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

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
26 July 2012 (26.07.2012)

WIPO | PCT

(10) **International Publication Number**
WO 2012/097868 A1

(51) **International Patent Classification**:
H01L 41/04 (2006.01) *H01L 41/09* (2006.01)

(21) **International Application Number**:
PCT/EP2011/050599

(22) **International Filing Date**:
18 January 2011 (18.01.2011)

(25) **Filing Language**: English

(26) **Publication Language**: English

(71) **Applicant** *(for all designated States except US)*: **PIEZOMOTOR UPPSALA AB** [SE/SE]; Stålgatan 14, SE-754 50 Uppsala (SE).

(72) **Inventor; and**
(75) **Inventor/Applicant** *(for US only)*: **BEXELL, Mats** [SE/SE]; Södra Tibblevägen 150, SE-743 64 Uppsala (SE).

(74) **Agents**: **STENBORG, Anders** et al.; P.O. Box 1544, SE-751 45 Uppsala (SE).

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

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: OPERATION OF ELECTROMECHANICAL ACTUATOR DEVICES

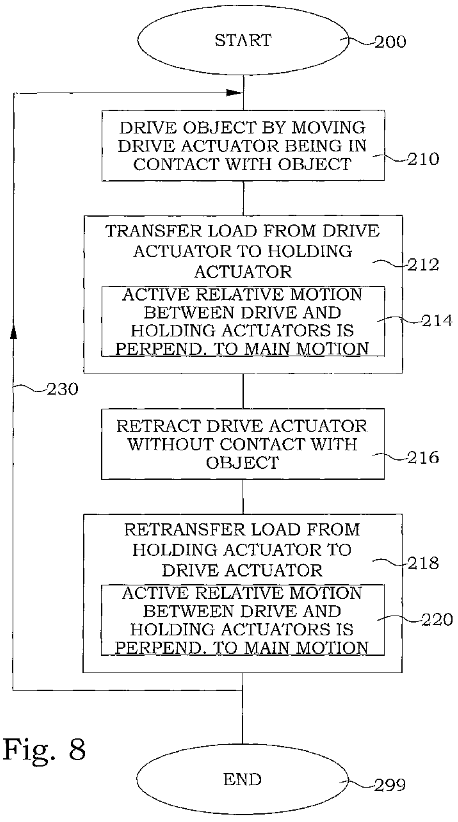


Fig. 8

(57) **Abstract**: A method for driving an electromechanical actuator device comprises driving (210) of an object by moving a driving interaction portion of a drive actuator in contact with an interaction surface of the object. A load is transferred (212) from the drive actuator to a holding actuator. An active relative motion between the holding interaction portion and the driving interaction portion is perpendicular (214) to the main motion direction during the entire removing of the deformation of the drive actuator and the entire releasing of the driving interaction portion from the interaction surface. The drive actuator is retracted (216) after the transferring free from mechanical contact with the interaction surface. The load of the object is retransferred (218) from the holding actuator to the drive actuator after the retracting. The driving, transferring, retracting and retransferring is repeated (230), thereby creating a stepwise motion of the object in the main motion direction.

WO 2012/097868 A1

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *of inventorship (Rule 4.17(iv))*

Published:

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

OPERATION OF ELECTROMECHANICAL ACTUATOR DEVICES

TECHNICAL FIELD

The present invention relates in general to operation of electromechanical actuators, and in particular to generating a motion by repetition of small steps by electromechanical actuators.

BACKGROUND

Electromechanical actuators, and particularly electromechanical motors, have been widely applied for many different tasks during recent years. High force, small size, high speed, high-precision positioning and inexpensive manufacturing are attractive characteristics of many of the prior-art motors. However, the attractive characteristics are often contradictory, and optimizing regarding one aspect often reduces other qualities.

Electromechanical actuator arrangements using a set of drive elements presenting a two-dimensional motion have been discussed for a while. In US 6,066,911, stacks of piezoelectric layers are formed side by side on a common piezoelectric base. This drive element was intended to be driven in the ultrasonic frequency range, and thereby benefit from high speed and high power efficiency. In US 6,337,532, a similar basic approach is used, but the operation is intended for a non-resonant walking operation. The excitation of the piezo-legs is performed in a very controlled manner, giving a smooth motion and a very accurate positioning. However, the operation frequencies are far below resonance.

When going to extremely precise positioning, there are certain considerations that has to be taken concerning the walking operation. When shifting the load of the object to be moved from one set of actuators to another set, the elastic deformation of the actuators and the relative length of the actuators will play a roll in the predictability and repeatability of the step length. Furthermore, in order to be able to utilize the maximum theoretical step length, the exact relative lengths of the actuators have to be known very accurately. This calls for extremely high requirements in the production of the actuators, and increase therefore the all-over manufacturing costs.

A similar approach is disclosed in US 7,067,958. In one of the embodiments presented therein, the idea of using one drive actuator and one holding actuator is presented in order to reduce the heat generation in the volumes of the active electromechanical material. The tip of the drive actuator is movable along a two-dimensional path relative the common support. The tip of the holding actuator(s) is instead only movable linearly perpendicular to the intended motion direction. In short, the drive actuator comes into mechanical interaction with an interaction surface of an object to be moved. By moving the tip of the drive actuator in the intended motion direction, a force is applied on the object, which essentially follows the tip. When the drive actuator is going to return to its original position, the object is allowed to rest on the holding actuator, while the drive actuator releases its mechanical contact with the object. In this way, a stepwise motion is created by use of only one two-dimensionally movable actuator. The holding actuators are intended to be more or less stationary during the driving, which means that very little heat is produced by these. The main displacement of the holding actuators is intended for adjusting the effective step length. Any motion of the holding actuators during the handing-over procedures is supposed to be used for giving a smooth transfer of the mechanical contact of the object to or from the drive actuator. To this end, the drive actuator and the holding actuator are thereby given essentially the same velocities in the Z direction during the transfer period, i.e. they are moving in the same Z-direction.

This main driving principle has proved to be operating well in most respects. In certain applications, however, minor drawbacks are noted. Since the motion of the driving actuator is the main action during the transfer of the load of the object between driving and holding actuators, and this motion typically is performed in a non-perpendicular direction with respect to the interaction surface of the object to be moved, the exact position at which the holding actuator takes over the main load becomes dependent on the exact relative lengths of the actuators. Also, in order to utilize the maximum available step length, the exact relative lengths of the actuators have to be known very accurately. This gives rise to a small but existing uncertainty in the main motion direction.

In the article "Development of compact high precision linear piezoelectric stepping positioner with nanometer accuracy and large travel range" by D. Kang et al in Review of Scientific Instruments 78, 075112, 2007, a piezoelectric stepping positioner is disclosed, having a feeding actuator based on a shear deformation in the actuator and clamping actuators based on linearly extendable actuators. In a feeding phase, the feeding actuator is in contact with the object to be moved, while during a recovering phase, the object rests on the clamping actuators. The object is thereby given a stepwise motion. The feeding actuator is driven by a sinusoidal voltage while the clamping actuators are fed by a stepped voltage.

The step of the clamping actuators is, however, not perfectly momentary. Furthermore, during the actual transfer of the load between the feeding actuator and the clamping actuators, elastic deformations are occurring at the party taking over the load and at the same time elastic deformations are removed from the party leaving the load. This means that the actual transfer takes a certain time to perform. In the article, a glitch is noticed at the transfer occasion. For shorter operation periods and for constant load conditions, such glitches are probably fairly repeatable. However, with time or with changing operation conditions, also such glitch will change and introduce an uncertainty in positioning.

SUMMARY

An object of the present invention is to improve predictability and repeatability in step length. Another object of the present invention is to reduce the sensitivity of the positioning accuracy to any uncertainties in actuator lengths.

These objects are achieved by electromechanical actuator devices and methods according to the enclosed independent claims. Preferred embodiments are defined in dependent claims. In general words, in a first aspect, a method for driving an electromechanical actuator device comprises driving of an object by causing a drive actuator to move a driving interaction portion thereof along a driving path section. The driving interaction portion is in mechanical contact with an interaction surface of the object during the driving. The driving path section has at least a component along a main motion direction of the object. A load of the object is transferred from the drive actuator to a holding actuator after the driving, thereby removing a deformation of the drive actuator caused by the load of the object and releasing the driving interaction portion from the interaction surface. The transferring causes the holding actuator to move a holding interaction portion along a gripping path into a mechanical contact with the interaction surface. An active relative motion between the holding interaction portion and the driving interaction portion is perpendicular to the main motion direction during a releasing period. The releasing period comprises the entire removing of the deformation of the drive actuator caused by the load of the object and the entire releasing of the driving interaction portion from the interaction surface. The drive actuator is retracted after the transferring by causing the drive actuator to move the driving interaction portion along a retracting path section. During the retraction, the driving interaction portion is free from mechanical contact with the interaction surface of the object. The retracting path section has at least a component in opposite direction to the main motion direction of the object. The load of the object is retransferred from the holding actuator to the drive actuator after the retracting, thereby generating a deformation of the drive actuator caused by the load of the object and creating a mechanical contact between the driving interaction portion and the interaction surface. The retransferring causes the holding actuator to move a holding interaction portion along a releasing path removing the mechanical contact with the interaction surface. The drive actuator is caused to move by exciting volumes of electromechanically active material within the drive actuator. Also the holding actuator is caused to move by exciting volumes of electromechanically active material within the holding actuator. The driving, transferring, retracting and retransferring is repeated, thereby creating a stepwise motion of the object in the main motion direction.

In a second aspect, a method for driving an electromechanical actuator device comprises driving of an object by causing a drive actuator to move a driving interaction portion thereof along a driving path section. The driving interaction portion is in mechanical contact with an interaction surface of the object during the driving. The driving path section has at least a component along a main motion direction of the object. A load of the object is transferred from the drive actuator to a holding actuator after the driving, thereby removing a deformation of the drive actuator caused by the load of the object and releasing the driving interaction portion from the interaction surface. The transferring causes the holding actuator to move a holding interaction portion along a gripping path into a mechanical contact with the interaction surface. The drive actuator is retracted after the transferring by causing the drive actuator to move the driving interaction portion along a retracting path section. During the retraction, the driving interaction portion is free from mechanical contact with the interaction surface of the object. The retracting path section has at least a component in opposite direction to the main motion direction of the object. The load of the object is retransferred from the holding actuator to the drive actuator after the retracting, thereby generating a deformation of the drive actuator caused by the load of the object and creating a mechanical contact between the driving interaction portion and the interaction surface. The retransferring causes the holding actuator to move a holding interaction portion along a releasing path removing the mechanical contact with the interaction surface. An active relative motion between the holding interaction portion and the driving interaction portion is perpendicular to the main motion direction during a gripping period. The gripping period comprises the entire generating of the deformation of the drive actuator caused by the load of the object and the entire creating of the mechanical contact between the driving interaction portion and the interaction surface. The drive actuator is caused to move by exciting volumes of electromechanically active material within the drive actuator. Also the holding actuator is caused to move by exciting volumes of electromechanically active material within the holding actuator. The driving, transferring, retracting and retransferring is repeated, thereby creating a stepwise motion of the object in the main motion direction.

In a third aspect, an electromechanical actuator device comprises a drive actuator, a holding actuator, an object to be moved in a main motion direction and drive electronics. The drive actuator has a driving interaction portion. The holding actuator has a holding interaction portion. The object has an interaction surface. The drive actuator comprises volumes of electromechanically active material and electrodes for exciting the electromechanically active material to cause geometrical changes of the drive actuator. The holding actuator similarly comprises volumes of electromechanically active material and electrodes for exciting the electromechanically active material to cause geometrical changes of the holding actuator. The drive electronics is connected to the electrodes of the drive actuator and the holding actuator. The drive electronics is arranged for providing electrical signals for exciting the volumes of electromechanically active material of the drive actuator and the holding actuator. The electrical signals are adapted to drive the object by causing the drive actuator to move the driving interaction portion along a driving path section while being in mechanical contact with said interaction surface of the object. The driving path section has at least a component along the main motion direction. The electrical signals are further adapted to transfer a load of the object from the drive actuator to the holding actuator after the driving, thereby removing a deformation of the drive actuator caused by the load of the object and releasing the driving interaction portion from the interaction surface. The transferring also causes the holding actuator to move the holding interaction portion along a gripping path into a mechanical contact with the interaction surface. The electrical signals are adapted to cause an active relative motion between the holding interaction portion and the driving interaction portion to be perpendicular to the main motion direction during a releasing period. The releasing period comprises the entire removing of the deformation of the drive actuator caused by the load of the object and the entire releasing of the driving interaction portion from the interaction surface. The electrical signals are further adapted to retract the drive actuator after the transferring by causing the drive actuator to move the driving interaction portion along a retracting path section. During the retracting, the driving interaction portion is free from mechanical contact with the interaction surface of the object. The retracting path section has at least a component in opposite direction to the main motion direction of the object. The electrical signals are further adapted to retransfer the load of the object from the holding actuator to the drive actuator after the retracting, thereby generating a deformation of the drive actuator caused by the load of the object and creating a mechanical contact between the driving interaction portion and the interaction surface. The retransferring causes the holding actuator to move the holding interaction portion along a releasing path removing the mechanical contact with the interaction surface. The electrical signals are further adapted to repeat the driving, transferring, retracting and retransferring, thereby creating a stepwise motion of the object in the main motion direction.

In a fourth aspect, an electromechanical actuator device comprises a drive actuator, a holding actuator, an object to be moved in a main motion direction and drive electronics. The drive actuator has a driving interaction portion. The holding actuator has a holding interaction portion. The object has an interaction surface. The drive actuator comprises volumes of electromechanically active material and electrodes for exciting the electromechanically active material to cause geometrical changes of the drive actuator. The holding actuator similarly comprises volumes of electromechanically active material and electrodes for exciting the electromechanically active material to cause geometrical changes of the holding actuator. The drive electronics is connected to the electrodes of the drive actuator and the holding actuator. The drive electronics is arranged for providing electrical signals for exciting the volumes of electromechanically active material of the drive actuator and the holding actuator. The electrical signals are adapted to drive the object by causing the drive actuator to move the driving interaction portion along a driving path section while being in mechanical contact with said interaction surface of the object. The driving path section has at least a component along the main motion direction. The electrical signals are further adapted to transfer a load of the object from the drive actuator to the holding actuator after the driving, thereby removing a deformation of the drive actuator caused by the load of the object and releasing the driving interaction portion from the interaction surface. The transferring also causes the holding actuator to move the holding interaction portion along a gripping path into a mechanical contact with the interaction surface. The electrical signals are further adapted to retract the drive actuator after the transferring by causing the drive actuator to move the driving interaction portion along a retracting path section. During the retracting, the driving interaction portion is free from mechanical contact with the interaction surface of the object. The retracting path section has at least a component in opposite direction to the main motion direction of the object. The electrical signals are further adapted to retransfer the load of the object from the holding actuator to the drive actuator after the retracting, thereby generating a deformation of the drive actuator caused by the load of the object and creating a mechanical contact between the driving interaction portion and the interaction surface. The retransferring causes the holding actuator to move the holding interaction portion along a releasing path removing the mechanical contact with the interaction surface. The electrical signals are adapted to cause an active relative motion between the holding interaction portion and the driving interaction portion to be perpendicular to the main motion direction during a gripping period. The gripping period comprises the entire generating of the deformation of the drive actuator caused by the load of the object and the entire creating of the mechanical contact between the driving interaction portion and the interaction surface. The electrical signals are further adapted to repeat the driving, transferring, retracting and retransferring, thereby creating a stepwise motion of the object in the main motion direction.

One advantage with the present invention is that the electromechanical actuator devices become more insensitive to errors in the actuator devices, and thereby to wear and temperature changes. Furthermore, it is easier to achieve the maximum step length allowed by the selected design and voltages. Also, the positioning becomes more predictable.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention, together with further objects and advantages thereof, may best be understood by making reference to the following description taken together with the accompanying drawings, in which:

FIGS. 1A-B are schematic illustrations of a prior art electromechanical actuator device;

FIGS. 2A-C are schematic illustrations of another prior art electromechanical actuator device;

FIGS. 3A-D are schematic illustrations of embodiments of electromechanical actuator devices;

FIGS. 4A-C are diagrams of embodiments of voltage curves provided to an electromechanical actuator;

FIG. 4D is a diagram illustrating an embodiment of motion patterns of actuator front ends obtained with the voltage curves of FIGS. 4A-C;

FIGS. 5A-C are diagrams of other embodiments of voltage curves provided to an electromechanical actuator;

FIG. 5D is a diagram illustrating an embodiment of motion patterns of actuator front ends obtained with the voltage curves of FIGS. 5A-C;

FIGS. 6A-C are diagrams of other embodiments of voltage curves provided to an electromechanical actuator;

FIGS. 7A-C are diagrams of other embodiments of voltage curves provided to an electromechanical actuator;

FIG. 8 is a flow diagram of steps of an embodiment of a method for driving an electromechanical actuator device;

FIGS. 9A-B are schematic illustrations of embodiments of electronics devices for supply of voltage signals to electromechanical actuators;

FIG. 9C is a diagram illustrating charging and discharging of actuators;

FIG. 9D is a diagram illustrating an embodiment of a pulse-width modulation for charging and discharging of actuators;

FIGS. 10A-B are schematic illustrations of embodiments of electrode connections in an electromechanical actuator device;

FIG. 11A is a diagram illustrating another embodiment of motion patterns of actuator front ends;

FIGS. 11B-D are diagrams of embodiments of voltage curves provided to an electromechanical actuator for giving rise to the motion pattern of Fig. 11A; and

FIG. 12 is a flow diagram of steps of an embodiment of a method for parking an electromechanical actuator device.

