the Figures described herein, for example, crimps holding multiple wire sections, the flexible element, the restoring element and the seal may be incorporated in any embodiment. Furthermore, although many of the Figures show the incorporation of the SMA actuators in a

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haptic assembly it will be appreciated that the SMA actuators may be incorporated in other devices requiring a high force such as latches or medical devices.

Figure 1 shows a cross-sectional view of a first arrangement of an SMA
5 actuator within a haptic assembly 100. The haptic assembly 100 comprises a
button 102 (but it will be appreciated that other touchable components, surfaces
or elements may be used interchangeably. For example, in embodiments the
haptic assembly 100 may not comprise a button which is directly touchable by a
user. The haptic assembly may instead comprise an element which moves in a
10 similar manner to the button described herein, but the element is provide below
a touchable surface or active surface, such as a touch screen. The element causes
the touchable surface to flex and thereby impart a haptic sensation, but the user
does not touch the element directly. In this sense, there may not be a button in
the haptic assembly). The button 102 may be pressed by a user to perform a
15 particular operation, such as making a selection, turning a device on/off, entering
data (e.g. typing on a keyboard), scrolling, turning a function of the device in
which the assembly 100 is located on/off or adjusting the function (e.g. adjusting
volume of audio output from the device), etc. Pressing or releasing the button
102 may cause haptic feedback or a haptic sensation to be delivered to the user,
20 so that the user is provided with some sensory feedback (particularly touch-based
feedback) to indicate that the operation has been performed.

In many of the arrangements described herein, the button 102 may be a
surface feature on a device/apparatus that incorporates the haptic assembly. In
25 this case the haptic button 102 may not be pressed by a user but may still be able
to provide haptic feedback. Instead of a button press triggering haptic feedback,
the haptic feedback may be triggered by software in response to another event.
For example, if a user makes a selection on a screen of their smartphone, the
selection may cause haptic feedback to be triggered, where the feedback is
30 provided by the button or surface feature. (Software triggered haptic feedback
may occur in particular applications, such as in gaming and/or virtual/augmented
reality devices). Thus, in many of the arrangements and embodiments described
herein, direct pressing of the haptic button 102 may not be required in order for
haptic feedback to be delivered. However, in each case, the mechanism to deliver
35 the haptic feedback is broadly the same whether or not the button itself is pressed.

In the arrangement shown in Figure 1, the haptic assembly 100 may comprise a housing (also referred to herein as "support", "chassis", "casework" and "casing"). The housing may comprise a cavity or recess which is between a first portion 104a of the housing and a second portion 104b of the housing. The button 102 may be provided within the cavity. As shown, the button may be arranged within the cavity such that a contact surface (may also be referred to as an outer surface, external surface or upper surface) of the button is substantially level with/flush with an external surface of the housing. Alternatively, the button may protrude from the housing. It will be understood that the housing may surround and encase the button 102, such that only the contact surface of the button 102 is visible/contactable by the user.

The SMA actuator may comprise a moveable element 106 which is provided within the cavity below the button 102. The moveable element 106 is moveable relative to the static part (i.e. the housing) in a first direction that is perpendicular to the external surface of the housing (i.e. vertical). Contact of a user's finger on the contact surface of the button may cause the button to move into the housing, e.g. in the direction of arrow 116, or out of the housing as appropriate. A sensor (not shown) may be mounted in the housing below the button 102 and the moveable element 106. The sensor is any suitable sensor for determining if a user has interacted with a device and if haptic feedback is to be provided. For example, the sensor may be a sensor suitable for detecting depression of the button by the user so that the haptic feedback is then caused to be generated. In another example, the sensor may be a capacitive sensor or an optical sensor (e.g. an ultrasonic sensor capable of fingerprint recognition). For instance, in the case of an optical sensor, the user's interaction with the sensor may be used to provide haptic feedback to indicate if a process (e.g. the reading of a fingerprint) was successful or not. It will be understood that these are merely some, non-limiting examples of the types of sensor which may be used. The sensor may be coupled to control circuitry (not shown), and the sensor may be configured to communicate with the control circuitry when the force on the sensor changes, or when the force on the sensor has been applied for a minimum duration. In embodiments, there may be multiple sensors (e.g. multiple force sensors) which are arranged to enable the position of a user's finger relative to the sensors to be determined. In this

case, the sensors may be configured to communicate with the control circuitry when a contact/force balance between the sensors shifts, indicating motion of the user's finger across a surface. An example of such an arrangement of sensors is described in United Kingdom Patent Application GB 813135.9. The detection by
5 the sensor of a user pressing the button causes the haptic feedback to be generated and applied by the haptic assembly.

In this arrangement, the button 102 and the moveable element 106 are attached by an attachment element 110 whereby movement of the button 102
10 causes the moveable element 106 to move in the same direction and similarly movement of the moveable element 106 causes the button to move in the same direction. The moveable element 106, the button 102 and the attachment element 110 may be integrally formed or may be separately formed. The connection in this manner means that both the moveable element 106 and the button 102 are
15 configured to move together in a generally vertical direction, i.e. in a direction perpendicular to the external/outer surface of the static element.

The SMA actuator comprises a plurality (e.g. n) of shape memory alloy (SMA) actuator wire sections 108a, 108b. In this arrangement, each wire section
20 may be a separate discrete piece of wire which is electrically and mechanically connected as described below. As illustrated in Figure 1 there is at least one pair of wire sections): a first wire section 108a connected between one edge of the moveable element 106 and an adjacent edge of the first portion 104a of the static element and a second wire section 108b connected between the opposed edge of
25 the moveable element 106 and an adjacent edge of the second portion 104b of the static element. Additional pairs of wire sections may be connected in a similar manner as described in more detail below. The first SMA actuator wire section 108a is connected to the first portion 104a of the static element using a coupling element in the form of a static crimp 112a and is connected to the moveable
30 element 106 by a moveable crimp 114a. Similarly, the second SMA actuator wire section 108b is connected to the second portion 104b of the static element using a coupling element in the form of a static crimp 112b and is connected to the moveable element 106 by a moveable crimp 114b. Each of the coupling elements may be both an electrical and mechanical connector to connect the SMA actuator
35 wire sections to a power supply as well as physically to the relevant element. The

term moveable crimp is used to denote the crimp connecting the SMA wire section to the moveable element; the moveable crimp will thus move with the moveable element but is not separately moveable on the moveable element.

5 When a haptic sensation is required, this requirement is communicated to control circuitry (not shown). Power is then delivered to each SMA actuator wire section 108a, 108b. When each SMA actuator wire section 108a, 108b is powered, the temperature of each wire section increases and thus, the wire section contracts. The force in the direction of movement of the moveable element which
10 is generated by the pair of wire sections combines to provide double the force compared to a single wire section coupled at the same angle to one side of the moveable element. In other words, the contraction of each wire section combines together so that the wire sections are mechanically acting in parallel. The contraction of each SMA actuator wire section 108a, 108b causes the moveable
15 element 106 to move vertically within the cavity and hence to force the button 102 to move upwards. The moveable element may cause the button to move by, for example, between 20 μ m to 0.5mm. A movement of between 40 μ m to 80 μ m may be sufficient to generate a strong haptic sensation. In some embodiments, the button may move by as much as 1mm. The moveable element may be
20 considered to be an intermediate moveable element because it acts as an intermediary which moves in response to contraction of the SMA wire sections and then causes the button to move.

In many applications, it is desirable that the height of the actuator assembly
25 is minimised, for example below 2mm, and thus as shown in Figure 1, each wire 108a, 108b is set at an angle relative to the direction of movement of both the moveable element 106 and the button 102. As shown, the moveable element 106 and the static element may be shaped to accommodate the angled wires. For example, an angled protrusion 118 extends along each edge of the moveable
30 element 106 and each moveable crimp 114a, 114b is connected to the corresponding angled protrusion 118. Similarly, each portion of the static element 104a, 104b comprises an angled recess 120a, 120b and each static crimp 112a, 112b is connected to the corresponding angled slope of the angled recesses 120a, 120b. Each SMA wire section 108a, 108b extends along the corresponding angled
35 slope into the respective angled recess 120a, 120b.

In embodiments, the angled slope may act as a heat sink. This may advantageously increase the rate of cooling of the wires, thus enabling a faster rate of actuation.

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Figure 8 is a schematic cross-sectional view of an SMA actuator within a haptic assembly 150. The SMA actuator is similar to that shown in Figure 1 and therefore, like reference numerals are used to denote like features. In the arrangement of Figure 8, the SMA actuator comprises a moveable element 106 which is provided within the cavity below the button 102. The moveable element 106 is moveable relative to the static part (i.e. the housing) in a first direction that is perpendicular to the external surface of the housing (i.e. vertical). As mentioned above, in Figure 1, the button 102 is caused to move upwards when each SMA wire section 108a, 108b contracts. However, in Figure 8, the contraction of each SMA actuator wire section 108a, 108b causes the moveable element 106 to move vertically downwards in the cavity and hence, to force the button 102 to move downwards. This is achieved by changing the location of the static crimps 112a, 112b. In Figure 1, the static crimps 112a, 112b are located above the moveable crimps 114a, 114b, such that when the temperature of the SMA actuator wire sections 108a, 108b increases and the wire sections contract, the button 102 is caused to move upwards. In contrast, in Figure 8, the static crimps 112a, 112b are located below the moveable crimps 114a, 114b, such that when the temperature of the SMA actuator wire sections 108a, 108b increases and the wire sections contract, the button 102 is caused to move downwards.

