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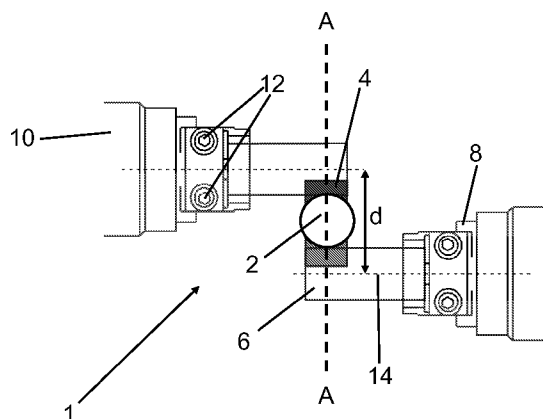


Fig. 1

(57) Abstract: An actuation device (1) comprises at least two rotational actuators (10). The axes of rotation (14) of the rotational actuators (10) are offset from each other. The rotational actuators (10) are coupled to an actuation member (2) such that rotation of the rotational actuators (10) moves the actuation member (2).

### Actuation Devices

5 This invention relates to actuation devices. It relates in particular to actuation devices which act over small distances and at high frequencies, for example to move a component in an optical system.

10 Components of an optical system, such as mirrors or lenses, often need to be moved precisely over very small distances, e.g. microns, or at a very high frequency, e.g. kHz, for a variety of different reasons. These can be to change the focus of a beam or to scan across different wavelengths. Conventionally piezo actuators have been employed to move these components but there is an inherent trade-off between length of travel and frequency of oscillation, i.e. a piezo-actuator can either move through a relatively large distance at a low frequency, or a shorter  
15 distance at a higher frequency. There therefore exists a need for a device which can move an object through a large distance, e.g. greater than 100 microns, at a high frequency, e.g. several kHz.

20 From a first aspect the present invention provides an actuation device comprising at least two rotational actuators wherein the axes of rotation of the rotational actuators are offset from each other, said rotational actuators being coupled to an actuation member such that rotation of said rotational actuators moves the actuation member.

25 Thus it will be seen that the invention provides a coupling between the rotational actuators and the actuation member which is arranged such that in use, rotation of the rotational actuators moves the actuation member.

30 The motion of the actuation member can be parallel to its surface, i.e. translational motion, but preferably the rotation of the rotational actuators moves the actuation member in a tilting movement and/or linearly along a normal to its surface depending upon their relative directions of rotation.

35 Thus it can be seen by those skilled in the art that in a preferred set of embodiments the present invention provides an actuator to which can be imparted linear and/or tilting motion. Linear motion is a translation of the actuation member

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along the normal to its surface (or along a direction making a small angle, i.e. less than 30 degrees, to the normal). Tilting movement is a rotation about an axis in or parallel with the surface of the actuator. Providing rotational actuators which have their axes of rotation offset from each other creates a moment which makes it possible to convert the rotational motion of the rotational actuators into either axial or tilting motion of the actuation member through the coupling. If the rotational actuators have a sufficiently high torque, large distances of travel and high frequencies of the actuation member can be obtained. The distance of the offset between the rotational actuators determines the amount of amplification of the rotational motion of the rotational actuators into the motion of the actuation member, e.g. if a large offset is chosen, this results in a large amplification.

Preferably the coupling is arranged so that the actuation member is moved linearly in a direction perpendicular to the axes of rotation of the rotational actuators. In addition to the axes of rotation of the rotational actuators being offset from each other, preferably the axis of rotation of each rotational actuator is offset from the centre of the actuation member. This arrangement allows for different combinations of axial and/or tilting motion to be generated for the actuation member.

The coupling between the rotational actuators and the actuation member could be a mechanical arrangement of rigid linkages, e.g. a ball and socket arrangement, but preferably the rotational actuators are coupled to the actuation member via a linkage which is at least partly flexible. The flexibility of the linkage allows the rotational motion of the rotational actuators to be converted into a linear axial or translational motion of the actuation member particularly in a simple manner. The flexible linkage is preferably resilient so that as the rotational actuator rotates, the end of the flexible linkage connected to it flexes and so transfers the torque of the rotational actuator through the linkage to the actuation member.