DETAILED DESCRIPTION

Throughout the drawings, the same reference numbers are used for similar or corresponding elements.

The problems under consideration by the present invention are generally very small and in most applications more or less negligible. However, in applications where extreme performance is requested, even small problems have to be solved in order to give a satisfactory operation. In order to fully understand the basic reasons for searching for a solution, two examples of prior art devices and their operation are going to be presented.

In a general motor according to the principles presented in e.g. the US patent 6,337,532, two sets of driving actuators are used, which are in alternating contact with the object to be moved. Since the motion is basically non-resonant, the mechanical contact between the interaction portion at the end of the actuators and the interaction surface of the object to be moved is maintained during essentially the entire time the mechanical contact exists. However, possible uncertainties arise during the transfer of the load of the object to be moved to the other set of actuators. In Fig. 1A, two actuators 2A and 2B are illustrated, which are movable in two dimensions by means of exciting volumes of electromechanically active material in the actuators. The actuators 2A and 2B can by suitable applied voltages be caused to bend in the plane of the paper and to expand or contract in the vertical direction of the drawing. Note that all motions are extremely exaggerated in the figure in order to illustrate the basic concepts. The tips of the actuators are alternating in contact with an interaction surface 52 of an object 50 to be moved and when an actuator in contact with the object 50 moves its tip, the object 50 will follow if a normal force N between the actuator and the object 50 is large enough to prohibit sliding.

The result will be a motion in a main motion direction 9. The situation in Fig. 1A is such that the actuator 2A is in mechanical contact with the interaction surface 52 of the object 50 and has reached the bending condition to the right direction in the figure at which a transferring of the load to the other actuator is to be performed. The actuator 2B is instead not loaded by the object 50 but also in position for taking over the load from the actuator 2A. Since the actuator 2A bears the normal force from the object 50, the actuator 2A exhibits an elastic deformation. This deformation is directed mainly downwards (as defined in the figure), but may also have some component in the main motion direction, depending on the bending conditions. Similarly, a force P applied between the object 50 and the actuator 1A needed for achieving the motion of the object 50 acts on the tip of the actuator 1A in a direction opposite to the main motion direction 9. In the figure, the arrows indicating the direction of the forces are of about equal size, however, in reality, the driving force P is typically smaller and usually much smaller than the normal force N if the driving surface is flat. In order to achieve a motion, the ratio P/N has to be smaller than the friction coefficient between the actuator and the object. This driving force P also causes the actuator 1A to deform elastically. The shape of the actuator 2A as it should have been at a similar excitation condition but without loads is illustrated by the broken lines. A discrepancy Δ1 in position in the main motion direction 9 will be present. The size of this discrepancy depends on the loads, i.e. the normal force N and the applied moving force P, and on the geometrical shape and material of the actuator 2A. In this situation the elastic deformations caused by the normal force N and the applied moving force P are in the same direction. The load from the object onto the actuator typically comprises a normal force component and a component in the main motion direction associated with the driving force.

Fig. 1B illustrates the situation when the load has been transferred to the actuator 2B instead. It is now the actuator 2B that exhibits a discrepancy Δ2 compared to its unloaded position. In this situation, the deformation caused by the normal force N acts in an opposite direction compared to the deformation caused by the force P. For this reason, it is in fact not even known in which direction the total discrepancy Δ2 is directed. The exact cause of events that occurs between the situations of the figures 1A and 1B is not completely known, at least not in prior art. The normal load has to be transferred as well as the force on the object 50 in the main motion direction, but if this is made successively, more abrupt or if there will be any sliding between the actuator tips and the interaction surface 52, is generally unknown. This also means that the exact position of the object 50 in the main motion direction 9 is not known with an accuracy better that the sum of the discrepancies Δ1 and Δ2. The conditions that influence the exact behaviour during the transfer may also change with time, e.g. as a result of wear, temperature changes or that the surface conditions vary over the interaction surface 52.

Furthermore, if the actuators 2A and 2B during the transfer are driven in any path having a relative component parallel to the main motion direction, a size of such motion component will add to the uncertainty of the positioning.

Fig. 2A illustrates a motor according to the principles presented in one of the embodiments of the US patent 7,067,958. A holding actuator 2C and a driving actuator 2A are illustrated. The driving actuator bears the load N of the normal force and exhibits a forces P relative the object 50, but is ready for transferring them onto the holding actuator 2C. As in Fig. 1A, the load N and the force P cause a certain elastic deformation of the driving actuator 2A. Besides the discrepancy Δ1 in the driving direction, there is also a discrepancy Δ3 in height. To cause the transferring to occur, the driving actuator 2A typically moves in a sloped direction, indicated by arrow 4.

The result is illustrated in Fig. 2B, where the holding actuator bears the normal force N and the load P from the object 50. The holding actuator has an elastic deformation component Δ4 that is directed in the direction of extension of the holding actuator 2C. Furthermore, the driving force P against the object 50 will also give a deformation component Δ6 in the main motion direction 9. Also in this case, the exact conditions for the load transfer are unknown. For instance, it is unknown at what height the holding actuator 2C takes over the non-sliding mechanical contact with the interaction surface 52. Since the relative motion between the tips of the driving and holding actuators is sloped, a height uncertainty, up to the sum of Δ3 and Δ4 automatically also becomes an uncertainty Δ5 in the main motion direction, as indicated in Fig. 2C, which adds to the uncertainty Δ6.

The general purpose of the present invention is to provide methods and devices which to an as large extent as possible avoid the situations described above. The uncertainties will not even according to the present invention be totally removed, but their size and influence on the performance will be reduced significantly and will be more predictable.

For being able to mitigate the uncertainty problems described above, one has to understand that the process of transferring the load is not a momentary event. Instead, the transfer takes some time, during which the loads, probably gradually, shifts from one actuator to another. This transfer is also associated with deformation of the participating actuators. The actuator taking the loads becomes deformed by the loads, while the actuator being released from the loads becomes re-deformed to an unloaded shape. Such processes occupy a non-negligible period of time.

Another understanding is also of benefit to properly realize the advantages of the present invention. The relative heights of actuators are difficult to control during the manufacturing. To achieve high relative height accuracy requires complex and expensive manufacturing steps, such as fine grinding, lapping etc. A height difference between two actuators that are going to transfer the loads of an object to move between them will give an increased uncertainty concerning the times when the transfer really occurs. If the actuators are driven with different velocities in the main motion direction, a height uncertainty is transferred directly into a position uncertainty.

One way to reduce positioning inaccuracies is to make sure that the motion in the main motion direction of one of the actuators relative the motion in the main motion direction of the other actuator becomes as small as possible during the entire transfer of load. The motion of the actuators can be divided into two parts. A first part comprises an active motion caused by excitation of the electromechanical material. A second part comprises a load induced motion, caused by forces applied to the actuators by the interaction with the object. One example to reduce positioning inaccuracies is to control the exciting voltages such that an active relative motion between the involved actuators is directed perpendicular to the main motion direction during the transfer period. In the case of a system having one or more drive actuators and one or more holding actuators, such transfer period occurs twice in each cycle; at the loading of the drive actuator and at the releasing of the drive actuator. However, the general principles are the same in both cases. If the active relative motion is controlled according to these ideas during just one of the two transfer occasions, there will still be advantages over prior art, however, smaller than if both transfers are considered.

Fig. 3A illustrates schematically an embodiment of an electromechanical actuator 10 according to the present invention. An actuator body 20 comprises a drive actuator 30 and, in this embodiment, two holding actuators 40. The drive actuator 30 has a driving interaction portion 32, intended for interaction with an interaction surface 52 of an object 50 to be moved in a main motion direction 9. Similarly, the holding actuators 40 have a respective holding interaction portion 42.

The drive actuator 30 comprises volumes 34, 35 of electromechanically active material and electrodes 36, 37 for exciting the electromechanically active material to cause geometrical changes of the drive actuator 30. In this particular embodiment, the drive actuator 30 is caused to move by separately exciting two volumes 34, 35 of electromechanically active material within a bimorph structure 38 of the drive actuator 30. The volumes 34 and 35 are possible to activate independently of each other, since they have respective electrodes 36, 37 that are not connected directly together. However, the volumes

34, 35 will anyway strongly influence each other due to the fact that they are firmly mechanically attached to each other along an entire side. In particular embodiments, the entire drive actuator 30 is made in one single piece of material and the bimorph structure 38 then becomes defined by the distribution of the respective electrodes 36, 37. For example, when one volume 35 is excited to be expanded in a length direction 7, but not the other volume 34, the bimorph structure 38 causes the entire drive actuator 30 to bend its tip in the main motion direction 9. By controlling the voltages provided to the electrodes 36, 37, the driving interaction portion 32 can be moved in two-dimensional paths, having components in both the main motion direction 9 and the length direction 7.

The holding actuator 40 also comprises a volume 44 of electromechanically active material and electrodes 46 for exciting the electromechanically active material to cause geometrical changes of the holding actuator 40. However, in this case, there is only one set of electrodes and the entire volume will be excited essentially homogeneously. By providing voltages between the electrodes 46, the volume 44 can be caused to extend in the length direction 7. In this embodiment, the two holding actuators are driven by the same set of electrical signals and since they are geometrically equivalent, they exhibit essentially the same motion behaviour.

In this embodiment, the electromechanically active material is a piezoelectric material, which is excited by applying a voltage across the material. The electrodes are therefore arranged for being connected to different voltage signals in order to creates suitable electrical fields over the piezoelectric material. Other electromechanically active materials can also be used, e.g. electrostrictive or antiferroelectric materials, and the electrical signals provided to the electrodes then have to be adapted accordingly for giving the requested mechanical shape changes.

The electromechanical actuator device 10 of fig. 3A comprises drive electronics 60 connected to the electrodes 36, 37, 46 of the drive actuator 30 and the holding actuators 40, respectively, by connections 62-64. The drive electronics 60 is arranged for providing electrical signals for exciting the volumes 34, 35, 44 of electromechanically active material of the drive actuator 30 and the holding actuators 40, respectively. Besides these connections, some electrodes in the drive actuator 30 and the holding actuators 40, respectively, are connected to ground potential. In this embodiment, three separate voltages are provided, two for controlling the motion of the drive actuator 30 and one for controlling the motion of the holding actuators 40. In a particular embodiment, the holding actuators 40 are wider, in the direction of the main motion direction, than the drive actuators 30. The holding actuators 40 then become stiffer and exhibits smaller deformations for given loads.

The embodiment of Fig. 3A will be used as a model system for explaining the driving principles of the present invention. However, many different alternative electromechanical systems can be used as well, as long as there are suitable drive actuators and holding actuators available. A few non-limiting embodiments are given in Figs. 3B-D.

The embodiment of an electromechanical actuator device 10 in Fig. 3B comprises two drive actuators 30 and one holding actuator 40. This enables a higher maximum driving force on the object. Furthermore, the stability against tiltings of the object during the actual driving phase is increased by providing two support positions against the object. In the embodiment of Fig. 3C, two drive actuators 30 and two holding actuators 40 are provided. This additionally increases the stability and reduces the impact of the deformation caused by the driving force from the object 50. In the embodiment of Fig. 3D, only one drive actuator 30 and one holding actuator 40 are comprised in the electromechanical actuator device 10. This embodiment has the advantage of having a small volume of electromechanical material, which saves costs and space.

Anyone skilled in the art realizes after having considering these examples that any number and configuration of drive actuators and holding actuators can be used. Advantages and disadvantages depend on the applications the devices are intended for.

Figs. 4A-C illustrate one embodiment of voltage signals provided to the drive actuator and the holding actuator, respectively. The voltage signal of Fig. 4A is provided to one side of a bimorph structure of a drive actuator and the voltage signal of Fig. 4B is provided to the other side of the bimorph structure of the drive actuator. The voltage signal of Fig. 4C is provided to a holding actuator. In Fig. 4D, a diagram illustrates the corresponding movements of the driving interaction portion and the holding interaction portion. At time t0, one half of the bimorph structure is non-excited, as seen in Fig. 4A, while the other half is fully excited, as seen in Fig. 4B. This means that the driving interaction portion 32 is moved to one of its extreme bent position, called A in the diagram of Fig. 4D. The holding actuator is kept unexcited as seen from Fig. 4C, which means that the holding interaction portion is provided in a contracted position, called E in the diagram of Fig. 4D. By increasing the excitation of the second part of the bimorph structure, which takes place in the time interval of t0 to t1, the bimorph structure is straightened and reaches its most extended condition at position B in the diagram of Fig. 4D. From this position, by gradually reducing the excitation of the first side of the bimorph, from time t1 to t2, the bimorph bends in the other direction and contracts somewhat until position C is reached. Since the holding actuator is in a contracted state, the object to be driven is held against the driving interaction portion of the drive actuator, and if a suitable friction is provided, the object to be driven follows the motion of the driving interaction portion. The drive electronics is in other words configured to provide electrical signals that are adapted to drive the object by causing the drive actuator to move the driving interaction portion along a driving path section 100 while being in mechanical contact with the interaction surface of the object. The driving path section 100, in this case the path from A to C, has at least a component along the main motion direction 9. The driving path section 100 is the theoretical driving path for a situation where the object does not provide any load onto the drive actuator. During the drive along the driving path section 100, the drive actuator is in practice always loaded with a normal force F, with which the object is pressed against the electromechanical actuator device. This normal force N typically causes the drive actuator to deform somewhat and so does the driving force P, so the actual driving path section would probably be along the broken line 101.

During the time interval t2 to t3, the voltages on the drive actuator are kept constant. Instead, the voltage to the holding actuator is increased, which causes the holding actuator to expand and move the holding interaction portion from position E to position F, along a gripping path 103, if the holding actuator would be unloaded in all positions. However, this expansion of the holding actuator causes the holding interaction portion to come into mechanical contact with the object and "lift off" the object from the stationary drive actuator. During this transfer, the load of the object will also be shifted to the holding actuator, which means that in practice, the position F will not be fully reached, but a somewhat compressed and possibly also sideward displaced position F'. At the same time, the load release from the drive actuator causes the drive actuators to regain their unloaded shape, i.e. move from the broken line path 101 to the point C. In other words, the drive electronics is configured to provide electrical signals that are adapted to transfer a load of the object from the drive actuator to the holding actuator after the driving, thereby removing a deformation of the drive actuator caused by the load of the object and releasing the driving interaction portion from the interaction surface. Also, the transferring causes the holding actuator to move the holding interaction portion along the gripping path 103 into a mechanical contact with the interaction surface.

In order to minimize any uncertainties during the transfer of the load, the active relative motion between the holding interaction portion and the driving interaction portion becomes important. Since the transfer takes place during a certain time period, during which the load probably successively is transferred from the drive actuator to the holding actuator, the relative motion in the direction of the main motion is preferably minimized, i.e. the active relative motion should be directed with no component at all in the main motion direction during a period that without doubt involves the entire transfer course of events. In other words, the electrical signals are according to the present embodiment also adapted to cause an active relative motion between the holding interaction portion and the driving interaction portion to be perpendicular to the main motion direction during a releasing period. This releasing period comprises the entire removal of the deformation of the drive actuator caused by the load of the object and the entire release of the driving interaction portion from the interaction surface.

During the time interval t3 to t4, the voltage on one of the drive actuator halves is reduced while the other is kept constant equal to zero. The voltage to the holding actuator is also kept constant at the high level, which keeps the object supported on the holding actuator. The drive actuator bends back into a straight condition and assumes in point D the shortest possible length. From t4 to t5, the voltage of the other actuator half is increased, which causes the drive actuator to expand and bend to the position A. During this retraction of the drive actuator, along a retraction path section 102, the driving interaction portion does not interact with the object and is free to move without any load. In other words, the drive electronics is configured to provide electrical signals that are adapted to retract the drive actuator after the transferring by causing the drive actuator to move the driving interaction portion along the retracting path section 102. The driving interaction portion of the drive actuator is free from mechanical contact with the interaction surface of the object during that retraction path section 102. The retracting path section 102 has at least a component in opposite direction to the main motion direction 9 of the object.

During the time interval t5 to t6, the voltages on the drive actuator are kept constant. Instead, the voltage to the holding actuator is decreased, which causes the holding actuator to contract and move the holding interaction portion from position F (or rather F') to position E, along a releasing path 104. During this contraction of the holding actuator the driving interaction portion of the stationary drive actuator comes into mechanical contact with the object and "lifts off" the object from the holding actuator. During this transfer, the load of the object will also be shifted to the drive actuator, which means that in practice, the driving interaction portion will move from position A somewhat downwards to the broken line 101. At the same time, the load release from the holding actuator causes the holding actuator to regain its unloaded shape. In other words, the drive electronics is configured to provide electrical signals that are adapted to retransfer the load of the object from the holding actuator to the drive actuator after the retracting. This generates a deformation of the drive actuator caused by the load of the object and creates a mechanical contact between the driving interaction portion and the interaction surface. Also, the retransferring causes the holding actuator to move the holding interaction portion along the releasing path 104, removing the mechanical contact with the interaction surface.