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Thus, as can be seen from Figures 1 and 8, an axis of each of the plurality of SMA wire sections is generally at an acute angle to the direction of movement of the moveable element.

Figure 10 shows a schematic cross-sectional view of another haptic assembly 1000. In the haptic assembly 1000, the moveable element and button are provided as a single element 1002. The moveable element/button 1002 is provided in a cavity or recess that is between a first portion 1004a of the housing/static element and a second portion 1004b of the housing/static element. Here, at least one wire section 1008 is provided on only one side of the moveable

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element 1002. It will be understood that multiple wire sections 1008 may be provided in this way on one side of the moveable element. The or each wire section 1008 is coupled at one end to the moveable element 1002 via a moveable crimp 1014, and at another end to one portion of the static element (e.g. the second portion 1004b of the static element). This will cause the button to not only move perpendicular to the outer surface of the static element, but also laterally by some amount. One or more bearings 1010 (e.g. ball bearings or rolling bearings) may be provided between the button 1002 and the static element to aid the movement of the button. Experimental tests have determined that that the human brain interprets a 'horizontal' motion as something that moves 'vertically'. Therefore, a button that moves in a direction that contains both horizontal and vertical components may be used to provide haptic feedback to a user.

Figure 2a schematically illustrates the functional arrangement of the SMA wire sections of Figure 1. One end of each wire section 208a, 208b is connected to the corresponding portion 204a, 204b of the static element and the opposed end of each wire section 208a, 208b is connected to the moveable element 206. In this arrangement, each wire section 208a, 208b has the same length L and the overall width of the cavity, i.e. the distance between the two portions 204a, 204b of the static element, is denoted by x . Each wire section 208a, 208b is set an acute angle θ to a plane which is parallel to the surface of the static element, i.e. the angle α between the axis of each wire section and the direction of movement is $90-\theta$. Each wire section 208a, 208b is symmetrically arranged on opposed sides of the moveable element 206. Thus, when each wire section 208a, 208b contracts, the lateral force on the moveable element 206 resulting from the contraction is cancelled because each wire is pulling the moveable element 206 in opposed lateral directions. By contrast, the contraction of each wire moves the moveable element 206 in the same vertical direction and thus the vertical movement of the moveable element 206 resulting from the contraction is effectively doubled.

The length of each wire section and the angle at which each wire section is set defines the minimum height t of the wire section, i.e. the vertical distance between the end connected to the static element and the end connected to the moveable element. The minimum height t is also shown in Figure 2a.

A displacement of, for example, between $40\mu\text{m}$ to $80\mu\text{m}$, is typically required to give the desired haptic sensation. Furthermore, a strong force is desired, e.g. to give the desired haptic sensation the force typically needs to be great enough to overcome the contact force (e.g. above 2N). The force generated by an SMA wire section is related to the total cross-sectional area of all mechanically parallel wires in the wire section. For a selected minimum target force (e.g. above 2N) from a wire section at a particular angle, each wire section must have a minimum cross-section to achieve that target force in the direction of movement. Similarly, the displacement generated by an SMA wire section is related to the length of the wire section. For a minimum target displacement from a wire section at a particular angle, each wire section must thus have a minimum length. The cross-section and length of each wire section define the resistance and thus each wire angle has an associated minimum resistance when constraints on the target force and displacement are set.

Figure 2b plots the minimum possible resistance (in Ohms) against angle θ where all wire sections are in parallel (or a single fat wire section is used, i.e. a single wire section having an equivalent cross-sectional area) and which generates a button stroke (or vertical movement of the button) of at least $50\mu\text{m}$ and a target force of at least 2N. As defined above, the angle θ is between an axis of the wire section and a plane which is parallel to the surface of the static element. For example, for an angle of 20 degrees, the minimum resistance is 0.05 Ohm. Assuming flexibility of wire diameter and flexibility of the number of series and parallel connections, the resistance may be changed to meet any target resistance above the minimum.

For example, the target resistance may be selected to be 50hm for a drive voltage of 5V because the maximum current draw of typical drive circuitry may be of the order 1-2A in some cases, and selecting a resistance of 50hm maximises the power. 5V is the USB power voltage and is thus a common standard in many consumer electronics devices. Other commonly available voltages, e.g. in mobile phones, are 2.8V and 3.3V. Thus more generally the target resistance R may be set to deliver the desired power using:

$$Power = \frac{V^2}{R}$$

For a selected target force (e.g. above 2N) and displacement (e.g. above 50µm), there is also a relationship between wire length and angle. Figure 2c shows the possible solutions. The minimum displacement of 50µm is the constraint 250 on the left side of the graph which for example sets a maximum angle of approximately 25 degrees for a wire section of 1mm and shows that above 2.2mm in length, there is effectively no constraint on the angle. The minimum target force controls the overall wire volume which is also shown as a constraint 260 on the right side. This constraint 260 shows that for a wire section of approximately 5mm, angles less than 20 degrees are not suitable solutions. The wire volume limit is set based on the requirement to achieve heating of the wire enabling target stroke within a target timeframe, given the power limit of the system.

In Figures 1, 2a and 8, only a single pair of wire sections acting in parallel is visible but there may be additional pairs of wire sections along the edges of the moveable element as described below. There may be many wires sections mechanically acting in parallel, for example between 12 to 30 wire sections may be typical, to achieve the desired solution. For a selected target force (e.g. above 2N) and displacement (e.g. above 50µm), there is also a relationship between wire length and angle and Figure 2d shows the possible solutions where 25µm and 36µm wire diameters are considered. As in Figure 2c, one constraint 270 (in this case the upper constraint) is the wire volume limit. The lower constraint 280 is a combined force/displacement limit. The combined limit results from the need to have shallower angles to achieve the desired stroke for shorter wire sections. This means that a larger cross-section of wire is needed to achieve the desired force. Merely as an example of a solution fitting between the two constraints, if the wire section is just 1mm in length, approximately 18 wire sections of diameter 36µm are required.

The table below gives examples of different solutions which have been designed using the constraints described above. It will be appreciated that these are merely illustrative:

Length L (mm)	Angle θ (degrees)	Diameter (μm)	Number of wire sections	Stroke (mm)	Force (N)	Number of //el paths
0.5	16	25	180	0.06	9.74	6
1.5	29	25	24	0.09	2.28	4
1.75	60	25	12	0.05	2.04	3
2.25	45	25	25	0.09	3.47	5
0.5	17	36	24	0.06	4.05	2
3.25	80	36	6	0.09	2.41	2
1	33	36	5	0.05	2.21	1

As explained above, although Figure 1 and 2a illustrate a single pair of wire sections, there may be additional wire sections arranged along the edges of the moveable element. Figure 3a shows one possible arrangement having multiple wire sections. In this arrangement, there are twelve wire sections which may be considered to form six pairs of wire sections with each pair of wire sections comprising a first wire section connecting to one part of the static element 304a and a second wire section connecting to the other part of the static element 304b. Each wire section is also connected to the moveable element 306. In this arrangement, the coupling elements are crimps but other coupling elements may be used. For ease of reference, the button is omitted from the Figure to show the multiple wire sections and their mechanical and electrical connections.

The first pair of wire sections comprises a first SMA wire section 308a which is connected to the first portion 304a of the static element by a static crimp 312a and to an adjacent edge of the moveable element 306 by a moveable crimp 314a and a second SMA wire section 308b which is connected to the second portion 304b of the static element by a static crimp 312b and to an adjacent edge of the moveable element 306 by a moveable crimp 314b. Similarly, the second pair of wire sections comprises a first SMA wire section 318a and a second SMA wire section 318b which are connected using moveable and static crimps to both the moveable element 306 and the respective portion 304a, 304b of the static

element. There are also four more pairs of wire sections: 328a, 328b; 338a, 338b; 348a, 348b; and 358a, 358b which are similarly connected.

5 In this arrangement, each wire section may be 1.75mm long, have a diameter of 25 μ m and an angle θ of 60 degrees. Thus, these specific parameters correspond to one of the lines in the table above and generate a force of 2.04N and a displacement of 50 μ m. The resistance is 4.75 Ohms. As indicated in the table, this arrangement has three parallel paths and this refers to the electrical connections between the wire sections. Each parallel path has four wire sections
10 electrically connected in series.

As shown in Figure 3a, the first pair of wire sections 308a, 308b is electrically connected by a moveable electrical connection 322 which is shown schematically on an upper surface of the moveable element 306. Similarly, the
15 second pair of wire sections 318a, 318b is also electrically connected by a moveable electrical connection 322. Each of the moveable electrical connections 322 is connected between the respective moveable crimps 314a, 314b for the respective pairs of wire sections. The first and second pairs of wire sections are also electrically connected by a static electrical connection 320 which is connected
20 between the two static crimps 312b which connect each of the second wire sections 308b, 318b to the second portion 304b of the static element. The terms static electrical connection and moveable electrical connection are used to denote the location of the electrical connection and do not describe any motion of the electrical connection.