The provision of a flexible linkage in accordance with at least some embodiments also allows for movement of the edge of the actuation member in a direction different to that induced by the rotation of the rotational actuator coupled it, e.g. through movements generated by the other rotational actuators. This occurs especially in embodiments which have more than two rotational actuators. For example, if an embodiment with four rotational actuators which are equally spaced

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around the actuation member is considered, two of the rotational actuators on opposite sides of the actuation member could be employed to rotate it in one direction, with the flexibility of the two linkages which are attached to the stationary rotational actuators enabling the actuation member to rotate freely in this direction, i.e. perpendicular to their normal direction of motion.

The coupling of the flexible linkage to the rotational actuators might be arranged dependent on the desired motion of the actuation member, e.g. this could be different depending on whether translational, or tilting and/or linear axial motion is required.

Although the apparatus could be used to move the actuation member through any desired distance, in preferred embodiments the apparatus is arranged to move the actuation member through distances more than  $100\mu\text{m}$ . In some embodiments it may move the actuation member through 1 mm or more, either in a linear or rotational motion. Whilst these are relatively small distances, they are large for one class of preferred uses of the apparatus: optical imaging, e.g. using a scanning microscope, as these distances are large compared to the size of the objects resolved in typical images and compared to the wavelength of light. Preferably the apparatus is arranged to move the actuation member with a frequency of greater than 1kHz, e.g. more than 5 kHz. In some embodiments the frequency could be 25kHz. For the preferred uses of this apparatus this is a very high frequency and gives a large sampling rate. Preferably the apparatus is arranged to move the actuation member through distances more than  $100\mu\text{m}$  at a frequency of more than 1kHz, e.g.  $200\mu\text{m}$  at 5 kHz. In some embodiments the actuation member could be moved through a distance of 1mm or more at 25kHz. Such a combination of large travel distance and high frequency is not possible to be achieved using previous devices, e.g. a piezo-actuator, but can be obtained in accordance with at least some embodiments of the present invention.

In one set of embodiments the flexible linkage comprises a metal strip. One suitable example would be a copper-beryllium strip. Copper-beryllium is a particularly suitable material to use as a linkage in an apparatus which performs a repetitive motion with very high frequency as it is flexible but resistant to metal fatigue. The metal strip could be straight, but preferably it is bent. Having a bent

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strip enables the relationship between the angular rotation of the rotational actuators and the displacement of the actuation member to be more easily set as the pivot point of the flexible linkage is well defined in such an arrangement.

5 The actuation member can be attached to the flexible linkage by any known means, e.g. screws, nuts and bolts, rivets, clamps or glue. Clamping the actuation member to the flexible linkage allows the actuation member to be changed easily and accurately positioned. Gluing the actuation member to the flexible linkage allows the actuation member to be accurately positioned on the flexible linkage and is  
10 lightweight.

In some embodiments, the rotational actuators are each coupled to the actuation member via respective extension members, e.g. in the form of rigid paddles. The skilled person will appreciate that there are many different suitable designs and  
15 materials for the extension members. The extension members can be attached to the respective rotational actuators by any known attachment means, e.g. glue, clamps, screws, nuts and bolts, rivets. Similarly the actuation member can be attached to the extension members by any known means, e.g. screws, nuts and bolts, rivets. In one set of embodiments, e.g. where the extension members  
20 comprise rigid paddles, the actuation member is glued to them.

In other embodiments the rotational actuators may themselves comprise suitable attachment means, such as a jaws to clamp the actuation member, thereby rendering any further coupling unnecessary. This arrangement also helps to  
25 reduce the moment of inertia of the apparatus and therefore obtain the best response of the actuation member from the rotational actuators.

Preferably the apparatus is arranged such that the moment of inertia is balanced between the rotational actuators. This ensures that the torque delivered by each of  
30 the rotational actuators to the actuation member has an equal effect on its motion. Ideally this is achieved by positioning the rotational actuators at an equal distance from the actuation member and, in the embodiments which possess these features, positioning the flexible linkage and the extension members identically for each of the rotational actuators.