In analogy with the releasing of the drive actuator from contact with the load, the active relative motion between the holding interaction portion and the driving interaction portion becomes important also during the gripping phase. Since the transfer takes place during a certain time period, during which the load probably successively is transferred from the holding actuator to the drive actuator, the relative motion in the direction of the main motion is preferably minimized, i.e. the active relative motion should be directed with no component at all in the main motion direction during a period that without doubt involves the entire transfer course of events. In other words, the electrical signals are according to the present embodiment also adapted to cause an active relative motion between the holding interaction portion and the driving interaction portion to be perpendicular to the main motion direction during a gripping period. The gripping period comprises the entire generation of the deformation of the drive actuator caused by the load of the object and the entire creation of the mechanical contact between the driving interaction portion and the interaction surface.

The original positions of the drive and holding actuators are now again reached. However, the object is moved a distance in the main motion direction, which ideally corresponds to the distance between the points A to C. In this embodiment, since the drive actuators are situated in their outermost positions during both the gripping and releasing actions, the maximum stroke of the drive actuator can be utilised. This is, for instance, not possible if the drive actuator is driven by sinusoidal voltages.

In order to achieve a continued motion, the driving, transferring, retracting and retransferring are repeated in a cyclic manner, thereby creating a stepwise motion of the object in the main motion direction.

In a preferred embodiment, the control of the active relative motion between holding actuator and drive actuator to be perpendicular to the main motion direction is performed during both the releasing and gripping phase. However, having such control during only either of the occasions will anyway give an improvement compared to prior art.

The voltage curves illustrated above are only examples of possible voltage curves. It can for instance be noted that the voltage curves in Figs. 4A-C causes the drive actuator to move its driving interaction surface in a path that comprises components perpendicular to the main motion direction. This is the conventional manner that the drive actuators are driven in e.g. US 6,337,532. However, since the holding actuators in the present disclosure are situated above the mean level of the drive actuator when being activated and below the mean level of the drive actuator when being deactivated, there is no particular need for any motion components perpendicular to the main motion direction. Such motion components may instead give rise to vibrations, unnecessary sounds, additional wear and additional heat generation.

Figs. 5A-D illustrates another embodiment of voltage signals provided to an embodiment of drive actuators and holding actuators. In this embodiment, the drive actuator is moved in a straight fashion from position A to position C, as seen from the path 102 in Fig. 5D. However, taking load into account in analogy with the above discussions, the broken line 101 is more likely to be the actual path taken. This behavior is achieved by the voltages of Figs. 5A-C. At time t7, the drive actuator is situated at position A, with one side of the bimorph excited and the other side with no electric field applied over the piezoelectric volume. In the period between t7 and 78, the voltage over the excited side is gradually decreasing while the voltage over the originally non-excited side of the bimorph is gradually increased. The result is that the driving interaction surface moves along a straight line in the main motion direction 9, until it reaches position C. Since the holding actuator is de-excited, positioned at position E, only the drive actuator is in contact with the object. In the period between t8 and t9, the voltages provided to the drive actuator are kept constant, while the holding actuator is excited. This means that the holding actuator extends and takes over the contact with the object to be moved. In the period between t9 and t10, the drive actuator is controlled to return to position A again, also along the straight path. Since the holding actuator supports the object to be moved at position F (or rather F'), the drive actuator can retract along the straight line without interfering with the object. In this embodiment, the voltage used for the holding actuator is reduced somewhat, which means that the positions E and F are closer to the centre. This can be performed if the margin between the paths of the drive actuator and the holding actuator end point is large enough to ensure undisturbed movements. A lower excitation voltage results in lower power consumption and low heat dissipation. In the period between t10 and t11, the voltages provided to the drive actuator are again kept constant, while the holding actuator is deexcited. This means that the holding actuator contracts and leaves over the contact with the object to be moved to the drive actuator.

One advantage with this embodiment is that it reduces the movements of the object in other directions than the main motions direction. A small lifting action will still be present, as caused by the holding actuator, but the overall movement up and down is significantly reduced. This in turn reduces vibrations, sound generation, wear and heat generation.

It can be seen from the voltage signals of Figs 4A-C that the object to be moved in fact is stationary in the main motion direction for quite a large part of the cycle. It only moves in the period between t0 and t2. In the periods t2 to t3 and t5 to t6, it moves, but only perpendicular to the main motion direction. The voltage signals of Figs. 5A-C are giving an even worse motion time. Here, only one out of four periods actually moves the object. In some applications, such low time usage is of no importance, and such voltage curves are perfectly usable. However, in applications, where a more constant motion is required, the applied voltages can be further improved.

In Figs. 6A-C, the same basic voltage signals as in Figs. 5A-C are provided with the exception of the size of the periods. By increasing the periods in which the actual moving of the object takes place and decreasing the periods in which the object rests or is moved perpendicularly, the time efficiency can be improved. In the embodiment of Figs 6A-C, the object moves during 5/8 of the total time. It is found that the gripping and releasing can be performed extremely fast without noticeable deterioration of e.g. sound level, wear or positioning accuracy. Furthermore, the retraction of the drive actuator can also be made extremely fast, since the driving interaction surface of the drive actuator does not have any mechanical contacts with the object. In Figs. 7A-C, the situation is even more extreme. Here, the object moves for more than 97% of the total time. With such driving, the motion of the object becomes more or less continuous.

Fig. 8 illustrates a flow diagram of steps of an embodiment of a method for driving an electromechanical actuator device. The method starts in step 200. In step 210, an object is driven by causing a drive actuator to move. A driving interaction portion of the drive actuator is during the driving in mechanical contact with an interaction surface of the object. The movement of the drive actuator moves the driving interaction portion along a driving path section. The driving path section has at least a component along a main motion direction of the object. A load of the object is in step 212 transferred from the drive actuator to a holding actuator. This takes place after the step of driving 210. A deformation of the drive actuator caused by the load of the object is thereby removed and the driving interaction portion is released from the interaction surface. The step of transferring 212 also comprises the causing of the holding actuator to move a holding interaction portion along a gripping path into a mechanical contact with the interaction surface. In one particular embodiment, as indicated by step 214, an active relative motion between the holding interaction portion and the driving interaction portion is controlled to be perpendicular to the main motion direction during a releasing period. The releasing period comprises the entire removing of the deformation of the drive actuator caused by the load of the object and the entire releasing of the driving interaction portion from the interaction surface. In step 216, the drive actuator is retracted after the step of transferring 212, by causing the drive actuator to move the driving interaction portion along a retracting path section. The driving interaction portion of the drive actuator is during this step free from mechanical contact with the interaction surface of the object. The retracting path section has at least a component in opposite direction to the main motion direction of the object. The load of the object is in step 218 retransferring from the holding actuator to the drive actuator after the step of retracting 216. A deformation of the drive actuator is thereby generated, caused by the load of the object. A mechanical contact is also created between the driving interaction portion and the interaction surface. The step of retransferring 218 also comprises the causing of the holding actuator to move a holding interaction portion along a releasing path removing the mechanical contact with the interaction surface. In one particular embodiment, as indicated by step 220, an active relative motion between the holding interaction portion and the driving interaction portion is controlled to be perpendicular to the main motion direction during a gripping period. The gripping period comprises the entire generating of the deformation of the drive actuator caused by the load of the object and the entire creating of the mechanical contact between the driving interaction portion and the interaction surface. The drive actuator is in all movements caused to move by exciting volumes of electromechanically active material within the drive actuator. The holding actuator is similarly in all movements caused to move by exciting volumes of electromechanically active material within the holding actuator. The steps of driving 210, transferring 212, retracting 216 and retransferring 218, are repeated as indicated by the arrow 230, thereby creating a stepwise motion of the object in the main motion direction. The procedure is ended in step 299.

At least one of the steps 214 and 220 are to be present in the method. In most applications, it is preferably to have both steps 214 and 220 implemented.

If one requires to utilize the maximum stroke of the drive actuator, the drive actuator has to be situated in one of the outermost positions (A, C in Fig. 5D) in the main motion direction or opposite to the main motion direction in the rhombic area (105 in Fig. 5D), within which the driving interaction surface is possible to drive. This means that the drive actuator cannot actively be driven in the vertical direction from these positions. If maximum strokes are requested, the drive actuator can consequently not be used to assist in the transferring and retransferring of the load. The exciting of the volumes of electromechanically active material within the drive actuator is thereby unchanged during the gripping period and/or the releasing period. However, such operations may be fully controlled by the holding actuator, as in the above examples. If the drive actuator is kept at constant voltages during the gripping, the holding actuator has to be moved towards the interaction surface along a direction perpendicular to the interaction surface. If the drive actuator is kept at constant voltages during the releasing the holding actuator has to be moved out from the interaction surface along the direction perpendicular to the interaction surface. Said interaction surface has a surface facing direction that is parallel to a surface normal of the interaction surface, perpendicular to the main motion direction and is directed outwards from the interaction surface. The above motions can then be expressed as that the gripping path is a linear gripping path directed in opposite direction to the surface facing direction of the interaction surface and/or that the releasing path is a linear releasing path directed in the surface facing direction of the driving interaction portion.

When the holding actuator receives the load from the object to be moved, the load causes the holding actuator to slightly deform, mainly in the direction of the normal force, but typically also somewhat in the main motion direction (or opposite thereto) depending on the driving force. In order not to introduce any additional uncertainties in positioning, a particular embodiment is arranged such that the deformation direction caused by the normal force component of the load coincides with the gripping and/or releasing path. Any deformation thus only influences the timing of the release or gripping, which is not any disadvantage concerning the positioning accuracy, since the relative motion between holding actuator and drive actuator anyway doesn't have any component in the main motion direction. In other words, at least one of the gripping path and the releasing path is arranged perpendicular to said interaction surface of said object.

Tests have been performed on electromechanical actuator devices according to the principles presented above. The explanations given here above have been confirmed, by comparing the operation of electromechanical actuator devices according to the principles presented above with electromechanical actuator devices of according to a standard solution e.g. basically according to US 6,337,532.

An actuator according to US 6,337,532 provides a longer step length per cycle, which is consistent with the fact that they drive using essentially two steps each cycle. The presently disclosed electromechanical actuator devices have a shorter cycle length, but present a higher stiffness, and each single step is longer. This trend is also valid for changes in the normal force. Generally, the presently disclosed electromechanical actuator devices also differ less in performance from unit to unit, probably due to the fact that they are more independent of the relative heights of the actuators. Furthermore, each step is made with exactly the same drive legs and not two or more sets.

As a conclusion from the tests, the presently disclosed electromechanical actuator devices present a number of useful advantages compared to prior art actuator devices. The cycle length is maintained better when the driving load is increased. The operation is also more insensitive to changes in the normal force. The actuator acts with a high stiffness during stationary conditions, e.g. at "long time parking", as well as during operation.

In the embodiment of Figs. 4A-D, a total driving path of the driving interaction portion, comprising at least the driving path section and the retracting path section, is a path in two dimensions. As will be discussed further below, a possibility for driving in two dimensions can be very useful in certain applications. In other applications, however, a one-dimensional driving path is to prefer.

When a one-dimensional driving path is used together with a bimorph structured drive actuator, one may notice that the voltage signals that are provided to the two halves are mirrored compared to each other. If a maximum excitation voltage is V, the voltage signals are mirrored at the V/2 line. This can also be expressed as that the voltage signals have time derivatives that are equal in magnitude but have different signs. The drive electronics is in such an embodiment configured to provide voltage signals to the two volumes of electromechanically active material, which voltage signals have time derivates of equal absolute magnitude but with opposite signs. This fact also makes it possible to simplify the drive electronics. As illustrated in Fig. 9A, in a particular embodiment, the two voltage signals can be generated by a single signal generator 70 and an inverter 71. The signal itself is provided at a first output 72 and an inverted copy of the signal is provided at a second output 73. The two outputs 72 and 73 are then connected to the drive actuator. For the holding actuator, the waveform could simply be the output of a binary voltage signal generator 74. For avoiding mechanical resonances, the binary voltage signal generator 74 can be connected to the holding actuator via a resistor 75. Since the piezoelectric actuator electrically is equivalent to a capacitor, a charging curve and discharging curve is obtained. For being able to match the charging and discharging, and more specifically the rising times, the resistor is preferably variable, and even more preferably digitally controlled. However, if the requested rising time is known beforehand, also non-variable resistors can be used. The waveform provided at a third output 76 can then be given a rising time or falling time which is suited for the drive signals that are used.

The voltage curves that are obtained when a capacitor is charged or discharged are mirror curves in the horizontal plane. Since the piezoelectric material in an electrical view acts as a capacitor, such charging/discharging curves could be used for controlling the voltages also to the drive actuators. In Fig. 9B, one embodiment utilizing a capacitor charging curve is schematically illustrated. A pulse generator 77A provides a voltage pulse with a predetermined amplitude. One part of the actuator is charged (or discharged) through a resistor 78, which causes the voltage a first output 72 applied over the actuator to vary according to the upper curve of Fig. 9C. Likewise, a pulse generator 77B provides a voltage pulse with predetermined amplitude. Another part of the actuator is charged (or discharged) through a resistor 78, which causes the voltage a first output 73 applied over the actuator to vary according to the lower curve of Fig. 9C. The pulse generator 77A is connected in opposite phase as pulse generator 77B, so that when the pulse generator 77A provides a voltage output, pulse generator 77B provides a zero output and vice versa. Preferably, the pulse generators 77A, 77B are provided as one common pulse generator unit 77. The voltage curves of Fig. 9C gives the drive actuator a fast movement in the beginning of the period and where the speed is reduced gradually with time.

If more linear (or other types of) behaviors are requested, the resistance of the resistors 78 can be reduced and the pulse generators 77A, 77B can be operated in a pulse-width modulation mode for achieving a requested shape of the outputted voltage curves. In order to provide a linear output for a loading of the capacitance of the drive actuator, the ratio between the time of the periods of applied voltage and the time of the periods of applied ground potential will be only slightly higher than unity in the beginning, but increases with time until the voltage is applied almost constantly in the end. This is schematically illustrated in Fig. 9D. An analogue change in the ratio between "on" and "off" times is performed for the discharging, however, then starting from a ratio slightly below 1 and which gradually decreases to almost zero. Other solutions are also feasible, e.g. longer periods of applied voltage interrupted by periods of very fast alternations between applied voltage and ground of equal durations. The "longer" periods of applied voltage can be controlled to be relatively short in the beginning and increase with increased charging. By a suitable control, a quasi-linear charging may be achieved.

The applied potentials can also in an embodiment based on pulse-width modulation be kept almost constant for a certain time period. For achieving such constant behavior, the ratio between "on" and "off" times is controlled in such a way that the total charge during the "on" time equals the total discharge during the "off" time.

In another embodiment of an electromechanical actuator, the electrodes of the bimorph structure are connected in a particular manner. In a conventional connection scheme, each half of the bimorph has ground electrodes and phase electrodes, as schematically illustrated in Fig. 10A. The phase electrodes are provided with different, mirrored, voltage signals. However, if, as illustrated in Fig. 10B, a fixed maximum voltage Vcc is provided instead of the ground potential to one side of the bimorph, and the same voltage signal is provided to the phase electrodes of both sides, the efficient electrical field applied over the piezoelectric volumes becomes the same as in the conventional case. This also reduces the demands to have only one voltage signal source for the complete drive actuator. The constant maximum voltage Vcc is assumed to be easily provided from the voltage signal source as well.

As mentioned further above, having a drive actuator operating with at least opportunities of having two-dimensional driving paths, may be advantageous in certain applications. If the load from the object is very high, the deformation of the drive actuator and the holding actuator may be non-negligible compared to the margin of free passage for the driving actuator during the retraction and the holding actuator during the driving phase. In such situations, a compromise between step length and height margin might be advantageous. In Fig. 11A, the rhombic driving area 105 of the drive actuator is illustrated. If the drive actuator is heavily loaded, the deformation may give a true position along the broken line 106. This line is so close to the retracted position E of the holding actuator that free passage can not be ascertained. By instead letting the drive actuator drive along a driving path section 108 that is somewhat elevated, a proper height margin can be achieved. Similarly, during the retraction, the holding actuator may be compressed down to the point F', which is situated too close to the horizontal symmetry line of the rhombic area 105. If the retracting path section 109 in such a case is provided at a lower level than the horizontal symmetry line, a proper height margin may be provided also here. The disadvantage is that the driving path section 108 and the retracting path section 109 are restricted in the main motion direction so that the step length becomes shorter. In such an embodiment, both the drive actuator and the holding actuator will move during the releasing and gripping phases, however, both are preferably moved perpendicular to the main motion direction and in opposite direction to each other.

Suitable voltage signals for such a solution are illustrated in Figs. 11B-D. Such signals thus give rise to a total driving path of the driving interaction portion, comprising at least the driving path section and the retracting path section, which total driving path is a path in at least two dimensions.

In an alternative embodiment, the releasing and gripping phases may be divided in to sub-phases. In one sub-phase, the drive actuator(s) can be moved perpendicular to the interaction surface of the object to be moved while the holding actuator(s) can be kept stationary. In another sub-phase, the situation is the opposite. In other words, even if both types of actuators are moved during the releasing and/or gripping, they may anyway be moved one at the time.

In order to provide a motion of the driving interaction portion in two dimensions, different solutions of actuator designs can be used. In the examples above, a bimorph structure has been used as a model example, where two volumes are attached together along a direction that is perpendicular to the main motion direction. The two bimorph halves are separately excited by electrodes. The electrodes can be provided in different directions; parallel to the interaction surface of the object, perpendicular to the interaction surface and parallel to the main motion direction, or perpendicular to both the interaction surface and the main motion direction. It is possible to provide the two-dimensional motion also by use of a combination of a linear actuator and a shear actuator. However, this solution has certain disadvantages concerning manufacturing processes and is presently at least not considered as a preferred embodiment.

