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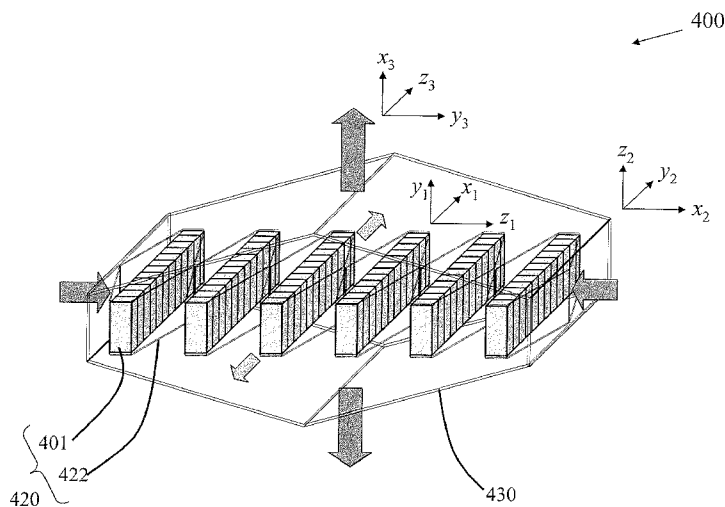


FIG. 6

(57) Abstract: A multi-layer strain-amplification device (400) includes at least one first amplifying layer unit comprising a plurality of actuators (420) and a second amplifying layer unit (430) positioned about the at least one first amplifying layer unit, particularly configured as a nested rhombus structure. A strain of the at least one first amplifying layer unit is amplified by the second amplifying layer unit.

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STRAIN AMPLIFICATION DEVICES AND METHODS

RELATED APPLICATIONS

This application claims the benefit of United States Provisional Patent Application No. 5 61/000,365, filed October 25, 2007, the content of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

The invention relates to strain amplification devices and methods, specifically to 10 multi-layer strain amplification devices and methods having hierarchical nested structures and comprising piezoelectric materials.

BACKGROUND OF THE INVENTION

The demand for high-force and compact actuators with large strain is increasing in 15 robotics. Piezoelectric (PZT) ceramic material, such as lead zirconium titanate, is known as one of the promising materials used in actuators because of its high power density, high bandwidth, and high efficiency. 20

FIG. 1 is a chart illustrating a comparison of characteristics between PZT and other 25 materials used to form actuators. As shown in FIG. 1, PZT outperforms other actuator materials, such as shape memory alloy (SMA), conducting polymers, such as polypyrrole-conducting polymers, and electrostrictive polymers, also referred to as elastomers, with respect to speed of response, large stress, and bandwidth. The maximum stress of PZT is comparable to that of SMA, and the efficiency of PZT is comparable to that of elastomers. Furthermore, PZT is a stable and reliable material that can be used in diverse, harsh 30 environments. Polypyrrole-conducting polymers, on the other hand, degrade quickly despite their attractive features such as relatively high stress.

However, PZT has two drawbacks. A first drawback of PZT is its extremely small 35 strain, as shown in section A of FIG. 1. A second drawback of PZT is hysteresis. However, hysteresis can be overcome by binary segmented control. See B. Selden, K.J. Cho, and H.

Asada, "Segmented Binary Control of Shape Memory Alloy Actuator Systems Using the Peltier Effect," Proceedings of 2004 IEEE International Conference on Robotics and Automation (ICRA) '04, vol. 5, April 26-May 1, 2004, pp. 4931-4936, incorporated herein in its entirety by reference.

5 The inherently small strain of PZT, i.e., approximately 0.1 %, can be a major issue for broad applications. Over the last several decades, several approaches have been taken to increase PZT strain, and generate displacements from PZT that are large enough to drive systems used in robotics and mechatronics, described for example, in C. Niezrecki, D. Brei, S. Balakrishnan, and A. Moskalik, A., entitled "Piezoelectric Actuation: State of the art,"
10 The Shock and Vibration Digest, 33(4), pp. 269–280, 2001, R. Newnham, A. Dogan, Q. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, "Flextensional Moonie Actuators," 1993 IEEE Proceedings, Ultrasonics Symposium, vol. 1, Oct. 31-Nov. 3, 1993, pp. 509-513, United States Patent Number 6,574,958 entitled "Shape Memory Alloy Actuators and Control Methods," issued June 10, 2003, A. Dogan, Q. Xu, K. Onitsuka, S. Yoshikawa, K. Uchino,
15 and R. Newnham, "High Displacement Ceramic Metal Composite Actuators (Moonies)," Ferroelectrics, 156(1), pp. 1-6, 1994, G. Haertling, "Rainbow Ceramics-A New Type of Ultra-High Displacement Actuator," American Ceramic Society Bulletin, 73(1), pp. 93-94, 1994, K. Onitsuka, A. Dogan, J. Tressler, Q. Xu, S. Yoshikawa, and R. Newnham, "Metal-Ceramic Composite Transducer, the 'Moonie'," Journal of Intelligent Material Systems and
20 Structures 6(4), pp. 447-455, 1995, A. Moskalik and D. Brei, "Quasi-Static Behavior of Individual C-Block Piezoelectric Actuators," Journal of Intelligent Material Systems and Structures, 8(7), pp. 571-587, 1997, K. Uchino, Piezoelectric Actuators and Ultrasonic Motors, Kluwer Academic Publishers, 1997, A. Dogan, K. Uchino, and R. Newnham, "Composite Piezoelectric Transducer with Truncated Conical Endcaps 'cymbal',"
25 Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, 44(3), pp. 597-605, May, 1997, United States Patent Number 4,435,666 entitled "Lever Actuator Comprising a Longitudinal-Effect Electroexpansive Transducer," issued March 6, 1994, P. Janker, M. Christmann, F. Hermle, T. Lorkowski, and S. Storm, "Mechatronics Using Piezoelectric Actuators," Journal of the European Ceramics Society, 19(6), pp. 1127-1131,
30 1999, C. Niezrecki, D. Brei, D. Balakrishnan, and A. Moskalik, "Piezoelectric Actuation: State of the Art," the Shock and Vibration Digest, 33(4), pp. 269-280, 2001, K. Seffen and E. Toews, "Hyperthetical Actuators: Coils and Coiled-Coils," 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference,

pp. 19-22, 2004, and N. Conway, Z. Traina, and S. Kim, "A Strain Amplifying Piezoelectric MEMS Actuator," *Journal of Micromechanics and Microengineering*, 17(4), pp. 781-787, 2007, each incorporated herein in its entirety by reference.

Such approaches include a) inching motion or periodic wave generation, b) bimetal-type bending, c) leverage-type motion amplification, and d) flextensional mechanisms. However, inching motion entails friction drive, which limits its applicability to a class of applications. Bimetal-type mechanisms, for example, described in K. Seffen and E. Toews, "Hyperthetical Actuators: Coils and Coiled-Coils," incorporated by reference above, can produce only small forces despite their large displacement and strain, which also limit applications to small loads. See Germano, Carmen P., entitled "Flexure Mode Piezoelectric Transducers", *IEEE Transactions on Audio and Electroacoustics*, vol. AU-19, No. 1, Mar. 1971, incorporated herein in its entirety by reference. Leverage-type motion amplification, for example, described in United States Patent Number 4,435,666 incorporated by reference above, is inefficient, producing only a marginal gain on the order of 10. Systems incorporating leverage-type motion amplification tend to be bulky and heavy if several leverages are connected together to produced a larger displacement.

A wide variety of flextensional mechanisms has been studied and developed. United States Patent Number 4,999,819, issued March 12, 1991, entitled "Transformed Stress Direction Acoustic Transducer," incorporated herein in its entirety by reference, provides a method for amplifying strain of an enclosed piezoelectric actuator sandwiched between two flexible, curved elements. The mechanism that applies this method is called a "Moonie" and has been widely used for strain amplification. See United States Patent Number 6,411,009, entitled "Piezoelectric Actuator System," issued June 25, 2002, incorporated herein in its entirety by reference. See also R. Newnham, A. Dogan, Q. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, "Flextensional Moonie Actuators," 1993 IEEE Proceedings, Ultrasonics Symposium, vol. 1, Oct. 31-Nov. 3, 1993, pp. 509-513, A. Dogan, Q. Xu, K. Onitsuka, S. Yoshikawa, K. Uchino, and R. Newnham, "High Displacement Ceramic Metal Composite Actuators (Moonies)," *Ferroelectrics*, 156(1), pp. 1-6, 1994, and K. Onitsuka, A. Dogan, J. Tressler, Q. Xu, S. Yoshikawa, and R. Newnham, "Metal-Ceramic Composite Transducer, the 'Moonie'," *Journal of Intelligent Material Systems and Structures* 6(4), pp. 447-455, 1995 each incorporated by reference above. Other flextensional mechanisms include "Cymbol," for example, described in A. Dogan, K. Uchino, and R. Newnham, "Composite Piezoelectric

Transducer with Truncated Conical Endcaps ‘cymbal’,” *Ultrasonics, Ferroelectrics and Frequency Control*, IEEE Transactions on, 44(3), pp. 597-605, May, 1997, incorporated by reference above, “Rainbow,” for example, described in G. Haertling “Rainbow Ceramics-A New Type of Ultra-High Displacement Actuator,” *American Ceramic Society Bulletin*, 73(1), pp. 93-94, 1994, and other conventional flextensional mechanisms, for example, described in P. Janker, M. Christmann, F. Hermle, T. Lorkowski, and S. Storm, “Mechatronics Using Piezoelectric Actuators,” *Journal of the European Ceramic Society*, 19(6), pp. 1127-1131, 1999, each incorporated by reference above.

Although the “Moonie” strain amplification methods described above, in particular, with regard to United States Patent Number 4,999,819 and United States Patent Number 6,411,009, are known to be relatively efficient methods, the resulting expected amplification gain produced by the Moonie is less than 20, resulting in less than a 2% effective strain.

Other methods, described in United States Patent Number 5,471,721, entitled “Method for Making Monolithic Prestressed Ceramic Devices,” issued December 5, 1995, incorporated herein in its entirety by reference, disclose making monolithic pre-stressed piezoelectric ceramics, referred to as a “rainbow actuator,” having a stress amplification mechanism. United States Patent Number 6,574,958, entitled “Shape Memory Alloy Actuators and Control Methods,” issued June 10, 2003, incorporated herein in its entirety by reference, provides stroke-multiplying shape memory alloy actuators by stacking several layers in a compact body. However, these methods likewise tend to be bulky and heavy, since the amplification gain produced by the actuators is only proportional to the dimension of the stacked layers.

Systematic design methods have also been studied, for example, S. Canfield and M. Frecker, “Topology Optimization of Compliant Mechanical Amplifiers for Piezoelectric Actuators,” *Structural and Multidisciplinary Optimization*, 20(4), pp. 269-279, 2000, E. Silva, S. Nishiwaki, and N. Kikuchi, “Topology Optimization Design of Flextensional Actuators,” *Ultrasonics, Ferroelectrics, and Frequency Control*, IEEE Transactions on, 47(3), pp. 657-671, 2000, and G. Nader, E. Silva, and J. Adamowski, “Characterization of Novel Flextensional Transducers Designed by Using Topology Optimization Method,” *Ultrasonics Symposium*, 2001 IEEE, 2, pp. 981-984, 2001, each incorporated herein in its entirety by reference. An individual actuator, such as C-block, for example, described in A. Moskalik and D. Brei, “Quasi-Static Behavior of Individual C-Block Piezoelectric Actuators,” *Journal*

of Intelligent Material Systems and Structures, 8(7), pp. 571-587, 1997 and Moonie, for example, described in K. Onitsuka, A. Dogan, J. Tressler, Q. Xu, S.Yoshikawa and R. Newnham, "Metal-Ceramic Composite Transducer, the 'Moonie'," Journal of Intelligent Material Systems and Structures 6(4), pp. 447-455, 1995, each incorporated by reference
5 above, can be stacked in series to increase the total displacement. However, this stacking also increases the size of the overall mechanism and does not improve the strain itself, which is limited to 2-3%, e.g., by conventional flextensional mechanisms.

Therefore, there is a need for a compact actuator with larger strain that is necessary for driving a wide variety of mechatronic systems.

10

SUMMARY OF INVENTION

Accordingly, a feature of the present invention is to provide devices and methods that comprise a hierarchical cellular structure for providing strain amplification, thereby achieving strain that is significantly greater than conventional strain amplification devices and methods.
15 Another feature of the present invention is to build a modular structure that is flexible and extensible.

In accordance with an aspect of the invention, a multi-layer strain amplification device comprises at least one first amplifying layer unit including a plurality of actuators; and a second amplifying layer unit positioned about the at least one first amplifying layer unit,
20 wherein a strain of the at least one first amplifying layer unit is amplified by the second amplifying layer unit.

In an embodiment, the at least one first amplifying layer unit and the second amplifying layer unit are configured as a nested rhombus structure.

In an embodiment, the actuators are in series with and/or parallel with each other.

25 In an embodiment, an output axis of the serially-connected actuators is perpendicular to an output axis of the second amplifying layer unit.

In an embodiment, the actuators are piezoelectric actuators.

In an embodiment, the at least one first amplifying unit is positioned in a first layer of

the device, the at least one second amplifying unit strain is positioned in a second layer of the device, wherein an amplification gain of the device increases exponentially as a number of layers of the device increases.

5 In an embodiment, the device further comprises a third amplifying layer unit positioned about at least one second amplifying layer unit.

In an embodiment, the at least one first amplifying layer unit, the at least one second amplifying layer unit, and the third amplifying unit are configured as a nested rhombus structure.

10 In an embodiment, the at least one first amplifying unit is positioned in a first layer of the device, the at least one second amplifying unit strain is positioned in a second layer of the device, and the third amplifying layer is positioned in a third layer of the device, wherein an amplification gain of the device increases exponentially as a number of layers of the device increases.

15 In an embodiment, displacements of each first actuator are aggregated and transmitted through the at least one first amplifying layer unit and the second amplifying layer unit, resulting in an output displacement at the second amplifying layer unit.

In an embodiment, a displacement of the device is amplified when the at least one first amplifying unit expands in a first direction and contracts in a second direction.

In an embodiment, the first direction is perpendicular to the second direction.

20 In an embodiment, the at least one first amplifying layer unit further comprises a rhombus structure positioned about each actuator, the rhombus structure including a rigid beam and a flexible joint.

In an embodiment, a plurality of first amplifying layer units are connected in series to increase an output displacement.

25 In an embodiment, a plurality of first amplifying layer units are connected in parallel to increase an output force.

In accordance with another aspect of the invention, a method of forming a multi-layer strain amplification device comprises providing at least one first amplifying layer unit

including a plurality of actuators; and positioning a second amplifying layer unit about the at least one first amplifying layer unit to amplify a strain of the at least one first amplifying layer unit.

In an embodiment, the at least one first amplifying layer unit and the second
5 amplifying layer unit are configured as a nested rhombus structure.

In an embodiment, the actuators are positioned to be in series with and/or parallel with each other.

In an embodiment, the at least one first amplifying unit is positioned in a first layer of the device, the at least one second amplifying unit strain is positioned in a second layer of the
10 device, wherein an amplification gain of the device increases exponentially as a number of layers of the device increases.

In an embodiment, a third amplifying layer unit is positioned about at least one second amplifying layer unit.

In an embodiment, the at least one first amplifying layer unit, the at least one second
15 amplifying layer unit, and the third amplifying unit are configured as a nested rhombus structure.

In an embodiment, the at least one first amplifying unit is positioned in a first layer of the device, the at least one second amplifying unit strain is positioned in a second layer of the device, and the third amplifying layer is positioned in a third layer of the device, wherein an
20 amplification gain of the device increases exponentially as a number of layers of the device increases.

In an embodiment, a displacement of the device is amplified when the at least one first amplifying unit expands in a first direction and contracts in a second direction.

In an embodiment, a rhombus structure is positioned about each actuator, the rhombus
25 structure including a rigid beam and a flexible joint.

In accordance with another aspect, a method of amplifying strain of an actuator comprises providing at least one first amplifying layer unit having a first strain; amplifying the first strain; positioning a second amplifying layer unit about the at least one first

amplifying layer unit; and amplifying the amplified first strain.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more apparent in view of the attached drawings
5 and accompanying detailed description. The embodiments depicted herein are provided by
way of example, not by way of limitation, wherein like reference numerals refer to the same
or similar elements throughout the different views. The drawings are not necessarily to scale,
emphasis instead being placed upon illustrating aspects of the invention. In the drawings:

FIG. 1 is a chart illustrating a comparison of characteristics between PZT and other
10 actuator materials;

FIGs. 2A and 2B are perspective views of a strain amplification mechanism having
first and second positions, respectively, according to embodiments of the invention;

FIG. 3 is a schematic illustration of a strain amplification mechanism, according to
embodiments of the invention;

15 FIG. 4 is a schematic view of the strain amplification mechanism of FIG. 3 illustrating
strain amplification, according to embodiments of the invention;

FIG. 5 is a two-dimensional schematic view of a multi-layer strain amplification
device, according to embodiments of the invention;

20 FIG. 6 is a three-dimensional schematic view of a multi-layer strain amplification
device, according to embodiments of the invention;

FIG. 7 is a diagram illustrating an actuator coordinate system of a PZT stack actuator,
according to embodiments of the invention;

FIG. 8A is a graph illustrating an amplified strain produced by the multi-layer strain
amplification mechanism of FIG. 6, according to embodiments of the invention;

25 FIG. 8B is a graph illustrating a reduced blocking force of the multi-layer strain
amplification mechanism of FIG. 6, according to embodiments of the invention;

FIG. 9 is a three-dimensional view of a three-layer strain amplification device, according to embodiments of the invention;

FIG. 10 is a view of a model of an actuator unit connected to a spring load, according to embodiments of the invention;

5 FIGs. 11A and 11B are views of a rhombus illustrating the effects of joint stiffness on free-load displacement, according to embodiments of the invention;

FIGs. 12A and 12B are views of a rhombus illustrating the effects of beam compliance on a blocking force, according to embodiments of the invention;

10 FIG. 13 is a view of a structural model of a Moonie, according to embodiments of the invention;

FIG. 14A is a view of a rhombus mechanism having structural flexibilities, according to embodiments of the invention;

FIG. 14B is a view of a lumped parameter model, according to embodiments of the invention;

15 FIG. 14C is a view of a model of a rhombus mechanism with flexibility, according to embodiments of the invention;

FIG. 15 is a simplified representation of a lumped parameter model, according to embodiments of the invention;

20 FIG. 16 is an illustration of a nested rhombus model, according to embodiments of the invention;

FIG. 17 is a graph illustrating a force-displacement relationship for the nested rhombus structure shown in FIG. 16, according to embodiments of the invention;

FIG. 18 is an illustration of a compliant joint for an amplifying layer unit, according to embodiments of the invention.

25 FIG. 19 is a view of an actuator for a first amplifying layer unit, according to embodiments of the invention;

FIG. 20 is a view of a second layer rhombus structure, according to embodiments of the invention;

FIG. 21 is a graph illustrating a calculated force and displacement property of the second layer rhombus structure of FIG. 20, according to embodiments of the invention;

5 FIG. 22A is a different view of the second layer rhombus structure of FIG. 19, according to embodiments of the invention;

FIG. 22B is an illustration of an amplification device having two amplification layers;

FIGs. 22C and 22D are views of the amplification device of FIG. 22B in OFF and ON positions, according to embodiments of the invention;

10 FIG. 23 is a view of two amplification devices connected in series, and in OFF and ON positions, respectively, according to embodiments of the invention;

FIGs. 24A and 24B are graphs illustrating experimental results, including free-load displacement: step response, and blocking-force, respectively, based on sinusoidal wave input, according to embodiments of the invention;

15 FIG. 25 is a graph showing aggregate displacements when ON-OFF controls are provided to internal units, according to embodiments of the invention;

FIG. 26A is an illustration of a cellular actuator comprising six units connected in series, according to embodiments of the invention;

20 FIG. 26B is an illustration of a cellular actuator comprising six stacks connected in series and four bundles connected in parallel, according to embodiments of the invention;

FIG. 26C is an illustration of a cellular actuator comprising six stacks connected in series and seven bundles connected in parallel, according to embodiments of the invention;

FIG. 27 is an illustration of the cellular actuator of FIG. 26B reconfigured by changing connectors.

25 FIG. 28 is a perspective view of a cell stack and bundle, according to embodiments of the invention;

FIG. 29 is a perspective view of an actuator incorporating the cell stack and bundle shown in FIG. 28, according to embodiments of the invention;

FIGs. 30A and 30B are views of test equipment designed to measure free displacement and blocked force of designs, according to embodiments of the invention;

5 FIGs. 31A – 31C are views of amplification mechanisms having different structures, according to embodiments of the invention;

FIGs. 32A and 32B are views of an amplification mechanism illustrating a blocked case and a free-load case, respectively, according to embodiments of the invention;

10 FIG. 33 is an illustration of characteristics of an amplification mechanism that is connected to a spring load by a fixed beam, according to embodiments of the invention;

FIG. 34 is an illustration of a parameter estimation of a three-spring model showing parameter estimation, according to embodiments of the invention;

FIGs. 35A and 35B are views of amplification mechanisms that are constrained, according to embodiments of the invention;

15 FIG. 36 is a view of lumped parameter model and simplified equivalent model, according to embodiments of the invention;

FIG. 37 is a view of lumped parameter model and simplified equivalent model showing a plurality of amplification mechanisms coupled to each other, according to embodiments of the invention; and

20 FIGs. 38A and 38B are graph illustrating ranges of gains for positive spring constants, according to embodiments of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

Hereinafter, aspects of the present invention will be described by describing illustrative embodiments in accordance therewith, with reference to the attached drawings. While
25 describing these embodiments, detailed descriptions of well-known items, functions, or configurations are typically omitted for conciseness.

It will be understood that, although the terms first, second, etc. are used herein to describe

various elements, these elements should not be limited by these terms. These terms are used to distinguish one element from another, but not to imply a required sequence of elements. For example, a first element can be termed a second element, and, similarly, a second element can be termed a first element, without departing from the scope of the present invention. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a," "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes" and/or "including," when used herein, specify the presence of stated features, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups thereof.

To address the abovementioned limitations of the prior art, in embodiments, systems and methods are provided that increase strain amplification by exponentially amplifying displacement of a PZT stack, which is particularly useful in applications related to robotics, for example, for increasing gain in a large strain in a compact body, wherein the gain is on the order of several hundreds, in an order of magnitude greater than a gain provided by conventional strain amplification mechanisms. For example, an original strain of a PZT stack is approximately 0.1%. However, the resultant nominal strain of the multi-layer strain amplification device in accordance with embodiments of the present invention can be at least 20%, which is comparable to that of natural skeletal muscles. Thus, the large strain PZT stack actuator in accordance with embodiments of the present invention can be used in a manner similar to biological muscles that are directly attached to skeletal structures. In other embodiments, the resultant nominal strain of the multi-layer strain amplification device in accordance with embodiments of the present invention can be at least 30%.

In order to drive a large load, however, care must be taken in the design of the strain amplification structure. In an embodiment, kinematic and static analysis can be performed to address how the output force and displacement are attenuated by joint stiffness and beam compliance with regard to the strain amplification device. In an embodiment, a lumped parameter model quantifies the performance degradation and facilitates design trade-offs.

In an embodiment, devices that produce this large strain amplification are based on a hierarchical nested structure. Such devices comprise two or more layers, wherein strain is amplified α times at each layer. This structure is fundamentally different from traditional

layered structures, such as telescoping cylindrical units, for example, as disclosed in Niezrecki, C., Brei, D., Balakrishnan, S., and Moskalik, A., 2001. entitled "Piezoelectric Actuation: State of the art," The Shock and Vibration Digest, 33(4), pp. 269–280, 2001, incorporated by reference above. This structure is also different from conventional approaches, which include stacking multiple plates that are connected by actuator wires, as disclosed for example in United States Patent Number 6,574,958, incorporated by reference above.

Unlike these conventional leverage mechanisms, where the gain α is proportional to the dimensions of the layer or number of stacks, the amplification gain of the multi-layer strain amplification device based on the hierarchical nested structure described in the embodiments herein increases exponentially as the number of layers in the device increases. In an embodiment, for K layers of the hierarchical nested structure, the resultant gain is given by α^K , the power of the number of layers. Accordingly, this hierarchical nested structure includes a nested rhombus structure, wherein an actuator stack comprising piezoelectric material, for example, PZT, is formed inside of a rhombus structure such as a Moonie actuator, which is then nested inside another rhombus structure, allowing a gain a large strain in a compact body to be achieved, preferably having an effective strain of 20-30%, or greater.