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Preferably the rotational actuators are arranged to rotate with an oscillatory motion. Such rotational oscillations of the rotational actuators are transformed via the coupling into the translational, linear axial or tilting movements of the actuation member. The rotational actuators may be arranged to oscillate through any angle  
5 desired, but preferably the angle of oscillation is less than 2 degrees. Although this is a relatively small angle it allows the actuation member to be moved through the required distances which, for example, are suitable for optical imaging, and uses a reasonably sized coupling or linkage, e.g. for a travel distance for the actuation member of 100µm and an angle of oscillation of 1 degree, the distance between the  
10 axis of rotation and the actuation member needs to be approximately 6 mm. As has been explained earlier the apparatus may be arranged to move the actuation member with a frequency of up to 25 kHz. Therefore the rotational actuators may be capable of operating at a frequency of up to 25 kHz e.g. between 1 kHz and 25 kHz. Such high frequencies are possible to achieve using resonant scanners.

15 Preferably the rotational actuators are synchronised with each other. As will be appreciated, to obtain accurate movements of the actuation member the movement of the rotational actuators needs to be controlled accurately. Although it is envisaged that in some embodiments the rotational actuators will operate at  
20 different frequencies, preferably the rotational actuators operate at the same frequency. This allows the actuation member to be moved in a linear or rotational motion at the frequency of the rotational actuators.

A number of different arrangements of the rotational actuators are envisaged. The  
25 apparatus may comprise more than two rotational actuators for example. Preferably the axes of rotation of the rotational actuators are all arranged to lie in the same plane. Embodiments of the invention with two, three or four rotational actuators are particularly advantageous. Preferably the rotational actuators are arranged to be equally spaced around the actuation member. For example with two  
30 rotational actuators the axes of rotation would be parallel, with three the axes would be at 120 degrees to each other, and with four they would be at 90 degrees. With two rotational actuators these can be arranged on opposite sides of the actuation member to rotate either in the opposite direction to each other to move the actuation member with a linear motion, or in the same direction to each other to  
35 move the actuation member with a tilting motion. Where the actuator member is

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disposed vertically, tilting about a horizontal axis is sometimes referred to as 'tipping'.

5 With three or four rotational actuators, movements of the actuation member can be achieved which are not possible with only two rotational actuators. For instance, the actuation member can be rotated about any desired axis by selectively rotating one or more of the rotational actuators, whereas with two rotational actuators arranged parallel to each other either side of the actuation member, the only axis of rotation available is that parallel to the rotational actuators. It is also possible with 10 more than two rotational actuators to move the actuation member in any combination of tilting and linear motion, including rotating or "spinning" the actuation member about its centre.

As will be appreciated by the skilled person, the actuation member could be used 15 for a variety of uses which require a precise, high frequency action to be delivered, e.g. switches, pistons, valves, transducers, etc. One important application is in optics where the actuation member may comprise an optical component, e.g. a lens or preferably a mirror. The mirror or the lens could be mounted on the actuation member or it could be the actuation member itself.

20 If the apparatus is used as part of an optical system, in one set of embodiments the linear motion of the actuation member is in a direction parallel to the optical axis of the system, i.e. linear axial motion. Therefore in the set of embodiments in which the actuation member comprises a mirror, preferably the linear motion is in a 25 direction normal to the reflecting face of the mirror. This is particularly advantageous in some envisaged uses of the apparatus, e.g. in a laser system to allow the laser to be scanned on its axis which could, for example, be used to alter the length of an optical cavity. Alternatively it could allow for the mechanical focussing of an optical system by moving a mirror or lens.

30 In another set of embodiments when the apparatus is used as a part of an optical system, the linear motion of the actuation member is in a direction perpendicular to the optical axis of the system, i.e. translational motion. Therefore in the set of embodiments in which the actuation member comprises a mirror, preferably the 35 linear motion is in a direction parallel to the reflecting face of the mirror.

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Also if the apparatus is used as part of an optical system, preferably the actuation member can be rotated about an axis which is perpendicular to the axis of the optical system. Where the actuation member comprises a mirror for example, this allows a beam of light to be deflected in a varying direction away from its incoming direction.