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The first and second pair of wire sections form a first path which as schematically illustrated is connected to a positive voltage via the static crimp 312a which is connected to the first wire section 308a in the first pair of wire sections and to ground via the static crimp 312a which is connected to the first
30 wire section 318a in the second pair of wire sections. The path thus comprises four wire sections 308a, 308b, 318a, 318b. Each of these four wire sections may be a separate individual piece of SMA wire (or groups of wires in parallel). The moveable and static crimps may comprise flying leads or other similar elements to make the static and moveable electrical connections. Alternatively, the static
35 and moveable crimps and electrical connections may be on the same etched part.

This may reduce the resistance of the electrical connections and may increase ease of manufacture.

In Figure 3a, there are two further paths comprising four SMA wire sections. A second path comprises a third pair of wire sections 328a, 328b and a fourth pair of wire sections 338a, 338b. A third path comprises a fifth pair of wire sections 348a, 348b and a sixth pair of wire sections 358a, 358b. In this arrangement, the three paths are equidistantly separated from one another with the first pair of wire sections in the first path at one end of the moveable element and the second pair of wire sections in the third path at the opposed end of the moveable element. However, the spacing between paths and/or the spacing between pairs of wire sections within the paths may be adjusted as required.

The wire sections in each pair of wire sections are electrically connected together by a moveable electrical connection 322. Similarly, each pair of wire sections is connected together via a static electrical connection 320 on the second portion 304b of the static element. A positive voltage is applied via the static crimp 312a which is connected to one of the first wire sections 308a, 328a, 348a in each path and the path is grounded via the static crimp 312a which is connected to one of the other first wire sections 318a, 338a, 358a in the same path.

The electrical connections are schematically illustrated in Figure 3b. The first path 340 comprises four wire sections 308a, 308b, 318a, 318b which are connected in series. Similarly, the second path 342 comprises four wire sections 328a, 328b, 338a, 338b which are connected in series and the third path 346 comprises four wire sections 348a, 348b, 358a, 358b which are connected in series. One end of each path is connected to a voltage (e.g. +V) and the opposed end of each path to ground. It will be appreciated that this Figure is merely indicative of the number of paths and the number of wire sections which can be electrically connected. Each path is thus electrically connected in parallel to the other paths. Thus the wire sections are connected in a mix of series and parallel connections which may be selected to create the desired overall resistance. In another possible arrangement, the number of paths doubles while the number of wire sections remain the same. In this case, there are twice as many terminals/electrical connections.

The wire sections are mechanically acting together. It will be appreciated that the SMA force will vary with the load applied to the wire sections but some values are provided merely for illustration of the increased force generated by the arrangements. For example, a wire section having a cross-section of 25 μ m typically generates a maximum force of approximately 200mN and thus twelve wire sections provide a maximum force of approximately 2.4N. Thus, as illustrated in the table above, in this arrangement, the contraction of the twelve wire sections sums together to create an overall stroke which is greater than 50 μ m and has a force greater than 2N.

Figures 9a and 9b are schematic perspective views showing further variations of attachment of SMA wire sections which can be used in the haptic assembly of Figure 1. The arrangements are similar to those shown in Figure 3a, and therefore, like reference numerals are used to denote like features.

Figure 9a shows one possible arrangement having multiple wire sections. In this arrangement, there are twelve wire sections which may be considered to form six pairs of wire sections, with each pair of wire sections comprising a first wire section connecting to one part of the static element 304a or 304b and a second wire section connecting to the same part of the static element 304a or 304b. Each wire section is also connected to the moveable element 306. In this arrangement, the coupling elements are crimps but other coupling elements may be used. For ease of reference, the button is omitted from the Figure to show the multiple wire sections and their mechanical and electrical connections.

In Figure 9a, a first pair of wire sections comprises a first SMA wire section 308a which is connected to the first portion 304a of the static element by a static crimp and to an adjacent edge of the moveable element 306 by a moveable crimp, and a second SMA wire section 318a which is connected to the first portion 304a of the static element by a static crimp and to an adjacent edge of the moveable element 306 by a moveable crimp. Similarly, a second pair of wire sections comprises a first SMA wire section 308b and a second SMA wire section 318b which are connected using moveable and static crimps to both the moveable element 306 and the second portion 304b of the static element. There are also

four more pairs of wire sections which are similarly connected. In this arrangement, each pair of wire sections is only connected to one portion of the static element. This is in contrast to Figure 3a in which each pair of wire sections is connected to both the first and second portions of the static element.

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The wire sections in each pair of wire sections are electrically connected together by a moveable electrical connection 322a or 322b, as illustrated in Figure 9a. In each pair of wire sections, a positive voltage is applied via the static crimp which is connected to the first wire section (e.g. wire section 308a), and the path
10 is grounded via the static crimp which is connected to the second wire section in the same path (e.g. wire section 318a).

Figure 9b shows another possible arrangement having multiple wire sections. The arrangement is similar to that of Figure 9a, except that the wire
15 sections in each pair of wire sections are electrically connected together by a static electrical connection 320a or 320b. In each pair of wire sections, a positive voltage is applied via the moveable crimp which is connected to the first wire section (e.g. wire section 308a), and the path is grounded via the moveable crimp which is connected to the second wire section in the same path (e.g. wire section
20 318a).

Figure 4 shows an alternative arrangement for attaching multiple wire sections to the moveable element so that the multiple wire sections are acting in parallel to create a relatively high force together with a significant displacement.
25 As in the other arrangements, Figure 4 shows an SMA actuator comprising a static element having a first portion 404a and a second portion 404b with a cavity or gap between the two portions 404a, 404b. A moveable element 406 is positioned between the two portions 404a and 404b. The SMA actuator may be incorporated in a haptic assembly, e.g. with a button arranged above the moveable element
30 406 but the button is omitted for clarity of viewing the SMA wire sections. It will be understood that the button may not be necessary. In some embodiments, the haptic sensation may be transferred to a user directly via the moveable element or by a button which is not directly contactable/touchable via a user (see above).

In this arrangement, there are a plurality of SMA wire sections coupling each of the first and second portions 404a, 404b of the static element to the moveable element 406. An equal number of wire sections (eight as shown) are attached to each of the first and second portions 404a, 404b. The plurality of wire sections comprises a first group 408a of four wire sections connected to the first portion 404a of the static element via a static crimp 412a and to one end of the moveable element 406 via a moveable crimp 414a. There is also a second group 408b of four wire sections connected to the second portion 404b of the static element via a static crimp 412b and to the same end of the moveable element 406 via a moveable crimp 414b. Similarly, a fourth group 418a of four wire sections is connected to the first portion 404a of the static element via a static crimp 422a and to the moveable element 406 via a moveable crimp 424a. There is also a third group 418b of four wire sections connected to the second portion 404b of the static element via a static crimp 422b and to the moveable element 406 via a moveable crimp 424b. The third and fourth groups of wire sections are coupled to the opposed end of the moveable element to the first and second groups of wire sections.

A first moveable electrical connection 430 is connected between the two moveable crimps 414a, 414b to electrically connect the wire sections in the first group to the wire sections in the second group. Similarly, a second moveable electrical connection 432 is connected between the two moveable crimps 424a, 424b to electrically connect the wire sections in the third group to the wire sections in the fourth group. A static electrical connection 420 is connected between the two static crimps 412b, 422b on the second portion 404b of the static element to electrically connect the wire sections in the second group to the wire sections in the third group. A voltage is applied via the static crimp 412a which connects to the first group of wire sections and the plurality of wire sections are grounded via the static crimp 412a which connects to the fourth group of wire sections. In this way, each of the four wire sections in each group forms a parallel path (i.e. parallel electrical path) so that there are four parallel paths each having four wire sections.

In each group, each of the four wire sections are held together in each individual coupling member (e.g. crimp) rather than a single wire section for each

crimp as illustrated in Figure 3a. It will be appreciated that four wire sections is illustrative, there may be any number of wire sections in each coupling member, e.g. between 2 to 6. There may be spacing between each wire section in the crimp and such spacing may be uniform. However, there may also be no or little spacing between the wire sections.

The width w of each crimp may be sufficient to hold and to connect to each of the four wire sections. The crimp width w is the size of the crimp parallel to the SMA wire sections within the crimps. The width thus defines how much of each SMA wire section is held in the crimp. The width may be between $400\mu\text{m}$ to $750\mu\text{m}$ with a standard crimp typically having a width of $500\mu\text{m}$. A larger crimp may form a better mechanical connection between the crimp and wire sections because there is more crimp material. The length is the dimension of the crimp which is perpendicular to the width and which is defined after the crimp has been folded over the wire sections. The length is typically $450\mu\text{m}$, i.e. an unfolded crimp is typically $900\mu\text{m}$. The crimp may have a thickness which is dependent on the material. Any suitable material which forms a mechanical and electrical connection may be used for the crimp, e.g. phosphor bronze, gold plated stainless steel or stainless steel. A very thick or thin piece of material may be more difficult to fold, or may not form a good mechanical connection with the wire. For example, the unfolded crimp may have a total thickness of $100\mu\text{m}$. The dimensions of the crimp may be selected to balance the requirements in relation to spacing between the wire sections, as well as providing an acceptable mechanical and electrical connection.

In this arrangement, each wire section may be 2.25mm and at an angle of 43 degrees. The diameter of each wire section may be $25\mu\text{m}$. Again, these numbers are merely indicative of one working solution. As explained above, various parameters including the number of wire sections, lengths and diameter may be adjusted to achieve a desired force, displacement and/or resistance.