Both the drive actuator and the holding actuator may be designed with multilayer structures, in order to reduce the voltage levels needed for achieving the shape changes.

A final consideration may be the properties of the electromechanical actuator when not being operated. In many applications, an actuator is used for transporting an object into a certain position. At this position, the object may rest for longer or shorter periods of time without experiencing any shifts in position. If the object is to be kept for longer times, it is an advantage if the driving mechanisms could be able to turn off and still keep the accurate position. The driving of the electromechanical actuator could therefore in a particular embodiment comprises the further step of parking the object with the volumes of electromechanically active material within the drive actuator and the volumes of electromechanically active material within the holding actuator unexcited.

In one embodiment, illustrated in Fig. 12, this parking could be achieved by a procedure starting in step 201. In step 250, the drive actuator is halted at a requested parking position of the object during the step of driving. When the requested parking position is achieved, the holding actuator is in step 252 caused to move the holding interaction portion along the linear gripping path into mechanical contact with the interaction surface, thereby releasing the driving interaction portion from the interaction surface. In step 254, the volumes of electromechanically active material within the drive actuator are then deexcited in such a way that the driving interaction portion does not comes into mechanical contact with the interaction surface. Finally, in step 256, the volumes of electromechanically active material within the holding actuator are deexcited in such a way that the holding interaction portion moves along a path opposite to the linear gripping path. The procedure ends in step 298.

The embodiments described above are to be understood as a few illustrative examples of the present invention. It will be understood by those skilled in the art that various modifications, combinations and changes may be made to the embodiments without departing from the scope of the present invention. In particular, different part solutions in the different embodiments can be combined in other configurations, where technically possible. The scope of the present invention is, however, defined by the appended claims.

CLAIMS

1. A method for driving an electromechanical actuator device, comprising the steps of:

- driving (210) an object by causing a drive actuator, a driving interaction portion of which during said driving being in mechanical contact with an interaction surface of said object, to move said driving interaction portion along a driving path section;

said driving path section having at least a component along a main motion direction of said object;

- transferring (212) a load of said object from said drive actuator to a holding actuator after said step of driving, thereby removing a deformation of said drive actuator caused by said load of said object and releasing said driving interaction portion from said interaction surface;

said step of transferring comprises causing said holding actuator to move a holding interaction portion along a gripping path into a mechanical contact with said interaction surface;

- retracting (216) said drive actuator after said step of transferring by causing said drive actuator, the driving interaction portion of which is free from mechanical contact with said interaction surface of said object, to move said driving interaction portion along a retracting path section;

said retracting path section having at least a component in opposite direction to said main motion direction of said object;

- retransferring (218) said load of said object from said holding actuator to said drive actuator after said step of retracting, thereby generating a deformation of said drive actuator caused by said load of said object and creating a mechanical contact between said driving interaction portion and said interaction surface;

said step of retransferring comprises causing said holding actuator to move a holding interaction portion along a releasing path removing said mechanical contact with said interaction surface;

said drive actuator being caused to move by exciting volumes of electromechanically active material within said drive actuator;

said holding actuator being caused to move by exciting volumes of electromechanically active material within said holding actuator; and

- repeating (230) said steps of driving, transferring, retracting and retransferring, thereby creating a stepwise motion of said object in said main motion direction,

characterized in that

an active relative motion between said holding interaction portion and said driving interaction portion is perpendicular (214) to said main motion direction during a releasing period comprising entire said removing of said deformation of said drive actuator caused by said load of said object and entire said releasing of said driving interaction portion from said interaction surface.

2. The method according to claim 1, **characterised in that**

said step of retransferring comprises causing said holding actuator to move said holding interaction portion along a releasing path releasing said mechanical contact with said interaction surface;

an active relative motion between said holding interaction portion and said driving interaction portion is perpendicular (220) to said main motion direction during a gripping period comprising entire said generating of said deformation of said drive actuator caused by said load of said object and entire said creating of a mechanical contact between said driving interaction portion and said interaction surface.

3. A method for driving an electromechanical actuator device, comprising the steps of:

- driving (210) an object by causing a drive actuator, a driving interaction portion of which during said driving being in mechanical contact with an interaction surface of said object, to move said driving interaction portion along a driving path section;

said driving path section having at least a component along a main motion direction of said object;

- transferring (212) a load of said object from said drive actuator to a holding actuator after said step of driving, thereby removing a deformation of said drive actuator caused by said load of said object and releasing said driving interaction portion from said interaction surface;

said step of transferring comprises causing said holding actuator to move a holding interaction portion along a gripping path into a mechanical contact with said interaction surface;

- retracting (216) said drive actuator after said step of transferring by causing said drive actuator, the driving interaction portion of which is free from mechanical contact with said interaction surface of said object, to move said driving interaction portion along a retracting path section;

said retracting path section having at least a component in opposite direction to said main motion direction of said object;

- retransferring (218) said load of said object from said holding actuator to said drive actuator after said step of retracting, thereby generating a deformation of said drive actuator caused by said load of said object and creating a mechanical contact between said driving interaction portion and said interaction surface;

said step of retransferring comprises causing said holding actuator to move said holding interaction portion along a releasing path removing said mechanical contact with said interaction surface;

said drive actuator being caused to move by exciting volumes of electromechanically active material within said drive actuator;

said holding actuator being caused to move by exciting volumes of electromechanically active material within said holding actuator; and

- repeating (230) said steps of driving, transferring, retracting and retransferring, thereby creating a stepwise motion of said object in said main motion direction,

characterized in that

an active relative motion between said holding interaction portion and said driving interaction portion is perpendicular (220) to said main motion direction during a gripping period comprising entire said generating of said deformation of said drive actuator caused by said load of said object and entire said creating of said mechanical contact between said driving interaction portion and said interaction surface.

4. The method according to any of the claims 1 to 3, **characterised in that**

said interaction surface has a surface facing direction being parallel to a surface normal of said interaction surface, perpendicular to said main motion direction and being directed outwards from said interaction surface; and at least one of:

said gripping path is a linear gripping path directed in opposite direction to said surface facing direction of said interaction surface; and

said releasing path is a linear releasing path directed in the surface facing direction of said driving interaction portion.

5. The method according to any of the claims 1 to 4, **characterised in that** at least one of said gripping path and said releasing path being arranged perpendicular to said interaction surface of said object.

6. The method according to any of the claims 1 to 5, **characterised in that**

said exciting of said volumes of electromechanically active material within said drive actuator is unchanged during at least one of said gripping period and said releasing period.

7. The method according to any of the claims 1 to 6, **characterised in that** a total driving path of said driving interaction portion, comprising at least said driving path section and said retracting path section, being a path in at least two dimensions.

8. The method according to any of the claims 1 to 6, **characterised in that** said drive actuator is caused to move by separately exciting two volumes of electromechanically active material within a bimorph structure of said drive actuator.

9. The method according to claim 8, **characterised in that** said two volumes of electromechanically active material are provided with voltage signals having time derivates of equal absolute magnitude but with opposite signs.

10. The method according to any of the claims 7 to 9, **characterised by** the further step of parking said object with said volumes of electromechanically active material within said drive actuator and said volumes of electromechanically active material within said holding actuator unexcited.

11. The method according to claim 10, **characterised in that** said step of parking in turn comprises the steps of:

halting (250) said drive actuator at a requested parking position of said object during said step of driving;

causing (252) said holding actuator to move said holding interaction portion along said linear gripping path into mechanical contact with said interaction surface, thereby releasing said driving interaction portion from said interaction surface;

deexciting (254) said volumes of electromechanically active material within said drive actuator such that said driving interaction portion does not comes into mechanical contact with said interaction surface; and

deexciting (256) said volumes of electromechanically active material within said holding actuator such that said holding interaction portion moves along a path opposite to said linear gripping path.

12. An electromechanical actuator device (10), comprising:

a drive actuator (30), having a driving interaction portion (32);

a holding actuator (40); having a holding interaction portion (42);

an object (50), having an interaction surface (52), to be moved in a main motion direction (9);

said drive actuator (30) comprises volumes (34, 35) of electromechanically active material and electrodes (36, 37) for exciting said electromechanically active material to cause geometrical changes of said drive actuator (30);

said holding actuator (40) comprises volumes (44) of electromechanically active material and electrodes (46) for exciting said electromechanically active material to cause geometrical changes of said holding actuator (40);

drive electronics (60), connected to said electrodes (36, 37, 46) of said drive actuator (30) and said holding actuator (40);

said drive electronics (60) being arranged for providing electrical signals for exciting said volumes (34, 35, 44) of electromechanically active material of said drive actuator (30) and said holding actuator (40);

said electrical signals being adapted to:

- drive said object (50) by causing said drive actuator (30) to move said driving interaction portion (32) along a driving path section (100) while being in mechanical contact with said interaction surface (52) of said object (50);

said driving path section (100) having at least a component along said main motion direction (9);

- transfer a load of said object (50) from said drive actuator (30) to said holding actuator (40) after said driving, thereby removing a deformation of said drive actuator (30) caused by said load of said object (50) and releasing said driving interaction portion (32) from said interaction surface (52);

said transferring comprises causing said holding actuator (40) to move said holding interaction portion (42) along a gripping path (103) into a mechanical contact with said interaction surface (52);

- retract said drive actuator (30) after said transferring by causing said drive actuator (30), the driving interaction portion (32) of which is free from mechanical contact with said interaction surface (52) of said object (50), to move said driving interaction portion (32) along a retracting path section (102);

said retracting path section (102) having at least a component in opposite direction to said main motion direction (9) of said object (50);

- retransfer said load of said object (50) from said holding actuator (40) to said drive actuator (30) after said retracting, thereby generating a deformation of said drive actuator (30) caused by said load of said object (50) and creating a mechanical contact between said driving interaction portion (32) and said interaction surface (52);

said retransferring comprises causing said holding actuator (40) to move said holding interaction portion (42) along a releasing path (104) removing said mechanical contact with said interaction surface (52);

- repeat said driving, transferring, retracting and retransferring, thereby creating a stepwise motion of said object (50) in said main motion direction (9),

characterized in that

said electrical signals being further adapted to cause an active relative motion between said holding interaction portion (42) and said driving interaction portion (32) to be perpendicular to said main motion direction (9) during a releasing period comprising entire said removing of said deformation of said drive actuator (30) caused by said load of said object (50) and entire said releasing of said driving interaction portion (42) from said interaction surface (52).

13. The electromechanical actuator device according to claim 12, **characterized in that**

said electrical signals being further adapted to cause an active relative motion between said holding interaction portion (42) and said driving interaction portion (32) to be perpendicular to said main motion direction (9) during a gripping period comprising entire said generating of said deformation of said drive actuator (30) caused by said load of said object (50) and entire said creating of a mechanical contact between said driving interaction portion (32) and said interaction surface (52).

14. An electromechanical actuator device (10), comprising:

a drive actuator (30), having a driving interaction portion (32);

a holding actuator (40); having a holding interaction portion (42);

an object (50), having an interaction surface (52), to be moved in a main motion direction (9);

said drive actuator (30) comprises volumes (34, 35) of electromechanically active material and electrodes (36, 37) for exciting said electromechanically active material to cause geometrical changes of said drive actuator (30);

said holding actuator (40) comprises volumes (44) of electromechanically active material and electrodes (46) for exciting said electromechanically active material to cause geometrical changes of said holding actuator (40);

drive electronics (60), connected to said electrodes (36, 37, 46) of said drive actuator (30) and said holding actuator (40);

said drive electronics (60) being arranged for providing electrical signals for exciting said volumes (34, 35, 44) of electromechanically active material of said drive actuator (30) and said holding actuator (40);

said electrical signals being adapted to:

- drive said object (50) by causing said drive actuator (30) to move said driving interaction portion (32) along a driving path section (100) while being in mechanical contact with said interaction surface (52) of said object (50);

said driving path section (100) having at least a component along said main motion direction (9);

- transfer a load of said object (50) from said drive actuator (30) to said holding actuator (40) after said driving, thereby removing a deformation of said drive actuator (30) caused by said load of said object (50) and releasing said driving interaction portion (32) from said interaction surface (52);

said transferring comprises causing said holding actuator (40) to move said holding interaction portion (42) along a gripping path (103) into a mechanical contact with said interaction surface (52);

- retract said drive actuator (30) after said transferring by causing said drive actuator (30), the driving interaction portion (32) of which is free from mechanical contact with said interaction surface (52) of said object (50), to move said driving interaction portion (32) along a retracting path section (102);

said retracting path section (102) having at least a component in opposite direction to said main motion direction (9) of said object (50);

- retransfer said load of said object (50) from said holding actuator (40) to said drive actuator (30) after said retracting, thereby generating a deformation of said drive actuator (30) caused by said load of said object (50) and creating a mechanical contact between said driving interaction portion (32) and said interaction surface (52);

said transferring comprises causing said holding actuator (40) to move said holding interaction portion (42) along a releasing path (104) removing said mechanical contact with said interaction surface (52);

- repeat said driving, transferring, retracting and retransferring, thereby creating a stepwise motion of said object (50) in said main motion direction (9),

characterized in that

said electrical signals being further adapted to cause an active relative motion between said holding interaction portion (42) and said driving interaction portion (32) to be perpendicular to said main motion direction (9) during a gripping period comprising entire said generating of said deformation of said drive actuator (30) caused by said load of said object (50) and entire said creating of a mechanical contact between said driving interaction portion (32) and said interaction surface (52).

15. The electromechanical actuator device according to any of the claims 12 to 14, **characterized in that** said drive actuator (30) has electrodes (36, 37) for exciting two different volumes (34, 35) of said electromechanically active material separately, said two volumes (34, 35) being arranged in a bimorph structure (38).

16. The electromechanical actuator device according to claim 15, **characterised in that** said drive electronics (60) is configured to provide voltage signals to said two volumes (34, 35) of electromechanically active material, said voltage signals having time derivates of equal absolute magnitude but with opposite signs.