The actuation member could be any size and shape, and will typically be designed to be suitable for the intended use of the apparatus, however, in one preferred set of embodiments the actuation member is less than 20 mm in diameter, e.g. less than 10 mm, e.g. 5 mm. Preferably the actuation member is circular. This gives the apparatus a rotational symmetry and allows the rotational actuators to be coupled to the edge of the actuation member. However, embodiments are envisaged in which the order of rotational symmetry of the actuation member is matched to or is a multiple of the number of rotational actuators used in the apparatus. For example, if three rotational actuators are used, the actuation member could conveniently be triangular or hexagonal.

Along with being any size or shape, the actuation member can be any suitable mass, but preferably the mass of the actuation member is less than 5g, preferably less than 1g, e.g. 0.1g. This reduces the amount of torque needed to be input by the rotational actuators in order to generate the desired motion of the actuation member.

Preferably the axis or pivot point about which the actuation member executes a tilting motion is arranged to be on the front face of the actuation member. This is particularly advantageous in the set of embodiments in which the apparatus is used as part of an optical system, especially when the actuation member comprises a mirror. It allows, for example, a beam to be reflected off its front surface which is where the axis of rotation or pivot point lies, i.e. the point of reflection and the axis or pivot point coincide spatially, giving accurate control over the deflection of the beam.

Preferably the rotational actuators comprise galvanometers. Galvanometers are suitable for delivering rotational motion, and particularly suitable for delivering



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oscillatory motion, as they can be driven with a current (an alternating current to produce oscillatory motion) which enables the motion of the galvanometers to be controlled with a high degree of accuracy, and also at a high frequency.

- 5 All the different types of motion previously discussed, e.g. linear, tip and tilt rotations, and spinning of the actuation member (or indeed any combination of these movements) can be achieved using galvanometers as the rotational actuators.
- 10 A suitable galvanometer for using in the apparatus of the invention is any available from GSI Group ([www.camtech.com](http://www.camtech.com)) although any other galvanometer could be used instead.

Certain preferred embodiments of the invention will now be described, by way of  
15 example only, with reference to the accompanying drawings in which:

- Fig. 1 shows a front view of a first embodiment of the invention;  
Figs. 2a, 2b and 2c show cross section views of a first embodiment of the invention;
- 20 Fig. 3 shows a front view of a second embodiment of the invention;  
Fig. 4 shows a front view of a third embodiment of the invention;  
Fig. 5 shows a front view of a fourth embodiment of the invention;  
Fig. 6 shows a perspective view of a fourth embodiment of the invention;  
and
- 25 Fig. 7 shows a perspective view of a fifth embodiment of the invention.

Fig. 1 shows a front view of a first embodiment of the invention. The apparatus 1 comprises a vertically-disposed circular mirror 2 which is glued onto a flexible copper-beryllium strip 4 which in turn is glued at both ends to two upper and lower  
30 paddles 6. Each paddle 6 is made from a stainless steel strip and is mounted onto the rotating arm 8 of a respective galvanometer 10 by means of a clamp comprising a pair of jaws held together by screws 12 which clamp it in place. The galvanometers 10 and paddles 6 are arranged so that the paddles 6 are attached to opposite sides of the mirror 2 with the axis of rotation 14 of the galvanometer arms

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8 being parallel to each other but offset from each other by a predetermined distance d.

5 The same embodiment can be seen in cross section Figs. 2a, 2b and 2c, taken from along the line A-A in Fig. 1, with the reflecting surface of the mirror 2 on its forward face. It can be seen that the copper-beryllium strip 4 is mounted in a bent configuration to move the mirror 2 away from the paddles 6. This ensures that when the paddles 6 rotate, the mirror 2 is clear of them and does not get trapped between them. With a bent copper-beryllium strip 4 it is also easier to set the  
10 relationship between the rotation of the galvanometers 10 and the displacement of the mirror 2 as the pivot point of the strip 4 is well defined in such an arrangement.