Figures 5a and 5b are variations of the arrangement shown in Figure 1 and thus the same elements have been labelled with the same reference numbers. In both Figures, there is shown a haptic assembly comprising a static element having a first portion 104a and a second portion 104b with a cavity or gap

between the two portions 104a, 104b. A moveable element 106 is positioned between the two portions 104a and 104b and is attached to a button 102 on which a user may apply a force in the direction of the arrow. A plurality of SMA wire sections 108a, 108b are attached using moveable crimps 114a, 114b to the
5 moveable element 106 and using static crimps 112a, 112b to the static element. Each wire section 108a, 108b is set at an acute angle relative to the direction of motion of the moveable element and the angle of the wire section is aligned with an angled surface of a recess 120a, 120b in the first and second portions 104a, 104b of the static element. Each wire section is at least partially received in the
10 corresponding recess and at least partially extends along the angled surface.

In each arrangement, there is a small gap between the button 102 and the housing at the upper surfaces of the first and second portions 104a, 104b. It is possible for dust, water or other contaminants to enter the device through this
15 gap. Accordingly, the arrangement in Figure 5a includes a seal 130 which is attached to the lower surface of the button and an upper surface of each recess 120a, 120b. The seal 130 is generally annular in shape and is flexible so that vertical movement of the button and/or moveable element is not impeded. The seal 130 may be used at least in part to control movement of the button and/or
20 moveable element in directions other than the primary direction of movement (i.e. vertical movement). In other words, the seal 130 may assist in preventing or at least reducing lateral or rotational movement of the button and/or moveable element.

25 The seal 130 may be formed of any one of: rubber, an elastic material, an elastomer, a polymer, a nitrile material and a silicone material. The seal 120 may be in the form of a sealing film which may be formed of any one of: a flexible material, an elastic material, an elastomer, a polymer, a silicone material, a thin metallic material, a composite material, a thin aluminium film, a thin titanium film,
30 an alloy, and a thin stainless steel film. The seal 130 may also be a liquid-impermeable material and/or a compressible material. It will be understood that these are non-limiting examples of materials which may form or provide the seal 130.

In the arrangement of Figure 5b, there is no seal 130 (although one may be incorporated to address the contaminant issue) but a flexible element (e.g. a biasing element) 132 is incorporated to control movement of the button 102 and/or moveable element 106, e.g. to prevent or at least reduce lateral or other non-vertical movement of the button and/or moveable element. The flexible element 132 may be made from steel and may comprise one or more rods or struts which are connected to lower surfaces of both the moveable element 106 and the static element 104a, 104b. The flexible element 132 may be a flexure, i.e. is flexible in the direction of movement of the moveable element but is not flexible in other directions. The moveable element 106 may thus incorporate an annular flange 140 which extends around the base of the moveable element 106 to facilitate attachment of the flexible element 132. Any other suitable biasing element may be used, such as a spring located below the moveable element, or a suspension system to suspend the moveable portion from the static portion using e.g. a spring or flexure.

In addition to the flexible element/biasing element, or as an alternative to the flexible/biasing element, the haptic assembly may comprise one or more end stops to restrict the motion of the button and/or moveable element. The end stops may prevent the SMA actuator wire sections from becoming overstretched such as when a user presses down on the button with excessive force, or when the haptic assembly (or device containing the haptic assembly) is dropped.

In each of the arrangements described above, the multiple SMA wire sections are symmetrically arranged on either side of the moveable element. Figure 6 shows an alternative arrangement in which the multiple wire sections are only connected along a single side of the moveable element 606. As in previous arrangements, the static element comprises a first portion 604a and a second portion 604b separated by a cavity or gap within which the moveable element 606 is located. The moveable element 106 is integrally formed with a button 602 on which a user may apply a force in the direction of the arrow.

A plurality of SMA wire sections 608 are attached using moveable crimps 614 to the moveable element 606 and attached using static crimps 612 to the first portion 604a of the static element. In this arrangement, only the first portion

of the static element has a recess 620 with receives at least part of the SMA wires. As before, each wire section 608 is set at an acute angle relative to the direction of motion of the moveable element and the angle is aligned with an angled surface of the recess 620. A relatively small recess 622 with an angled surface aligned with the angled surface of the recess 620 in the static element is also formed in the moveable element 606 to receive the moveable crimps 614.

The assembly also comprises a restoring element 630 which opposes the force of the SMA actuator wire sections 608. The restoring element 630 is also provided in the recess 620 and as shown is attached at one end to an upper surface of the recess and at the other end to an adjacent surface of the moveable element. The restoring element 630 (e.g. a return spring or any suitable biasing resilient element) may be arranged to oppose the contraction of the SMA wire sections 608 and thereby move the moveable element in the opposite direction when the SMA wire section 608 is not powered. It will also be appreciated that the restoring element 630 may comprise one or more additional SMA wire sections which on contraction pulls the moveable element 606 in the opposite direction to the plurality of SMA wire sections 608.

The moveable element 606 abuts the first portion 604a of the static element below both angled recesses 620, 622 on a bearing surface 624. Movement of the moveable element 606 against the bearing surface 624 is facilitated by bearings. It will be appreciated that bearings may be incorporated into the other arrangements where there are adjacent surfaces which move relative to one another.

The term "bearing" is used interchangeably herein with the terms "sliding bearing", "plain bearing", "rolling bearing", "ball bearing", "flexure", and "roller bearing". The term "bearing" is used herein to generally mean any element or combination of elements that functions to constrain motion to only the desired motion and reduce friction between moving parts. The term "sliding bearing" is used to mean a bearing in which a bearing element slides on a bearing surface, and includes a "plain bearing". The term "rolling bearing" is used to mean a bearing in which a rolling bearing element, for example a ball or roller, rolls on a bearing surface. The bearing may be provided on, or may comprise, non-linear

bearing surfaces. In some embodiments of the present techniques, more than one type of bearing element may be used in combination to provide the bearing functionality. Accordingly, the term "bearing" used herein includes any combination of, for example, plain bearings, ball bearings, roller bearings and flexures. In embodiments, a suspension system may be used to suspend the intermediate moveable element and/or the button within the haptic assembly and to constrain motion to only the desired motion. For example, a suspension system of the type described in WO2011/104518 may be used. Thus, it will be understood that the term "bearing" used herein also means "suspension system". In embodiments, the bearing may be provided on, or may comprise, non-linear bearing surfaces. The bearing may be formed from any suitable material, e.g. ceramic, steel, stainless steel, mild steel, plastic, and polytetrafluoroethylene (PTFE).

A restoring element such as that shown in Figure 6 may be incorporated into the other arrangements above. Alternatively, the restoring force may be provided by the activation by the user, e.g. by pressing the button down, the contraction of the SMA wire sections is effectively restoring the button to its original position. As mentioned above, one or more end stops may be provided to restrict the amount by which the SMA wire sections are able to stretch.

Figure 7 shows an alternative arrangement in which the moveable element is configured for lateral movement in the direction of the arrow A. Figure 7 shows an SMA actuator comprising a static element 904 which is a housing surrounding a cavity or gap. The SMA actuator may be incorporated in a haptic assembly, e.g. with a button arranged above the gap (which may thus be termed a button hole) but the button is omitted for clarity of viewing the SMA wires. A moveable element 906 is positioned within the gap so that it is surrounded by the static element.

In this arrangement, there are a plurality of separate SMA wire sections 908 formed from an individual piece of wire and each of which is coupled to both the static element 904 and the moveable element 906. There are five wire

sections 908 shown but it will be appreciated that this number is merely illustrative. One end of each SMA wire section 908 is attached to the moveable element 906 by a moveable crimp connector 912 and the opposed end of each SMA wire section 908 is attached to the static element 904 by a static crimp connector 914.

Each SMA wire section is set at an angle α to the direction of movement. Thus, each angle is set at an angle θ ($90-\alpha$) to a line which is parallel to one edge of the moveable element 906. The moveable element 906 is also shaped with a plurality of angled recesses 920. Each angled recess 920 comprises an angled surface having an angle which matches the angle of each SMA wire section. Each SMA wire section extends along the angled surface and is attached at an innermost point of the corresponding recess 920. The static element may be formed with a flange or protrusion to which the static crimp connectors 914 can be attached.

The moveable element 906 abuts the static element on a bearing surface 924 similar to the one used in Figure 6. In this arrangement, four bearing surfaces are shown but it will be appreciated that this is illustrative. The bearing surfaces 924 constraint movement of the moveable element to a single direction, namely lateral movement in the direction of arrow A. When each SMA wire section 908 contracts, the angle of the wire section 908 means that the moveable element is drawn towards the static element in an angled direction. However, the constraint imposed by the bearing surfaces means that only the movement in the lateral direction is effective. Furthermore, the lateral movement generated by each SMA wire section is summed together to provide an overall total displacement (or stroke) for the moveable element 906.

The arrangement also comprises a restoring element 930 in the form of a pair of compression springs. The restoring element 903 returns the moveable element to its rest position once the wires are no longer in contraction. As mentioned above, one or more end stops may be provided to restrict the amount by which the SMA wire sections are able to stretch.