The basic module of the hierarchical nested structure is an actuator unit, referred to herein as an internal unit, which, in an embodiment, is based on a Moonie mechanism, for example, R. Newnham, A. Dogan, Q. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, "Flextensional Moonie Actuators," 1993 IEEE Proceedings, Ultrasonics Symposium, vol. 1, Oct. 31-Nov. 3, 1993, pp. 509-513, incorporated by reference above. In an embodiment, the actuator unit is a piezoelectric actuator or a compact modular PZT stack actuator. In other embodiments, a plurality of modular actuator units can be connected to each other in series to increase the output displacement, or connected to each other in parallel to increase the output force, or connected as a combination of both serial and parallel to increase both displacement and output force. In this manner, an hierarchical structure can be formed, wherein one or more actuator units are enclosed within a larger amplifying layer unit structure, referred to herein as an amplification mechanism or amplifying mechanism, resulting in the amplifying layer unit having desirable diverse stroke, force, and impedance characteristics. In embodiments, these characteristics can be adjusted so that the amplifying layer unit has predetermined stroke, force, and impedance characteristics by changing the parallel and serial combinations of the actuator units. Further, in other embodiments, a plurality of first

amplifying layer units can be combined together in a hierarchical structure in serial, in parallel, or a combination of both, to form a second amplifying layer unit, resulting in greater amplification of the total displacement and/or output force. Thus, an amplifying layer unit constructed from many actuator modules according to embodiments similar to those described herein can permit new control and drive systems to implement the amplifying layer units.

As described above, an output force and displacement of an amplifying layer unit are the aggregate effects of a plurality of modular actuator units combined together in an hierarchical nested structure, illustrated for example in FIGs. 5, 6, and 9. Simple ON-OFF controls can suffice to drive individual actuator units, illustrated for example in FIGs. 2A, 2B, since the aggregate outputs will be smooth and approximately continuous if a large number of modules are involved. See Ueda, J., Odhner, L., and Asada, H., "A Broadcast-Probability Approach to the Control of Vast DOF Cellular Actuators," Proceedings of 2006 IEEE International Conference on Robotics and Automation (ICRA '06), May 15-19, 2006, pp. 1456-1461 and Ueda, J., Odhner, L., and Asada, H., "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," The International Journal of Robotics Research," 26(11-12), pp. 1251-1265, 2007, each incorporated herein in its entirety by reference. Accordingly, expensive analog drive amplifiers are not required. Moreover, ON-OFF controls are effective to overcome prominent hysteresis and nonlinearity of actuator materials, as addressed in J. Ueda, L. Odhner, S.-G. Kim, and H. Asada, "Distributed Stochastic Control of Mems-PZT Cellular Actuators with Broadcast Feedback," The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechanics (BioRob 2006), February 20-22, 2006, pp. 272-277 and J. Ueda, L. Odhner, and H. Asada, "A Broadcast-Probability Approach to the Control of Vast DOF Cellular Actuators," Proceedings of 2006 IEEE International Conference on Robotics and Automation (ICRA '06), May 15-19, 2006, pp. 1456-1461, each incorporated herein in its entirety by reference. Thus, a modular actuator unit can be used as a building block for a cellular actuator inspired by biological muscles, in which a single actuator system is synthesized by connecting numerous small actuator units in serial, in parallel, or a mixture of both.

FIGs. 2A and 2B are perspective views of an amplification mechanism 100 in first and second positions, respectively, according to embodiments of the invention. In an embodiment, the amplification mechanism 100, referred to herein as a first amplifying layer

unit, comprises an internal unit 110 and a rhombus structure 120. In an embodiment, the internal unit 110 comprises piezoelectric material known to those of ordinary skill in the art, such as PZT. In an embodiment, the internal unit 110 is a PZT stack actuator, for example, illustrated at least at FIG. 7. In an embodiment, the amplification mechanism 100 comprises
5 a Moonie mechanism similar to that described herein.

As shown in FIG. 2A, the first position can be an OFF position. As shown in FIG. 2B, the second position can be an ON position. A local control unit (not shown) can control an internal unit 110 by applying binary controls in an ON-OFF manner, which can overcome the hysteresis of the material of the internal unit 110. As shown in FIG. 2B, the rhombus
10 structure 120 is a rhombus-like hexagon that contracts vertically in the direction of 3 as the internal unit 110 expands in the direction of 2. As a result, the vertical displacement 3, that is, the output of the mechanism 100, is amplified if the angle of the oblique beams 122 relative to the horizontal axis is less than 45 degrees (θ).

In an embodiment, the amplification mechanism 100 is a first layer unit that is
15 connected to other amplification mechanisms in serial, in parallel, or a mixture of both, which are positioned in a second rhombus structure to form a hierarchical nested structure.

FIG. 3 is a schematic view of an amplification mechanism 200, according to
embodiments of the invention. As shown in FIG. 3, the amplification mechanism 200, also referred to as a first amplifying layer unit or a rhombus mechanism, comprises a rhombus
20 structure 220 comprising a plurality of rigid beams 222 that are connected together by flexible joints 221. The amplification mechanism 200 can be configured as a rhombus-like hexagon which is attached to an internal unit 110. A local control unit (not shown) can cause the internal unit 110 to expand or contract by applying binary controls in a manner similar to that described above with regard to FIG. 2B. The compliant joints 221 can therefore deform
25 as the internal unit 110 deforms. As a result, an output 3 of the amplification mechanism 200 is amplified.

FIG. 4 is a schematic illustration of the amplification mechanism of FIG. 3 illustrating how strain is amplified, according to embodiments of the invention. In an embodiment, the internal unit 110 is extensible. The following formulation is readily applied to the structure
30 with a contractive internal unit. Let h_1 , w_1 , and ε_0 be the height, width, and strain, respectively of the internal unit 110. Also let d_1 be the initial gap between the surface of the

internal unit 110 and the apex of the amplification mechanism. Assume that all the joints (not shown) are purely or freely rotational revolving and all the beams 222 are completely rigid.

Also assume that the internal unit 110 is extensible, and can be extended to a contractive case in accordance with the following formulation. In an embodiment, as the internal unit 110

5 expands, the gap d_1 contracts to d'_1 by the extension of the internal unit 110:

$$d'_1 = \sqrt{d_1^2 - (\varepsilon_0^2 + 2\varepsilon_0)w_1^2/4}. \quad (1)$$

Then, the amplification gain a_1 of the displacement is given by

$$10 \quad a_1 = \frac{2\Delta x_1}{\varepsilon_0 w_1} \quad (2)$$

where $\Delta x_1 \triangleq d_1 - d'_1$. For small ε_0 this can be approximated to:

$$a_1 = \frac{w_1}{2d_1} = \cot\theta \quad (3)$$

15 where θ is the angle of the oblique beam 222 relative to the horizontal axis. In an embodiment, the instantaneous amplification gain does not apply to large strain because of the nonlinearity in equation (1). A smaller value for the angle θ of the oblique beams 222 results in a large amplification gain. However, the angle θ needs to be carefully determined in order to avoid buckling of the beams 222. In an embodiment, this amplification gain alone
20 can increase displacement to 3-5 times larger.

In an embodiment, the initial length of the amplification mechanism is $2d_1+h_1$ along the output axis. Since the displacement created in this output direction is $2\Delta x_1$, the effective strain (ε_1) along the output axis can be defined as:

$$25 \quad \varepsilon_1 \triangleq \frac{2|\Delta x_1|}{2d_1 + h_1} \quad (4)$$

Comparing this to the input strain ε_0 yields the strain amplification defined by:

$$30 \quad \alpha_1 \triangleq \frac{\varepsilon_1}{\varepsilon_0} = a_1 \frac{w_1}{2d_1 + h_1} \quad (5)$$

where $w_1/(2d_1+h_1)$ is the ratio of the width to the height of the rhombus structure, i.e. the aspect ratio of the mechanism. In an embodiment, both the displacement amplification and the aspect ratio of the mechanism contribute to the resultant strain amplification α_1 .

5 Although the aspect ratio is not a strain amplifier, since 1) the effective strain amplification is defined to be the ratio of output displacement to the natural body length in the same direction as the output, and since 2) the direction of input strain and that of the output displacement are perpendicular to each other, the effective gain can nevertheless be amplified by the aspect ratio. Thus, increasing the aspect ratio increases the strain amplification gain α_1 . However,
10 space constraints as well as buckling of the internal unit 110, which, in an embodiment can be a PZT stack actuator, must be considered in determining the aspect ratio.

Amplification mechanisms for amplifying small displacements of PZT actuators have been developed both in macro scale, for example, described in R. Newnham, A. Dogan, Q. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, "Flextensional Moonie Actuators," 1993
15 IEEE Proceedings, Ultrasonics Symposium, vol. 1, Oct. 31-Nov. 3, 1993, pp. 509-513, incorporated by reference above, and in micro scale, for described in N. Conway, Z. Traina, and S. Kim, "A Strain Amplifying Piezoelectric MEMS Actuator," Journal of Micromechanics and Microengineering, 17(4), pp. 781-787, 2007, incorporated by reference above. In addition, conventional amplification mechanisms have been applied to commercial
20 products, for example, described Cedrat, Inc., <http://www.cedrat.com>, last downloaded on October 24, 2007, the contents of which are incorporated herein in its entirety by reference. However, embodiments of the present invention extend this technique to gain an order-of-magnitude larger strain amplification and to build a modular structure that is flexible and extensible.

25 FIG. 5 is a two-dimensional schematic view of a multi-layer strain amplification device 300 according to embodiments of the invention. The multi-layer strain amplification device 300 comprises a plurality of amplification mechanisms 322 (i.e., 322₁, 322₂...322_{NI}), also referred to as first amplifying layer units or rhombus mechanisms, which are arranged in an hierarchical structure. In an embodiment, the first amplifying layer units 322 can be
30 similar to the amplification mechanism 200 described above with regard to FIGs. 3 and 4.

A feature of the multi-layer strain amplification device 300 is that, in an embodiment,

two or more planes of rhombi in different layers may be arranged to be perpendicular to each other, as shown in FIG. 5, in order to construct three-dimensional structures with diverse configurations. Accordingly, this construction results in a gain of an order-of-magnitude larger strain amplification, as well as a modular structure that is flexible and extensible.

5 Further, in an embodiment, a three-dimensional arrangement of nested rhombus structures permits many rhombus units to be densely enclosed in a limited space, to form a “nested rhombus” strain amplifier.

In an embodiment, each first amplifying layer unit 322 amplifies the strain of an enclosed internal unit 301. In an embodiment, the internal unit 301 comprises a PZT stack
10 actuator. In an embodiment, the first amplifying layer units 322 are connected in series to increase an output displacement 304. In another embodiment, the first layer units 322 can be arranged in parallel to increase an output force. A salient feature of this hierarchical mechanism is that the first amplifying layer units 322 are enclosed within a larger structure to form a second amplifying layer unit 330 that further amplifies the total displacement 304
15 and/or output force (not shown) of the smaller first amplifying layer units 322. In an embodiment, the second amplifying layer unit 330 has a rhombus configuration. In an embodiment, a plurality of second amplifying layer units 330 (i.e., (i.e., $330_1, 322_2 \dots 322_j, 322_{N2}$), are connected together and enclosed with an even larger structure to form a third amplifying layer unit 340 to further amplify the total displacement 302. In an embodiment,
20 the third amplifying layer unit 340 has a rhombus configuration. As this enclosure and amplification process is repeated, a multi-layer strain-amplification mechanism is constructed, and the resultant displacement 302 increases exponentially. Thus, the embodiment illustrated in FIG. 5 provides an example in which a plurality of first amplifying layer units 322 are connected in series and/or in parallel and enclosed by the second
25 amplifying layer unit 330, and a plurality of second amplifying layer units 330 are connected in series and/or in parallel and enclosed by the third amplifying layer unit 340.

As described above, a unique feature of this hierarchical structure described herein is that a plurality of amplifying layer units or rhombus units can be enclosed within a larger amplifying layer unit or rhombus unit to amplify the total displacement of the smaller
30 rhombus units. A plurality of these larger amplifying layer units or rhombus units in turn can be connected together and enclosed with an even larger amplifying layer unit or rhombus unit to further amplify the total displacement. Thus, since this enclosure and amplification

procedure is repeated K times, the resultant displacement amplification increases exponentially.

This hierarchical nested structure can have a number of variations, depending on the number of the hierarchical layers and the numbers of serial and parallel units arranged in each layer. For example, let K be the number of layers of amplifying layer units, and assume that each amplifying layer unit amplified strain α times. The resultant amplification gain is given by α to the power of K :

$$\alpha_{total} = \alpha^K. \tag{6}$$

For $\alpha = 15$ the gain is $\alpha_{total} = 225$ by nesting two layers of amplifying layer units, for example, as shown in FIG. 6, and the gain is $\alpha_{total} = 3375$ by nesting three layers of amplifying units in a hierarchical configuration, for example, as shown in FIG. 9. The multi-layer strain amplification device that applies the abovementioned hierarchical nested structure is a powerful concept for gaining an order-of-magnitude large amplification of displacement. As a result, the multi-layer strain amplification device 300 shown in FIG. 5 can produce a strain that is at least 20%. This goal can be accomplished by $\alpha = 15$ and $K = 2$: $0.1\% \times 15 \times 15 = 22.5\%$. Strictly speaking, the resultant amplification gain is given by the multiplication of each gain:

$$\alpha_{total} = \prod_{k=1}^K \alpha_k. \tag{7}$$

where $\alpha_k = \frac{\Delta \epsilon_k}{\epsilon_{k-1}}$ is the k -th layer's effective gain of strain amplification computed recursively according to the following formula:

$$\epsilon_k = \frac{\sqrt{4d_k^2 - (\epsilon_{k-1}^2 + 2\epsilon_{k-1})h_k^2} - 2d_k}{2d_k + h_k} \quad (k = 1, \dots, K) \tag{8}$$

FIG. 6 is a three-dimensional schematic view of a multi-layer strain amplification device 400, according to embodiments of the invention. Another important feature of the strain amplification devices and methods of the present invention is that, as described above, two or more planes of rhombi in different layers may be arranged to be perpendicular to each other. Accordingly, in FIG. 6, the multi-layer strain amplification device 400 is formed by serially connecting a plurality of first amplifying layer units 420 to each other, each being

rotated 90 degrees about their respective output axes x_1 . The first amplifying layer units 420 each comprise at least one actuator unit 401 and a first rhombus structure 422, which is attached to the actuator unit 401. In an embodiment, the actuator unit 401 is a PZT stack actuator. This permits a second rhombus structure 430, which encloses the first amplifying layer units 420, to be more compact, since the length of the first amplifying layer unit 420 in the x_2 direction is reduced. Namely, the height of the actuator unit 401, also shown in FIG. 2 as internal unit 1 having a height h , which is a non-functional dimension for strain amplification, can be reduced. In FIG. 6, a total of two layers, $K=2$, amplify the strain of the PZT stack actuators. These size reductions permit not only packing many PZT units together densely, but also increase the effective strain along the output axis ε_1 , since h_1 is included in the denominator of equation (4) above.

In FIG. 6, six first layer rhombus units 420 are connected in series. As described above, a 3-dimensional structure plays a key role for large strain. Further, as described above, to achieve this, the serially connected units 420 are rotated 90 degrees and inserted into the second rhombus structure 430. Note that the second amplifying layer unit 430 extends in at least one of the x_3 , y_3 , and z_3 directions when in an ON state, as shown by the arrows, since the PZT stack actuators 401 are extensible and since the number of amplifying layers is 2.

20 Properties of Ideal Nested Rhombus PZT Actuators

A. Aggregate Force and Displacement

In an embodiment, displacements of the individual PZT actuators are aggregated and transmitted through multiple layers of strain amplification mechanisms, resulting in an output displacement at the final layer, for example, a final layer comprising the second amplifying layer unit 430 shown in FIG. 6, and a final layer comprising the third amplifying layer unit 540 shown in FIG. 9. Similarly, the output force is the resultant force of many PZT actuators. In this section, these aggregate force and displacement are analyzed in relation to the individual PZT actuator outputs based on an ideal kinematic and static model of the nested rhombus structure.

30 Consider the PZT stack actuator 401 described above with regard to FIG. 7. Let l_{pzt} , w_{pzt} , and h_{pzt} be the length, width, and height of the PZT stack actuator 401, respectively.

The x -axis is defined as the actuation direction. Choice of y and z axis is arbitrary. For descriptive purposes, the y axis is chosen to the direction of w_{pzt} as shown in FIG. 8.

The displacement of this PZT stack actuator 401 when no load is connected to the actuator 401 is given by

$$\Delta x_{pzt} = N_{film} \cdot d_{33} \cdot V, \quad (9)$$

where N_{film} is the number of PZT films along the actuation direction, d_{33} is a piezoelectric coefficient, and V (>0) is a voltage applied to each PZT film. In an embodiment, the piezoelectric coefficient d_{33} is not a constant, according to A. Mezheritsky, "Invariants of Electromechanical Coupling Coefficients in Piezoceramics," Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on, 50(12) pp. 1742-1751, 2003, incorporated herein by reference in its entirety, but may vary significantly as strain gets larger. In this example, however, it is assumed to be constant. The inherent stiffness of the PZT stack actuator 401 is give by

$$k_{pzt} = \frac{E_{pzt} h_{pzt} w_{pzt}}{l_{pzt}}, \quad (10)$$

where E_{pzt} is the elastic modulus of PZT material.

The no-load displacement given by equation (9) results from the balance between the net force produced by the PZT f_{pzt} and the restoring force due to the stiffness k_{pzt} , which is proportional to Δx_{pzt} . Unlike standard electromagnetic actuators, e.g. DC and AC motors, PZT and other actuator materials cannot produce force independent of its displacement. Due to its inherent structural stiffness, the net output force of these actuator materials is substantially lower when producing a displacement at the same time.

Consider the following force-displacement relationship, the force generated by the PZT stack actuator 401 while producing displacement Δx_{pzt} is given by

$$f_{pzt} = k_{pzt} (\beta V - \Delta x_{pzt}) \quad (11)$$

where $\beta = N_{film} d_{33}$. As this PZT stack is imbedded in a first amplifying layer unit, the force is reduced to $1/a_1$ and the displacement is amplified a_1 times. Assuming that the first amplifying layer unit is loss-less and that the beams are completely rigid and are connected with freejoints, the force-displacement relationship at the output axis of the first amplifying

layer unit is given by

$$f_1 = \frac{f_{pzt}}{a_1} = \frac{k_{pzt}}{a_1} \beta V - \frac{k_{pzt}}{(a_1)^2} \Delta x_1 \quad (12)$$

In an embodiment, the equivalent stiffness of the PZT stack viewed from the output side of the rhombus mechanism is attenuated by a factor of $1/(a_1)^2$.

5 In an embodiment, where N_1 units of the first amplifying layer unit are connected in series and enclosed in a rhombus structure to form a second amplifying layer unit, each unit is numbered from 1 to N_1 . Parallel connections in a given layer are not considered since they may form a closed kinematic chain for ideal rhombus mechanisms; thus, solving the kinematic chain problem is not essential. Let V^i , f_1^i , and Δx_1^i ($i = 1, \dots, N_1$), respectively, is
 10 the voltage, force, and displacement, respectively, of the i -th unit in the serial connection of the first layers. The force is common to all the N_1 units:

$$f_1^1 = f_1^2 = \dots = f_1^{N_1} = f_1^{com} \quad (13)$$

From (12), we have

$$\frac{k_{PZT}}{a_1} \beta V^i - \frac{k_{PZT}}{(a_1)^2} \Delta x_1^i = f_1^{com}, \quad (i = 1, \dots, N_1). \quad (14)$$

15 In an embodiment, where the second amplifying layer unit amplifies displacement and attenuates force a_2 times, the resultant displacement at this layer is given by

$$\Delta x_1^1 + \dots + \Delta x_1^{N_1} = \frac{\Delta x_2}{a_2}. \quad (15)$$

20 From (14) and (15), the relationship between the output force and displacement for the second layer is given by

$$f_2 = \frac{f_1^{com}}{a_2} = \frac{\beta k_{pzt}}{N_1 a_1 a_2} \sum_{i=1}^{N_1} V^i - \frac{k_{pzt}}{N_1 (a_1)^2 (a_2)^2} \Delta x_2. \quad (16)$$

Repeating the same process yields the relationship between the aggregate displacement and
 25 force along the K -th layer output axis:

$$f_K = \frac{\beta_{k_{pzt}}}{\prod_{k=1}^K \alpha_k} \cdot \frac{1}{\prod_{k=1}^{K-1} N_k} \sum_1^{N_{K-1}} \dots \sum_1^{N_2} \sum_1^{N_1} V^{i,j,\dots} - \frac{k_{pzt}}{\prod_{k=1}^{K-1} N_k \prod_{k=1}^K (\alpha_k)^2} \Delta x_K \quad (17)$$

A total of $N_{K-1} \cdot N_{K-2} \dots N_1$ PZT actuator units are included in the system, and $V^{i,j}$ in the above equation represents the voltage applied to the each PZT unit. See, for example, FIG. 5 for $K=3$ where $V^{i,j}$ is applied to the i -th internal unit in the first player involved in the j -th unit ($j = 1, \dots, N_2$) of the second layer. This process can be repeated as many times needed to attain desired results.

From the above results it is noted that:

1. Given applied voltages, the maximum of the aggregate displacement is obtained when no force is generated, i.e. free load. This aggregate free-load displacement Δx_3^{free} is

proportional to the total sum of the inputs $\sum_1^{N_{K-1}} \dots \sum_1^{N_2} \sum_1^{N_1} V^{i,j,\dots}$ amplified by a factor of $\prod_{k=1}^K \alpha_k$,

2. The maximum of the aggregate force is obtained when the output displacement is totally blocked. This aggregate blocking force f_K^{block} is proportional to the average of the entire inputs:

$$\frac{1}{\prod_{k=1}^{K-1} N_k} \sum_1^{N_{K-1}} \dots \sum_1^{N_2} \sum_1^{N_1} V^{i,j,\dots} \quad (18)$$

If the total number of PZT actuators is large, the individual PZT stack actuators can be driven with simple ON-OFF controls, for example, described in Ueda, J., Odhner, L., and Asada, H., "A Broadcast-Probability Approach to the Control of Vast DOF Cellular Actuators," Proceedings of 2006 IEEE International Conference on Robotics and Automation (ICRA '06), May 15-19, 2006, pp. 1456-1461 and Ueda, J., Odhner, L., and Asada, H., "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," The International Journal of Robotics Research," 26(11-12), pp. 1251-1265, 2007, each incorporated herein in its entirety by reference, since the net effect upon the output displacement and force is the summation and average of many PZT actuators. Expensive

analog drivers and controllers are unnecessary for the cellular actuators. As the number of PZT actuator cells increases, discretization error becomes small and smooth output displacement and force can be expected.

B. Feasibility Check for at least 20% Strain

5 As described above, with regard to FIG. 6, six first-layer actuator units 420 are connected in series. Further, as described above, a three-dimensional structure, as shown in FIG. 6, is important for generating large strain. In an embodiment, the serially-connected first amplifying layer units 420 can be rotated 90 degrees and inserted into the second rhombus structure 430. Accordingly, the second rhombus structure 430 extends when the
10 PZT actuators are turned on since they are extensible and the number of amplifying layers is two.

In an embodiment, to achieve a strain of 23.9%, a size of each actuator unit 401 is approximately 12.8 mm (l_{pzt} shown in FIG. 7) x 9 mm (w_{pzt} shown in FIG. 7) x 2.5 mm (h_{pzt} shown in FIG. 7). In an embodiment, an initial gap d_1 between the surface of the PZT stack actuator 401 and the apex of a rhombus structure 422 of the first amplifying layer unit 420 is approximately 1.1 mm. Further, typical values of PZT-ceramics for Young's modulus and strain can be applied, i.e., $E_{pzt} = 36.6$ GPa and $\varepsilon_{pzt} (= \varepsilon_0) = 0.1\%$, respectively. In an
15 embodiment, these dimensional parameters are determined according to commercially available PZT actuators, for example, Cedrat APA50XS, as being a first layer unit. In an
20 embodiment, the size of the multi-layer strain amplification device 400 shown in FIG. 6 is 12.0 mm x 28.2 mm x 12.8 mm.

As shown in FIG. 8A, a typical value of PZT ceramics for strain is 0.1 %. However, by performing iterative calculations by applying equations (12)-(16) above, the amplified strain and reduced blocking force are obtained as shown in FIGs. 8A and 8B. In particular,
25 the prospective displacement is 2.8mm for an actuator length of 12mm, which is equivalent to $\varepsilon_2 = 23.9\%$. Thus, over 20% strain is achieved by the amplification device.

Furthermore, it should be noted that diverse configurations can be built simply by changing the serial and parallel arrangements of the same building blocks. This modular design is a powerful method for building diverse actuators with matched load impedance and
30 stroke and force requirements. As a result, as shown in FIG. 8A, the multi-layer strain

amplification device 400 can produce an amplified strain ϵ_2 of at least 20% (specifically, 23.9%) as compared to the strain ϵ_{pzt} of PZT stack actuator 401 (0.1%) and the strain ϵ_1 of a first amplifying layer unit 420. In addition, as shown in FIG. 8B, the multi-layer strain amplification device 400 can produce a lower blocking force f_2^{block} of 15.1N as compared to
 5 the blocking force f_{pzt}^{block} of PZT stack actuator 401 and the blocking force f_1^{block} of a first amplifying layer unit 422.

FIG. 9 is a three-dimensional view of a three-layer strain amplification device 500, according to embodiments of the invention. In FIG. 9, the three-layer strain amplification device 500 is formed by serially connecting a plurality of first amplifying layer units 520 to each other, each first amplifying layer units 520 comprising an actuator unit 501 and a first
 10 rhombus structure 522. A second rhombus structure 530 is positioned about the first amplifying layer units 520 to form a second amplifying unit. A third rhombus structure 540 is positioned about a plurality of second amplifying layer units to form the three-layer strain amplification device 500, which, in an embodiment, has a strain of at least 30%.