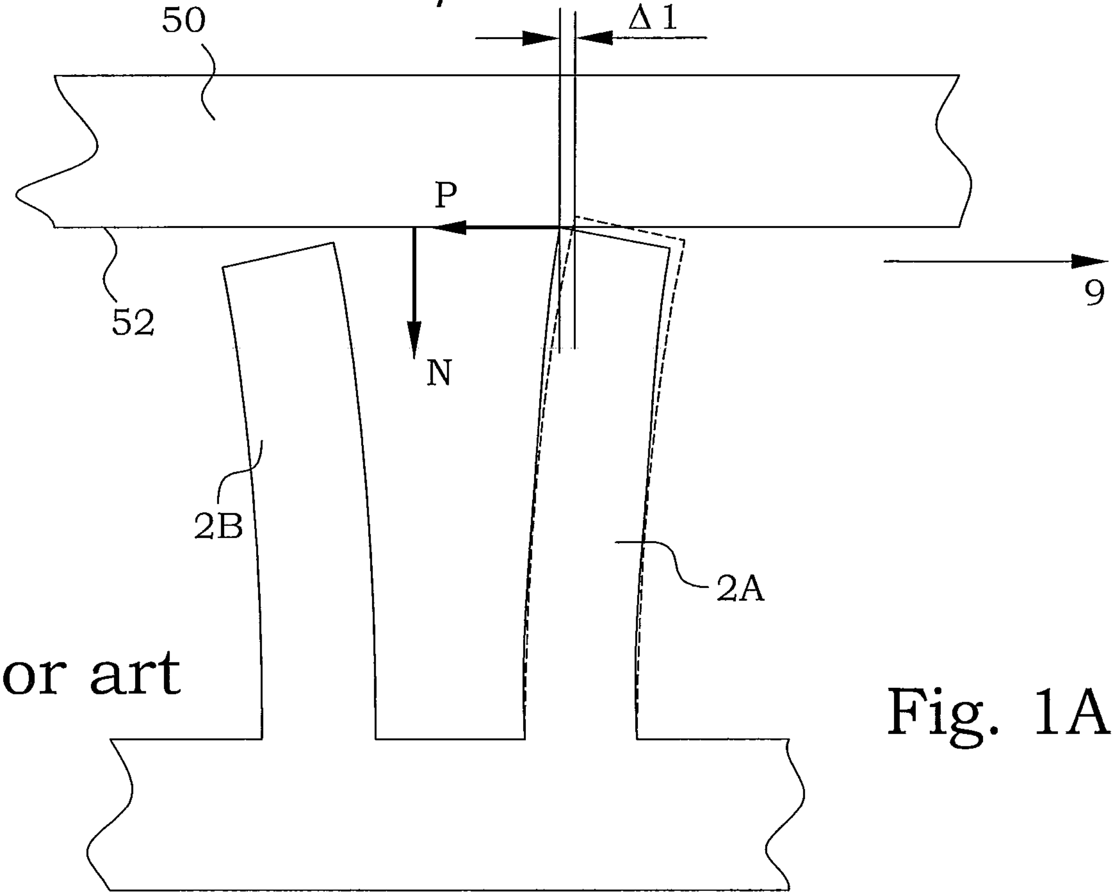


Fig. 1A

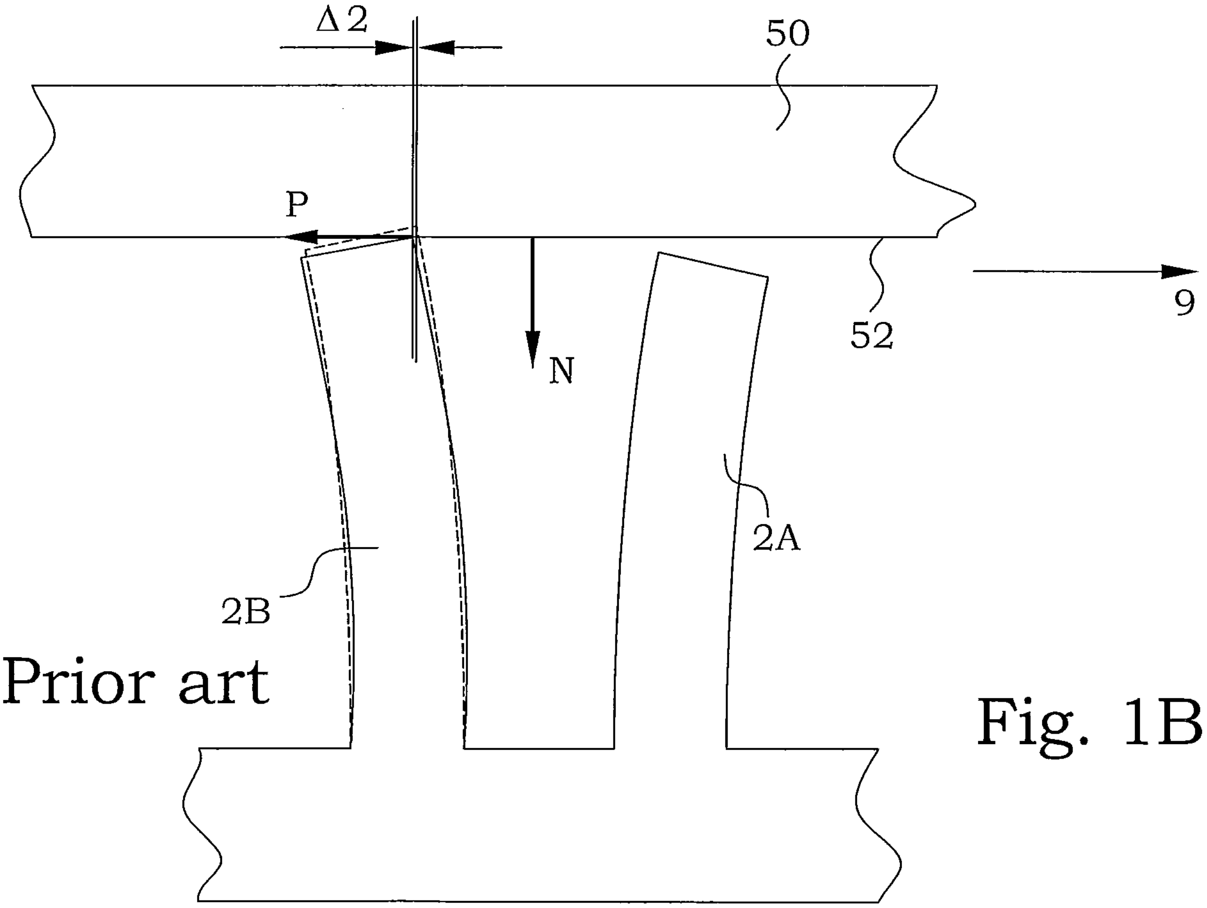


Fig. 1B

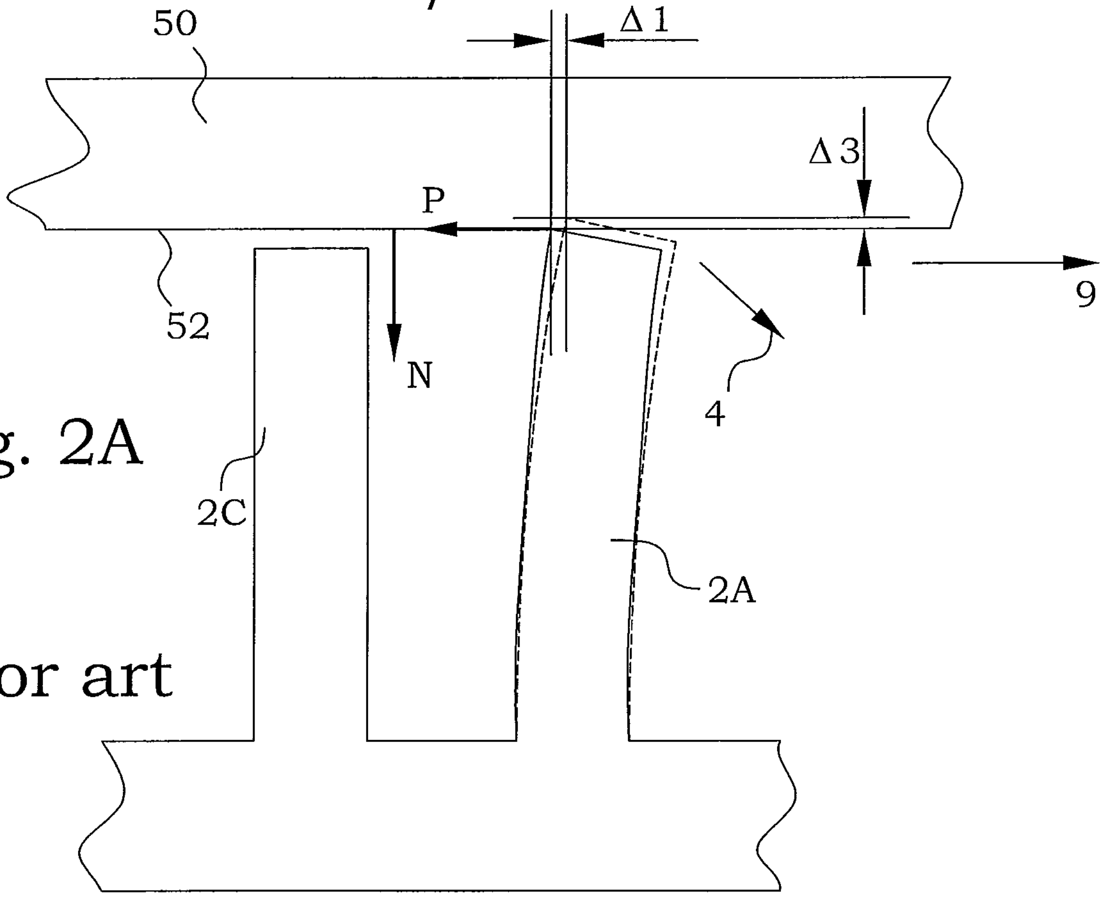


Fig. 2A

Prior art

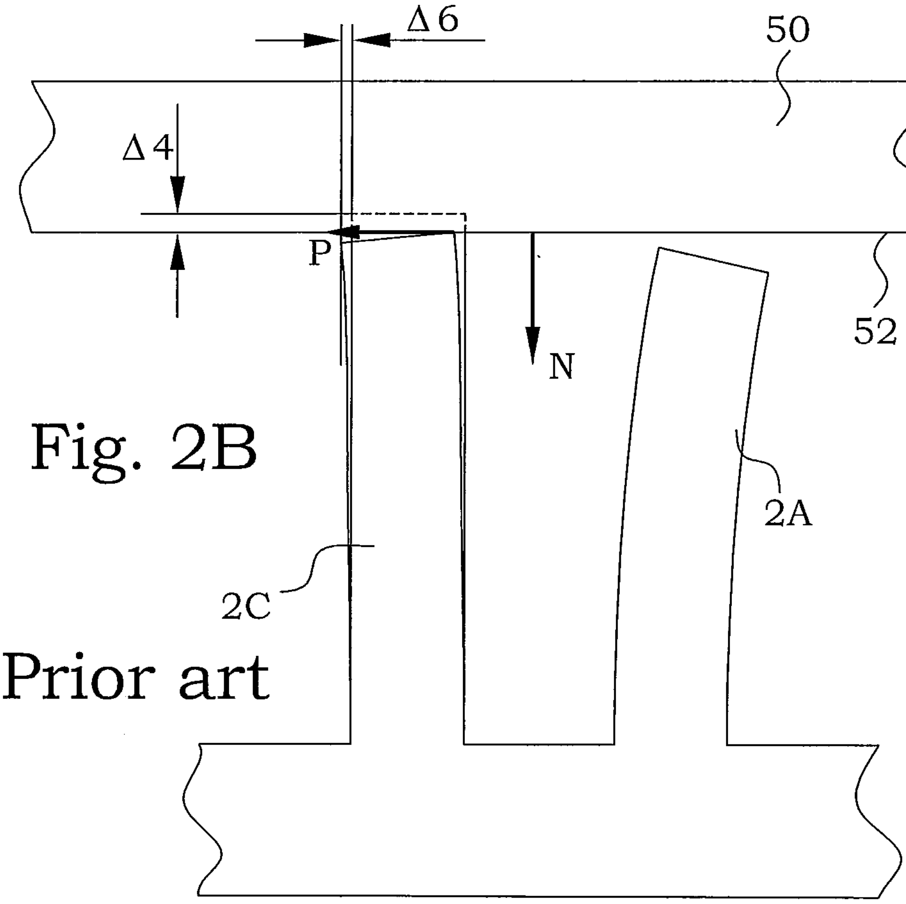


Fig. 2B

Prior art

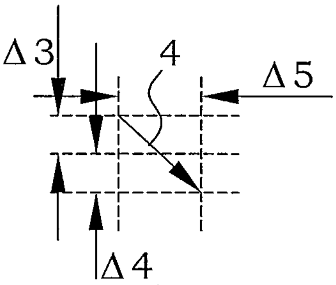


Fig. 2C

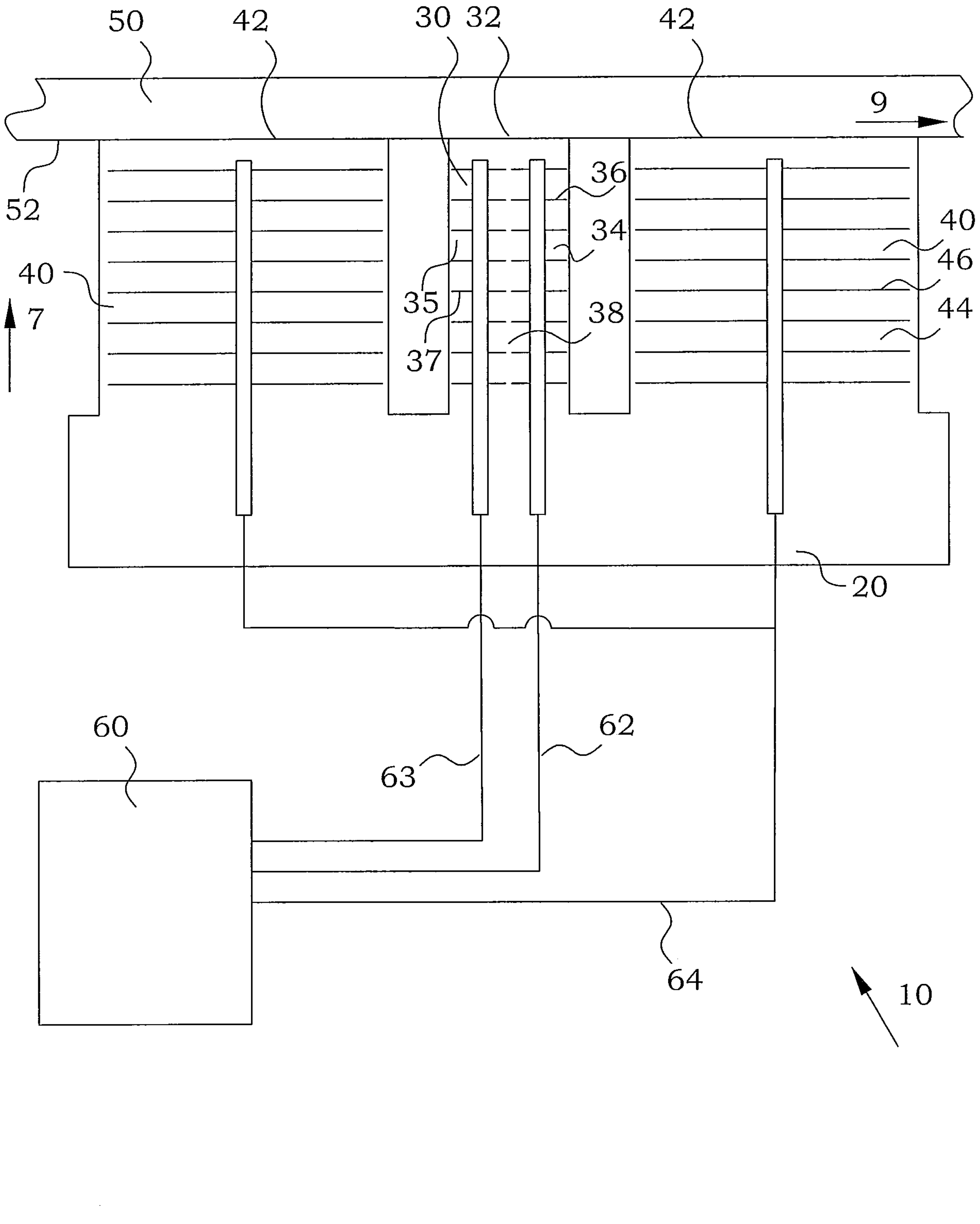


Fig. 3A

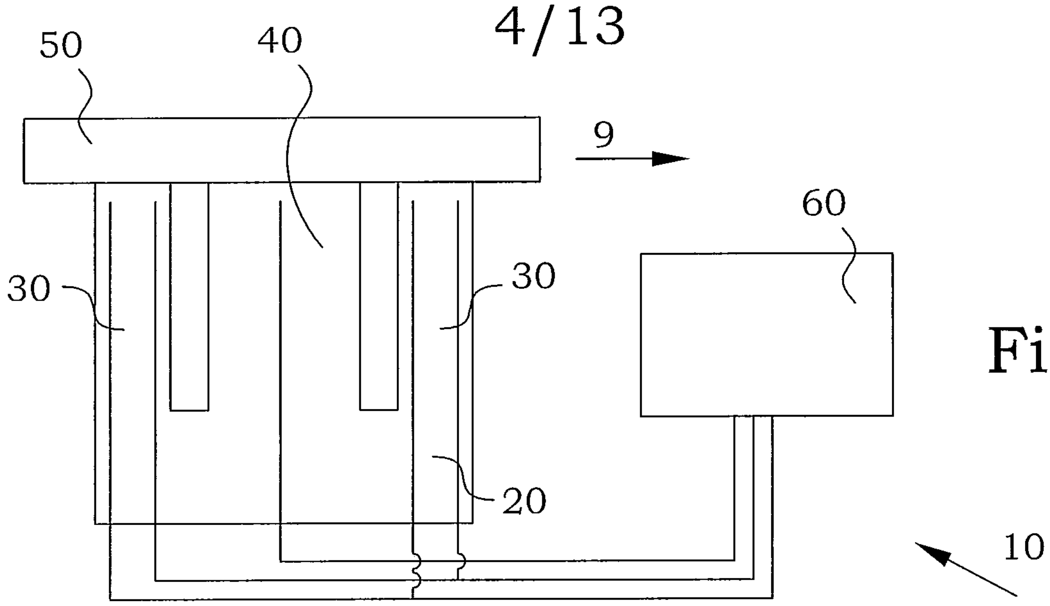


Fig. 3B

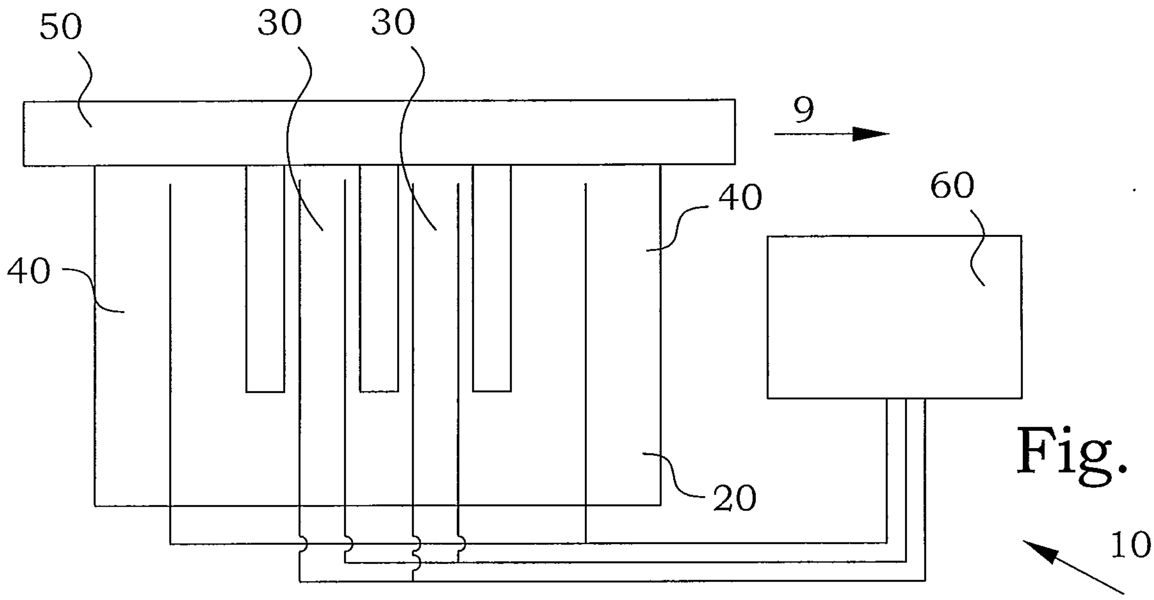


Fig. 3C

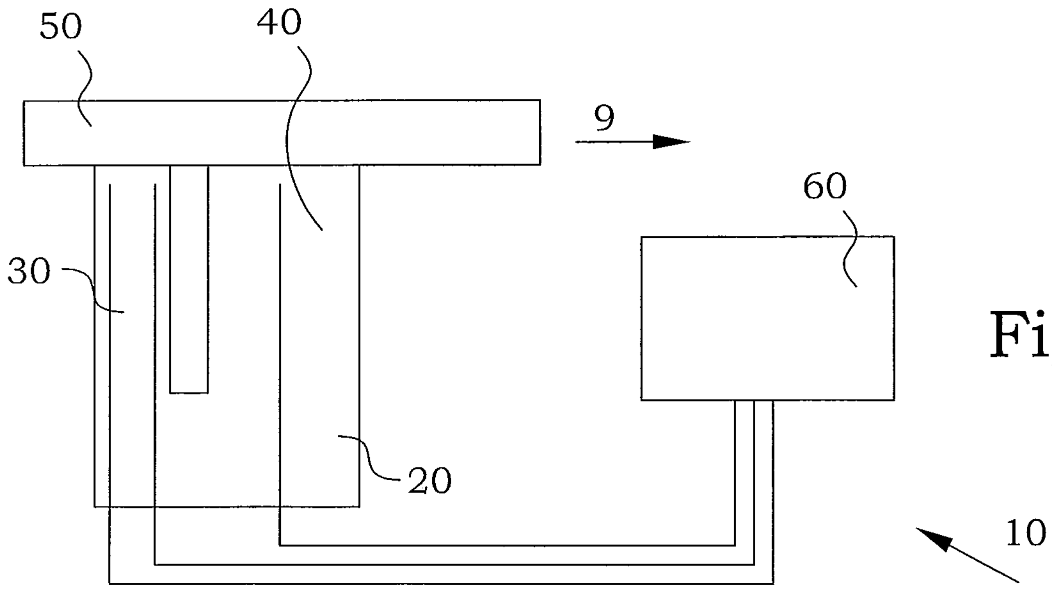


Fig. 3D

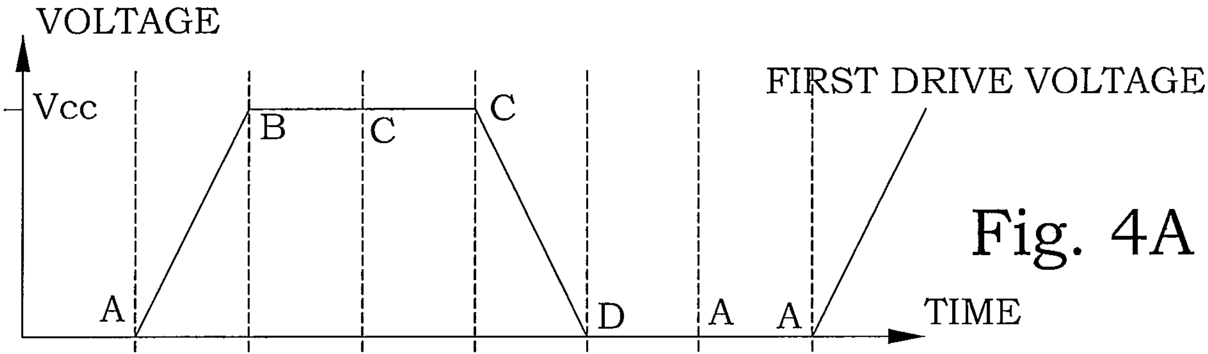


Fig. 4A

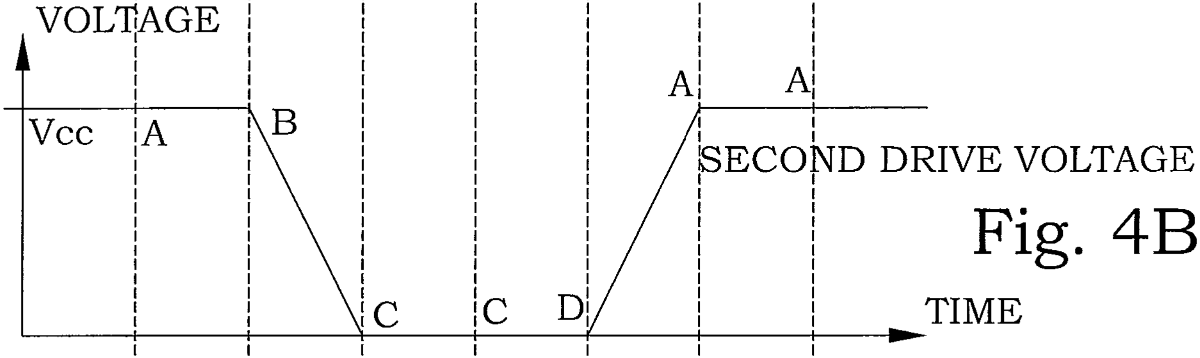