In each of the arrangements described above, the SMA wire section may be made from any suitable shape memory alloy and may be coated (e.g. with polyimide or similar material) to reduce the risk of shorting with other components in the SMA actuator if the wire sections are in contact with them.

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As an alternative to crimping, the ends of the wire sections may be connected in place using welding (e.g. arc welding, welding using a weld bar, laser/heat-based welding). By welding the wire sections in place, it may be possible to more accurately control any spacing between the wire sections. During the welding process, care needs to be taken to control the welding so that damage to the wire section, e.g. melting or loss of material, is minimised.

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Each of the arrangements described above may optionally incorporate an endstop which may be formed as part of the housing within the cavity or may be a separate element within the cavity. The endstop may be provided at a location in the cavity to restrict movement of the moveable element. Generally speaking if the SMA actuator wire sections are stretched too far (i.e. a certain tension is exceeded), the SMA actuator wire sections may weaken or become damaged, or even break. Where there is a restoring element, the force it exerts on the moveable element may cause the SMA actuator wire sections to become overstretched. Therefore, the endstop may restrict the movement of the moveable element so that the SMA actuator wire sections do not overstretch. Similarly, a force applied to the button surface by the user's finger may cause the wires to overstretch if there is no endstop.

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The arrangements above typically use wire sections having a small diameter, e.g. 25µm or 36µm. Larger diameter wires cool more slowly and thus cannot be activated rapidly in succession. In a haptics assembly, this may lead to a "soft" haptic feedback sensation because the wire cooling time is significant relative to the time of pressing a button. Each of the arrangements described above may optionally comprise at least one heatsink adjacent to the plurality of SMA wires. For example, as shown in Figure 7, both the moveable element and the static portion are in close proximity to the wire section 708 and may act as a heat sink. The wire sections are typically driven at high power, thus achieving near instantaneous heating where the impact of a nearby heatsink is minimal. The

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heatsink may assist in cooling the small diameter wire sections suggested above because cooling typically takes place over a longer timeframe and/or may allow larger diameter wire sections to be used. The at least one heatsink may be close to the wire sections or may be touching the wires. The at least one heatsink and/or the plurality of wire sections may be moveable relative to one another between a first position in which the heatsink is adjacent or touching the plurality of wire sections and a second position in which the heatsink is further from the plurality of wire sections.

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

CLAIMS

1. A shape memory alloy (SMA) actuator comprising:
a static element;
5 a moveable element which is moveable relative to the static element;
a plurality of SMA wire sections each of which are coupled to the static element and the moveable element and which on contraction cause the moveable element to move in a direction of movement; and
wherein an axis of each of the plurality of SMA wire sections is generally at
10 an acute angle to the direction of movement of the moveable element.
2. The SMA actuator of claim 1, wherein the plurality of SMA wire sections are electrically connected to form at least one electrical path wherein each electrical path comprises at least two SMA wire sections which are electrically connected in
15 series.
3. The SMA actuator of claim 1 or claim 2, wherein the plurality of SMA wire sections are connected to form at least two separate electrical paths which are electrically connected in parallel.
20
4. The SMA actuator of claim 2 or claim 3, wherein each electrical path comprises SMA wire sections which form a continuous SMA wire.
5. The SMA actuator of any one of claims 2 to 4, wherein the number of SMA
25 wire sections which are electrically connected in series and the number of SMA wire sections which are electrically connected in parallel is selected to generate a predetermined resistance.
6. The SMA actuator of any preceding claim, wherein at least one parameter
30 of the plurality of SMA wire sections is selected so that when the plurality of SMA wire sections contract a minimum force in the direction of movement of the moveable element is generated and the moveable element moves a minimum distance.

7 The SMA actuator of claim 6, wherein the at least one parameter is selected
from the group comprising the acute angle between the axis of each of the plurality
of SMA wire sections, the diameter of each of the plurality of SMA wire sections,
the length of each of the plurality of SMA wire sections and the number of SMA
5 wire sections.

8. The SMA actuator of any preceding claim, wherein each of the plurality of
SMA wire sections is less than 3mm in length, preferably between 1mm and
2.5mm in length.

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9. The SMA actuator of any preceding claim, wherein the acute angle is less
than 70 degrees.

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10. The SMA actuator of any preceding claim, wherein each of the plurality of
SMA wire sections is at the same acute angle.

11. The SMA actuator of any preceding claim, wherein there are between 12
and 30 SMA wire sections.

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12. The SMA actuator of any preceding claim, wherein one end of each of the
plurality of SMA wire sections is coupled to one edge of the moveable element and
the opposed end of each of the plurality of SMA wire section is coupled to an
adjacent edge of the static element.

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13. The SMA actuator of claim 12, wherein the adjacent edge of the static
element comprises a recess having an angled slope and each of the plurality of
SMA wire sections extends along the angled slope.

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14. The SMA actuator of any one of claims 1 to 11, wherein the moveable
element is located between first and second portions of the static element and the
plurality of SMA wire sections comprise a plurality of pairs of SMA wires with a
first SMA wire in each pair having one end coupled to the first portion of the static
element and the opposed end coupled to an adjacent edge of the moveable
element and a second SMA wire in each pair having one end coupled to the second

portion of the static element and the opposed end coupled to an adjacent edge of the moveable element.

15. The SMA actuator of claim 13, wherein each of the first and second portions
5 comprises a recess having an angled slope and each of the plurality of SMA wire sections extends along the angled slope of the respective recess.

16. The SMA actuator of any one of claims 11 to 15, wherein the moveable
10 element comprises an angled flange to which an end of each SMA wire section is attached.

17. The SMA actuator of any preceding claim, wherein at least one of the
plurality of SMA wires sections is coupled to at least one of the static element and the moveable element using a crimp connector.

18. The SMA actuator of claim 17, wherein the crimp connector holds a plurality
of SMA wires sections.

19. The SMA actuator of any preceding claim, wherein at least one of the
20 plurality of SMA wires sections is coupled to at least one of the static element and the moveable element using a protruding element around which the SMA wire section is looped.

20. A haptic assembly comprising
25 a touchable component and

the SMA actuator of any one of claims 1 to 19, wherein when a user presses the touchable component, the actuator module is activated to provide haptic feedback to the user by moving the touchable component using the moveable element.