15 Effects of Joint Stiffness and Beam Compliance

As described above, a nested Rhombus PZT actuator can produce an effective strain of at least 20% and a blocking force of approximately 15N. In an embodiment, these parameters are based on an ideal kinematic model having rigid beams and free joints at the strain amplification mechanism. Actual mechanisms, however, have some compliance in the
 20 structure, which may degrade the aggregate force and displacement. For example, intricate interplays between the structural stiffness and the inherent stiffness of the actuator units, for example, PZT stack actuators, can exist in the mechanism. Thus, in an embodiment, the nested strain amplification mechanism can be configured to minimize this adverse effect.

FIG. 10 is a diagram illustrating a model of an actuator unit 701 connected to a spring
 25 load 750, according to embodiments of the invention. In an embodiment, the model shown in FIG. 10 demonstrates the potential of a multi-layer strain amplification device, for example, the device shown in FIG. 6, to produce an effective strain of 20% with a blocking force of 15 N. Let k_{load} be a spring constant of the load 750, and Δx_{pzt} be the displacement of the load 750. The following equations hold:

$$f_{pzt} = (k_{load} + k_{pzt})\Delta x_{pzt} \quad (19)$$

$$f = k_{load}\Delta x_{pzt}, \quad (20)$$

5 where f is the output force applied to the load. The free-load displacement Δx_{pzt}^{free} is calculated by letting $k_{load} = 0$.

Eliminating Δx_{pzt} yields

$$f = \frac{k_{load}}{k_{pzt} + k_{load}} f_{pzt} \quad (21)$$

10 Note that the output force f becomes significantly lower than the original PZT force f_{pzt} when k_{pzt} increases the load stiffness k_{load} is reduced. Similarly, the output displacement Δx_{pzt} , too, gets attenuated:

$$\Delta x_{pzt} = \frac{k_{pzt}}{k_{pzt} + k_{load}} \Delta x_{pzt}^{free} \quad (22)$$

15 The simple model described above shows that both output force and displacement are attenuated due to the compliance of the connected load as well as the stiffness of the PZT itself. When this PZT stack actuator 701 is connected to a multi-layer strain amplification device, an external load 750 having properties similar to the above k_{load} and k_{pzt} will be imposed on the PZT stack actuator 701. As many layers of the amplification device are
 20 attached to the PZT stack actuator 701, these structural effects will be even more prominent. In the ideal mechanism, for example, shown in FIG. 4, it is assumed that the four beams 722 of the rhombus-type structure 720 are completely rigid and that all the joints are free to rotate and purely revolving. However, these assumptions do not hold in real structures.

Further, fabrication of free joints is difficult in small scale due to mechanical tolerance and play. For the first and second layers of the multi-layer strain amplification device, in particular, where the displacement is extremely small, the displacement created by the PZT is likely to diminish due to the play at the joints. Therefore, flexural pivots and flexible beams, such as those described in N. Conway, and S. Kim, "Large-strain, piezo-electric, in-plane, micro-actuator," 17th IEEE International Conference on Micro Electro Mechanical Systems (IEEEEM MEMS), pp. 454-457, 2004, N. Conway, and S. Kim, and Z. Traina, "A Strain Amplifying Piezoelectric MEMS Actuator," Journal of Micromechanics and Microengineering, 17(4), pp. 781-787, 2007, Cedrat, Inc., <http://www.cedrat.com/>, and P. Jenker, M. Christmann, F. Hermle, T. Lorkowski, and S. Storm, Mechatronics Using Piezoelectric Actuators," Journal of the European Ceramics Society, 19(6), pp. 1127-1131, 1999, each incorporated herein in its entirety by reference, have been used for amplifying PZT displacement. FIG. 3 shows an example embodiment of a rhombus mechanism. However, these flexural joints and beams inevitably bring undesirable properties to the multi-layer strain amplification device. There are three types of undesirable properties:

First, the joints are no longer free joints, but they impose a spring load that a PZT has to overcome. FIGs. 11A and 11B are illustrative views of a rhombus illustrating this parasitic effect of joint stiffness on free-load displacement, according to embodiments of the invention. In particular, FIG. 11A is an illustration of an ideal rhombus 720a comprising rigid beams and free joints 721a. FIG. 11B is an illustration of a rhombus 720b comprising rigid beams and elastic joints 721b. Accordingly, some fraction of the PZT force is wasted for coping with the joint stiffness. This results in, for example, a reduction in free-load displacement, as indicated in the difference between gap d shown in FIG. 11A and gap d' shown in FIG. 11B. This implies that the joint stiffness has an equivalent effect to that of the PZT stiffness k_{pzt} in FIG. 10. The stiffness of the joints results in a corresponding increased stiffness k_{pzt} for the PZT to overcome.

Second, flexibility at the beams may attenuate the displacement and force created by the PZT. Consider the case where the output displacement is blocked, as shown in FIGs. 12A and 12B. As the PZT generates a displacement, the beams 722b of the rhombus 720d shown in FIG. 12B are deformed and thereby the transmitted force becomes lower; at least it does not reach the same level as that of the rigid beams 722a of the rhombus 720c shown in FIG. 12A. Similarly, if the output axis is coupled to another compliant load, the output force and

displacement will be prorated between the load compliance and the beam compliance. As the beam stiffness becomes lower, the output force and displacement decrease.

Third, flexural joints not only create pure rotational displacements but also often cause unwanted translational displacements. These elastic deformations at the joint along the direction of the beam incur the same problem as the beam compliance; the force and displacement created by the PZT tend to diminish at the joints.

It is important to distinguish two different types of compliance in the above cases. The first type of compliance occurs in the constrained space of the ideal rhombus mechanism. The second type of compliance occurs in a kinematically admissible space of the ideal rhombus mechanism. The joint stiffness described above with regard to the first property is in the admissible motion space, while the second and third properties are in the constrained space. As shown in FIG. 13, curved beams, such as those provided in Moonies, contain compliance in both constrained and admissible spaces. The distributed compliance can be approximated into the two types of lumped compliant elements. To minimize the adverse effects of the nested rhombus structure, the stiffness in the admissible space must be minimized and the stiffness in the constrained space must be maximized. Accordingly, as multiple layers of strain amplification devices can be used, the compliances in the admissible and constrained spaces become more intricate.

In the following sections, the kinematic and static characteristics of multi-layer compliant rhombus mechanisms will be analyzed.

Nested Rhombus Mechanisms with Structure Flexibility

A. Modeling of Single-Layer Flexible Rhombus Mechanisms

FIG. 14A illustrates a rhombus structure 720 of an amplification mechanism 700 that is connected to a spring load 750. In an embodiment, the rhombus structure 720 comprises at least one Moonie. Here, only the static case is considered and the effect of the distribution of mass and damper is neglected. In FIG. 14A, k_{load} is elastic modulus of the load and k_{pzt} is the elastic modulus of the internal unit 701, for example, a PZT stack actuator, Δx_{pzt} is the displacement of the internal unit 701, f_{pzt} is the force applied to the amplification mechanism 700 from the internal unit 701, f_1 is the force applied to the load from the actuator, and Δx_1 is

the displacement of the load. In an embodiment, the internal unit 701 is extensible.

In an embodiment, the rhombus strain amplification mechanism 700 is a two-port compliance element, whose constitutive law is given by a 2x2 stiffness matrix defined as:

$$\begin{bmatrix} f_I \\ f_O \end{bmatrix} = S \begin{bmatrix} \Delta x_{PZT} \\ \Delta x_1 \end{bmatrix} \quad (23)$$

5

where $S^{2 \times 2} = \begin{bmatrix} s_1 & s_3 \\ s_3 & s_2 \end{bmatrix}$ is a stiffness matrix, f_I is the net force applied to the mechanism 700 from the internal unit 701, and f_O is the reaction force from the external load 750. The stiffness matrix S is non-singular, symmetric, and positive-definite; $s_1 > 0$, $s_2 > 0$ and $s_1 s_2 - s_3^2 > 0$.

10 The symmetric nature of the stiffness matrix follows Castigliano's theorems. When the input port of this mechanism is connected to a PZT stack actuator producing force f_{PZT} with inherent stiffness k_{PZT} and the output port is connected to a load of stiffness k_{load} , we have

$$f_I = f_{PZT} - k_{PZT} \Delta x_{PZT} = s_1 \Delta x_{PZT} + s_3 \Delta x_1 \quad (24)$$

$$f_O = -f_I = -k_{load} \Delta x_1 = s_3 \Delta x_{PZT} + s_2 \Delta x_1 \quad (25)$$

15 Eliminating Δx_{PZT} from the above equations yields:

$$f_{PZT} = - \left(\frac{k_{PZT} + s_1}{s_3} k_{load} + \frac{s_2(k_{PZT} + s_1) - s_3^2}{s_3} \right) \Delta x_1 \quad (26)$$

Defining:

$$\tilde{f} \triangleq \frac{-s_3}{k_{PZT} + s_1} f_{PZT} \quad (27)$$

$$20 \quad \tilde{k} \triangleq \frac{s_2(k_{PZT} + s_1) - s_3^2}{k_{PZT} + s_1} = \frac{s_2 k_{PZT} + \det S}{k_{PZT} + s_1} > 0, \quad (28)$$

The above equation (26) reduces to

$$\tilde{f} = (k_{load} + \tilde{k}) \Delta x_1 \quad (29)$$

25

Force \tilde{f} and stiffness \tilde{k} represent the effective PZT force and the resultant stiffness of the PZT stack all viewed from the output port of the amplification mechanism 700.

A drawback with the above two-port model representation is that it is hard to gain physical insights as to which elements degrade actuator performance and how to improve it through design. In the previous section two distinct compliances were introduced, one in the admissible motion space and the other in the constrained space. To improve performance with respect to output force and displacement, the stiffness in the admissible motion space must be minimized, while the one in the constrained space must be maximized. To manifest these structural compliances, consider a lumped parameter model 720' shown in FIG. 14B with three spring elements, k_J , k_{BI} and k_{BO} , and one amplification leverage a . As the spring constants, k_{BI} and k_{BO} , tend to infinity, the system reduces to the one consisting of all rigid links, where the output Δx_1 is directly proportional to the input displacement Δx_{pzt} . Stiffness k_J impedes this rigid body motion, representing the stiffness in the admissible motion space. Elastic deformation at k_{BI} and k_{BO} represent deviation from the rigid body motion.

From Figure 14B,

$$f_{pzt} + k_{BI}(\Delta x_c - \Delta x_{pzt}) - k_{pzt}\Delta x_{pzt} = 0 \quad (30)$$

$$a \cdot k_{BO}(a \cdot \Delta x_c - \Delta x_1) + k_J \Delta x_c + k_{BI}(\Delta x_c - \Delta x_{pzt}) = 0 \quad (31)$$

$$f_1 = k_{load}\Delta x_1 = k_{BO}(a \cdot \Delta x_c - \Delta x_1) \quad (32)$$

where Δx_c is the displacement at the connecting point between the leverage and springs; however this point is virtual and Δx_c does not correspond to a physical displacement. This model is applicable to a wide variety of "rhombus-type" amplification mechanisms including Moonies.

Consider the blocking force when the PZT stack actuator 701 generates its maximum force, $f_{pzt \max}$, given as follows:

$$f_1^{block} = \frac{ak_{BI}k_{BO}}{(a^2k_{BI}k_{BO} + k_{BI}k_J) + k_{pzt}(a^2k_{BO} + k_J + k_{BI})} f_{pzt \max} \quad (33)$$

Similarly, the free-load displacement for this rhombus mechanism, where $k_{load} \rightarrow 0$, is given by

$$\Delta x_1^{free} = \frac{ak_{BI}}{k_{pzt}(k_{BI} + k_J) + k_Jk_{BI}} f_{pzt \max} \quad (34)$$

As addressed above, these equations imply that the blocking force will be maximized by $k_{BI}, k_{BO} \rightarrow \infty$. Similarly, $k_J \rightarrow 0$ maximizes Δx_1^{free} .

The other advantage is that the three-spring model is able to represent the ideal rhombus shown in FIG. 12A as a special case 720'' as shown in FIG. 14C. See equation (47) to confirm that the stiffness matrix S cannot be defined for both $k_{BI}, k_{BO} \rightarrow \infty$ and $k_J \rightarrow 0$. As described in below, the four unknown parameters occur as the rigid amplification leverage is explicitly included, which makes the calibration problem ill-posed. However, this amplification leverage is necessary to include the ideal case. In addition, three lumped springs are considered minimum to satisfy the input-output bidirectionality, which is a basic requirement of Castigliano's theorems described herein.

B. Model Simplification

From equations (30) to (32), the relationship between f_{pzt} and Δx_1 is given by

$$\begin{aligned} (a k_{BI} k_{BO}) f_{pzt} = & \\ & [k_{load} \{a^2 k_{BI} k_{BO} + k_{BI} k_J + k_{pzt} (a^2 k_{BO} + k_J + k_{BI})\} \\ & + k_{BO} (k_{BI} k_J + k_{pzt} k_J + k_{BI} k_{pzt})] \Delta x_1. \end{aligned} \quad (35)$$

The above equation can be written as

$$\tilde{f}_1 = (k_{load} + \tilde{k}_1) \Delta x_1 \quad (36)$$

where

$$\tilde{k}_1 \triangleq \frac{k_{BO} (k_{BI} k_J + k_{pzt} k_J + k_{BI} k_{pzt})}{(a^2 k_{BI} k_{BO} + k_{BI} k_J) + k_{pzt} (a^2 k_{BO} + k_J + k_{BI})} \quad (37)$$

$$\tilde{f}_1 \triangleq \frac{a k_{BI} k_{BO}}{(a^2 k_{BI} k_{BO} + k_{BI} k_J) + k_{pzt} (a^2 k_{BO} + k_J + k_{BI})} f_{pzt} \quad (38)$$

This implies that the proposed lumped parameter model shown in FIG. 14B can be further simplified in the model 720''' shown in FIG. 15. Note that the direction of \tilde{f}_1 is opposite to f_{pzt} due to the amplification leverage. This simplified model has a similar form as in equation (29) above. As described in the following section, this simplification enables performance evaluation for complex nested mechanisms simply by nesting a simplified model of lower layers into a lumped parameter model. As a result, the performance of the overall mechanism such as aggregate displacement and force can be predicted in a recursive manner.

In another embodiment, a free-load displacement with known k_{pzt} can be determined as follows to calculate for f_{pzt} and x_1 :

$$f_{pzt} = \frac{k_{PZT} (k_{BI} + k_J) + k_J k_{BI}}{a k_{BI}} x_1 \quad (39)$$

$$x_1 = \frac{ak_{BI}}{k_{PZT}(k_{BI} + k_J) + k_J k_{BI}} f_{pzt} \tag{40}$$

5 C. Recursive Formula of Aggregate Force and Displacement of Flexible Nested Mechanisms

The following describes a recursive formula to obtain an equivalent model for a general nested mechanism. FIG. 16 is a multi-layer strain amplification device 800 having a nested rhombus structure in accordance with embodiments of the invention. As addressed in the previous sections, each nested layer 810, 820, 830 can be represented by its equivalent model, for example, equivalent model 840, where the force-displacement property for the nested structure can be represented in an iterative manner. Let K be the number of nesting layers. Also, let k_{Jk} , k_{BIk} , k_{BOk} , N_k be the joint compliance, beam compliances, and the number of serial connection for the k -th ($k = 1, \dots, K$) layer. This mechanism involves $N_{K-1} \cdot N_{K-2} \dots N_1$ PZT stack actuators. N_2 refers to a plurality of serially connected internal units or stack actuators 825. N_3 refers to a plurality of serially connected internal units or stack actuators 835. By applying equations (37) and (38), the equivalent model for the k -th layer can be represented by

$$\tilde{k}_k = \frac{k_{BOk}(k_{BIk}k_{Jk} + \frac{\tilde{k}_{k-1}}{N_{k-1}}k_{Jk} + k_{BIk}k_{PZT})}{(a_k^2 k_{BIk}k_{BOk} + k_{BIk}k_{Jk}) + \frac{\tilde{k}_{k-1}}{N_{k-1}}(a_k^2 k_{BOk} + k_{Jk} + k_{BIk})} \tag{41}$$

$$\tilde{f}_k = \frac{a_k k_{BIk} k_{BOk}}{(a_k^2 k_{BIk} k_{BOk} + k_{BIk} k_{Jk}) + \frac{\tilde{k}_{k-1}}{N_{k-1}}(a_k^2 k_{BOk} + k_{Jk} + k_{BIk})} \times \frac{1}{N_{k-1}} \sum_{i=1}^{N_{k-1}} \tilde{f}_{k-1}^i, \tag{42}$$

where \tilde{f}_{k-1}^i is the equivalent force of the i -th unit in the $(k-1)$ -th layer. Recall that \tilde{f}_k is proportional to the average of the entire forces at the $(k-1)$ -th layer as described above in equation (18). Assume that all actuators in the $(k-1)$ -th layer are controlled in a binary manner, i.e.,

$$V_{k-1}^i = \begin{cases} V_{\max} & ON \\ 0 & OFF \end{cases} \quad (43)$$

Also assume that all units are uniform and each unit generates \tilde{f}_{k-1}^{block} as its blocking force. Therefore, when n units out of N_{k-1} actuators are ON, the last term of equation (42) can be replaced as

$$\frac{1}{N_{k-1}} \sum_{i=1}^{N_{k-1}} \tilde{f}_{k-1}^i \dots = \frac{n}{N_{k-1}} \tilde{f}_{k-1}^{block} \quad (44)$$

In an embodiment, the free-load displacement changes accordingly. In an embodiment, both the aggregate free-load displacement and the blocking force are proportional to the number of ON units.

Accordingly, as shown in FIG. 17, a force-displacement relationship is provided when N cells are in an ON position.

Mechanical Design of Amplification mechanism

In an embodiment, a nested actuator with over 20% effective strain can be designed based on the structural compliance analysis above. Consider a nested structure with two amplification layers as described above with regard to FIG. 6. In an embodiment, the actuator 920 shown in FIG. 19 can be a prototype nested actuator, for example, a Cedrat APA50XS Moonie piezoelectric actuator, which can be used in a first amplifying layer unit such as the first amplifying layer unit described in FIG. 3. According to the preliminary design described above, over 20% of effective strain can be obtained by a two-layer mechanism; $K = 2$ and $\alpha = 15$. By stacking 6 APA50XS actuators for the first layer, i.e., $N_1 = 6$, this large strain may be achieved with a proper design of the second layer. From Table 1, we have $\tilde{k}_1 = 0.225 \times 10^6$ N/m, and $\tilde{f}_1^{block} = 18.0$ N for the first layer units. The remainder of this section focuses on the design of the second-layer rhombus mechanism.

From equations (39) and (40) we obtain an equivalent model for the second layer by substituting equations (37) and (38), which provide a design guideline in terms of k_{B12} , k_{BO2} and k_{J2} for the target effective strain, i.e., 20%.

FIG. 18 is an illustration of a compliant joint 921 for an amplifying layer unit, according to embodiments of the invention. As described above, the stiffness in the admissible space, i.e., k_{J2} , must be minimized. The rotational stiffness of this structure is

given by $k_{\phi} = \frac{Eb_Jh_J^3}{12L_J}$

5 where E is Young's modulus of the material. In order to reduce this stiffness, either the width b_J or thickness h_J must be reduced, or length of the gap L_J must be increased. Note that the reduction of h_J is the most effective for reducing k_{J2} since it is proportional to h_{3J} . However, the thickness must be carefully determined considering manufacturing process. The maximum stress must be lower than the yield stress of material. In addition, in order to
 10 increase the stiffness in the constrained space, i.e., k_{B12} and k_{BO2} , the oblique beam need to have a sufficient thickness except the thin part for the compliant joint 921.

In an embodiment, the actuator 920 shown in FIG. 19 can be a prototype nested actuator, for example, a Cedrat APA50XS Moonie piezoelectric actuator, which can be used in a first amplifying layer unit such as the first amplifying layer unit described in FIG. 3.

15 Table 1 below includes characteristics of the Cedrat APA50XS Actuator, described above, details of which can be found at www.cedrat.com, last downloaded on October 24, 2007, incorporated by reference above. The results shown in Table 1 can be modified as a result of incorporating embodiments of the invention described herein.

Displacement	80 μ m
Blocking Force \tilde{f}_1^{block}	18.0 N
Stiffness \tilde{k}	0.225 N/ μ m
Voltage range	-20 – 150 V
Length (output actuation direction)	4.7 mm
Width (pzt stack actuation direction)	12.8 mm
Height	9.0 mm
Mass	2.0 g

20

Table 1

FIG. 20 is an illustration of a second layer rhombus structure 930, according to

embodiments of the invention. In an embodiment, the structural parameters for the second layer rhombus structure 930 are obtained as $k_{J2} = 0.0402 \text{ N}/\mu\text{m}$, $k_{B2} = 0.051 \text{ N}/\mu\text{m}$, and $a_2 = 11.23$. The second layer rhombus structure 930 also includes joint 921 similar to the joint shown in FIG. 18 having dimensions including a length (l) and height (h). In an embodiment, the second layer rhombus structure 930 shown in FIG. 20 can have a length (l) of approximately 30mm and a height (h) of approximately 12mm. In an embodiment, the minimum thickness h_J of joint 931 is approximately 0.1mm for electrical discharging. In an embodiment, a length L_J of the joint 931 between beams 932 is approximately 3.5mm. In an embodiment, the oblique beams 932 have a thickness of approximately 1.3mm for sufficient stiffness. In an embodiment, the oblique angle of the beams 932 is approximately 4.97 degrees that gives the displacement amplification ratio of approximately 11.5 assuming the mechanism is ideal.

In an embodiment, the parameters for the lumped parameter model are therefore calculated using the calibration method described herein as $\hat{k}_{B\Omega} = 6.72 \times 10^6 \text{ N/m}$, $\hat{k}_{BO2} = 5.21 \times 10^4 \text{ N/m}$, $\hat{k}_{B\Omega} = 3.98 \times 10^4 \text{ N/m}$ by determining the amplification gain as $\hat{a}_2 = 11.4$.

FIG. 21 is a graph illustrating a calculated force and displacement property of the second layer rhombus structure of FIG. 20, according to embodiments of the invention. The analysis herein predicts that the maximum free-load displacement is 2.64mm, which is equivalent to 22% effective strain.

20 Development and Performance Evaluation

FIG. 22A is an illustration of a second layer rhombus structure 930, according to embodiments of the invention. FIG. 22B is an illustration of an amplification device 900 having two amplification layers, wherein one of the amplification layers comprises the second layer rhombus structure 930 of FIG. 22A, according to embodiments of the invention. In particular, FIG. 22A shows a second layer rhombus structure 930, which can be configured as part of a second layer of a multi-layer strain amplification device, such as the assembled multi-layer strain amplification device 900 shown in FIG. 22B. The serially connected first layer units 920, which amplify the strain of PZT stack actuators 901 powered from the wires 905, are rotated 90 degrees and inserted into the second layer rhombus structure 930. In an embodiment, the second layer rhombus structure 930 weighs approximately 3g. In another

embodiment, the device 900 weighs approximately 15g. In an embodiment, phosphor bronze (C54400, H08) is applied for material used to form the device 900. FIGs. 22C and 22D are views of the second layer rhombus structure of FIG. 22A in OFF and ON positions, according to embodiments of the invention.

5 FIG. 23 is a view of two amplification mechanisms 1000 connected in series, and in OFF and ON positions, respectively, according to embodiments of the invention. In an embodiment, the amplification mechanisms 1000 are configured as an actuator, wherein the actuator extends when first layer units 1020 of the amplification mechanisms 1000 are in a contractive state.

10 The performance of an actuator, such as the actuators shown in FIGs. 22B and 23, can be evaluated by measuring free-load displacement and blocking force. FIG. 24A shows the maximum free-load displacement measured using a laser displacement sensor, for example, a Micro-Epsilon optoNCDT 1401 sensor, when all six first layer units are ON by applying 150V actuation voltage. The measured displacement is 2.49mm that is equivalent to 20.8% effective strain. FIG. 24B shows the blocking force where a sinusoidal wave input ranging from 0 – 150V is applied. The maximum blocking force measured using a compact load cell (Transducer Techniques MLP) is 1.7N. As shown in FIG. 24A and 24B, the estimated values by using the lumped parameter model agree well with the experiment, which confirms the validity of the approach taken in accordance with embodiments described herein.

20 FIG. 25 is a graph showing aggregate displacements when ON-OFF controls are provided to six internal units by applying a constant actuation voltage when ON, in accordance with embodiments of the invention. For convenience, the measured displacements are normalized by the maximum displacement when all six units are turned on. As described in herein, the distribution of the ON units in a layer does not theoretically affect on the aggregate displacement if an amplification mechanism encloses serially-connected internal units. As shown in FIG. 25, the measured displacement is not largely affected by the combination of ON units. For example, there are twenty ($=_6C_3$) combinations when the number of ON units is three; however, the standard variation is at most 0.007, showing a sufficient repeatability. Another observation is that the increment of the displacement is not uniform, which is considered due to the nonlinearity of equation (1). In the preliminary kinematic analysis described above, this issue is not discussed for simplicity. However, this characteristic should be further reflected to the design and control if rhombus mechanisms are

used for creating large strain.