Fig. 4B

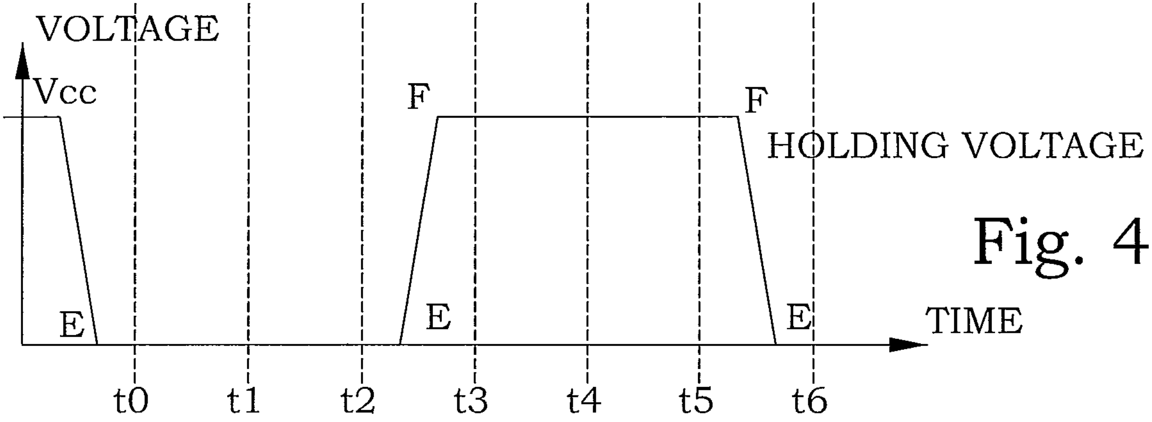


Fig. 4C

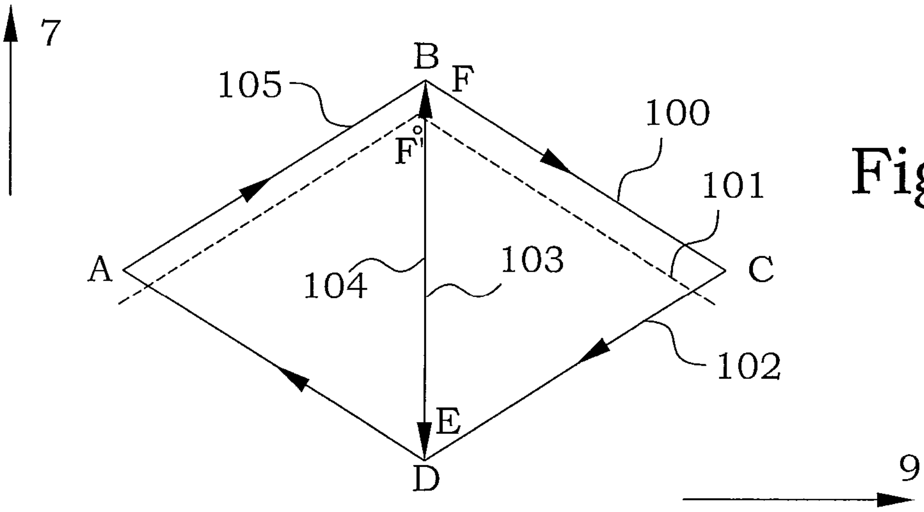


Fig. 4D

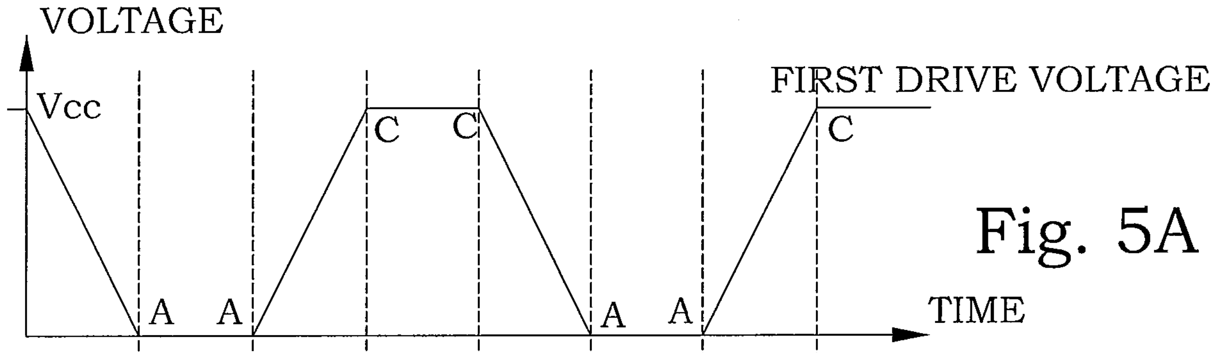


Fig. 5A

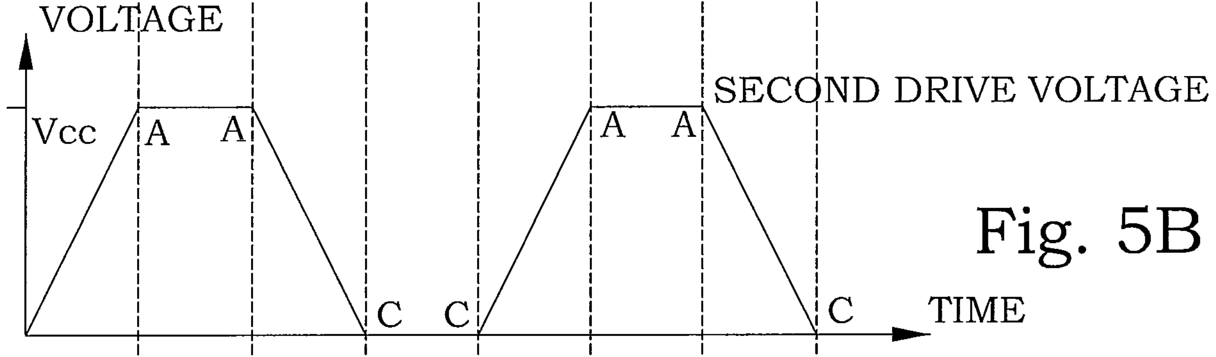


Fig. 5B

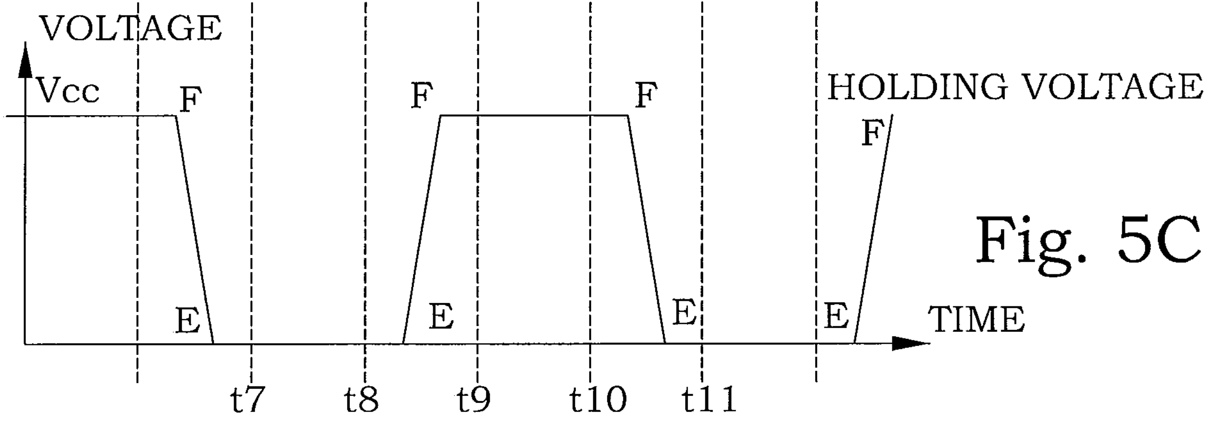


Fig. 5C

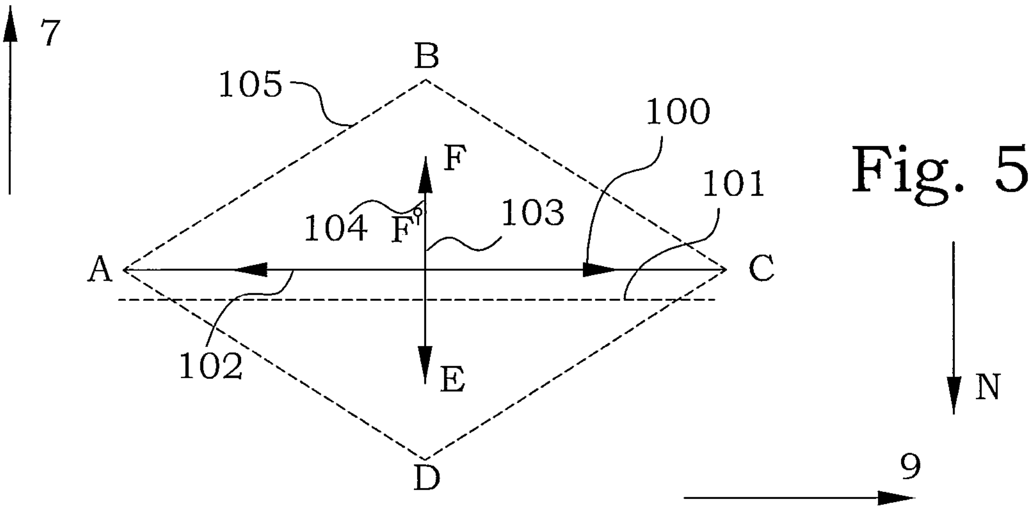


Fig. 5D

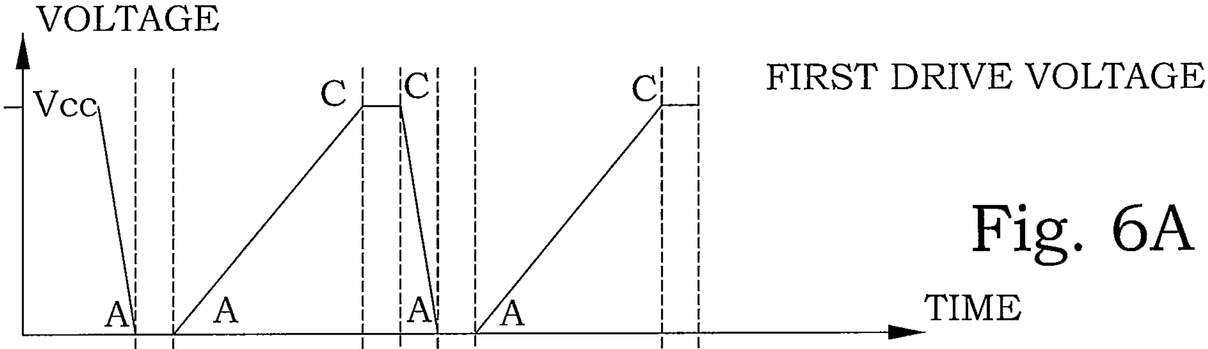


Fig. 6A

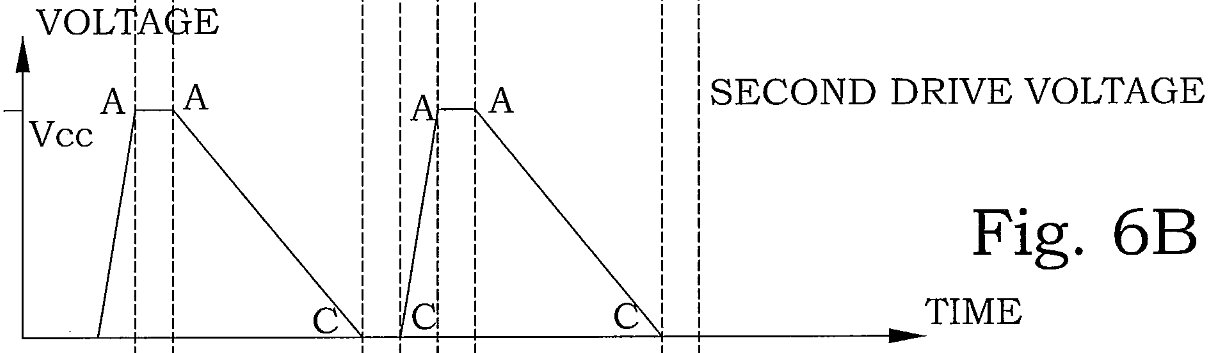


Fig. 6B

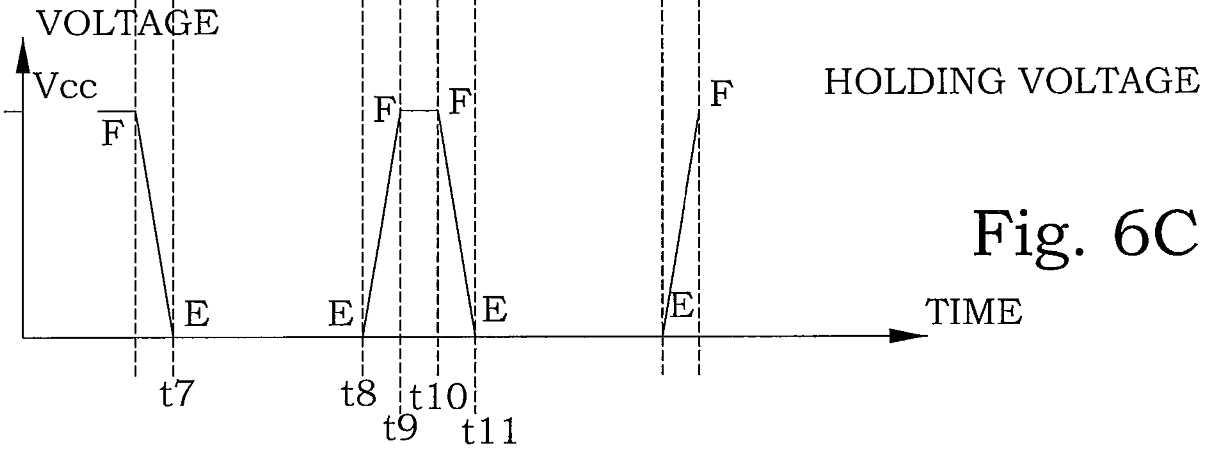


Fig. 6C

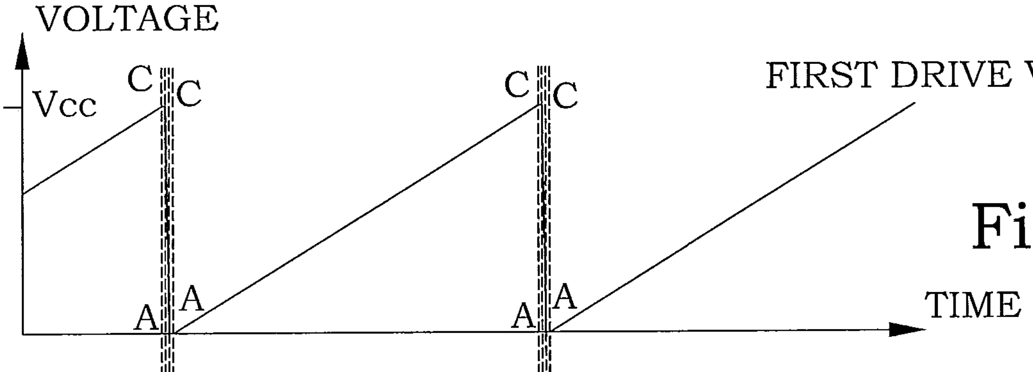


Fig. 7A

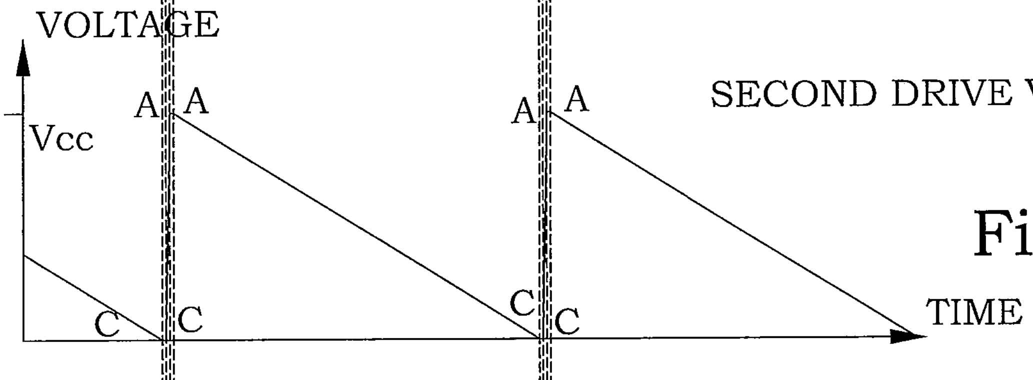