Operation of the first embodiment of the invention as shown in Figs. 1 and 2 will now be described. The apparatus 1 is arranged as part of a scanning microscope  
15 (not shown) in the path of a focusing optical beam such that the beam axis is perpendicular to the face of the mirror 2. This allows the mirror 2 to be moved either in a linear motion in order to change the focus of the beam, e.g. to scan into and out of a sample being investigated by the microscope, or in a rotational motion in order to sweep the beam across the sample.

20 A synchronised alternating current is supplied to the galvanometers 10 which causes the galvanometer arms 8 to oscillate. The amplitude and frequency of the oscillations is controlled by the amplitude and frequency of the alternating current. The oscillations of the galvanometer arms 8 impart motion into the mirror 2 via the  
25 paddles 6 and the flexible strip 4. Different types of motion of the mirror 2 can be created by controlling the relative oscillations of the galvanometer arms 8.

Three different views of the same embodiment are shown, at different stages of operation of the apparatus 1. Fig. 2b shows the paddles 6 in a neutral position  
30 such that they are parallel and therefore place the mirror 2 in the centre of its allowed motion. This has the effect of moving the mirror 2 downwards away from its central position. Fig. 2c shows the opposite position in which the mirror 2 is moved upwards away from its central position by the paddles 6 which have been rotated in the opposite direction such that the inside edges of the paddles 6 move  
35 upwards and the outside edges move downwards.

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Figs. 2a, 2b and 2c show the mirror 2 being moved in a linear motion. Fig. 2b shows the neutral position where the paddles 6 are parallel and the mirror 2 is at the centre of its motion. From this position, the mirror 2 can be moved backwards to the position in Fig. 2a, i.e. lengthening the optical path, by rotating the upper galvanometer arm 6 (shown on the left in Figs. 2a - 2c) clockwise relative to the view of Fig. 2a and the lower galvanometer arm 6 (shown on the right) anticlockwise. This causes the inside edges of the paddles 6 to move backwards and the outside edges to move forwards. Rotating the galvanometer arms 8 in the opposite direction, i.e. the upper one anticlockwise and the lower one clockwise, moves the mirror 2 forwards to the position in Fig. 2c which shortens the optical path. Thus the oscillating rotational motion of the galvanometer arms 8 is converted into an oscillating linear motion of the mirror 2 as the mirror 2 moves between the different positions shown in Figs. 2a, 2b and 2c and back again.

Alternatively the mirror 2 can be made to tilt back and forth. This is achieved by oscillating the galvanometer arms 8 in a synchronised manner, i.e. at the same frequency, but from the view of Figs. 2a, 2b and 2c, the galvanometer arms 8 are rotated in the same direction. Therefore if both galvanometer arms 8 were rotated clockwise, this would cause the mirror 2 to be tilted into a position in which the upper half was projected forward and the lower half retracted back. The mirror would thus reflect an incident beam of light downwardly. Conversely, if both galvanometer arms 8 were rotated anticlockwise, this would cause the mirror 2 to be tilted into a position in which the upper half were pulled back and the lower half projected forward, thus reflecting an incident beam of light upwardly. Therefore by moving the mirror 2 in this tilting manner causes an incident beam to be swept up and down.

Fig. 3 shows a second embodiment of the invention in which three galvanometers 110 are used. In all other aspects the second embodiment is the same as the first: a circular mirror 102 is glued to a flexible copper-beryllium portion actuation member 104 which has three tabs 105. The tabs 105 are glued onto three respective paddles 106 thereby connecting the mirror 102 to the paddles 106 via the copper-beryllium portion 104. As before, the each paddle 106 is mounted on the rotating arm 108 of a galvanometer 110 by means of screws 112. The paddles

106 are equally spaced around the edge of the mirror 102, i.e. separated by 120 degrees, with the respective axes of rotation 114 of the galvanometers offset from each other and from the centre of the mirror 102 such that they have no common point of intersection.

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Fig. 4 shows a third embodiment of the invention which has all the same components and features as the second embodiment shown in Fig. 3 except that four galvanometers 210 are used. The paddles 206 which are attached to the galvanometers 210 are equally spaced around the edge of the mirror 202, i.e. separated by 90 degrees, with the axes of rotation 214 of the galvanometers offset from each other and from the centre of the mirror 202 such that they have no common point of intersection.