The comparison between FIG. 8 and FIG. 21 suggests that the aggregated force has been considerably attenuated, while the aggregated displacement or strain is as large as predicted by the idealized analysis. One of the difficulties in mechanical design is that physical structural parameters are intricately related to lumped parameters. For example, the increase of the gap L_J in FIG. 18 contributes to reducing the joint stiffness but it also reduces the beam stiffness by having a long thin gap in the longitudinal direction. This gap may be reduced if the design focus is more on producing a larger blocking force.

Modular Design of Cellular Actuators

In accordance with embodiments of the present invention, an architecture for robot actuators is provided that is inspired by the muscle behavior, which in turn has the potential to be a novel approach to controlling of a vast number of cellular units, for example, described in J. Ueda, L. Odhner, and H. Asada, "A broadcast-probability approach to the control of vast dof cellular actuators," Proceedings of 2006 IEEE International Conference on Robotics and Automation (ICRA '06), May 15-19, 2006, pp. 1456-1461, Ueda, J., Odhner, L., and Asada, H., "Broadcast Feedback of Stochastic Cellular Actuators Inspired by Biological Muscle Control," The International Journal of Robotics Research," 26(11-12), pp. 1251-1265, 2007, and J. Ueda, L. Odhner, and H. Asada, "Broadcast Feedback for Stochastic Cellular Actuator Systems consisting of Nonuniform Actuator Units," In Proceedings of 2007 IEEE International Conference on Robotics and Automation (ICRA '07), pp. 642-647, 2007, each incorporated by reference above. Instead of wiring many control lines to each individual cells, each cellular actuator has a stochastic local control unit that receives the broadcasted signal from the central control unit, and turn its state in a simple ON-OFF manner as described above. A wide variety of sizes and shapes is configurable using the designed actuator as a building-block.

A wide variety of sizes and shapes is configurable using the designed actuator as a building-block. For example, as shown in FIG. 26A, a cellular actuator 1410 can comprise an array of six units connected in series, according to embodiments of the invention, which increases a displacement of the actuator.

The number of stacks and bundles can determined according to a specific application. In one embodiment, as shown in FIG. 26B, a cellular actuator 1420 can comprise twelve

stacks or cells and four bundles. The twelve cells are connected in series and four arrays are connected in parallel. These arrays are easily reconfigurable by changing the connectors. In another embodiment, as shown in FIG. 26C, a cellular actuator 1430 can comprise six stacks and seven bundles, which is a configuration for larger force and shorter displacement.

5 Another salient feature of the proposed actuator is modularity. The basic module of this hierarchical system is a compact PZT stack actuator. The multitude of modular actuator units are connected in series and parallel to build various actuators with diverse stroke, force, and impedance characteristics. This can be done by simply changing the parallel and serial combinations of the same modules.

10 FIG. 27 shows the concept of modular design. The number of stacks and bundles are determined according to a specific application. As shown in FIG. 27, twelve cells are connected in series and four arrays are connected in parallel. In an embodiment, arrays of amplifying units 1401 of an actuator 1420 can be reconfigured by changing connectors 1405. This modular design is based on a powerful method for building diverse actuators with
15 matched load impedance and stroke and force requirements.

FIG. 28 is a perspective view of a cell stack and bundle, according to embodiments of the invention. As shown in FIG. 28, a layer of a multi-layer strain amplification device 1450 can be configured by connecting a plurality of amplifying layer units 1460 together in serial and parallel. Hereafter, the term "stack" refers to serial connections of the amplifying layer
20 units 1460. Similarly, the term "bundle" refers to parallel connections of the amplifying layer units 1460. In an embodiment, N_k , D_k , and M_k are the number of stacks in the L_k direction for the k -th layer, the number of bundles in the direction of W_k , and the number of bundles in the direction of H_k , respectively.

FIG. 29 is a perspective view of a final actuator 1400 incorporating a cell stack 1480
25 and bundle 1490, according to embodiments of the invention. As shown in FIG. 11, the final actuator 1400 can be configured by connecting a plurality of N_k units of at least one final layer 1470 in serial and a plurality of M_k units in parallel. Considering the spatial constraint for the final configuration of the actuator 1400, for example, the final layers can be configured relatively freely.

In sum, embodiments of the present invention include a nested rhombus multi-layer mechanism for PZT actuators. The idealized analysis has been given for fundamental design of the nested structure. Through kinematic and static analysis this paper has addressed how the output force and displacement are attenuated by the structural compliances involved in the strain amplification mechanism. A lumped parameter model has been developed to quantify the performance degradation. In an embodiment, nested PZT cellular actuator that weighs only 15 g has produced 21% effective strain 2.49 mm displacement from 12 mm actuator length and a 1.7 N blocking force. A modular design concept has been presented for building reconfigurable cellular actuators with matched stroke and force requirements.

In other embodiments, nonlinear and dynamic modeling such as frequency response can be applied to the devices and methods of the present invention. In other embodiments, analysis of a closed kinematic chain can be formed by serial-parallel mixed configurations described herein. In other embodiments, the devices and methods of the present invention can be applied to practical systems such as robotics.

FIGs. 30A and 30B are illustrations of test equipment designed to measure free displacement and blocked force of a multi-layer strain amplification device, according to embodiments of the invention. Specifically, FIG. 30A is an illustration of a blocked force testing stand 1510, and FIG. 30B is an illustration of a free displacement test stand 1520, according to embodiments of the invention.

Verification of Three-Spring Lumped Parameter Model

The validity of the proposed lumped parameter model is confirmed by FEM (Finite Element Method). Consider the two amplification mechanisms 1610, 1620 shown in FIGS. 31A and 31B, for example, also referred to as Structure 1 and Structure 2, respectively. The size of each mechanism 1610, 1620 is 40mm (length, actuation direction) \times 96mm (width) \times 5mm (thickness). In another embodiment, material such as brass (Young's modulus = 100.0 GPa) is used. In an embodiment, an amplification mechanism 1630 shown in FIG. 31C can be provided with similar dimensions as those with regard to FIGs. 31A and 31B, also referred to as Structure 3.

The four structural lumped parameters, i.e., a , k_{BL} , k_{BO} , and k_J , are calibrated by the displacements and forces from two different conditions; one case is a "blocked case," for example, shown in FIG. 31A, where the output displacement is totally constrained (or letting

$k_{load} \rightarrow \infty$), and the other one is “free-load case” (or letting $k_{load} = 0$), for example, shown in FIG. 31B. By applying an input force, f_{pzt} , Δx_{pzt}^{block} and f_1^{block} are measured for the blocked case, and Δx_{pzt}^{free} and Δx_1^{free} are measured for the free-load case. From equations (30) to (32) we have

$$5 \quad \frac{f_{pzt}^{block}}{\Delta x_{pzt}^{block}} = \frac{a^2 k_{BI} k_{BO} + k_J k_{BI}}{a^2 k_{BO} + k_J + k_{BI}} \triangleq X_1 \quad (45)$$

$$\frac{f_1^{block}}{\Delta x_{pzt}^{block}} = \frac{a k_{BI} k_{BO}}{a^2 k_{BO} + k_J + k_{BI}} \triangleq X_2 \quad (46)$$

$$\frac{\Delta x_1^{free}}{\Delta x_{pzt}^{free}} = \frac{a k_{BI}}{k_J + k_{BI}} \triangleq X_3 \quad (47)$$

$$\frac{f_{pzt}^{free}}{\Delta x_1^{free}} = \frac{k_J}{a} \triangleq X_4. \quad (48)$$

Note that the actual number of independent equations described above is three, which can be confirmed by $X_1 = X_3(X_2 + X_4)$. This implies that the calibration of the four structural parameters, $[a, k_{BI}, k_{BO}, k_J]$, is an ill-posed problem. This can be confirmed by the two-port model representation above with regard to equation (23). The stiffness matrix S is generally given as follows:

$$S = \begin{bmatrix} X_1 & -X_2 \\ -X_2 & \frac{X_3}{X_2} \end{bmatrix} \quad (49)$$

15 Recall $S = S^T$ and it fully represents the relation between the displacements and forces. Therefore, the number of independent elements is three by calibrating S . Unlike the ideal rhombus mechanism consisting of all rigid links, the displacement amplification gain a cannot be defined uniquely as long as the stiffness in the constrained space is finite, i.e., $k_J > 0$. Note that the choice of a does not change S or the characteristics of the estimated model; however, a nominal gain \hat{a} should be determined to have a physically feasible lumped parameter model, that is, $k_{BI}, k_{BO}, k_J > 0$. One way of determining \hat{a} is based on free-displacement characteristics and kinematic characteristics of the structure such as the angle of

the oblique beam θ , i.e., $X_3 < \hat{a} < \cot\theta$, to satisfy the requirement. X_3 can be assumed as a lower bound of \hat{a} since X_3 is always lower than the actual a if k_J is positive. In addition, $\cot(\theta)$ can be assumed as an upper bound of \hat{a} since this gain is realized only when $k_J=0$.

The following steps estimate the remaining parameters:

5
$$\hat{k}_J = \hat{a} X_4, \hat{k}_{BI} = \frac{X_3 \hat{k}_J}{\hat{a} - X_3}, \text{ and } \hat{k}_{BO} = \frac{(\hat{k}_{BI} + \hat{k}_J) X_2}{\hat{a} \hat{k}_{BI} - \hat{a}^2 X_2}$$

Table 2A shows the observed values from FEM when applying $f_{pzt}=10\text{N}$ to the Structures 1-2 shown in FIGs. 31A and 31B, respectively.

	Structure 1	Structure 2
Δx_1^{free} [m] (@ $f_{pzt}=10$)	1.95e-05	2.61e-04
f_1^{block} [N] (@ $f_{pzt}=10$)	2.73	2.51

Table 2A

10 Table 2B shows additional observed values from FEM when applying $f_{pzt}=10\text{N}$ to the Structures 1-3 shown in FIGs. 31A-31C, respectively.

	Structure 1	Structure 2	Structure 3
$X_1 \left(= \frac{f_{PZT}^{block}}{x_{PZT}^{block}} \right)$	6.64E+06	1.25E+07	7.67E+05
$X_2 \left(= \frac{f_{out}^{block}}{x_{PZT}^{block}} \right)$	1.81E+06	3.14E+06	2.87E+05
$X_3 \left(= \frac{x_{out}^{free}}{x_{PZT}^{free}} \right)$	2.876218036	3.886319558	1.811862187
$X_4 \left(= \frac{f_{out}^{free}}{x_{out}^{free}} \right)$	5.13E+05	3.84E+04	1.25E+05

15

Table 2B

The structural lumped parameters are calculated as shown in Table 3.

	Structure 1	Structure 2
\hat{a}	3.2	3.9
\hat{k}_J [N/m]	1.64e+06	1.50e+05
\hat{k}_{BI} [N/m]	1.46e+07	4.25e+07
\hat{k}_{BO} [N/m]	1.05e+06	1.13e+06
σ_{max} [N/m ²]	5.35e+06	2.75e+07

Table 3

The nominal amplification gains are determined accordingly based on the observed X_3 and kinematic characteristics to keep all spring constants positive. As shown in Table 2A, the structure 1620 shown in FIG. 31B provides approximately 13 times larger free-load displacement than the structure 1610 shown in FIG. 31A, while the blocking forces of the two structures are almost the same magnitude. This observation suggests that the structure 1620 shown in FIG. 31B has a more favorable structure than the structure 1610 shown in FIG. 31A as an amplification mechanism. This can be explained based on the estimated lumped parameters: The effective stiffness in the constrained space \bar{k}_B viewed from the input port is calculated as

$$\bar{k}_B \triangleq \frac{1}{\frac{1}{\hat{k}_{BI}} + \frac{1}{a^2 \hat{k}_{BO}}} \tag{50}$$

This expression $\bar{k}_B = 6.18e+06$ for the structure shown in FIG. 31A and $\bar{k}_B = 1.23e+07$ for the structure shown in FIG. 31B. As a result, the structure shown in FIG. 31B has a smaller stiffness in the admissible space, k_J , and a larger stiffness in the constrained space, \bar{k}_B , compared with that of FIG. 31A. Although the structure shown in FIG. 31B provides relatively good performances, it could also involve a few problems in development due to its complex shape and in strength due to stress concentration at thin sections having large deformation. Maximum stress when producing the free-load displacement is also shown in Table 3.

The validity of the calibrated models is confirmed by examining Δx_{pzt} and Δx_1 when connecting the amplification mechanism 1640 to a spring load realized by a fixed beam 1650 shown in FIG. 33. The length of the beam 1650 is $L = 100\text{mm}$. In an embodiment, brass is used as a material. Three different thicknesses, from 1mm, 2mm, to 3mm, are used to vary the stiffness. Table 4A shows the comparison of the estimated displacements of Structures 1 and 2 shown in FIGs. 31A and 31B from the proposed lumped parameter model and the true values from FEM analysis. As can be observed in the Table 4A, the estimated values agree well with the true values, confirming the validity of the model. Table 4B shows estimated displacements of Structure 3 shown in FIG. 31C from the proposed lumped parameter model and the true values from FEM analysis.

Thickness	Disp. [μm]	Structure 1			Structure 2		
		FEM	Estimated	Error [%]	FEM	Estimated	Error [%]
1 [mm]	Δx_{pzt}	6.48	6.49	0.035	36.76	37.20	1.184
	Δx_1	18.40	18.42	0.172	141.5	143.1	1.163
2 [mm]	Δx_{pzt}	5.10	5.11	0.187	9.47	9.57	1.098
	Δx_1	13.28	13.34	0.467	34.09	34.46	1.098
3 [mm]	Δx_{pzt}	3.56	3.56	0.051	3.65	3.67	0.492
	Δx_1	7.61	7.63	0.301	11.23	11.30	0.267
Average [%]		0.202			0.884		

Table 4A

Structure 3				
Thickness	Disp. [μm]	FEM	estimated	error(%)
1 [mm]	Δx_{pzt}	39.83	39.90	0.104
	Δx_1	68.61	68.80	0.247
2 [mm]	Δx_{pzt}	26.44	26.63	0.736
	Δx_1	34.35	34.38	0.085
3 [mm]	Δx_{pzt}	18.76	19.01	1.351
	Δx_1	14.71	14.58	0.867
Average [%]		0.565		

Table 4B

In another embodiment, the parameter estimation based on the lumped parameter model can be provided based on the following:

$$\frac{f_{PZT1}}{x_{PZT1}} = \frac{a^2 k_1 k_2 + k_3 k_1}{a^2 k_2 + k_3 + k_1} = X_1 \tag{51}$$

5

$$\frac{f_{out1}}{x_{PZT1}} = \frac{a^2 k_1 k_2}{a^2 k_2 + k_3 + k_1} = X_2 \tag{52}$$

$$\frac{x_{out2}}{x_{PZT2}} = \frac{a k_1}{k_1 + k_3} = X_3 \tag{53}$$

10

$$\frac{f_{PZT2}}{x_{out2}} = \frac{k_3}{a} = X_4 \tag{54}$$

wherein a , k_1 , k_2 , k_3 are four structural lumped parameters.

However, in this embodiment, $X_1 = X_3(X_4 + X_2)$.

15 Accordingly, in accordance with other embodiments, parameter estimation of a three-spring model as shown in FIG. 34 is performed by setting a , wherein a good approximation is given by equations (55)-(58)

$$X_3 = \frac{a k_1}{k_1 + k_3} \tag{55}$$

$$k_3 = a X_4 \tag{56}$$

20

$$k_1 = \frac{k_3 X_4}{a - X_3} \tag{57}$$

$$k_2 = \frac{(k_1 + k_3) X_2}{a k_1 - a^2 X_2} \tag{58}$$

Necessity of Three Lumped Springs

Consider two constrained cases shown in FIGs. 35A and 35B to confirm the necessity of three lumped springs. For simplicity, the amplification mechanism is designed to have a square shape resulting in $a = 1$. $\Delta x_1 = \Delta x_{pzt}$ must hold for the displacements when applying the same magnitude of force f , which is a basic requirement of Castigliano’s theorems. By using the proposed lumped parameter model, these constrained cases are represented by the illustrative figures herein. The condition $\Delta x_1 = \Delta x_{pzt}$ is satisfied if $k_{BI} = k_{BO}$. This can also be confirmed in equation (49) where the off-diagonal elements are the same. As described herein, this lumped parameter model has a redundancy in parameter calibration; however, three spring elements are minimally required to satisfy this condition.

In another embodiment, a lumped parameter model 1800 and simplified equivalent model 1850 shown in FIG. 36 are described as follows based on parameters described herein:

$$\tilde{k}_1 = \frac{k_{BO}(k_{BI}k_J + k_{PZT}k_J + k_{BI}k_{PZT})}{(a^2k_{BI}k_{BO} + k_{BI}k_J) + k_{PZT}(a^2k_{BO} + k_J + k_{BI})} \tag{59}$$

$$\tilde{f}_1 = \frac{ak_{BI}k_{BO}}{(a^2k_{BI}k_{BO} + k_{BI}k_J) + k_{PZT}(a^2k_{BO} + k_J + k_{BI})} f_{pzt} \tag{60}$$

In another embodiment, as shown in FIG. 37, a lumped parameter model 1860 and simplified equivalent model 1880 can include a plurality of units 1870 coupled to each other. The simplified equivalent model being determined in part by:

$$f_{block,n} = \frac{n}{N} f_1^{block} \tag{61}$$

Parameter Calibration of Second Layer Rhombus Mechanism

$X_1 = 3.39 \times 10^6$, $X_2 = 2.95 \times 10^5$, $X_3 = 11.33$, and $X_4 = 3.50 \times 10^3$ are obtained from FEM analysis. The range of a_2 that makes all spring constants positive is shown in FIG. 38A and 38B. Finally $\hat{a}_2 = 11.4$ is chosen, which is between X_3 and $\cot\theta (=11.5)$.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood to those skilled in the art that various

changes in form and details may be made herein without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A multi-layer strain amplification device, comprising:
5 at least one first amplifying layer unit comprising a plurality of actuators; and
a second amplifying layer unit positioned about the at least one first amplifying layer
unit, wherein a strain of the at least one first amplifying layer unit is amplified by the second
amplifying layer unit.
- 10 2. The device of claim 1, wherein the at least one first amplifying layer unit and the
second amplifying layer unit are configured as a nested rhombus structure.
3. The device of claim 1, wherein the actuators are at least one of in series with and
in parallel with each other.
- 15 4. The device of claim 3, wherein an output axis of the serially-connected actuators is
perpendicular to an output axis of the second amplifying layer unit.
5. The device of claim 1, wherein the actuators are piezoelectric actuators.
- 20 6. The device of claim 1, wherein the at least one first amplifying unit is positioned in
a first layer of the device, the at least one second amplifying unit strain is positioned in a
second layer of the device, wherein an amplification gain of the device increases
exponentially as a number of layers of the device increases.
- 25 7. The device of claim 1, wherein displacements of each first actuator are aggregated
and transmitted through the at least one first amplifying layer unit and the second amplifying
layer unit, resulting in an output displacement at the second amplifying layer unit.
- 30 8. The device of claim 1, wherein a displacement of the device is amplified when the
at least one first amplifying unit expands in a first direction and contracts in a second
direction.

9. The device of claim 8, wherein the first direction is perpendicular to the second direction.

5 10. The device of claim 1, wherein the at least one first amplifying layer unit further comprises a rhombus structure positioned about each actuator, the rhombus structure including a rigid beam and a flexible joint.

10 11. The device of claim 1, wherein a plurality of first amplifying layer units are connected in series to increase an output displacement.

12. The device of claim 1, wherein a plurality of first amplifying layer units are connected in parallel to increase an output force.

15 13. A method of forming a multi-layer strain amplification device, comprising: providing at least one first amplifying layer unit including a plurality of actuators; and positioning a second amplifying layer unit about the at least one first amplifying layer unit to amplify a strain of the at least one first amplifying layer unit.

20 14. The method of claim 13 further comprising configuring the at least one first amplifying layer unit and the second amplifying layer unit as a nested rhombus structure.

15. The method of claim 13 further comprising positioning the actuators to be at least one of in series with and in parallel with each other.

25 16. The method of claim 13, wherein the at least one first amplifying unit is positioned in a first layer of the device, the at least one second amplifying unit strain is positioned in a second layer of the device, wherein an amplification gain of the device increases exponentially as a number of layers of the device increases.

30 17. The method of claim 13, wherein a displacement of the device is amplified when the at least one first amplifying unit expands in a first direction and contracts in a second direction.

18. The method of claim 13, wherein providing at least one first amplifying layer unit comprises positioning a rhombus structure about each actuator, the rhombus structure including a rigid beam and a flexible joint.

- 5 19. A method of amplifying strain of an actuator, comprising:
providing at least one first amplifying layer unit having a first strain;
amplifying the first strain;
positioning a second amplifying layer unit about the at least one first amplifying layer
unit; and
10 amplifying the amplified first strain.

15

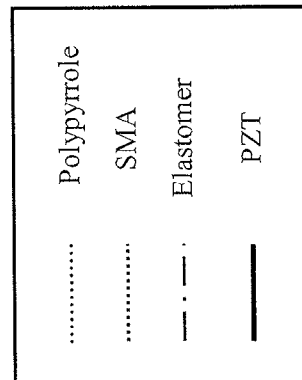
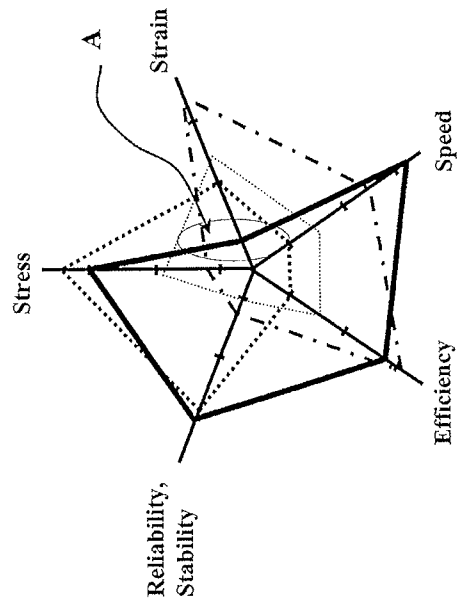