Fig. 7B

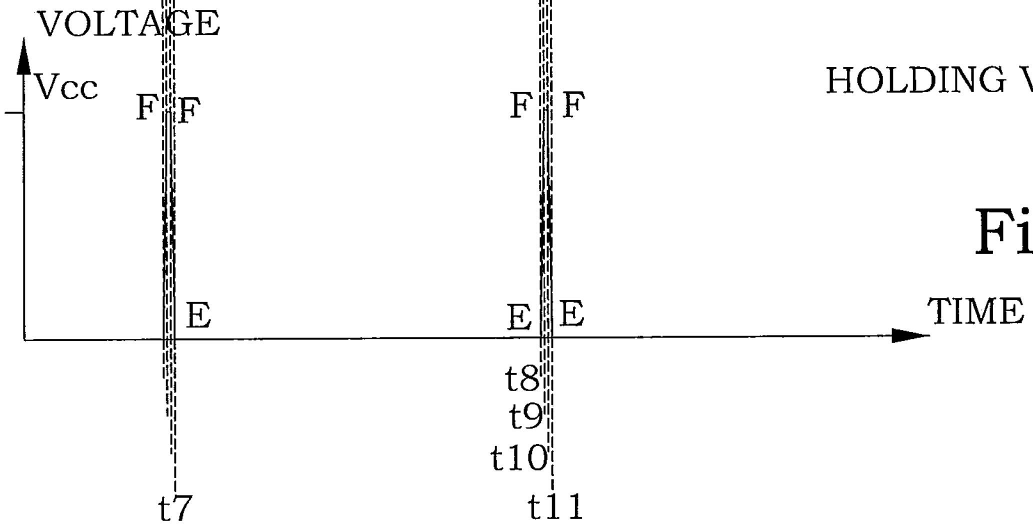


Fig. 7C

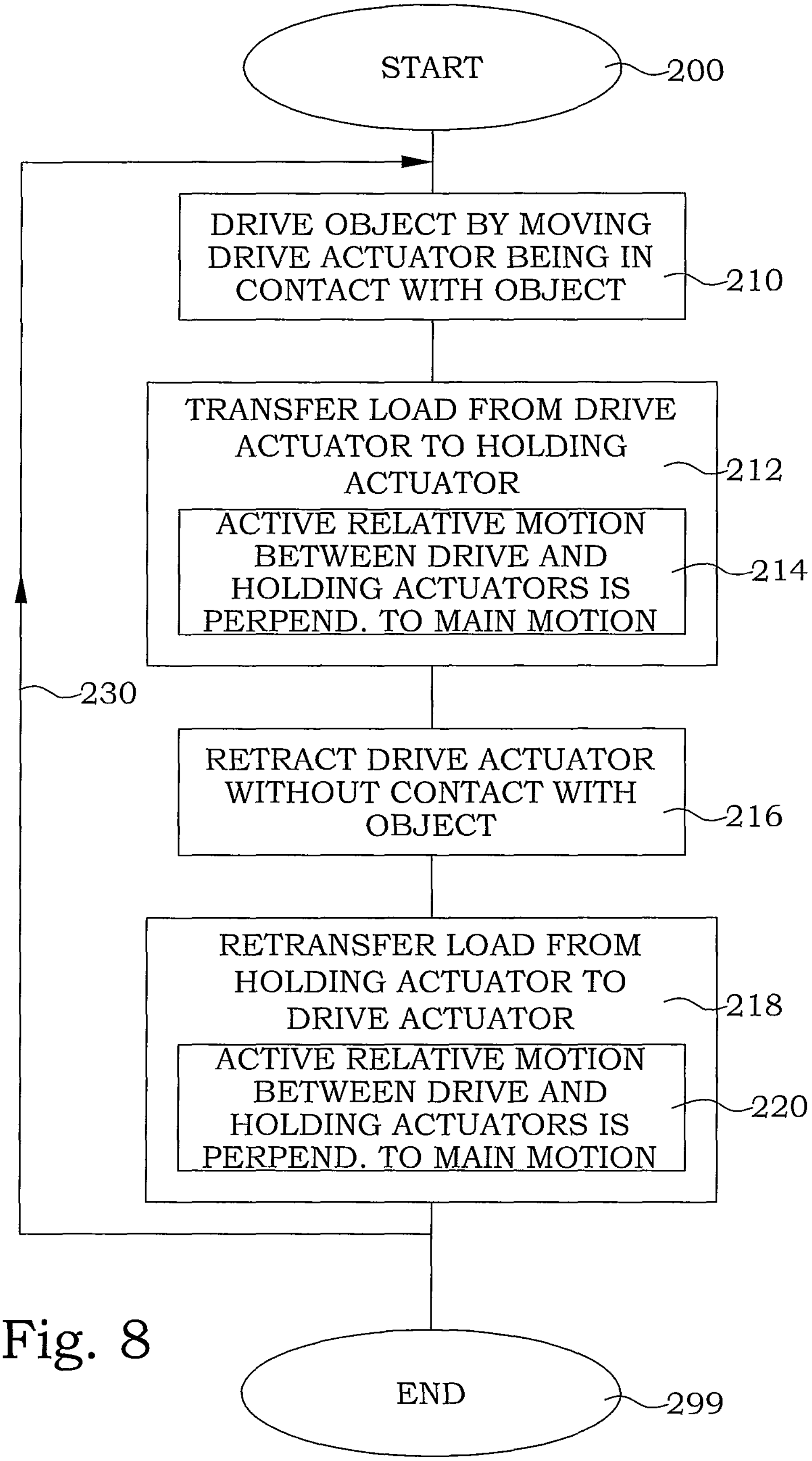

START
200
DRIVE OBJECT BY MOVING DRIVE ACTUATOR BEING IN CONTACT WITH OBJECT
210
TRANSFER LOAD FROM DRIVE ACTUATOR TO HOLDING ACTUATOR
212
ACTIVE RELATIVE MOTION BETWEEN DRIVE AND HOLDING ACTUATORS IS PERPEND. TO MAIN MOTION
214
230
RETRACT DRIVE ACTUATOR WITHOUT CONTACT WITH OBJECT
216
RETRANSFER LOAD FROM HOLDING ACTUATOR TO DRIVE ACTUATOR
218
ACTIVE RELATIVE MOTION BETWEEN DRIVE AND HOLDING ACTUATORS IS PERPEND. TO MAIN MOTION
220
END
299