21. A latch comprising the SMA actuator of any one of claims 1 to 19.

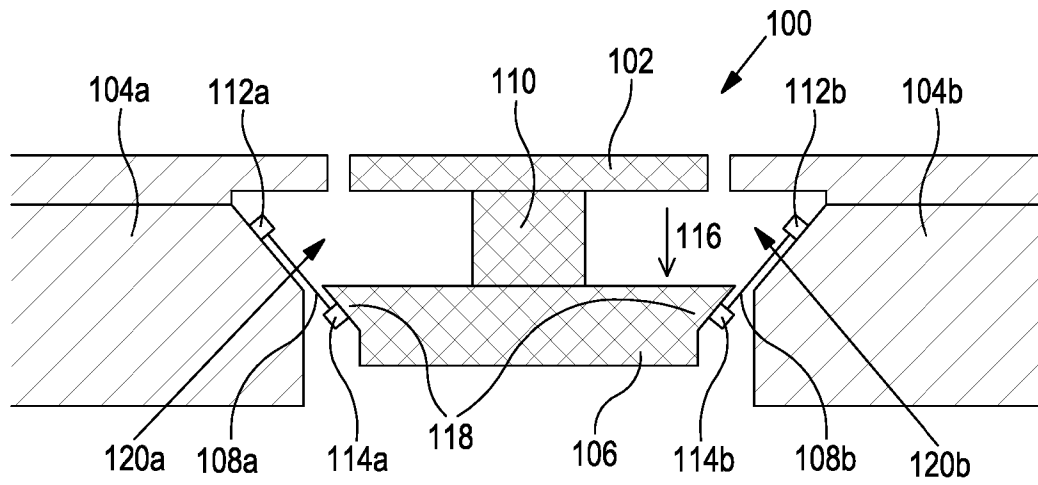


FIGURE 1

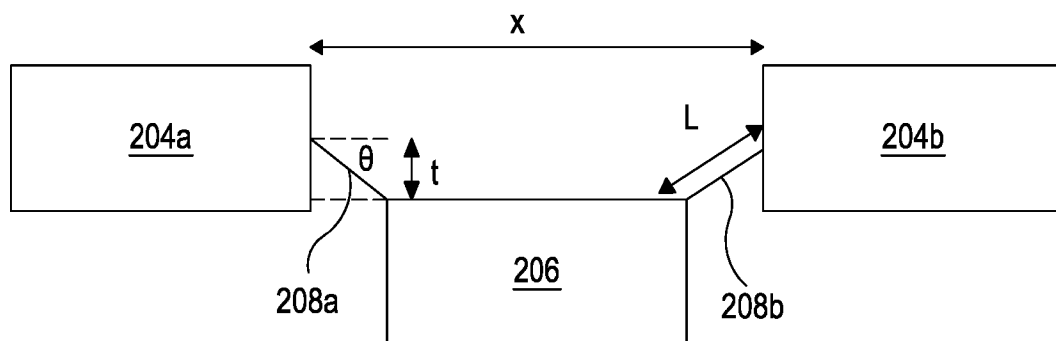


FIGURE 2A

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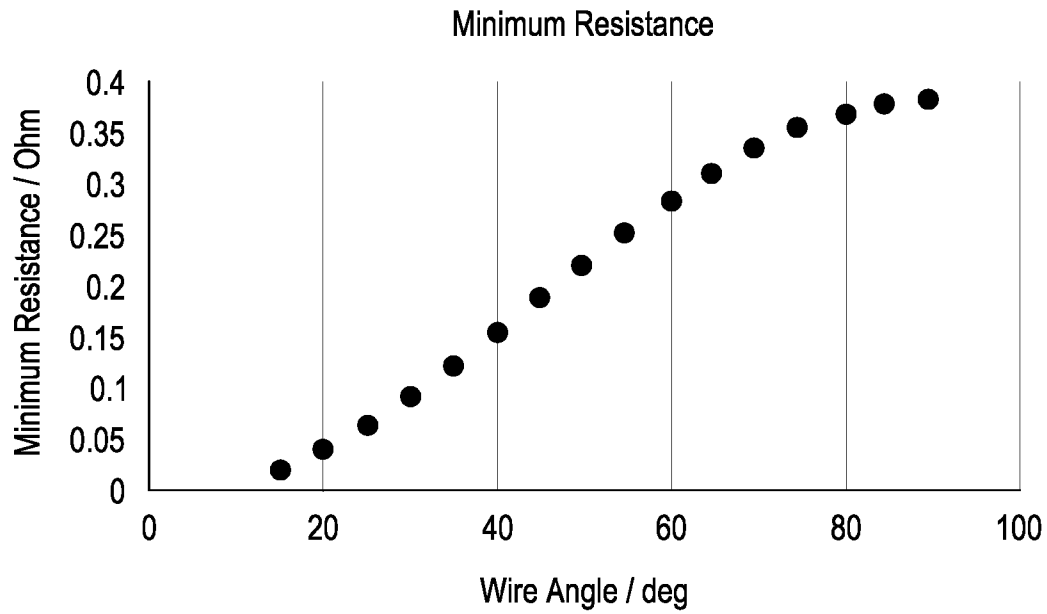


FIGURE 2B

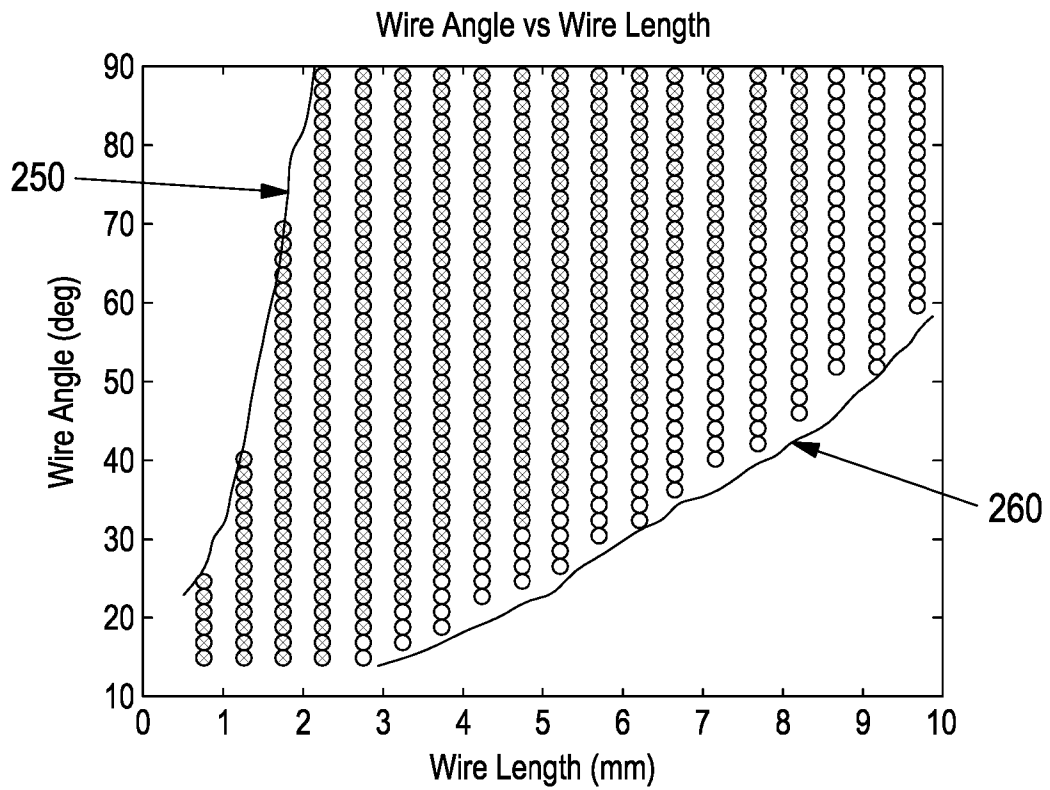


FIGURE 2C

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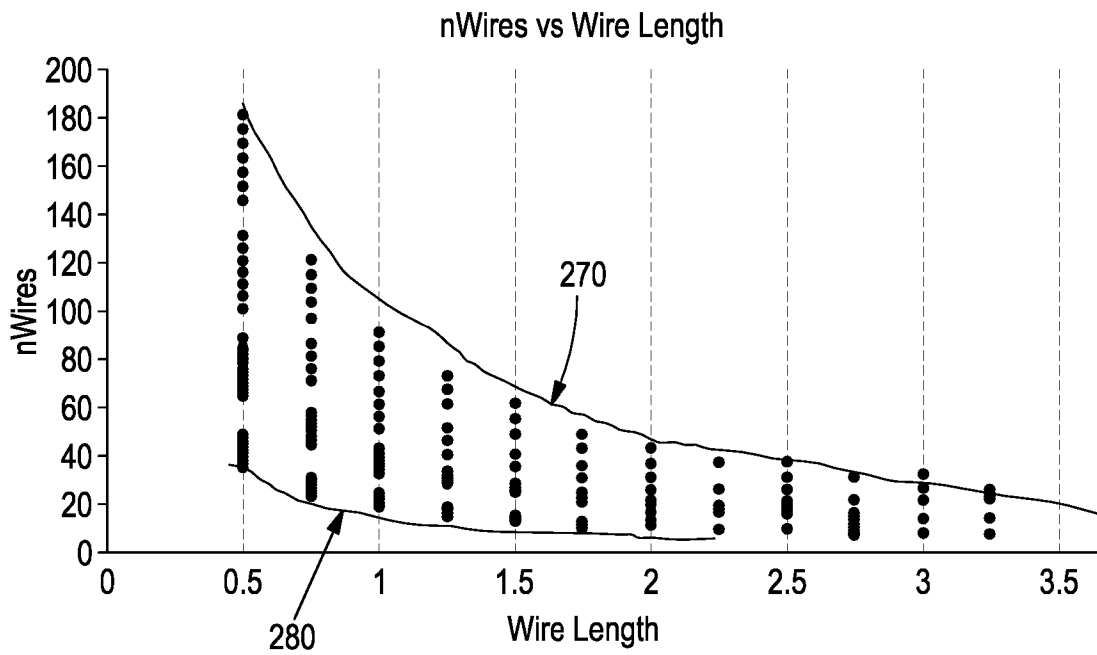