FIG. 1

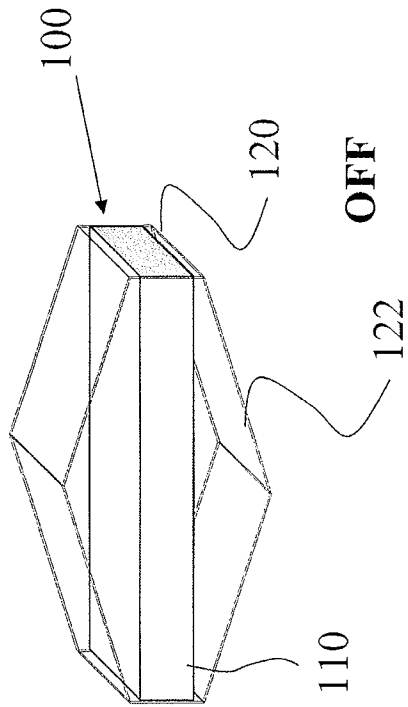


FIG. 2A

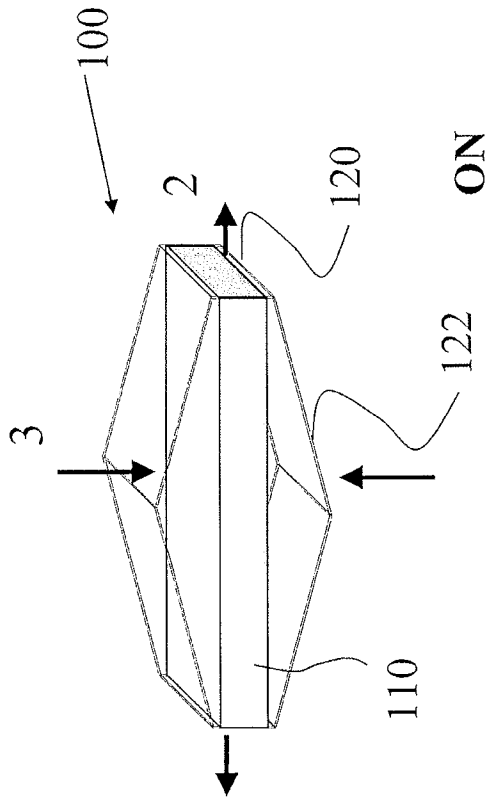


FIG. 2B

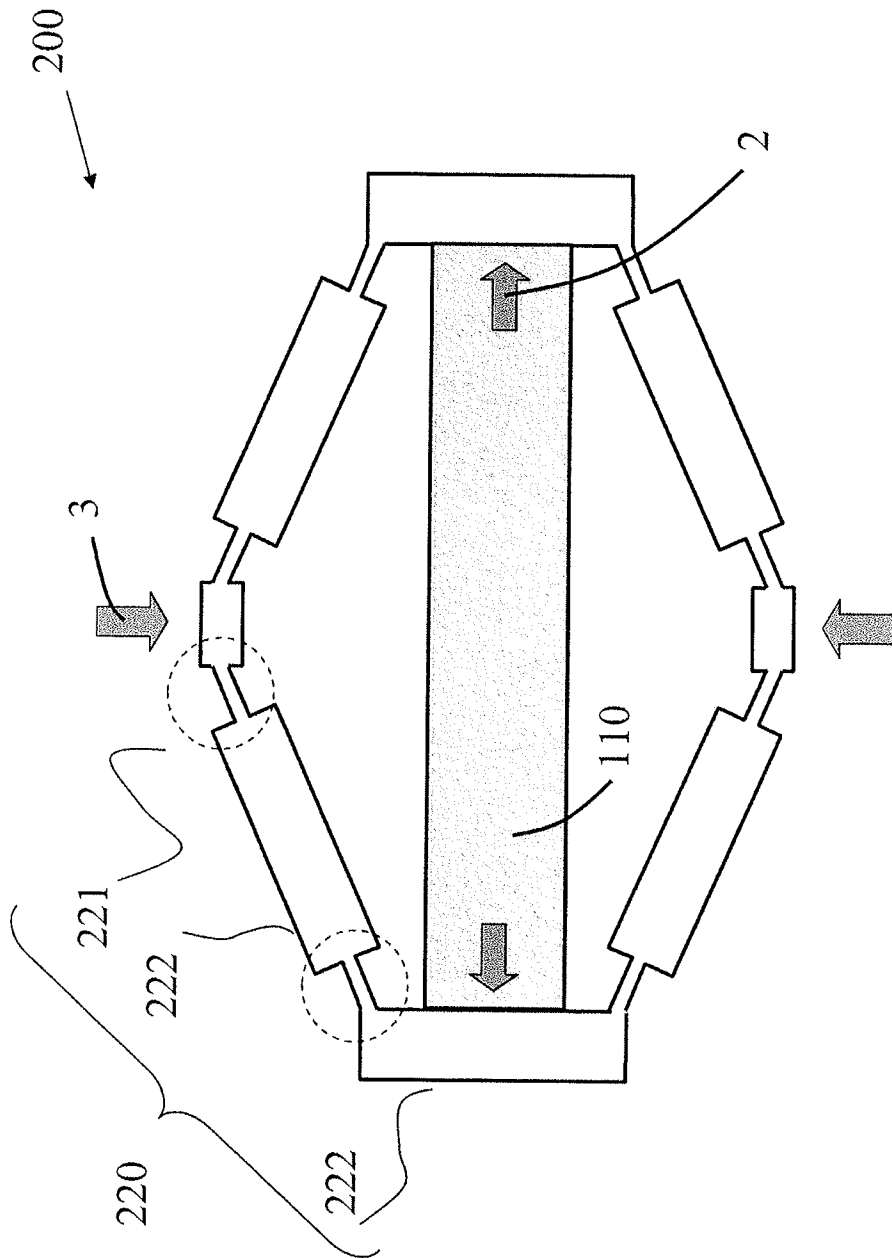


FIG. 3

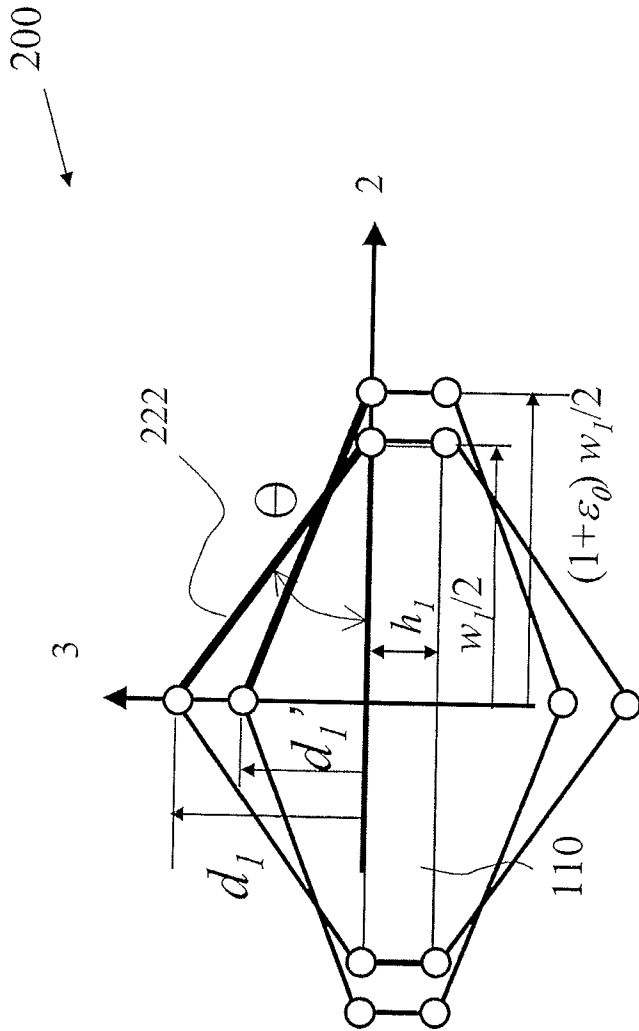


FIG. 4

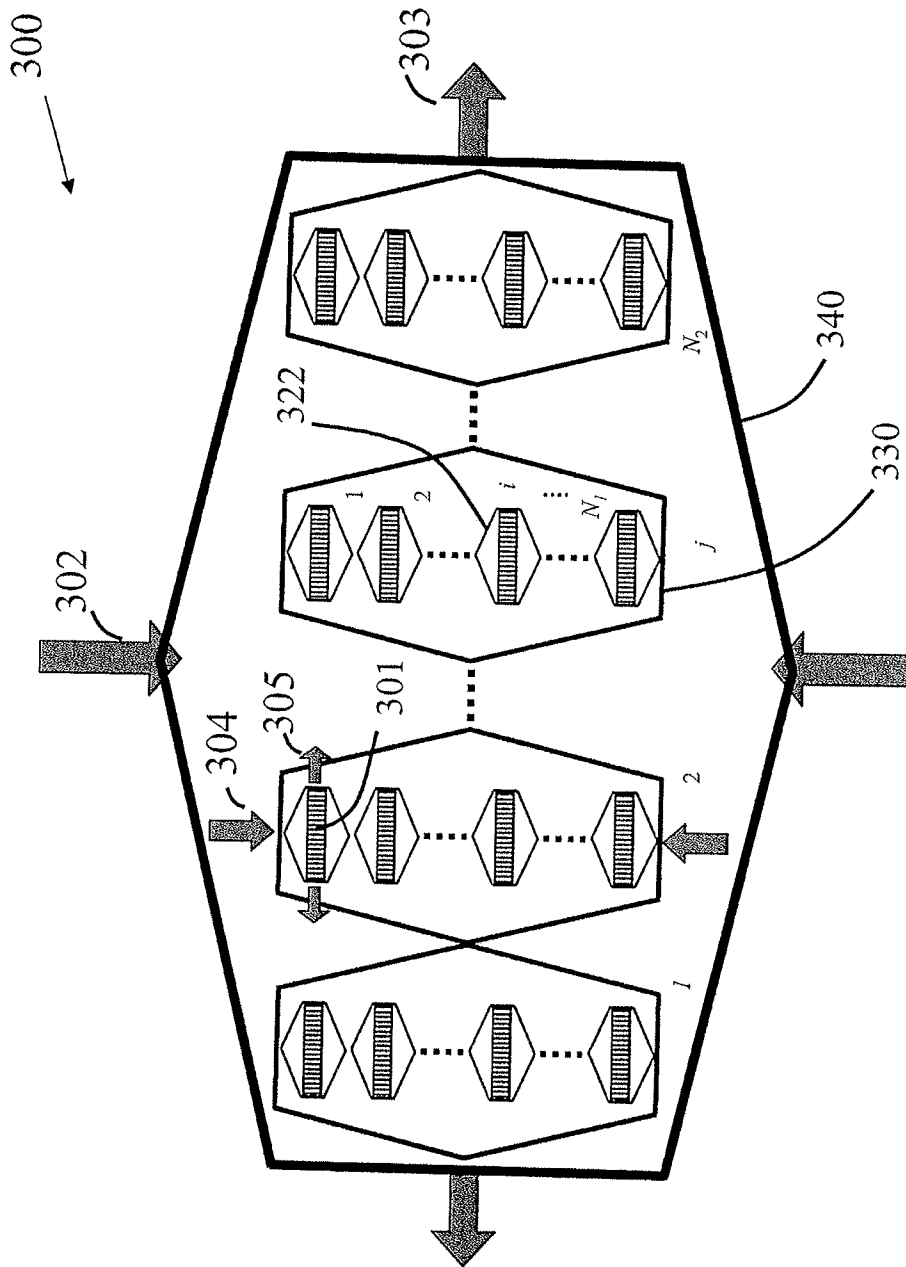


FIG. 5

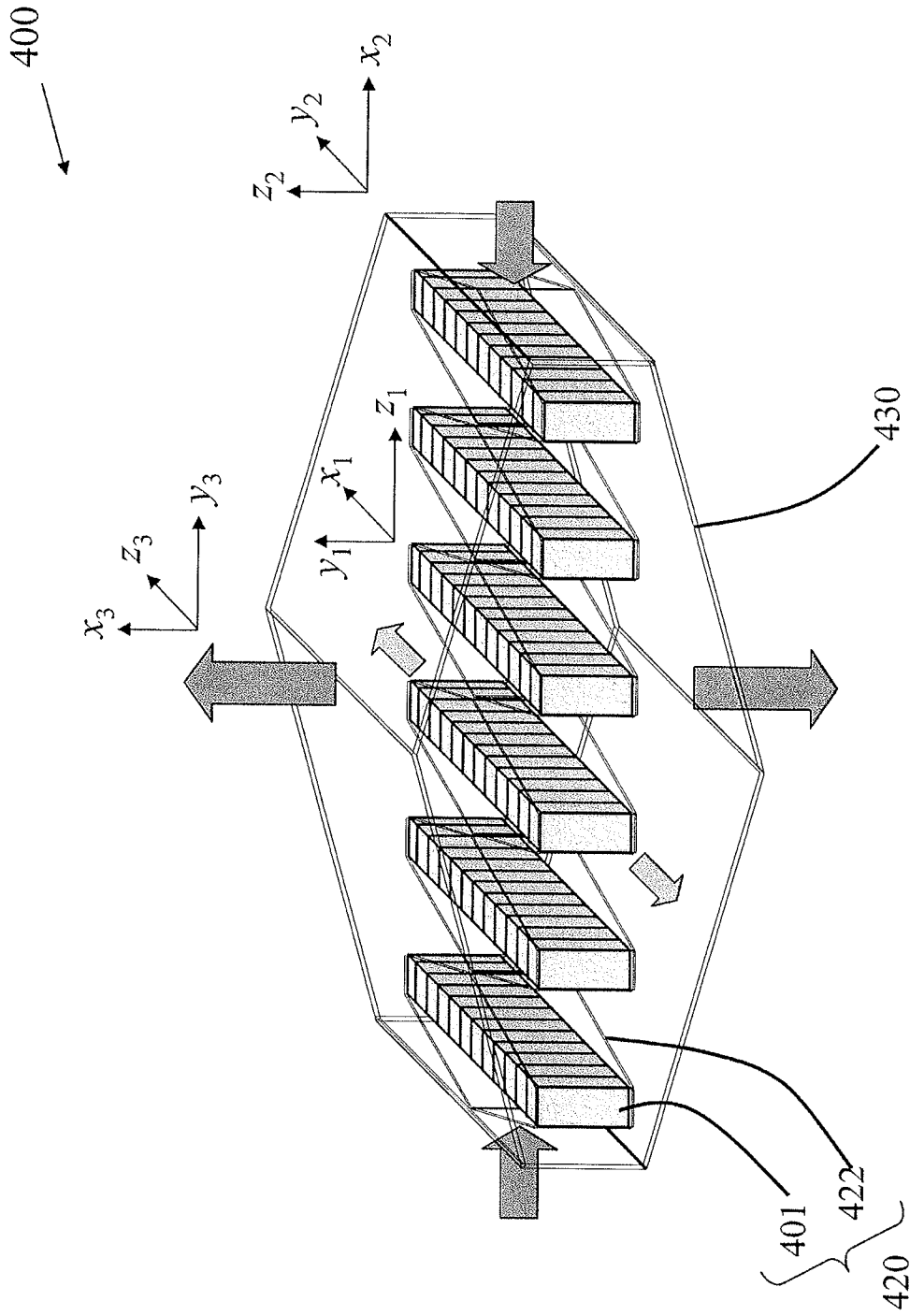


FIG. 6

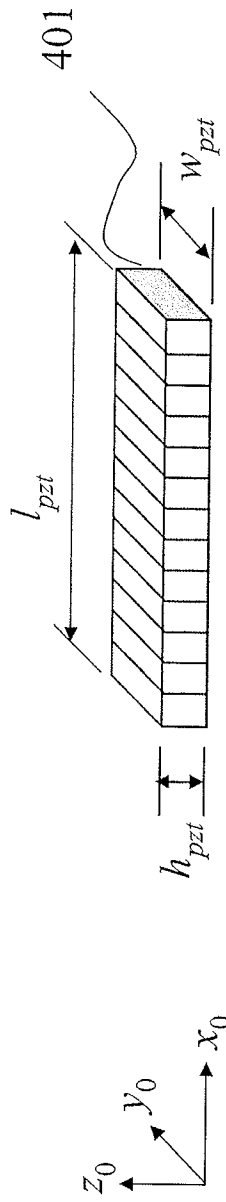


FIG. 7

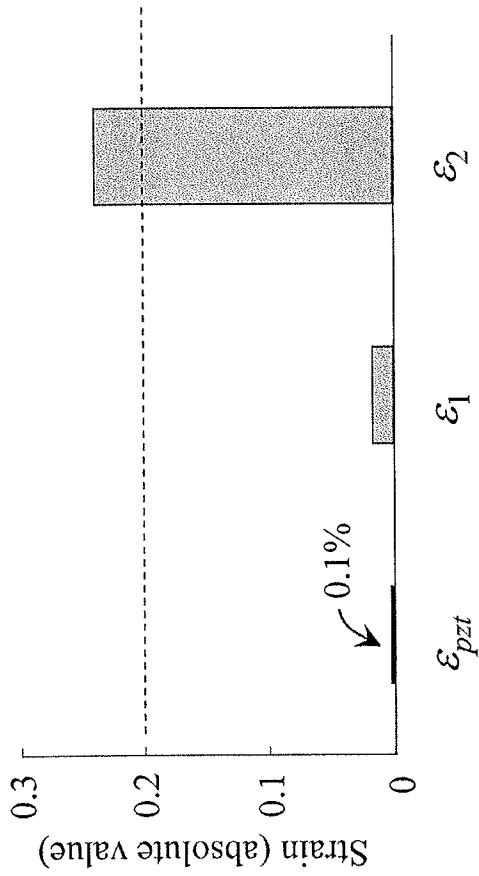


FIG. 8A

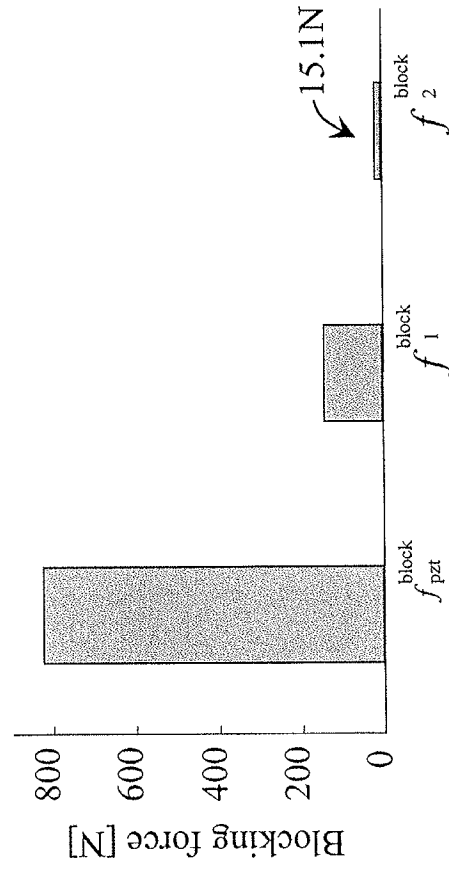


FIG. 8B

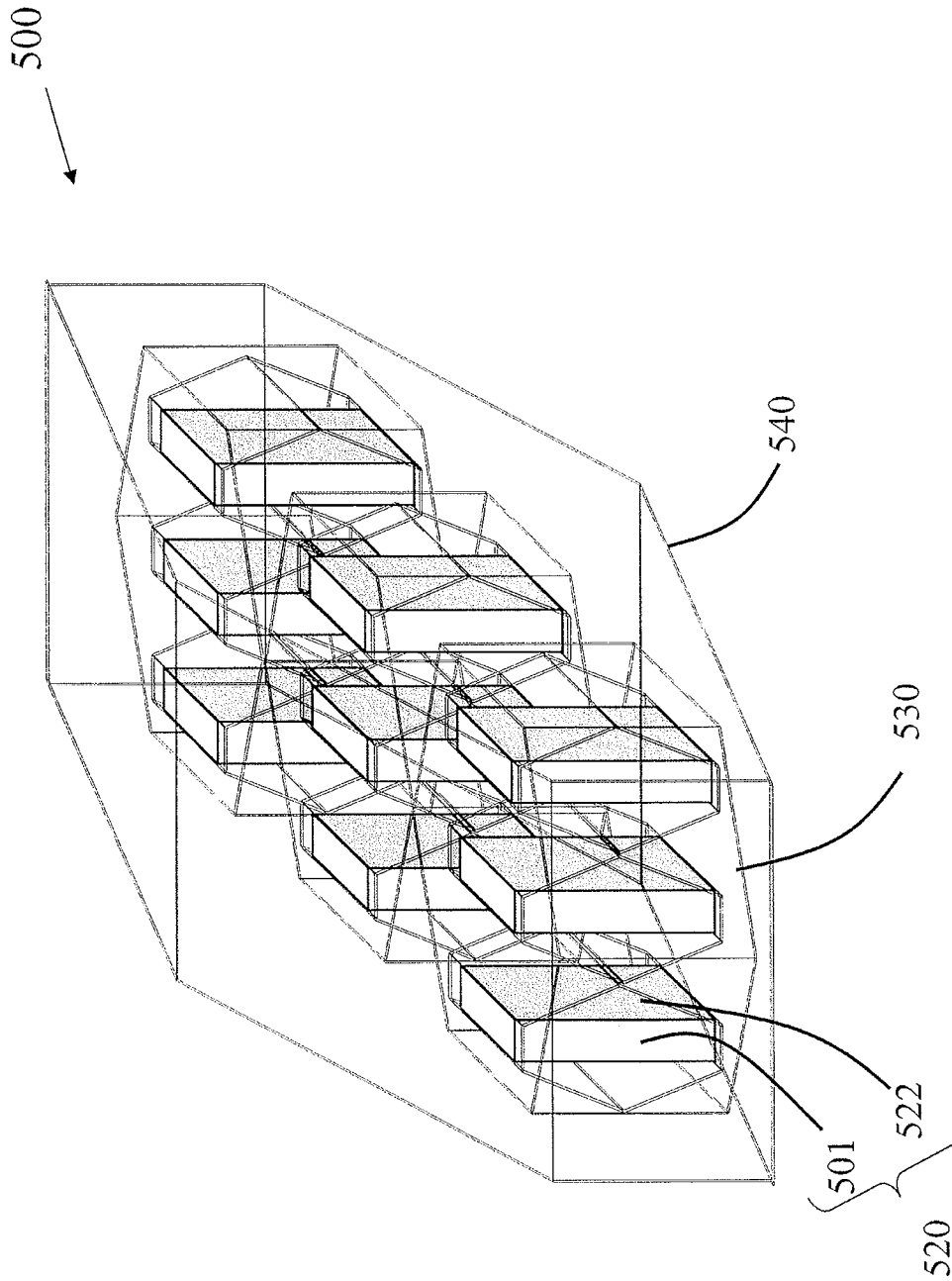


FIG. 9

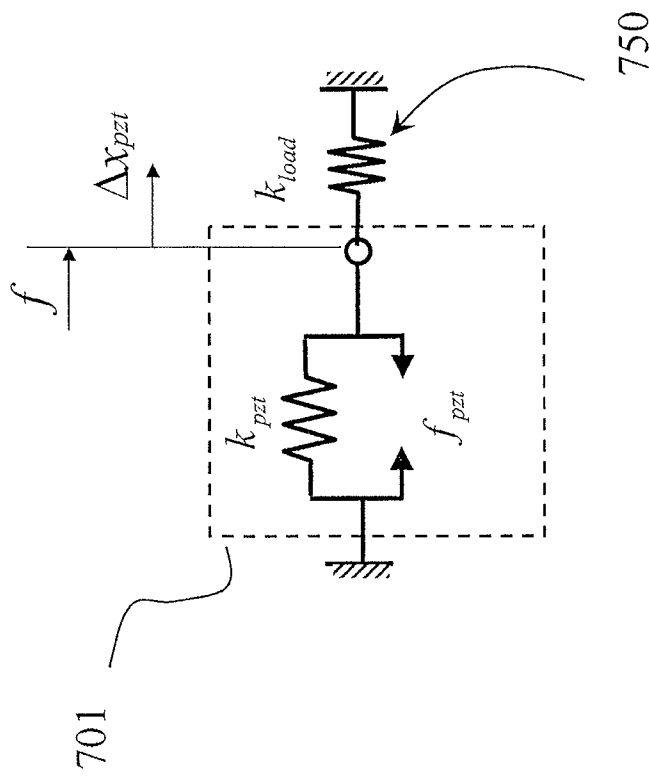


FIG. 10

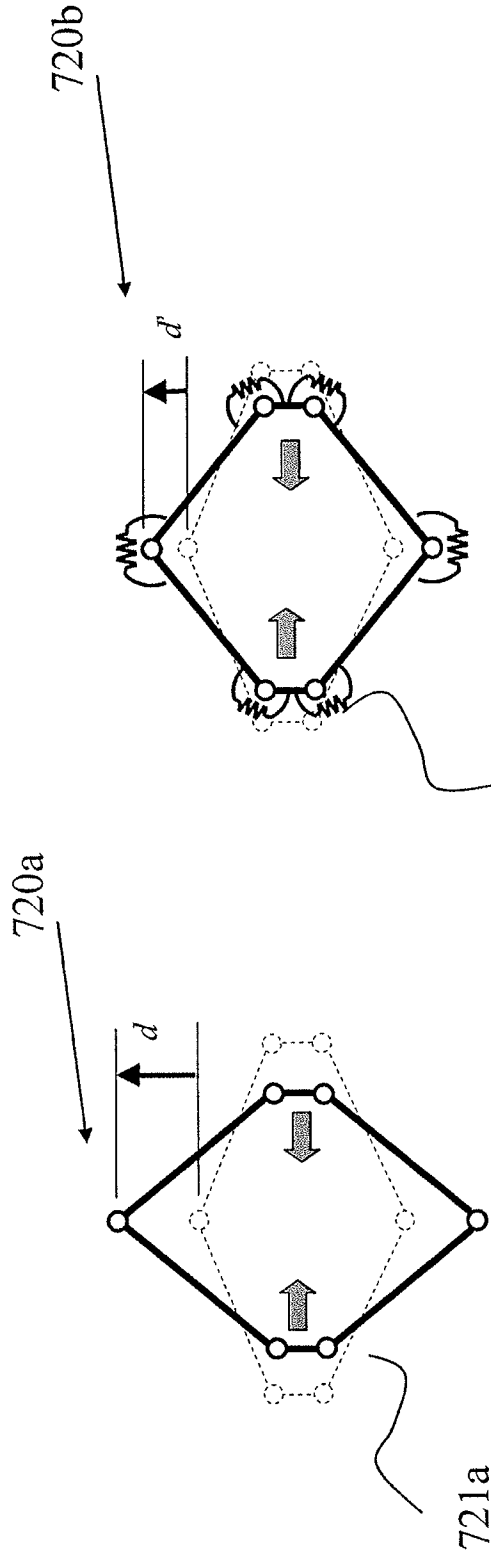
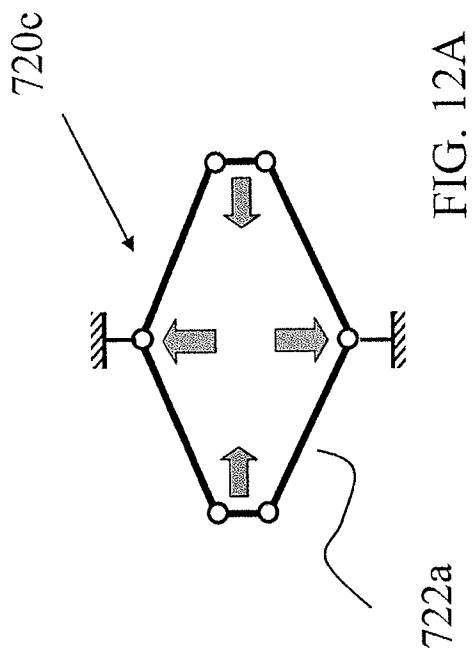
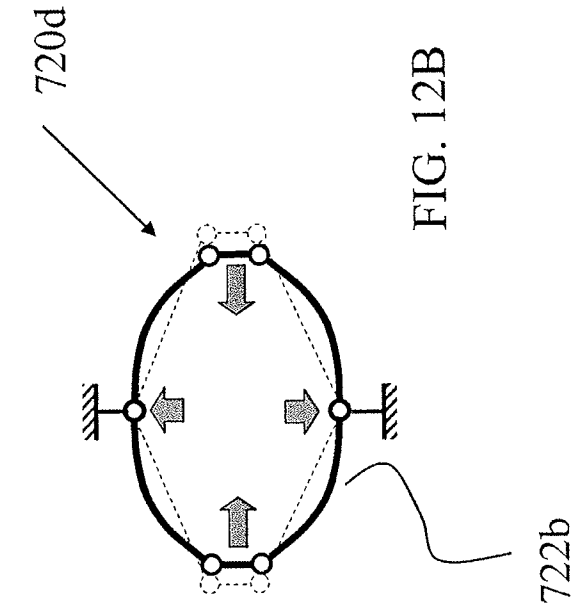