Fig. 8

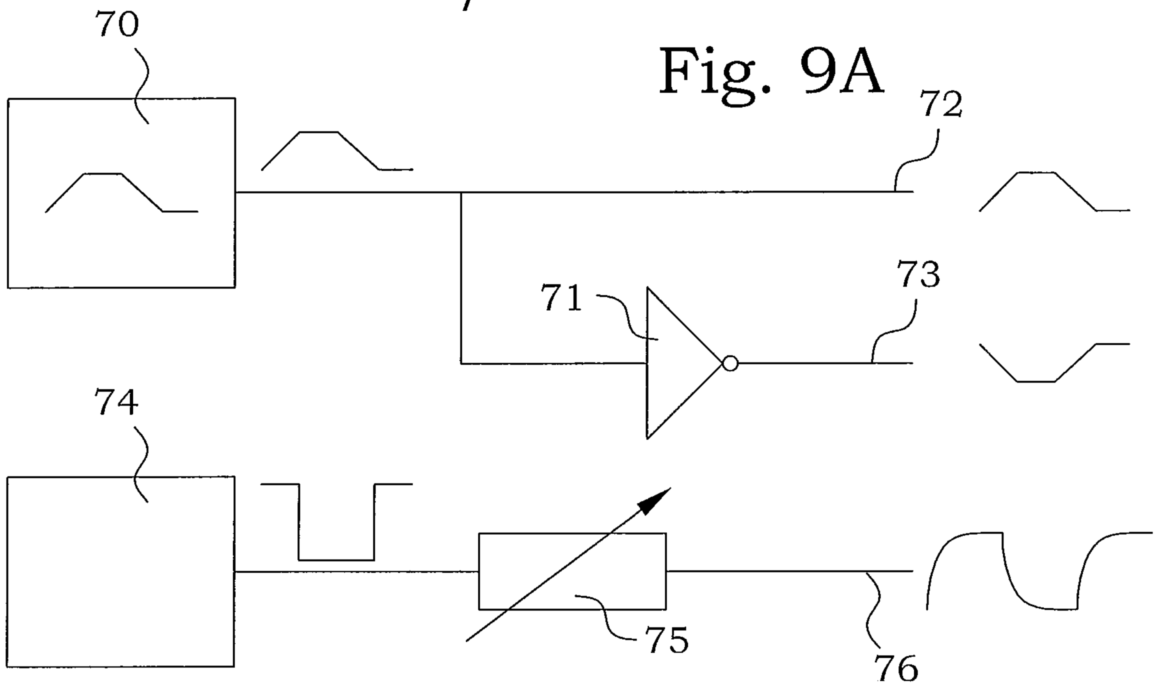


Fig. 9A

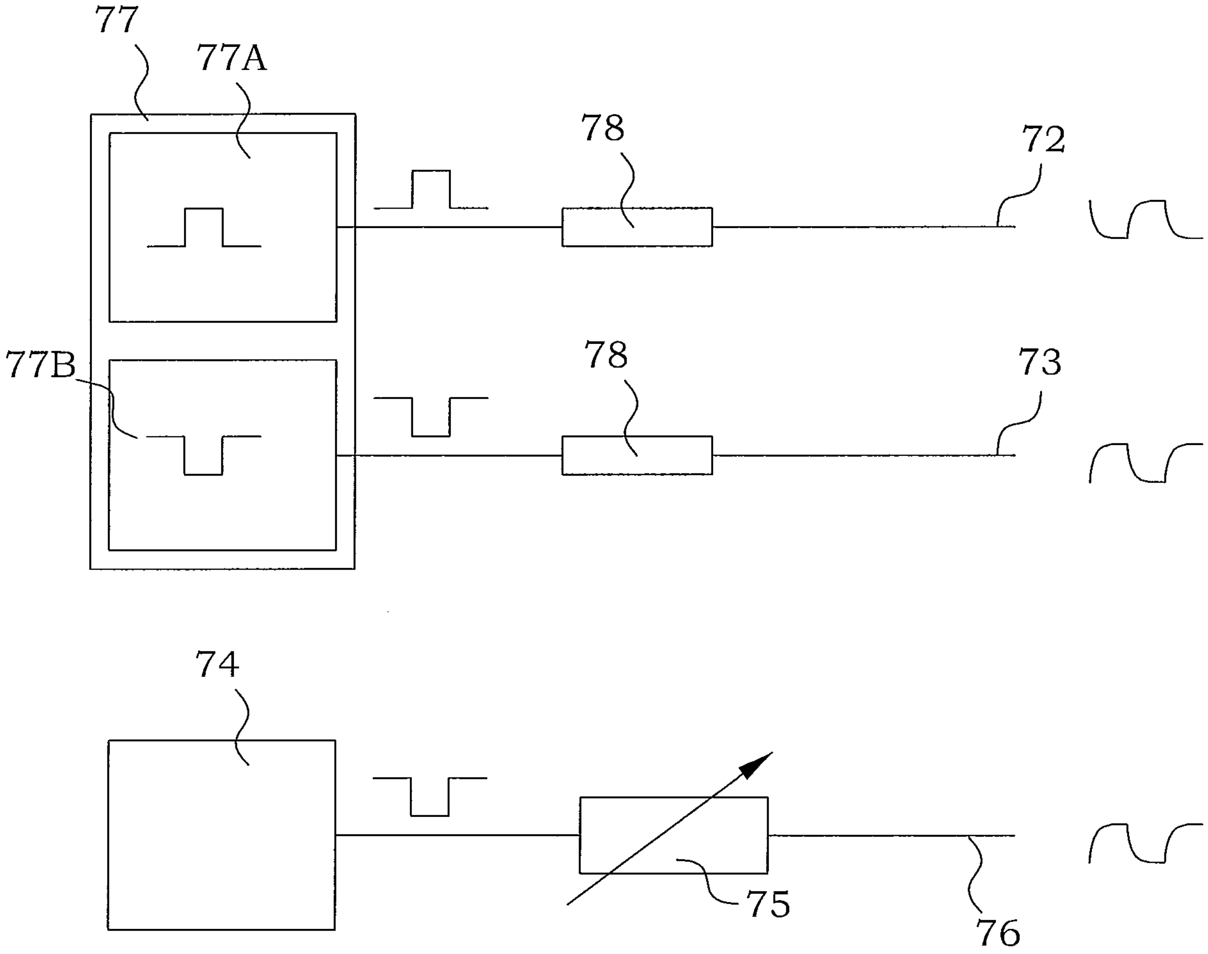


Fig. 9B

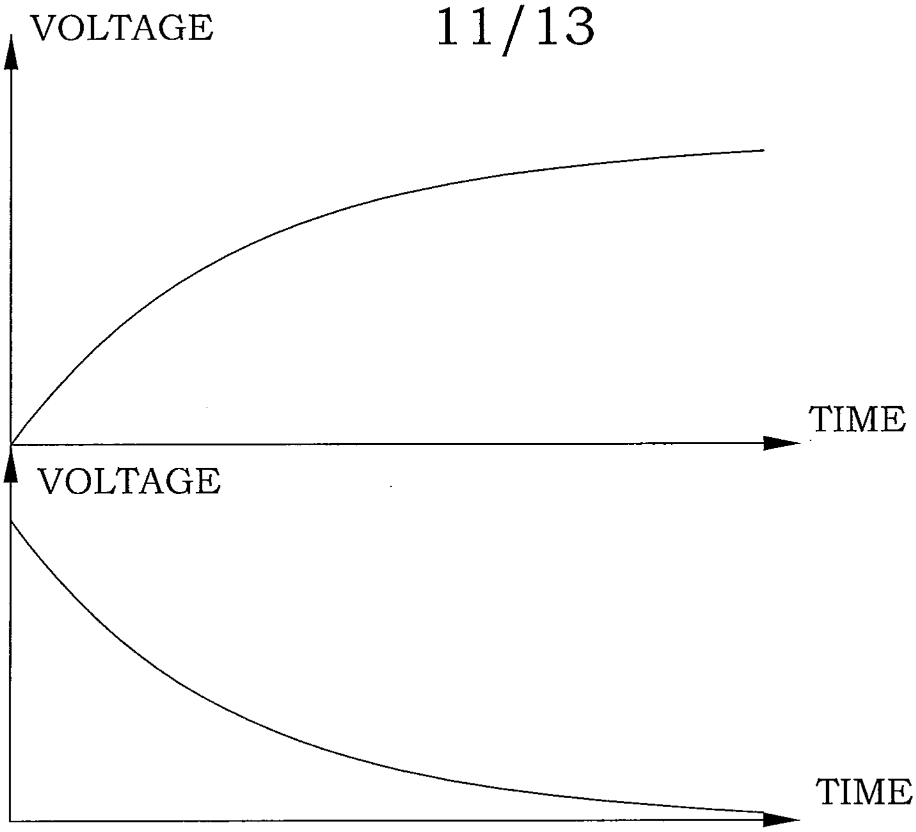
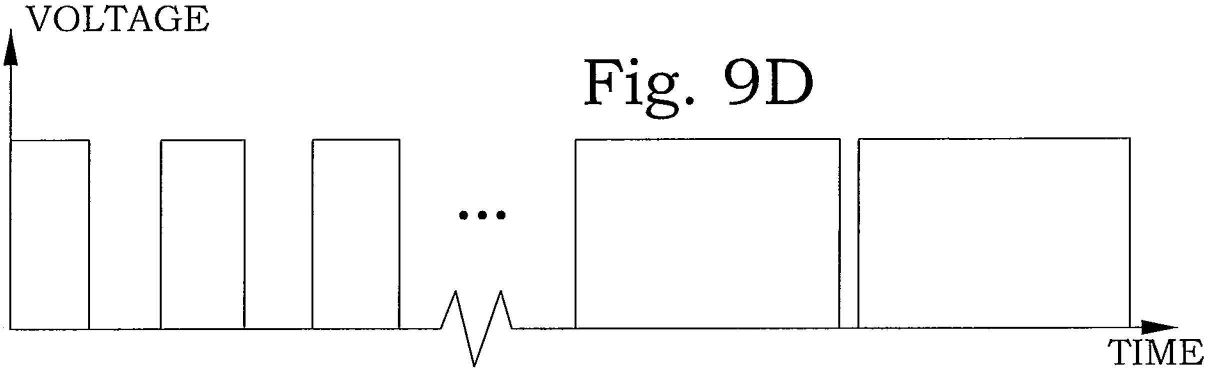


Fig. 9C

Fig. 9D



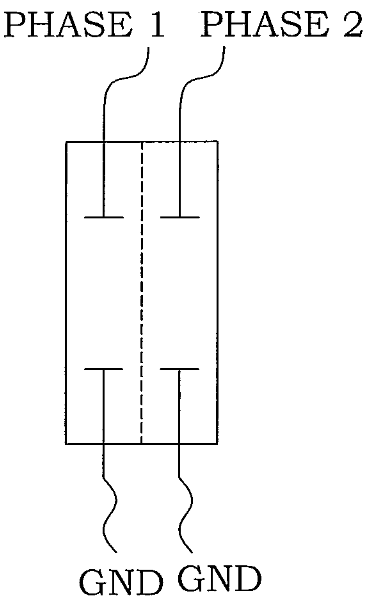


Fig. 10A

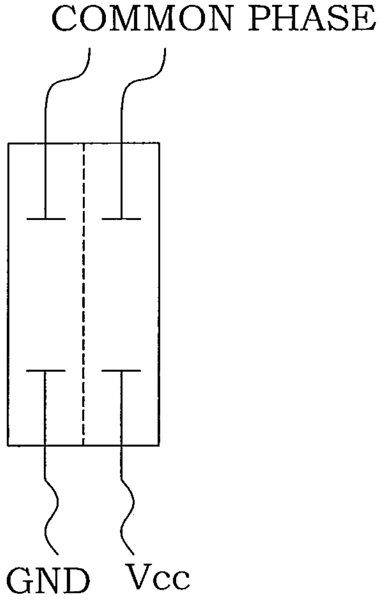


Fig. 10B

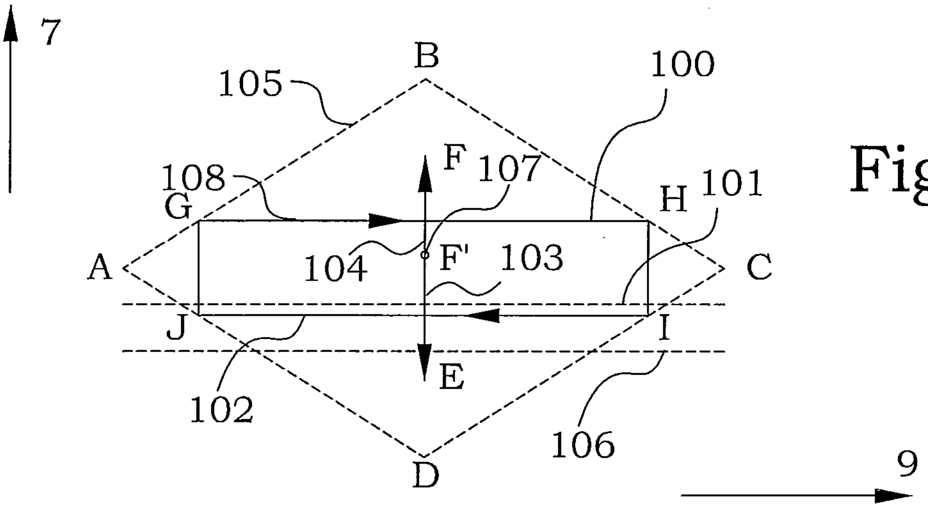


Fig. 11A

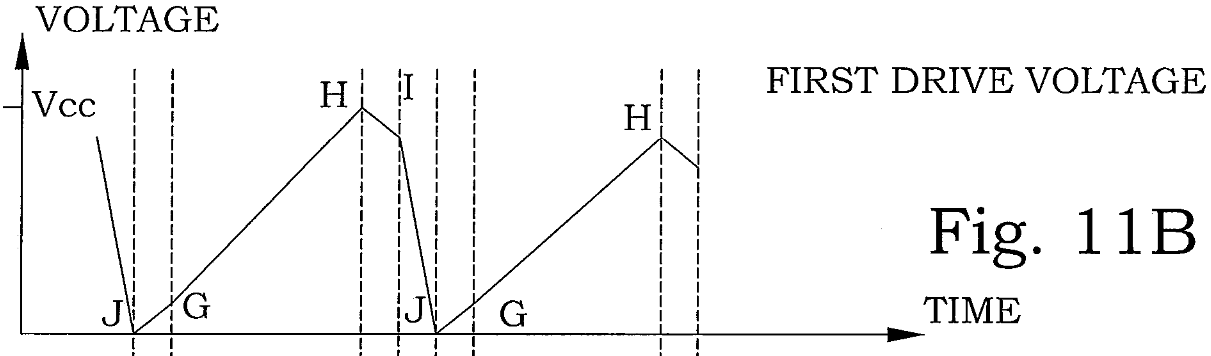


Fig. 11B

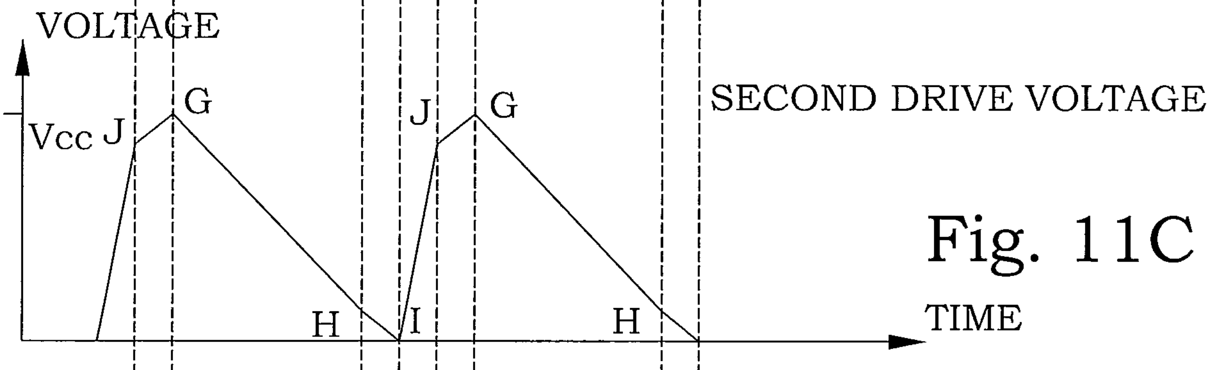


Fig. 11C

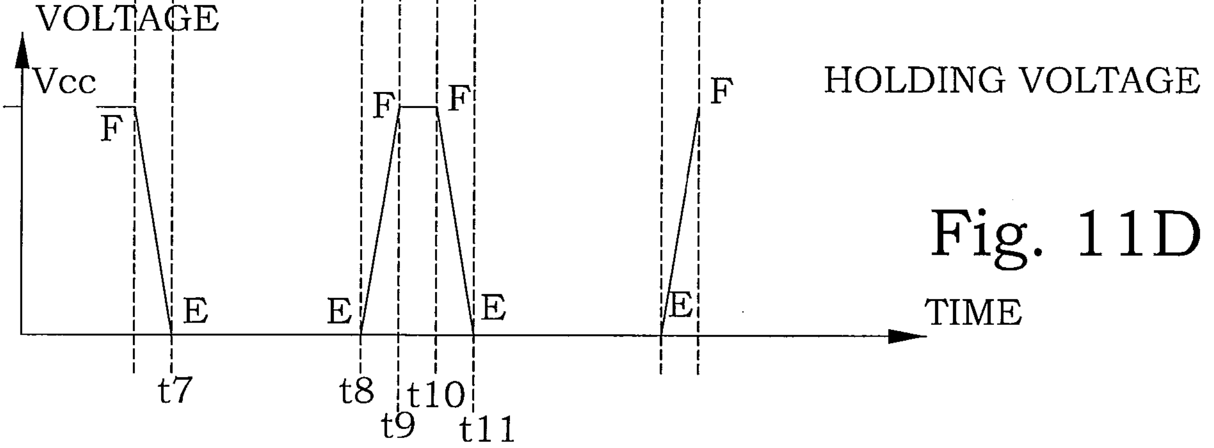


Fig. 11D

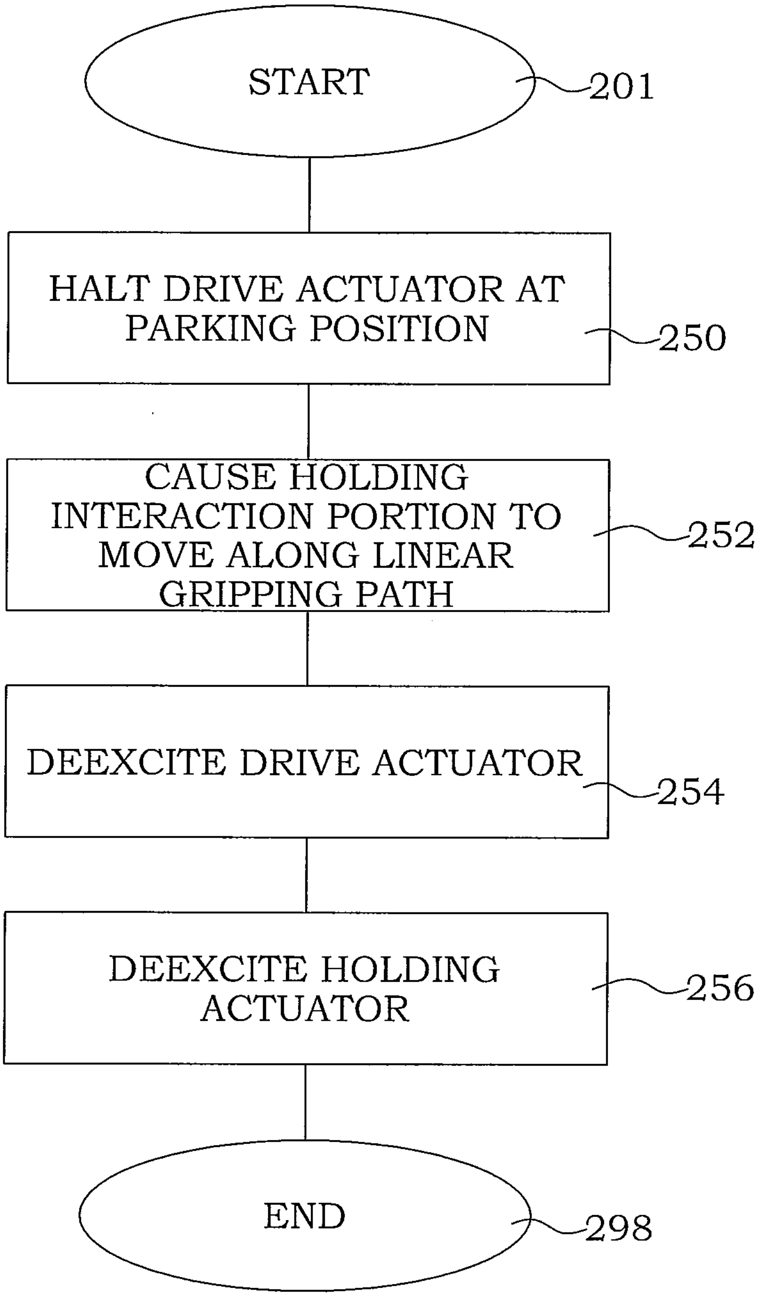

START
201
HALT DRIVE ACTUATOR AT PARKING POSITION
250
CAUSE HOLDING INTERACTION PORTION TO MOVE ALONG LINEAR GRIPPING PATH
252
DEEXCITE DRIVE ACTUATOR
254
DEEXCITE HOLDING ACTUATOR
256
END
298

Fig. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/050599

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L41/04 H01L41/09
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	DE 10 2006 039821 A1 (ZEISS CARL SMT AG [DE]) 13 March 2008 (2008-03-13) paragraph [0046] - paragraph [0052]; figures 5a-5f	1-5, 7-14,16 6,15
A	WO 2010/009807 A1 (ZEISS CARL SMT AG [DE]; WEBER ULRICH [DE]; HEMBACHER STEFAN [DE]; SCHO) 28 January 2010 (2010-01-28) figures 4a-4e	1-16
A	US 6 066 911 A (LINDEMANN GERT [DE] ET AL) 23 May 2000 (2000-05-23) figure 9	1-16

-/--

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier 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
18 May 2011

Date of mailing of the international search report
06/06/2011

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
Gröger, Andreas

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SANG WON LEE ET AL: "Development of a piezoelectric multi-axis stage based on stick-and-clamping actuation technology", SMART MATERIALS AND STRUCTURES, IOP PUBLISHING LTD., BRISTOL, GB, vol. 16, no. 6, 1 December 2007 (2007-12-01), pages 2354-2367, XP020130081, ISSN: 0964-1726 figure 3 -----	1-16
A	ZHAO MEIRONG ET AL: "A new linear piezoelectric motor for large range nano-positioning system", PACIFIC RIM WORKSHOP ON TRANSDUCERS AND MICRO/NANO TECHNOLOGIES XIAMEN UNIV. XIAMEN, CHINA, 2002, pages 489-492, XP009148398, page 490; figures 1,2 -----	1-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2011/050599

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102006039821 A1	13-03-2008	WO 2008022797 A1	28-02-2008
		US 2009225297 A1	10-09-2009
WO 2010009807 A1	28-01-2010	DE 102008034285 A1	04-02-2010
		EP 2300877 A1	30-03-2011
US 6066911 A	23-05-2000	WO 9626551 A1	29-08-1996
		DE 19605214 A1	29-08-1996
		DE 59602003 D1	01-07-1999
		EP 0811252 A1	10-12-1997
		ES 2134591 T3	01-10-1999
		JP 11500598 T	12-01-1999