FIGURE 2D

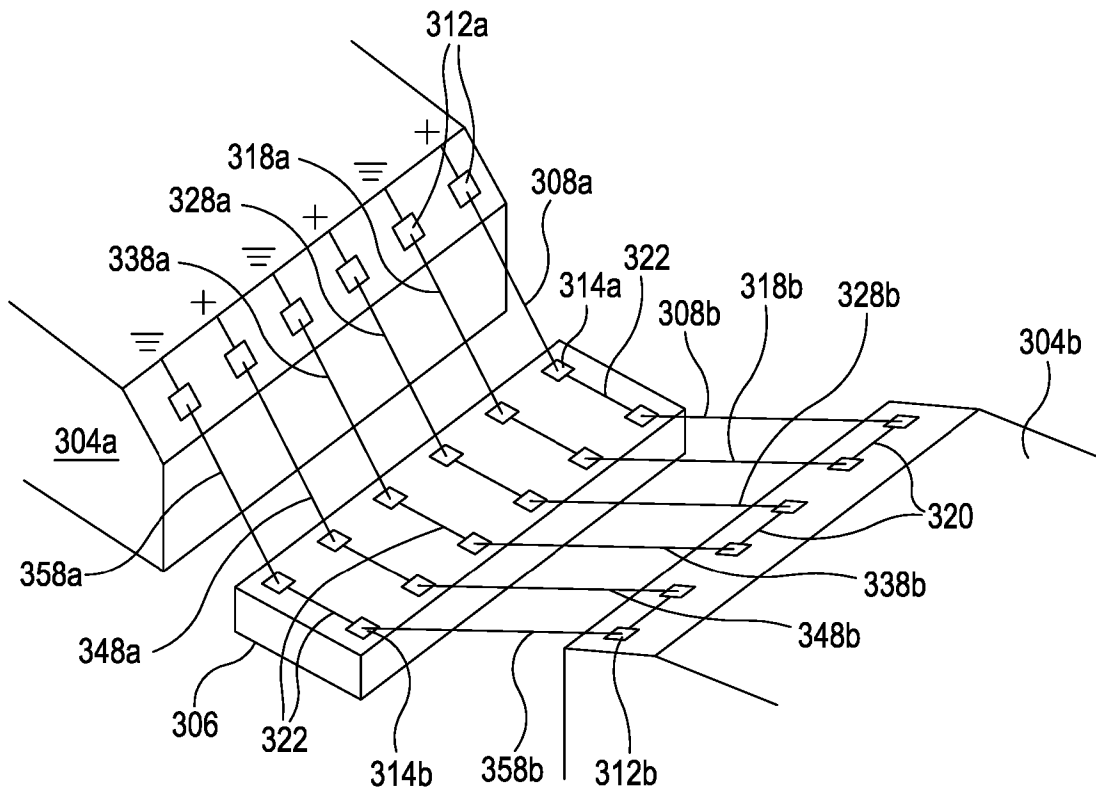


FIGURE 3A

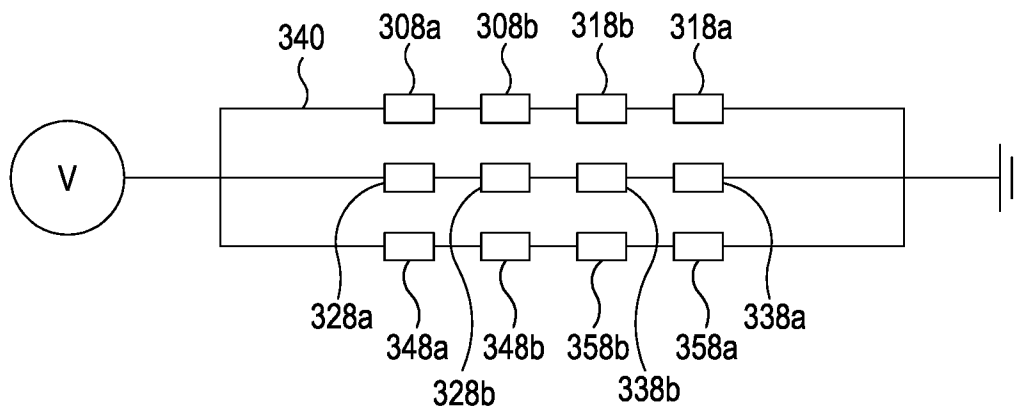


FIGURE 3B

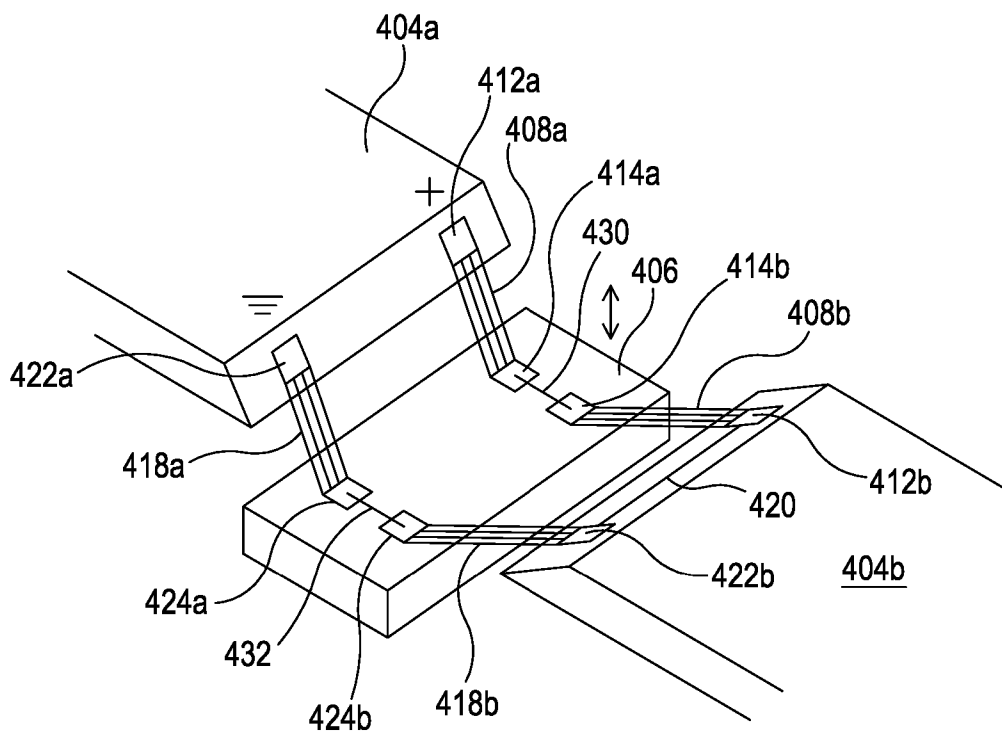


FIGURE 4

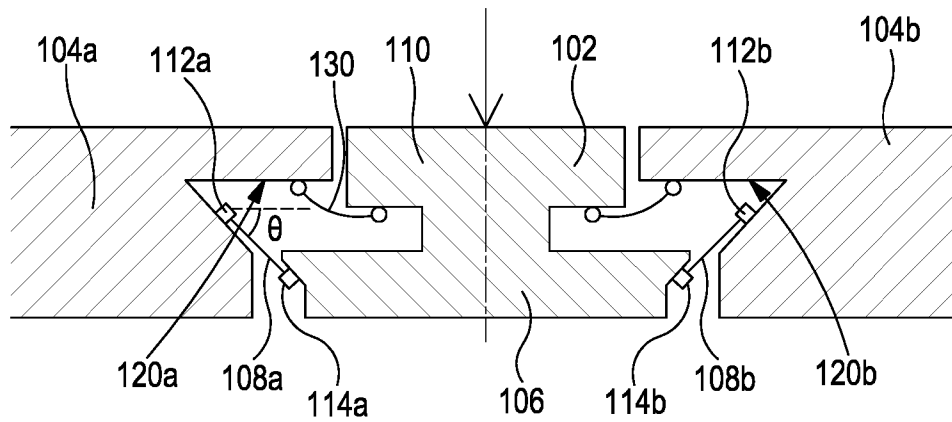


FIGURE 5A

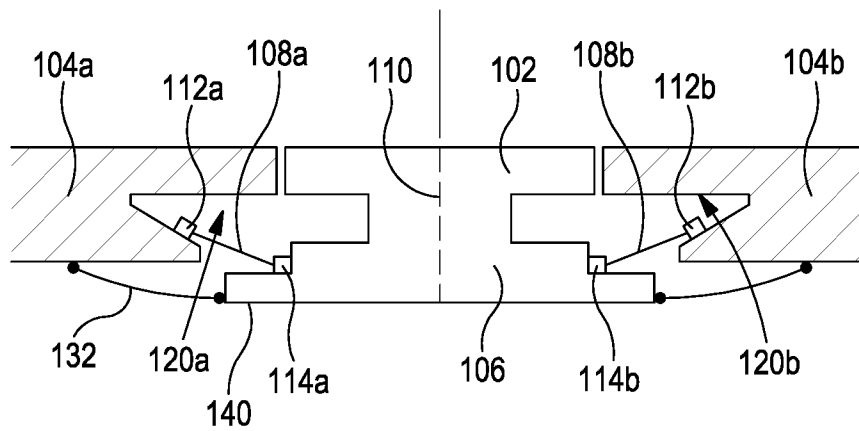


FIGURE 5B

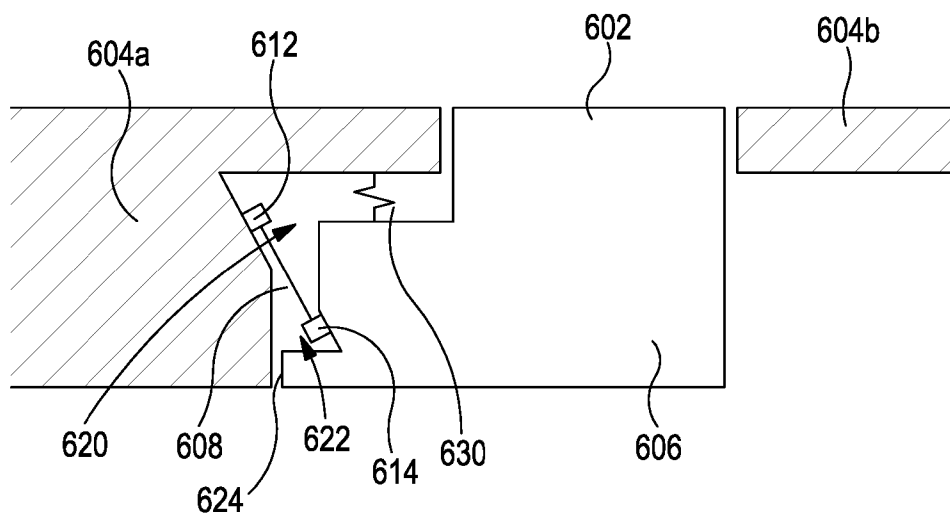


FIGURE 6

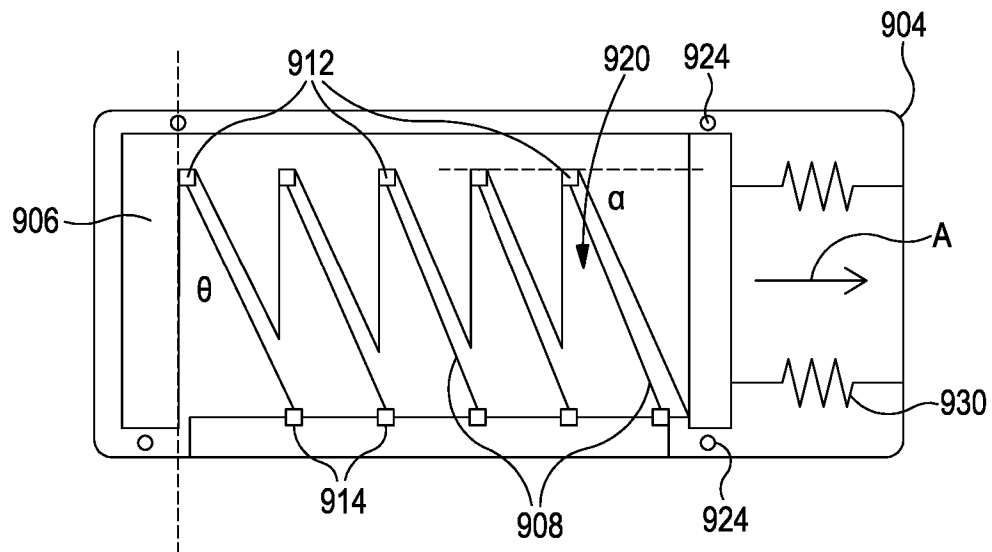


FIGURE 7

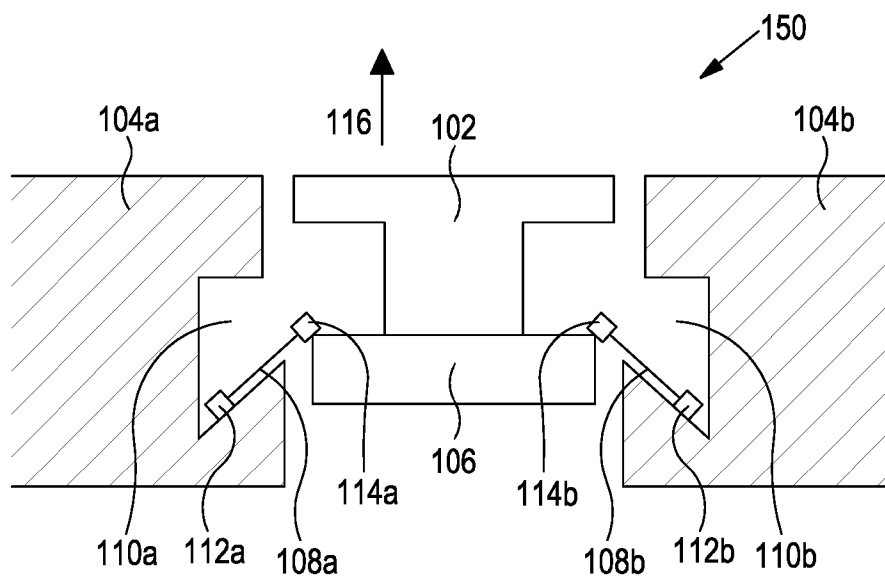


FIGURE 8

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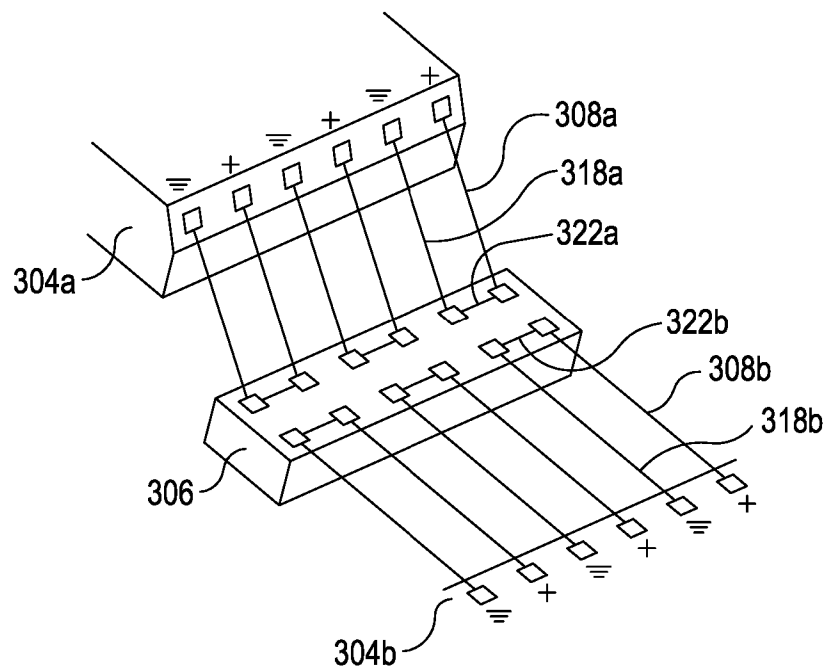


FIGURE 9A

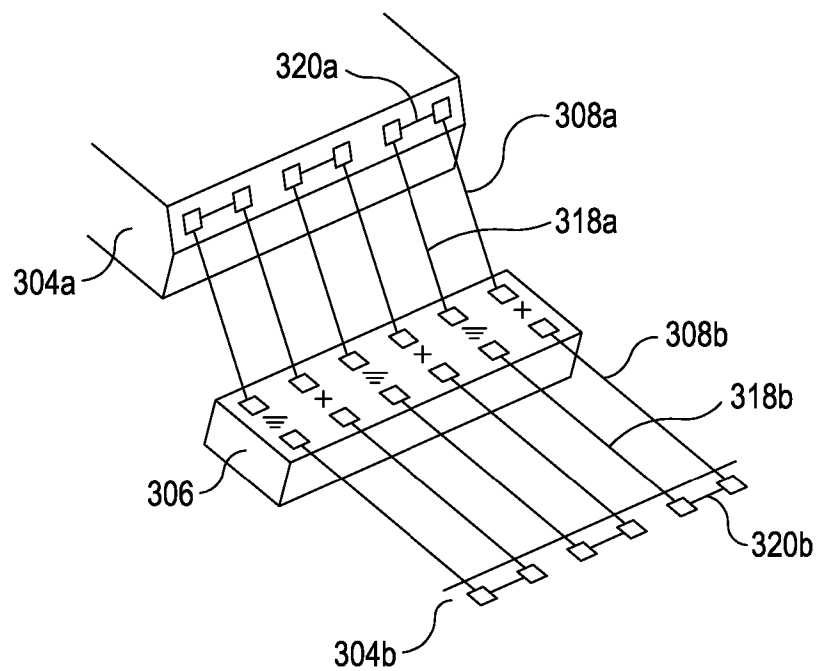


FIGURE 9B

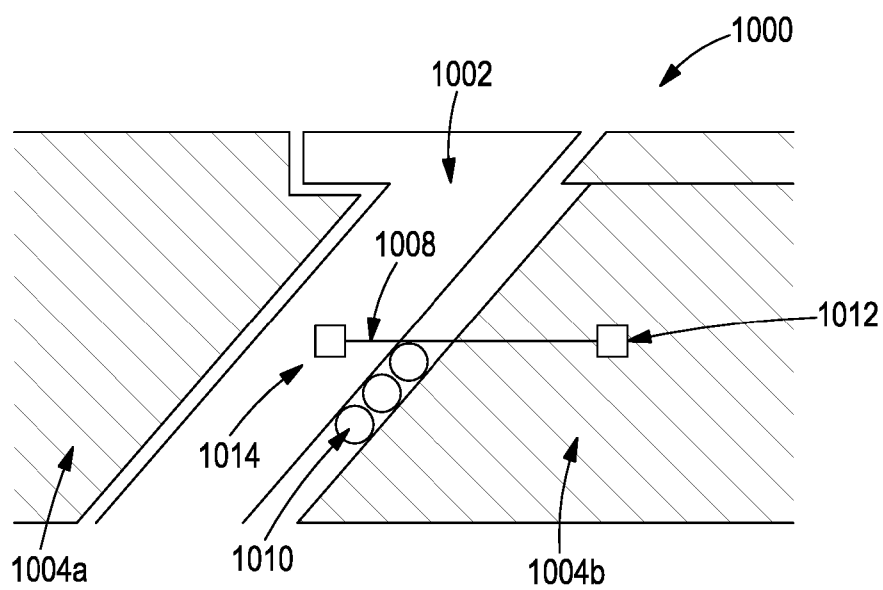


FIGURE 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/050161

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

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03G

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2012 002119 B3 (FRAUNHOFER GES FORSCHUNG [DE]) 18 July 2013 (2013-07-18) paragraph [0055] - paragraph [0065]; figure 1	1-21
X	----- WO 2018/046937 A1 (CAMBRIDGE MECHATRONICS LTD [GB]) 15 March 2018 (2018-03-15) cited in the application page 10, line 22 - page 13; figures 6-12	1-21
X	----- JP 2009 047179 A (PANASONIC ELEC WORKS CO LTD) 5 March 2009 (2009-03-05) figures 1-3	1-21
A	----- JP S61 297091 A (OKI ELECTRIC IND CO LTD) 27 December 1986 (1986-12-27) the whole document	1-21



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

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

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"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

17 March 2020

Date of mailing of the international search report

26/03/2020

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Authorized officer

Alquezar Getan, M

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2020/050161

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