Fig. 11B

FIG. 11A



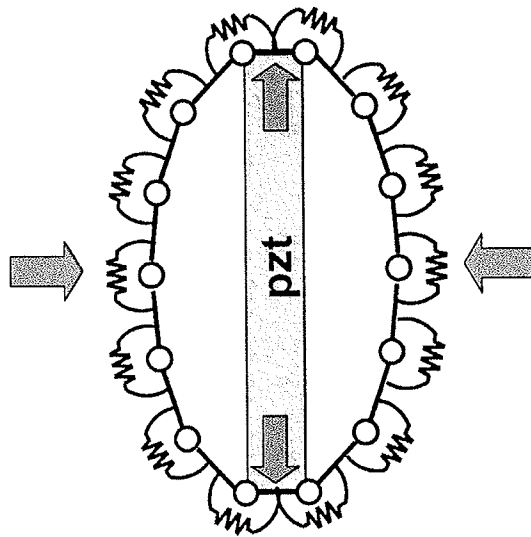


FIG. 13

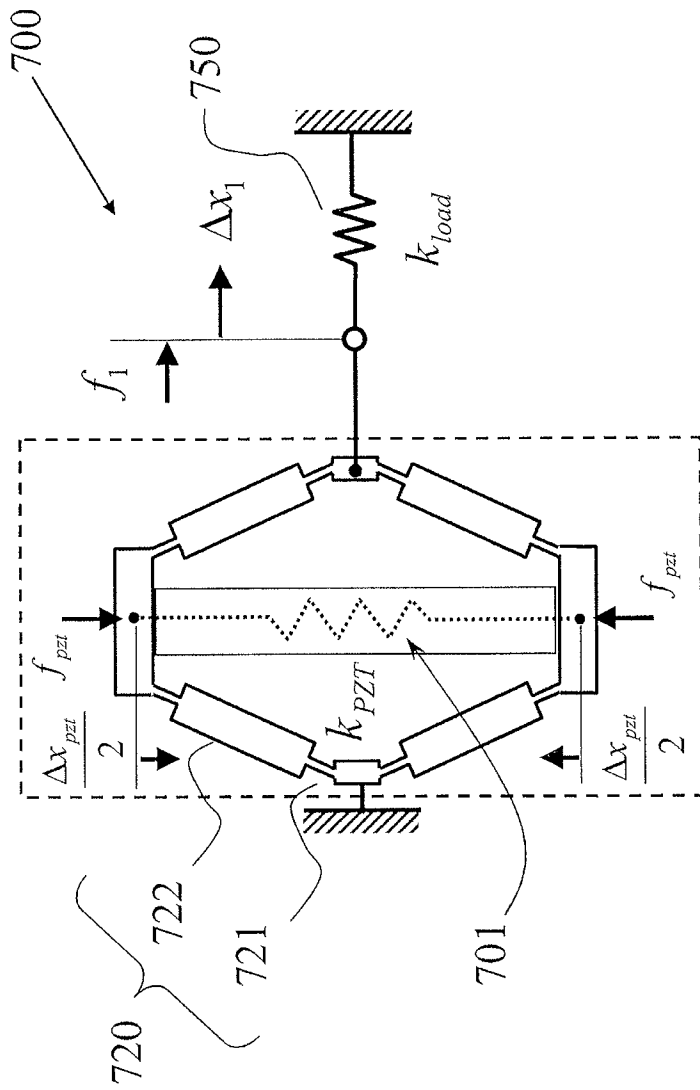


FIG. 14A

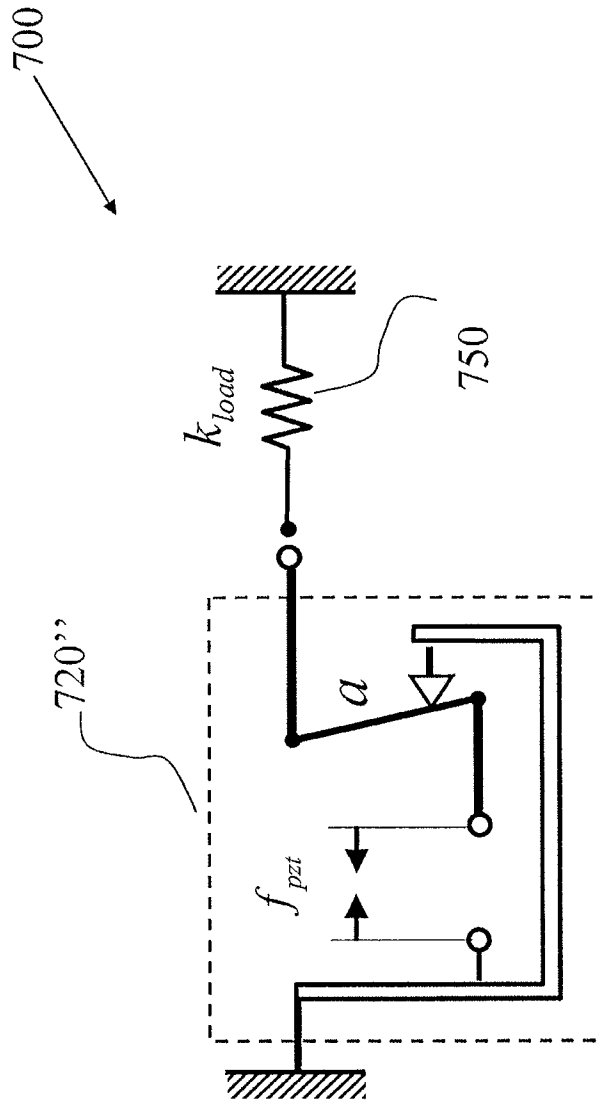


FIG. 14C

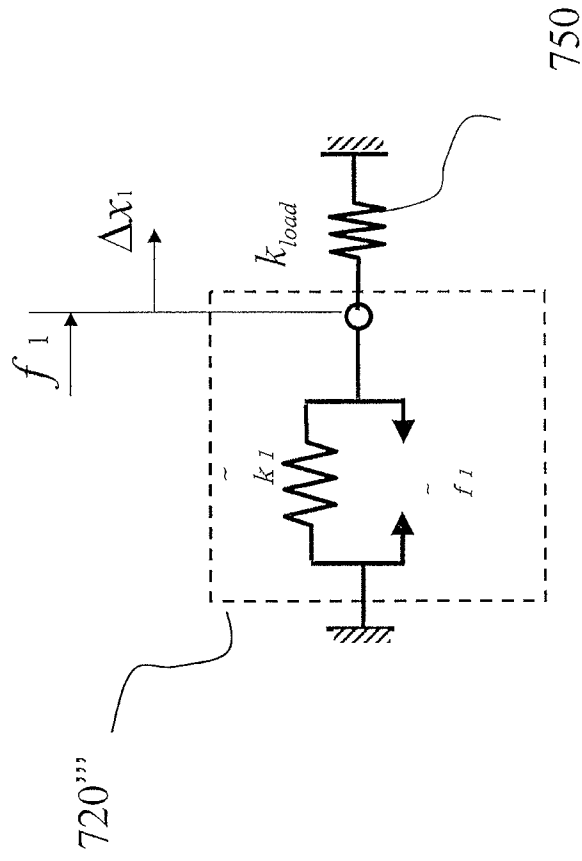


FIG. 15

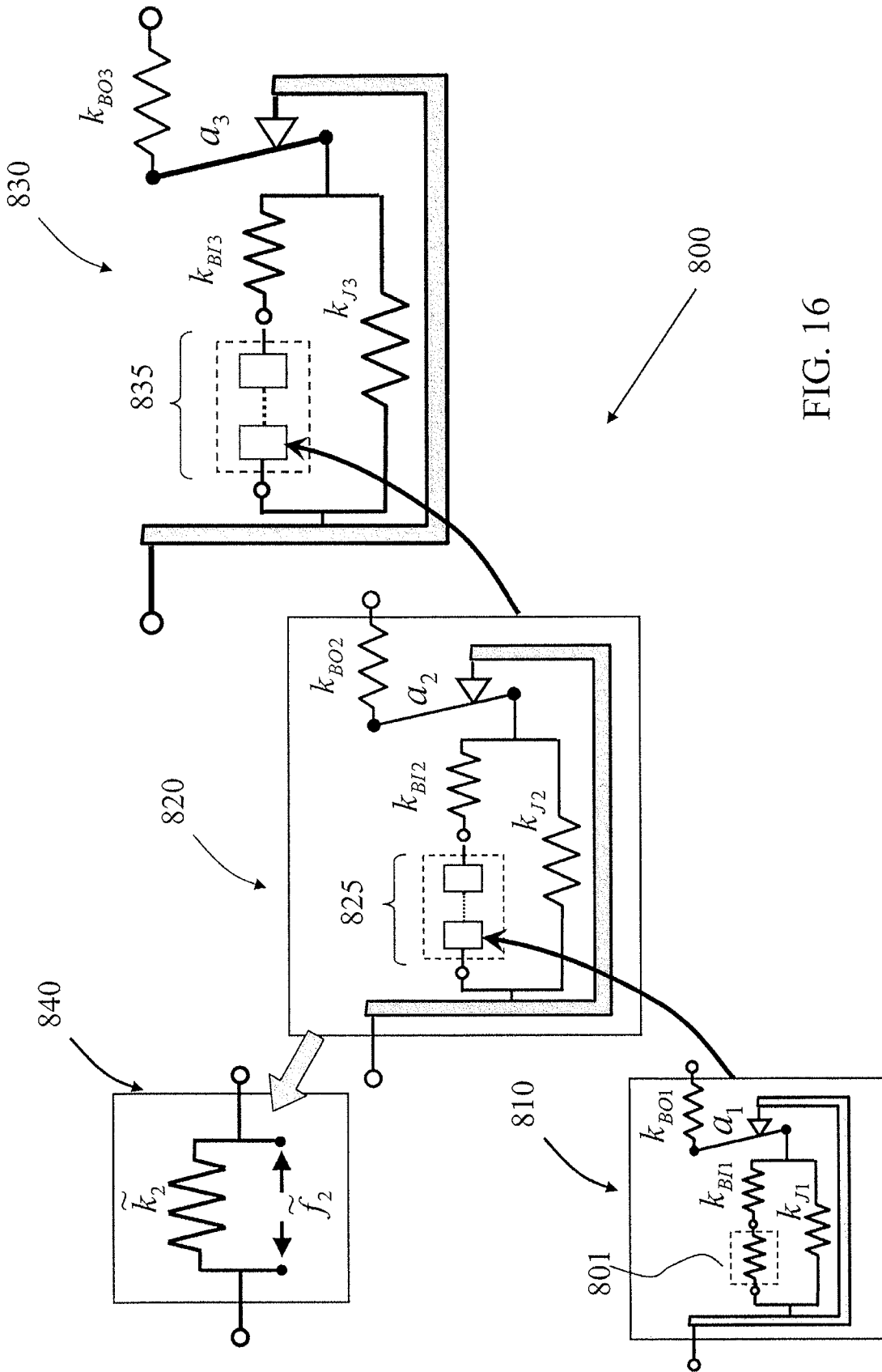


FIG. 16

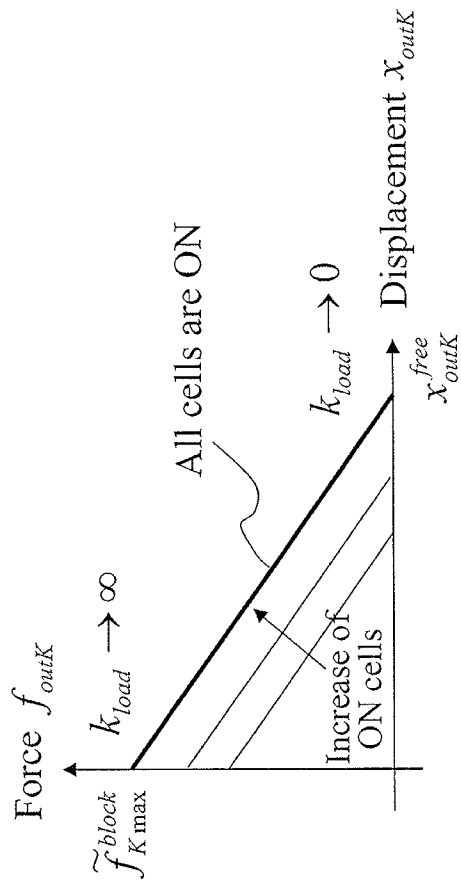


FIG. 17

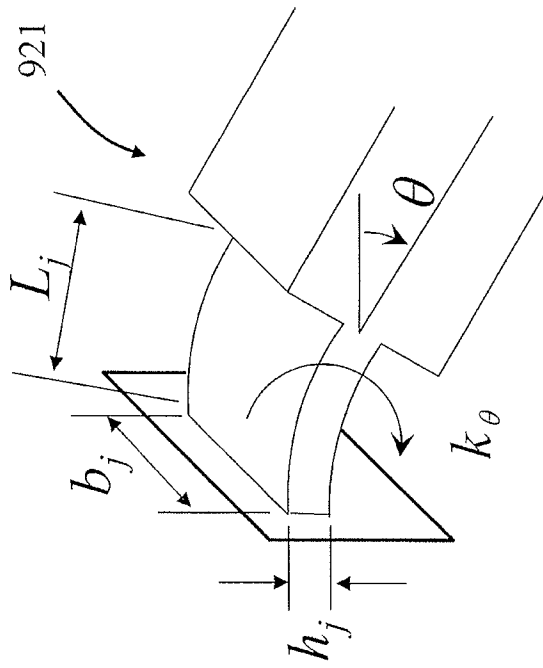


FIG. 18

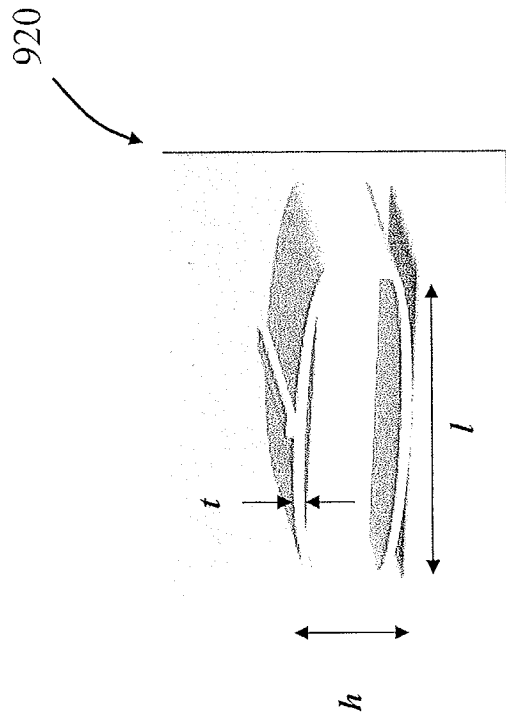


FIG. 19

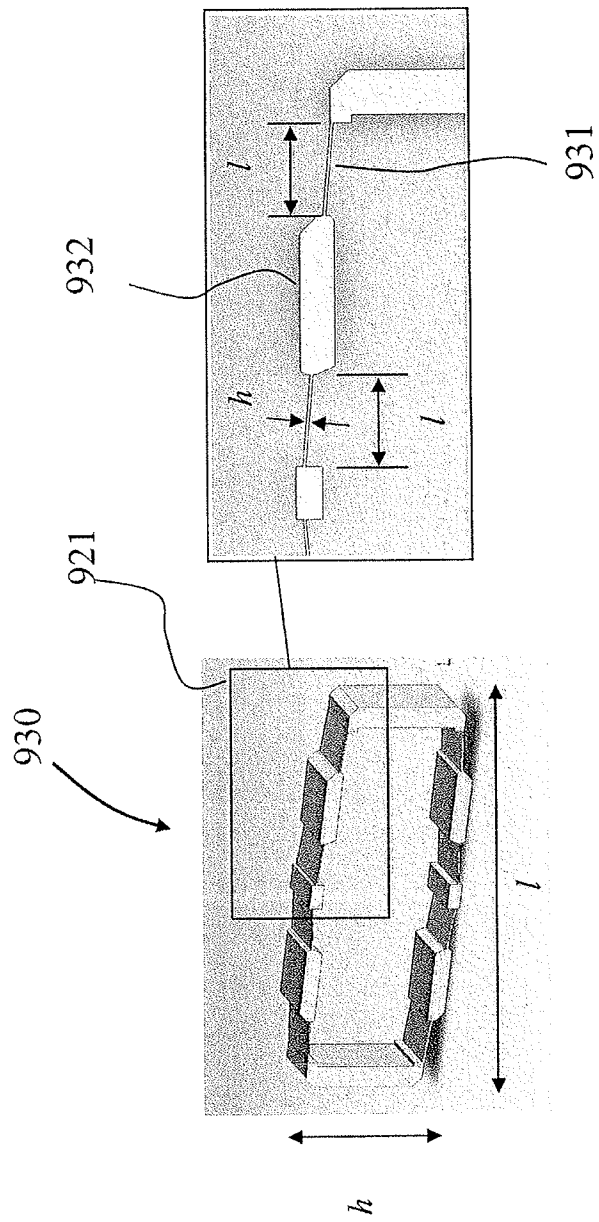


FIG. 20

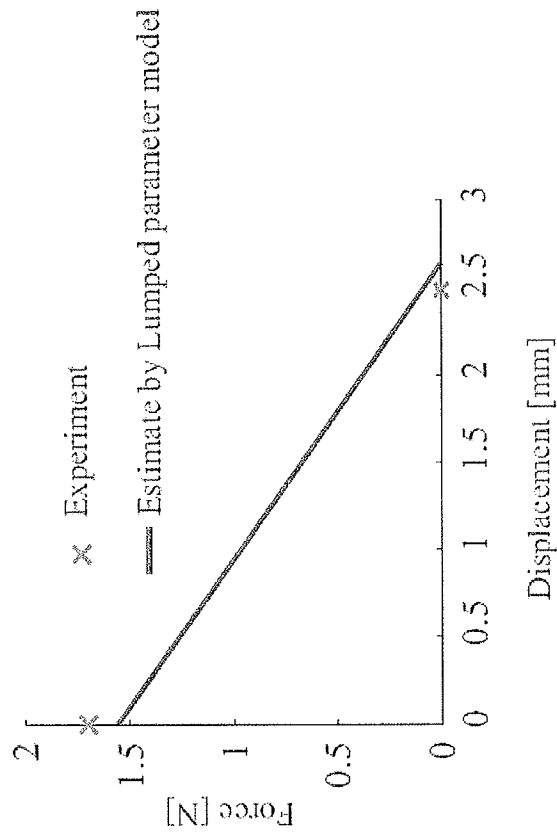