10

Operation of the embodiments shown in Figs. 3 and 4 is similar to that of the embodiment shown in Figs. 1 and 2, i.e. rotating the galvanometer arms 108, 208 in an oscillatory motion causes the mirror 102, 202 to move, but now many more types and combinations of motion of the mirror 102, 202 are able to be performed. A linear motion normal to the face of the mirror can be obtained by synchronously oscillating the galvanometer arms 108, 208 so that their motion is identical to each other, e.g. all the galvanometer arms 108, 208 are rotated clockwise at the same time to move the mirror 102, 202 out of the plane of the page. This is the case for both the three galvanometer embodiment and the four galvanometer embodiment.

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The mirror 102, 202 in these embodiments can also be made to move with a rotating motion, i.e. tipping or tilting. This is most easily seen with the four galvanometer embodiment shown in Fig. 4. To tilt the mirror 202 about a vertical axis (i.e. tilting it from side to side), the two horizontal galvanometers 210a, 210b are kept still, and the two vertical galvanometers 210c, 210d are operated so that their respective paddles 206 twist in opposite senses. To tip the mirror 202 about a horizontal axis (i.e. up and down), the two vertical galvanometers 210c, 210d are held still and the horizontal ones 210a, 210b operated in opposite senses.

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Both of these types of motion of the mirror 102 are also possible in the embodiment with three galvanometers, but the relative motion of the galvanometer arms 108 is more complicated. In addition, many other types of motion can be achieved in both

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the three and four galvanometer embodiments, e.g. rotating the mirror about any desired axis, having a superposition of linear and rotational motion, and even spinning the mirror 102, 202 about an axis normal to the mirror surface.

- 5 Figs. 5 and 6 show a fourth embodiment of the invention which is very similar to the first embodiment shown in Figs. 1 and 2. As with the first embodiment the apparatus of the fourth embodiment comprises two galvanometers 310 which are coupled to a circular mirror 302 by means of a flexible copper-beryllium strip 304.
- 10 The difference in this embodiment is that instead of paddles, the galvanometers 310 comprise hollow circular section clamps 316, as may be seen more clearly in Fig. 6, which hold the flexible strip 304. These could be made e.g. out of titanium or aluminium. The titanium clamps 316 are tightened by screws 312. This arrangement has a lower moment of inertia as the mass of the moving parts of the
- 15 apparatus is confined more closely to the axis than in the previous embodiments and therefore improves the response of the mirror 302.

Operation of the embodiment of the invention shown in Figs. 5 and 6 is the same as has previously been described for the embodiment shown in Figs. 1 and 2.

20

- Fig. 7 shows a fifth embodiment of the invention which is similar to the fourth embodiment shown in Figs. 5 and 6. As the with the fourth embodiment the apparatus of the fifth embodiment comprises two galvanometers which comprise hollow circular section clamps 416 which hold a flexible copper-beryllium strip 404
- 25 that couples the galvanometers to a circular mirror 402 attached to the flexible strip 404. The clamps 416 are tightened by screws 412. The difference in this embodiment is that the splits 418 between the clamps 416 are perpendicular to the plane of the flexible strip 404 and the face of the mirror 402. This results in a different motion of the mirror when the galvanometers are rotated as will now be
- 30 described.

- Rotating the galvanometer clamps 416 with a synchronised oscillatory motion - in this embodiment with an identical oscillatory motion - causes the flexible strip 404 to be moved laterally in its plane, thus moving the mirror 402 back and forth with a
- 35 sideways motion parallel to the plane of its face.

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5 In the embodiments shown the circular mirror is 5 mm in diameter, 2 mm thick and made from silver on glass, though of course the scope of the invention covers any different shape, size and material of mirror, as well as mounting other components as the actuation member, e.g. a lens. The axis of rotation of the galvanometers is offset from the centre of the mirror by 5 mm.