FIG. 21

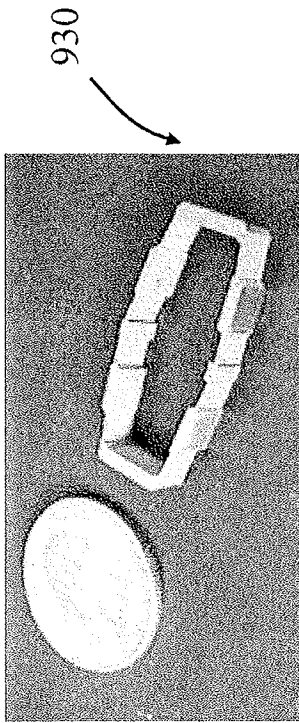


FIG. 22A

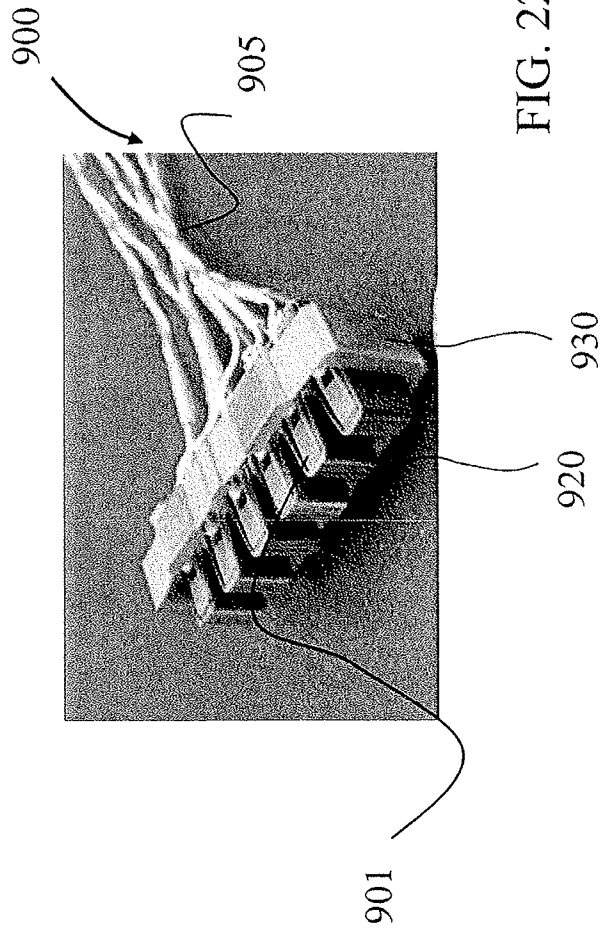


FIG. 22B

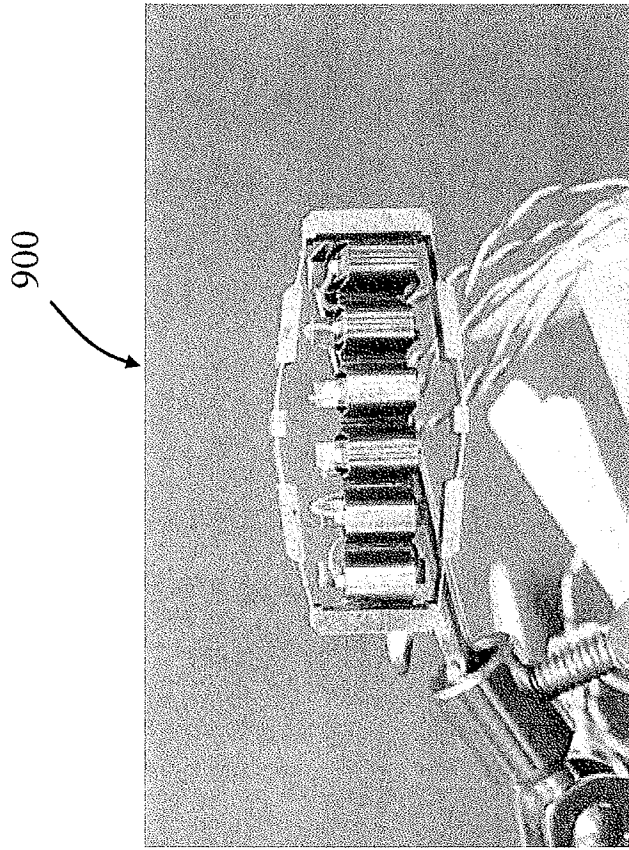


FIG. 22C

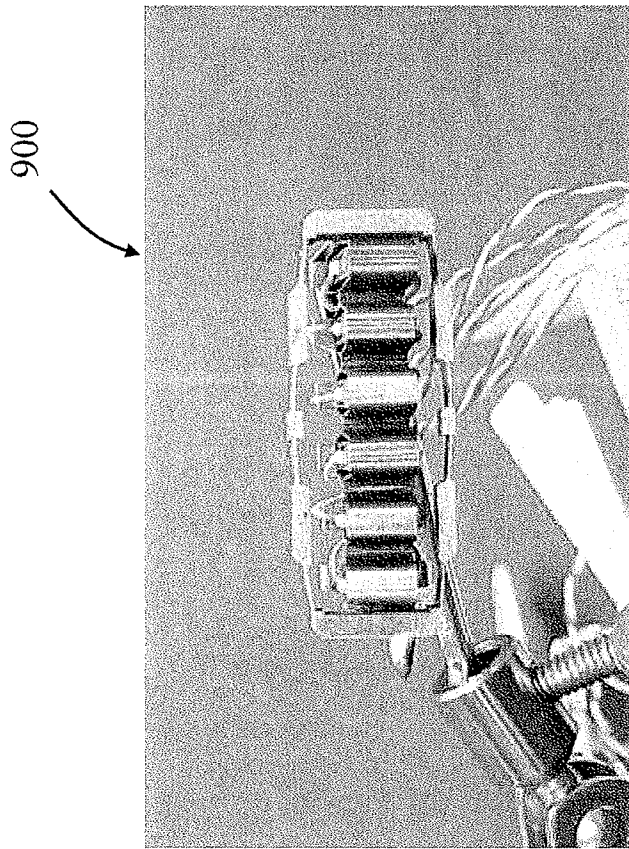
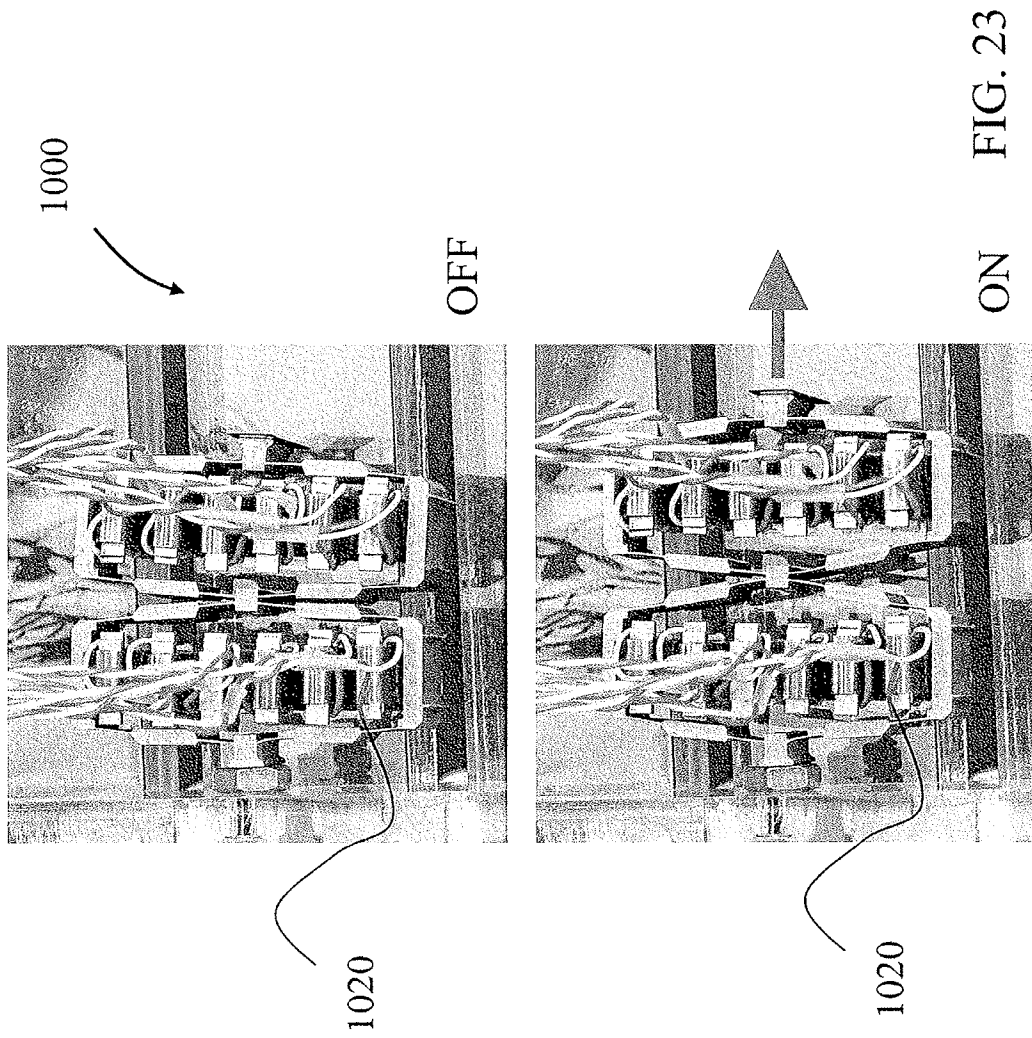
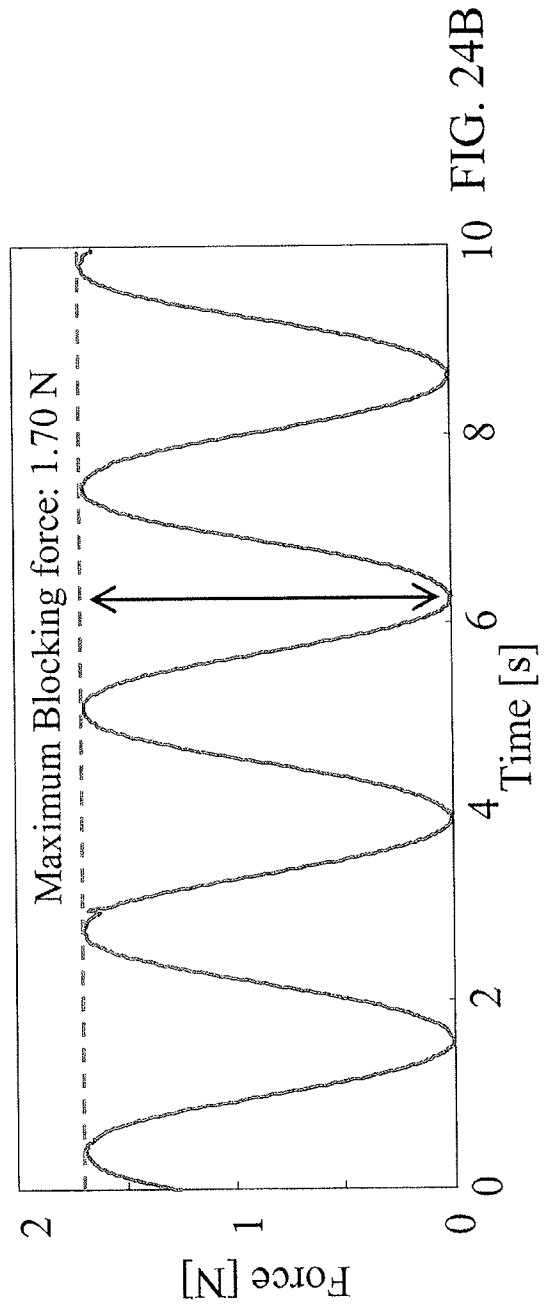
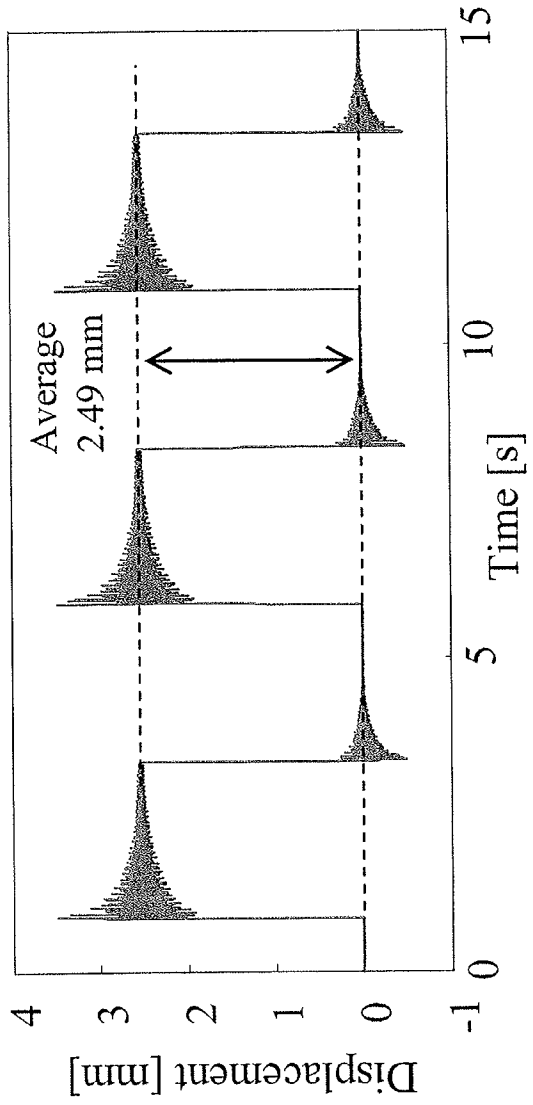


FIG. 22D





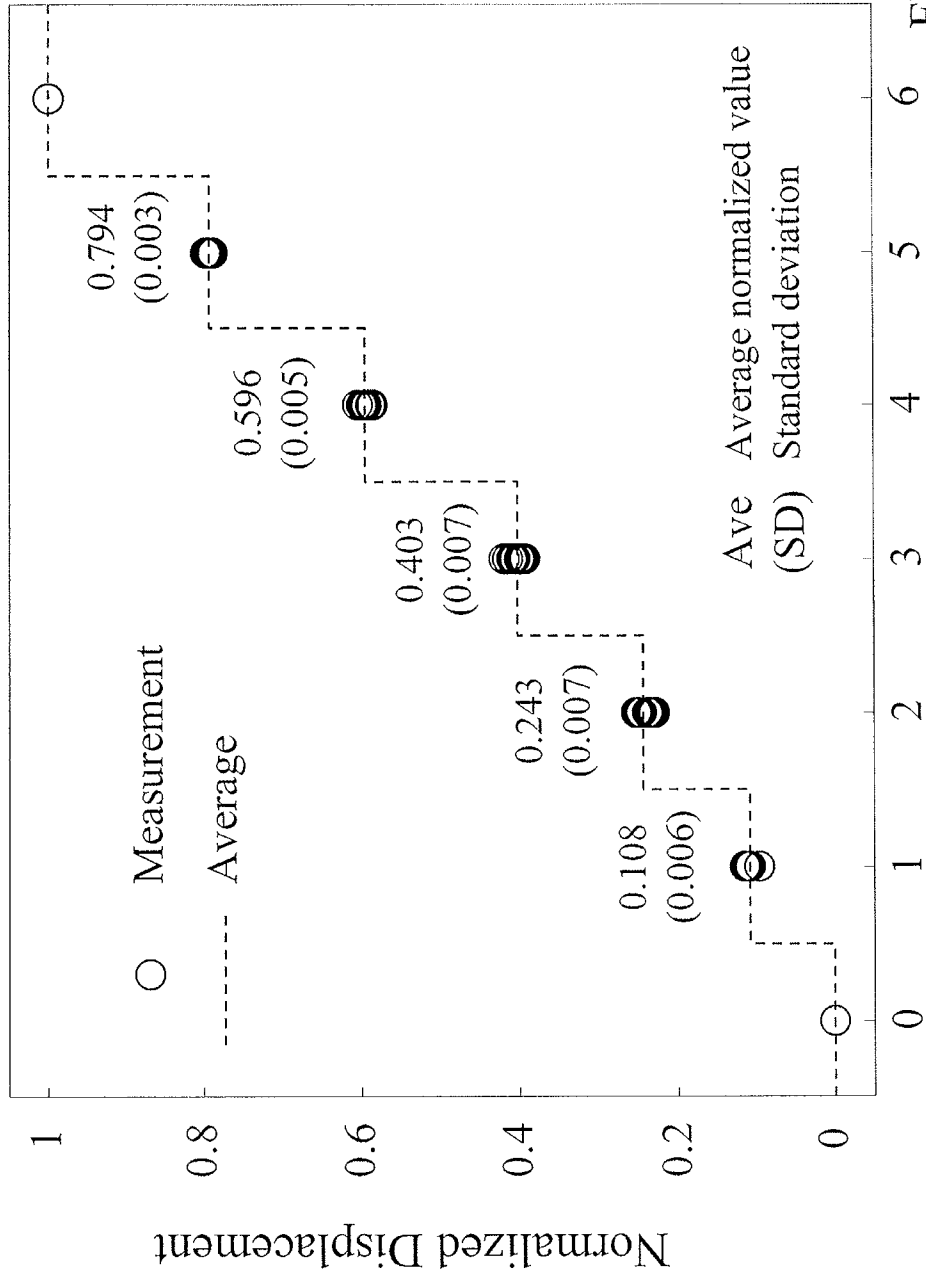
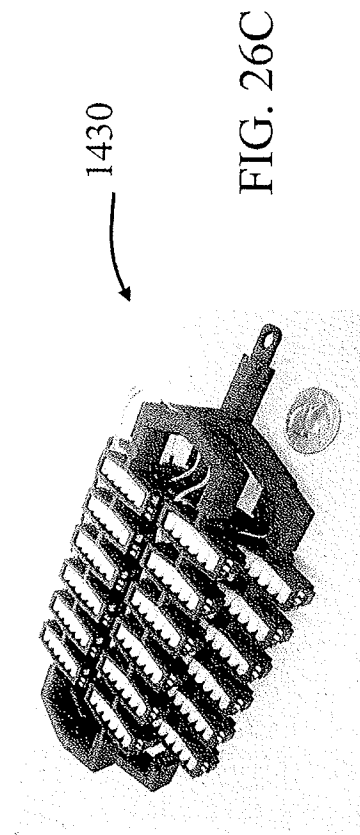
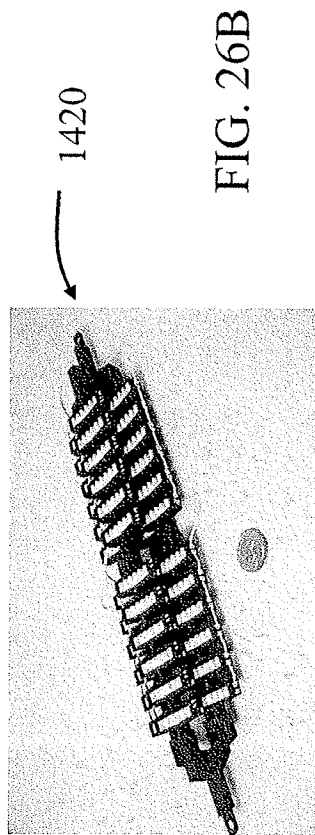
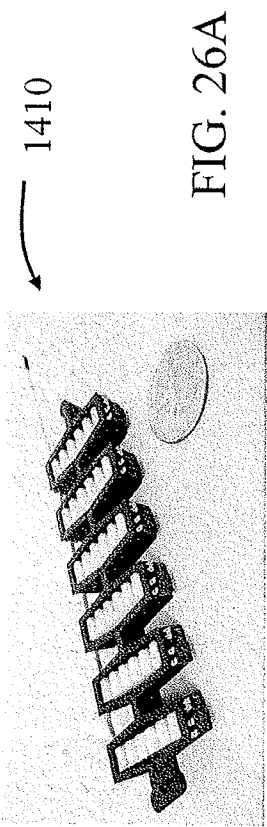


FIG. 25
Number of Units Turned On



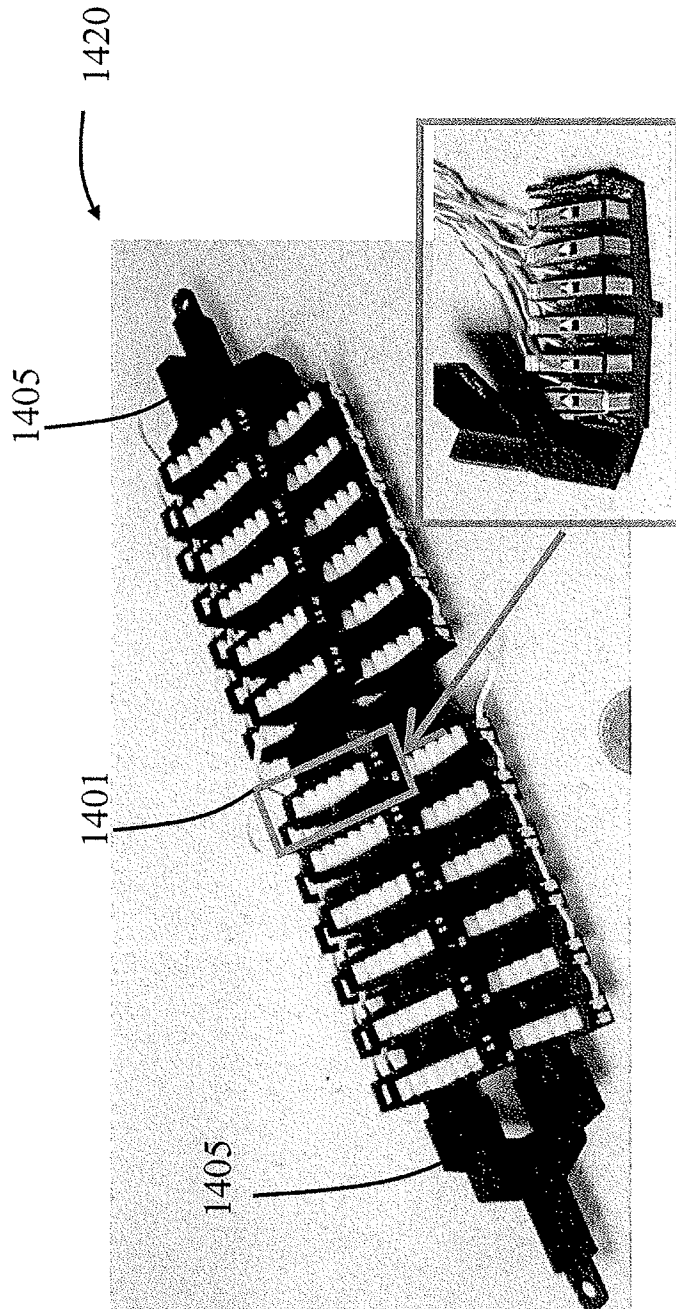


FIG. 27

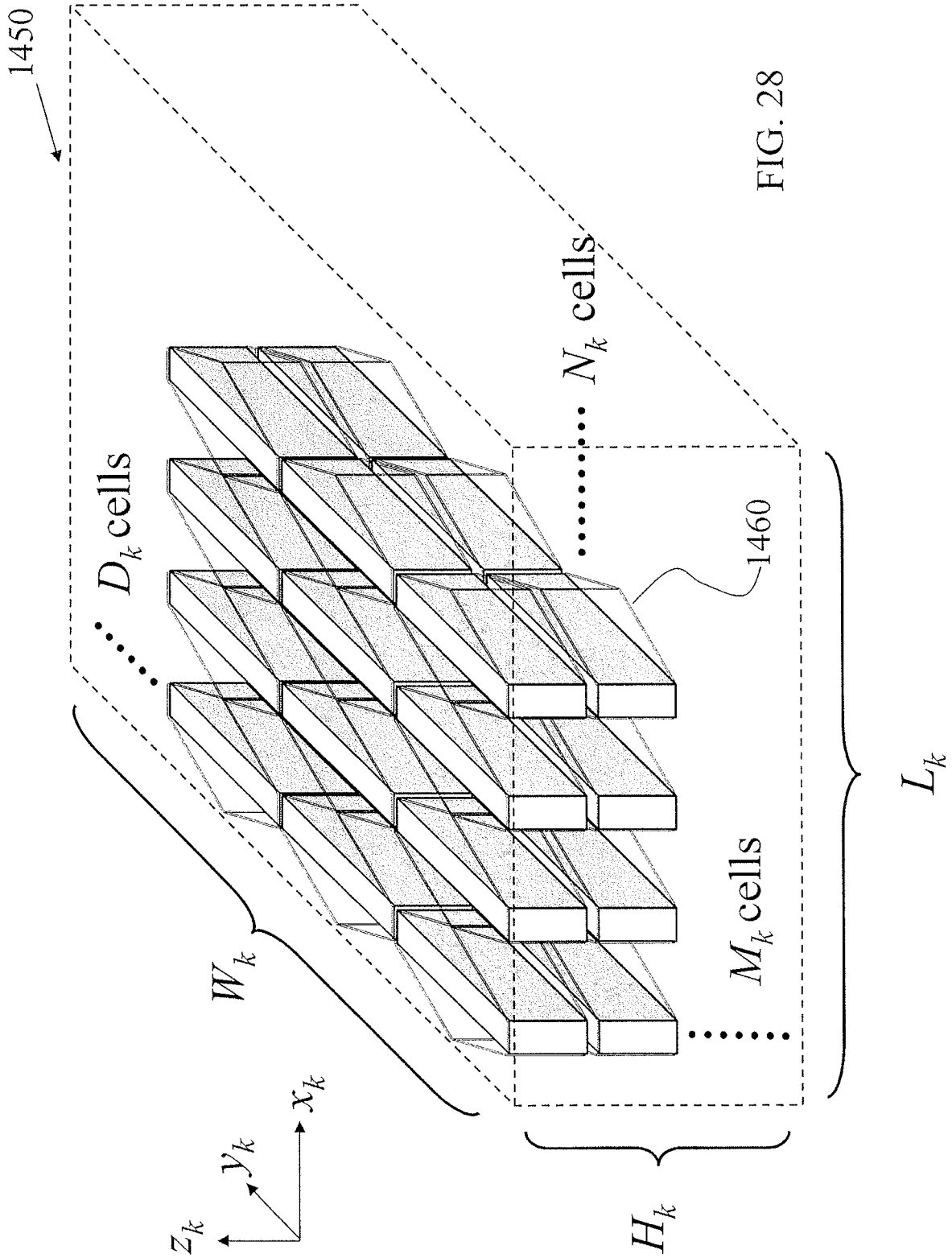


FIG. 28

1510

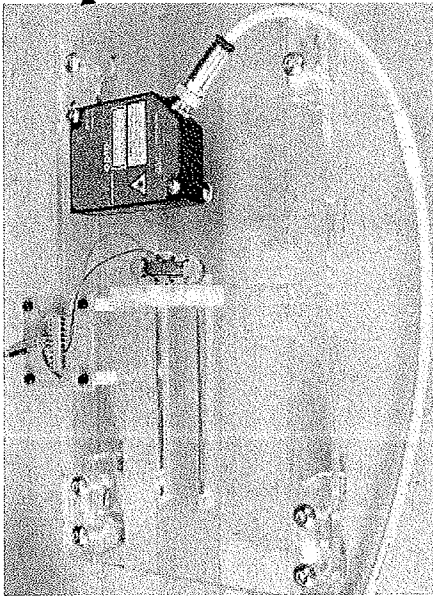


FIG. 30A

1520

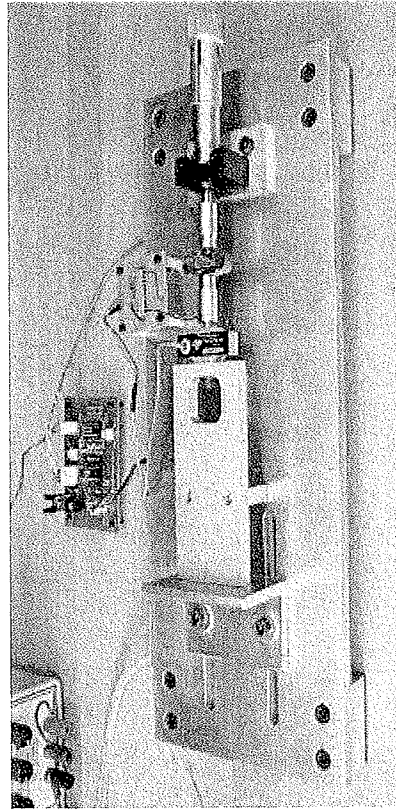


FIG. 30B

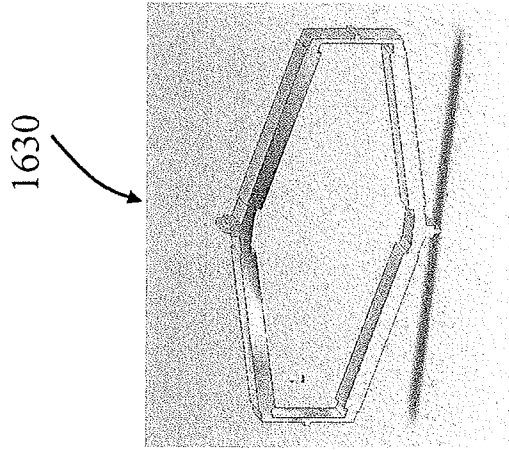


FIG. 31C

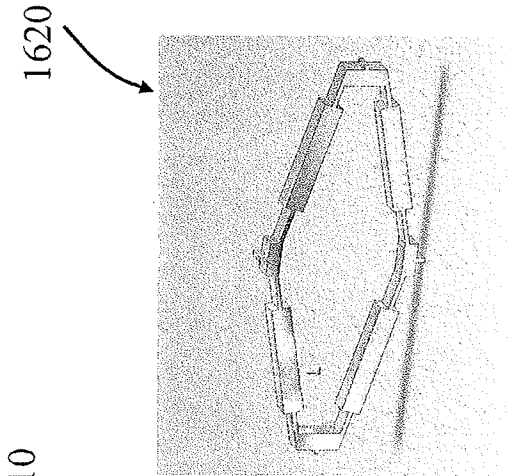


FIG. 31B

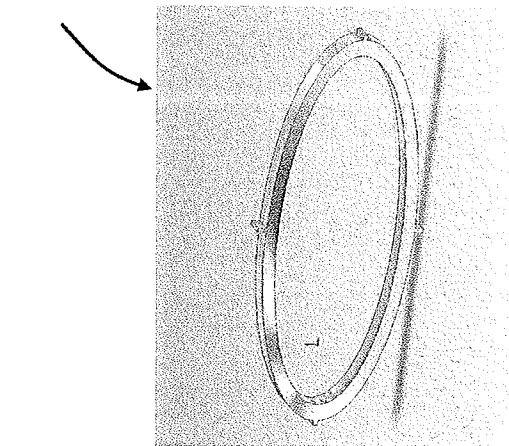


FIG. 31A

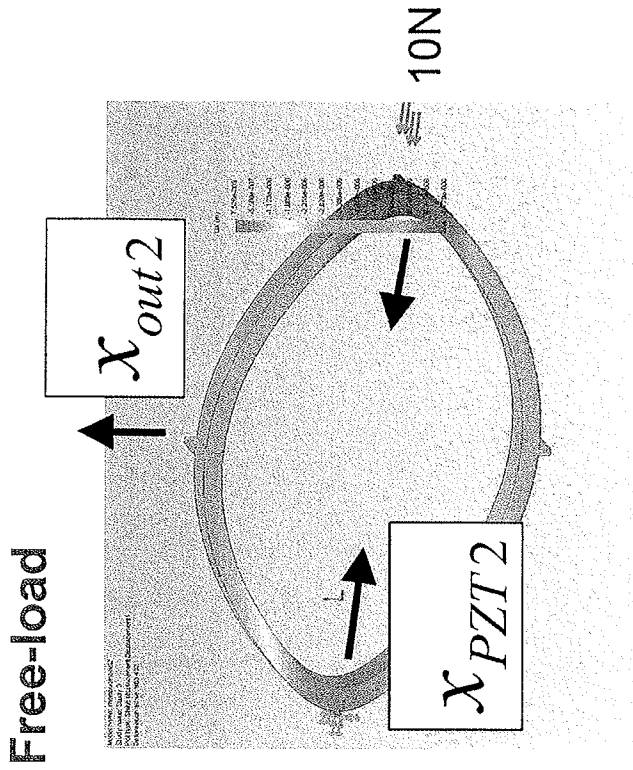


FIG. 32B

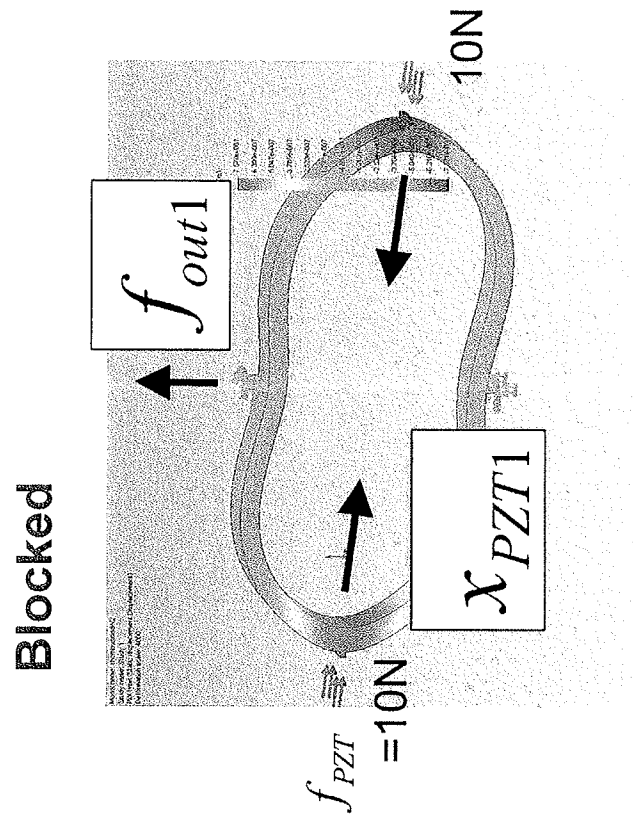


FIG. 32A

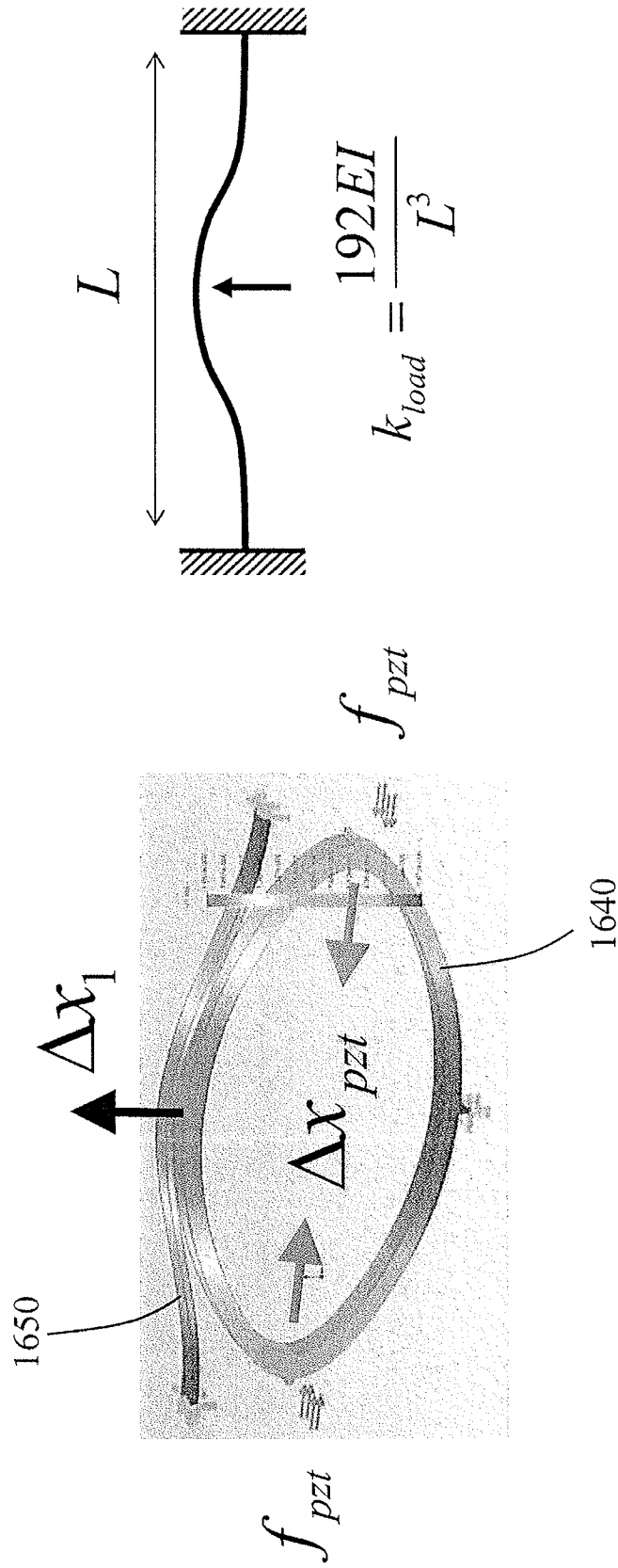


FIG. 33

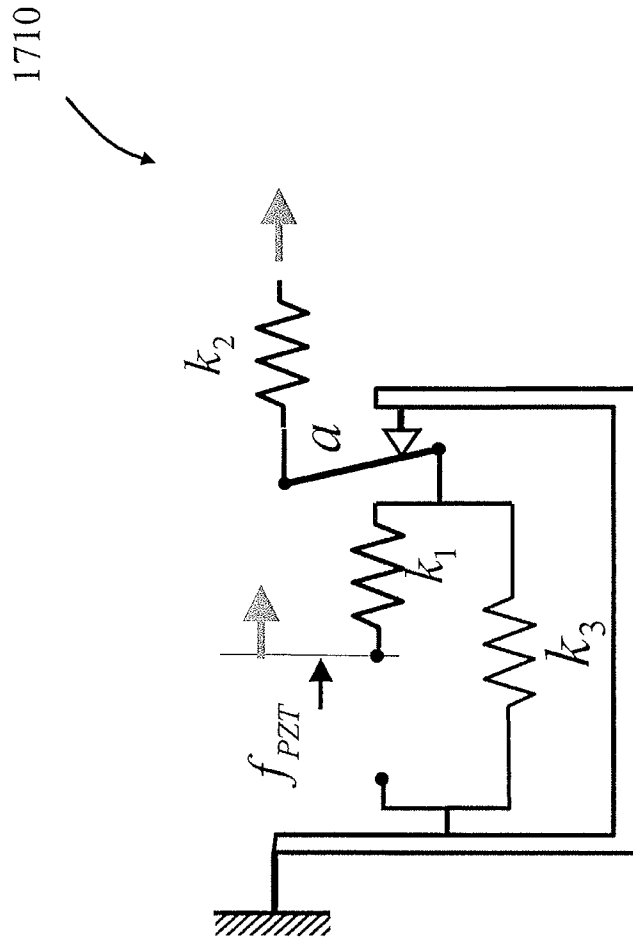


FIG. 34

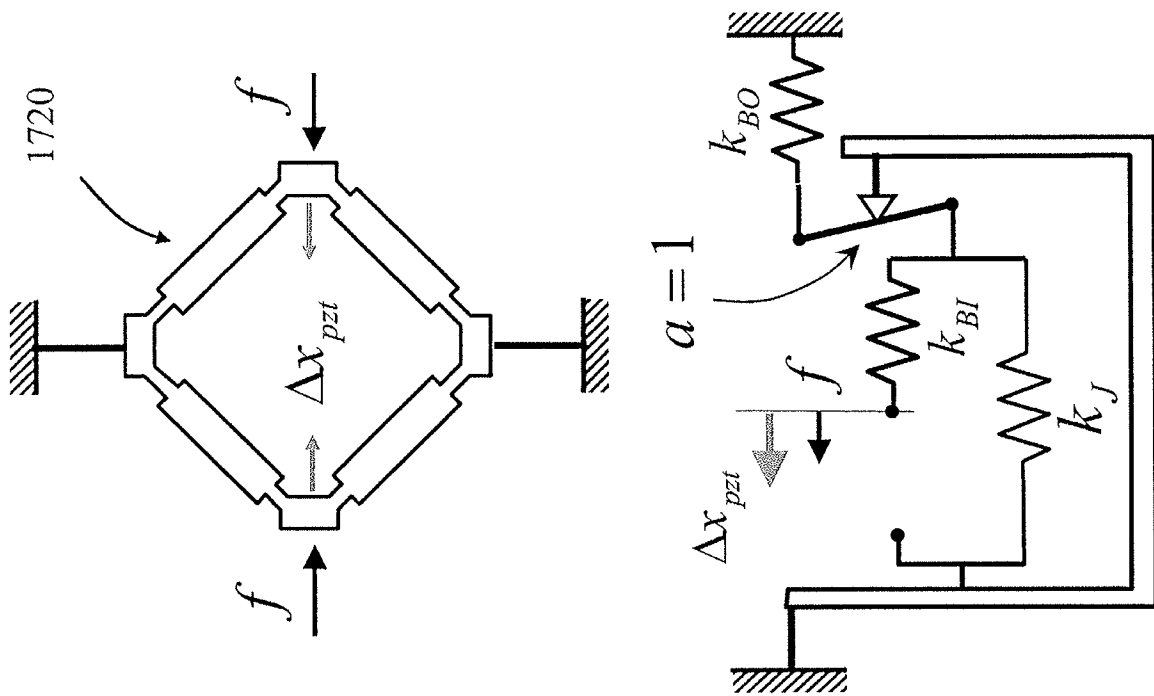
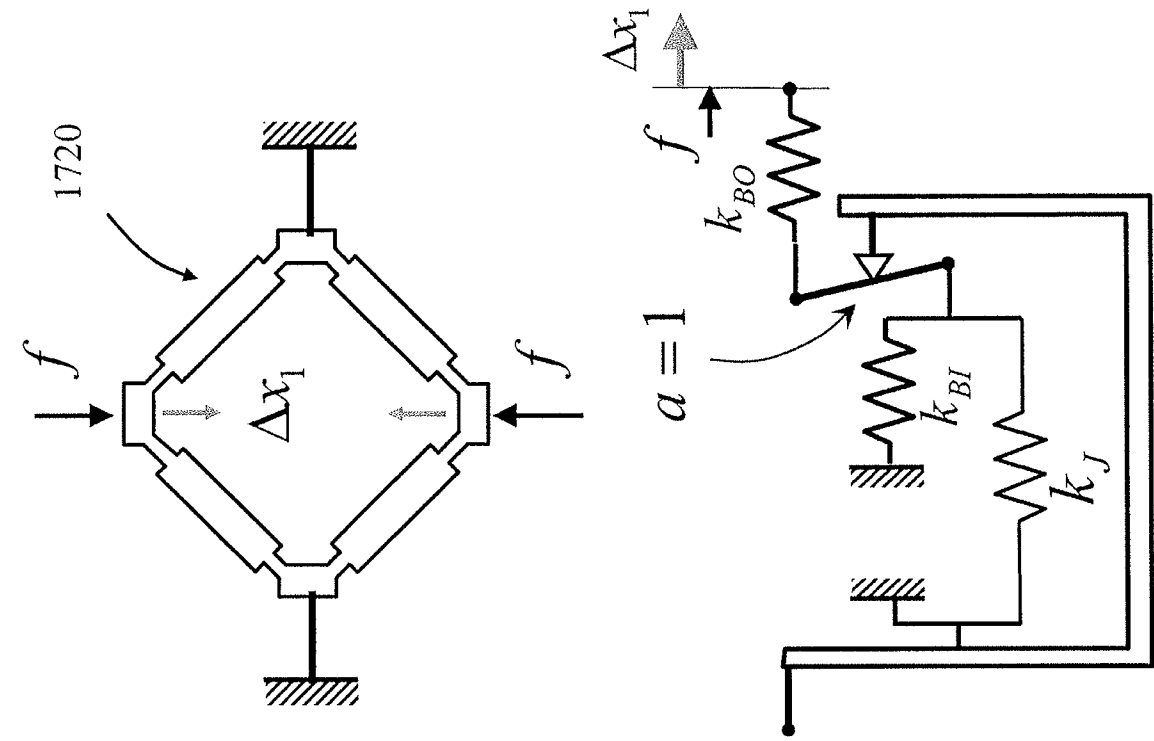


FIG. 35A

FIG. 35B

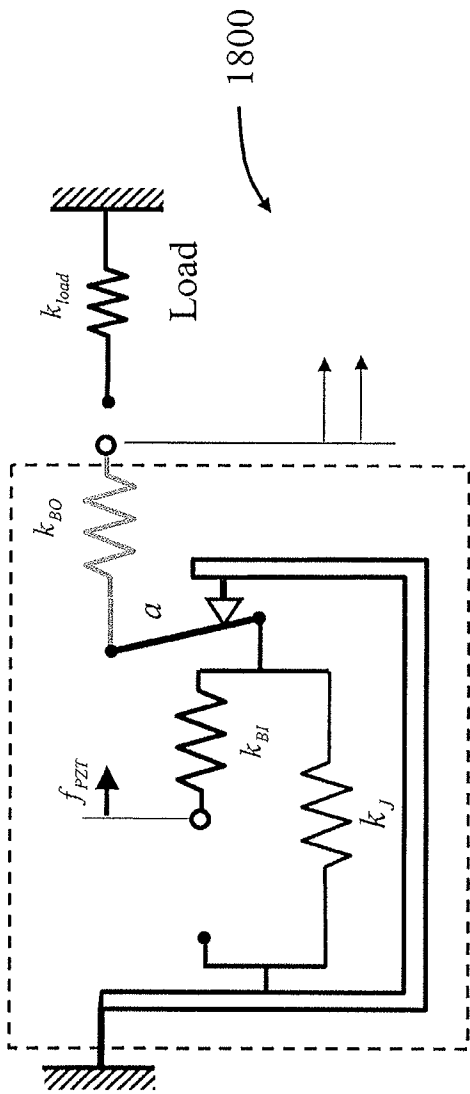
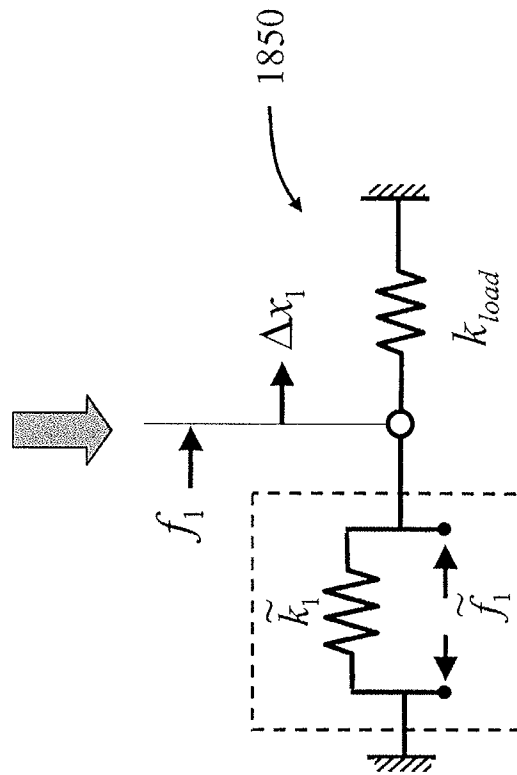


FIG. 36



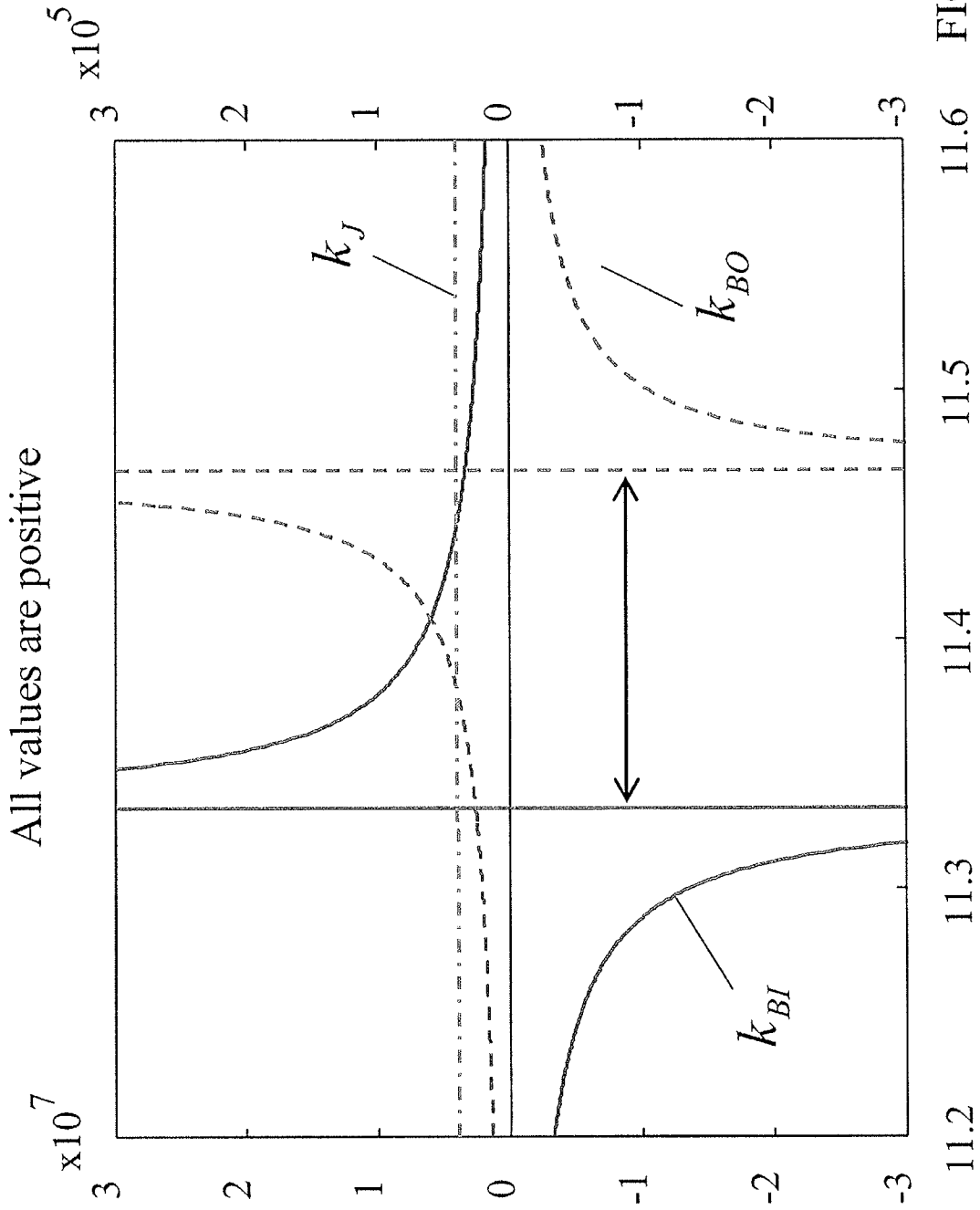
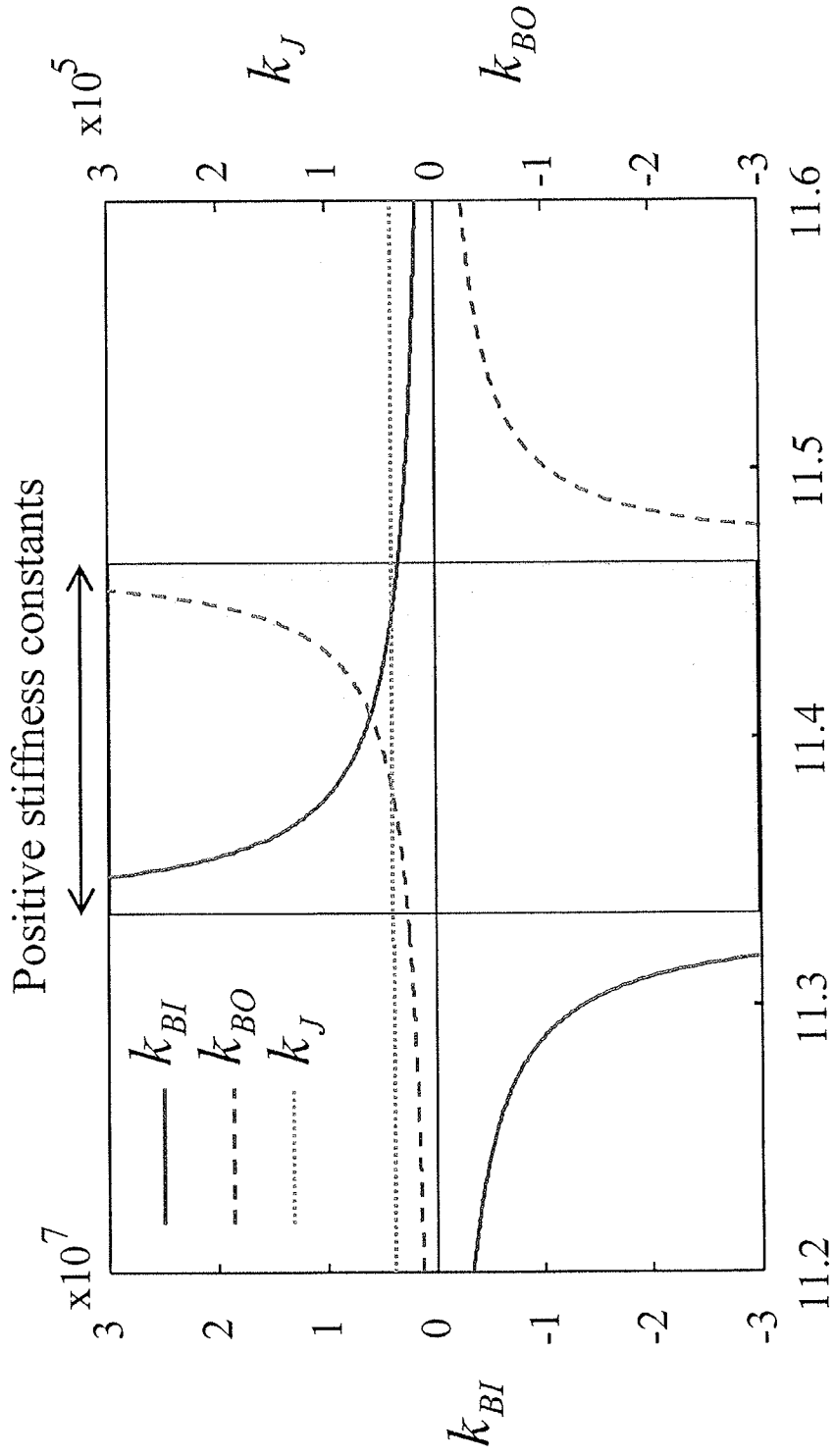


FIG. 38A



a

FIG. 38B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/081153

A. CLASSIFICATION OF SUBJECT MATTER INV. H01L41/09		
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) H01L		
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 practical, search terms used) EPO-Internal, WPI Data, INSPEC, COMPENDEX		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 465 936 B1 (KNOWLES GARETH J ET AL) 15 October 2002 (2002-10-15) column 3, lines 27-67; figure 1 column 5, lines 25-57; figures 6-8	1-19
P, X	UEDA J ET AL: "Design of PZT cellular actuators with power-law strain amplification" 2007 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, 29 OCTOBER -2 NOVEMBER 2007, SAN DIEGO, CA, USA, 2007, pages 1160-1165, XP031222298 sections II.B, V; figures 4,9	1-19
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> 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 document 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	
25 February 2009	09/03/2009	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Köpf, Christian	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2008/081153

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6465936	B1	15-10-2002	NONE