10 It will be appreciated by those skilled in the art that only a small number of possible embodiments have been described and that many variations and modifications are possible within the scope of the invention. For example the actuation member has been described as a mirror in an optical imaging system, however many other uses of the actuation member are envisaged, for example as a moving component which exerts a force on other components within a system such as a switch. The technique of moving an actuation member using rotational actuators is scalable to  
15 different regimes, e.g. different distances and frequencies. Therefore whilst the embodiments described are relevant for distances up to 1 mm and frequencies up to 25 kHz, the apparatus could be used for any distances and frequencies that were suitable for the intended use. These values can all be scaled by adjusting the necessary mechanical parameters of the apparatus. The apparatus could also be  
20 smaller or bigger as necessary, e.g. a smaller or bigger actuation member to suit the use.

## Claims

- 5        1.        An actuation device comprising at least two rotational actuators wherein the axes of rotation of the rotational actuators are offset from each other, said rotational actuators being coupled to an actuation member such that rotation of said rotational actuators moves the actuation member.
- 10       2.        An actuation device as claimed in claim 1, wherein the rotation of the rotational actuators moves the actuation member in a tilting movement and/or linearly along a normal to its surface.
- 15       3.        An actuation device as claimed in claim 2, wherein the axis or pivot point about which the actuation member executes a tilting movement is arranged to be on the front face of the actuation member.
- 20       4.        An actuation device as claimed in claim 1, 2 or 3, wherein the coupling is arranged so that the actuation member is moved linearly in a direction perpendicular to the axes of rotation of the rotational actuators.
- 25       5.        An actuation device as claimed in any preceding claim, wherein the axis of rotation of each rotational actuator is offset from the centre of the actuation member.
- 30       6.        An actuation device as claimed in any preceding claim, wherein the rotational actuators are coupled to the actuation member via a linkage which is at least partly flexible.
- 35       7.        An actuation device as claimed in claim 6, wherein the linkage is resilient.
8.        An actuation device as claimed in claim 6 or 7, wherein the linkage comprises a metal strip, e.g. a copper-beryllium strip.
9.        An actuation device as claimed in claim 8 wherein the metal strip is bent.

10. An actuation device as claimed in any preceding claim, arranged to move the actuation member through distances more than 100 $\mu$ m.
- 5 11. An actuation device as claimed in any preceding claim, arranged to move the actuation member with a frequency of greater than 1kHz, e.g. more than 5 kHz.
12. An actuation device as claimed in any preceding claim, arranged such that the moment of inertia is balanced between the rotational actuators.
- 10 13. An actuation device as claimed in any preceding claim, wherein the rotational actuators are arranged to rotate with an oscillatory motion.
14. An actuation device as claimed in any preceding claim, wherein the rotational actuators are arranged to oscillate through an angle of less than 2 degrees.
- 15 15. An actuation device as claimed in any preceding claim, wherein the rotational actuators are synchronised with each other.
- 20 16. An actuation device as claimed in claim 15, wherein the rotational actuators operate at the same frequency.
17. An actuation device as claimed in any preceding claim, wherein the axes of rotation of the rotational actuators are all arranged to lie in the same plane.
- 25 18. An actuation device as claimed in any preceding claim, wherein the rotational actuators are arranged to be equally spaced around the actuation member.
- 30 19. An actuation device as claimed in any preceding claim, wherein the actuation member comprises an optical component.
20. An actuation device as claimed in claim 19, wherein the optical component comprises a mirror.
- 35



21. An actuation device as claimed in claim 19 or 20, wherein the linear motion of the actuation member is in a direction parallel to the optical axis of the system.
- 5 22. An actuation device as claimed in claim 19 or 20, wherein the linear motion of the actuation member is in a direction perpendicular to the optical axis of the system.
- 10 23. An actuation device as claimed in any of claims 19 to 22, wherein the actuation member can be rotated about an axis which is perpendicular to the axis of the optical system.
24. An actuation device as claimed in any preceding claim, wherein the actuation member is less than 20 mm in diameter, e.g. less than 10 mm, e.g. 5 mm.
- 15 25. An actuation device as claimed in any preceding claim, wherein the actuation member is circular.
26. An actuation device as claimed in any preceding claim, wherein the mass of the actuation member is less than 5g, preferably less than 1g, e.g. 0.1g.
- 20 27. An actuation device as claimed in any preceding claim, wherein the rotational actuators comprise galvanometers.

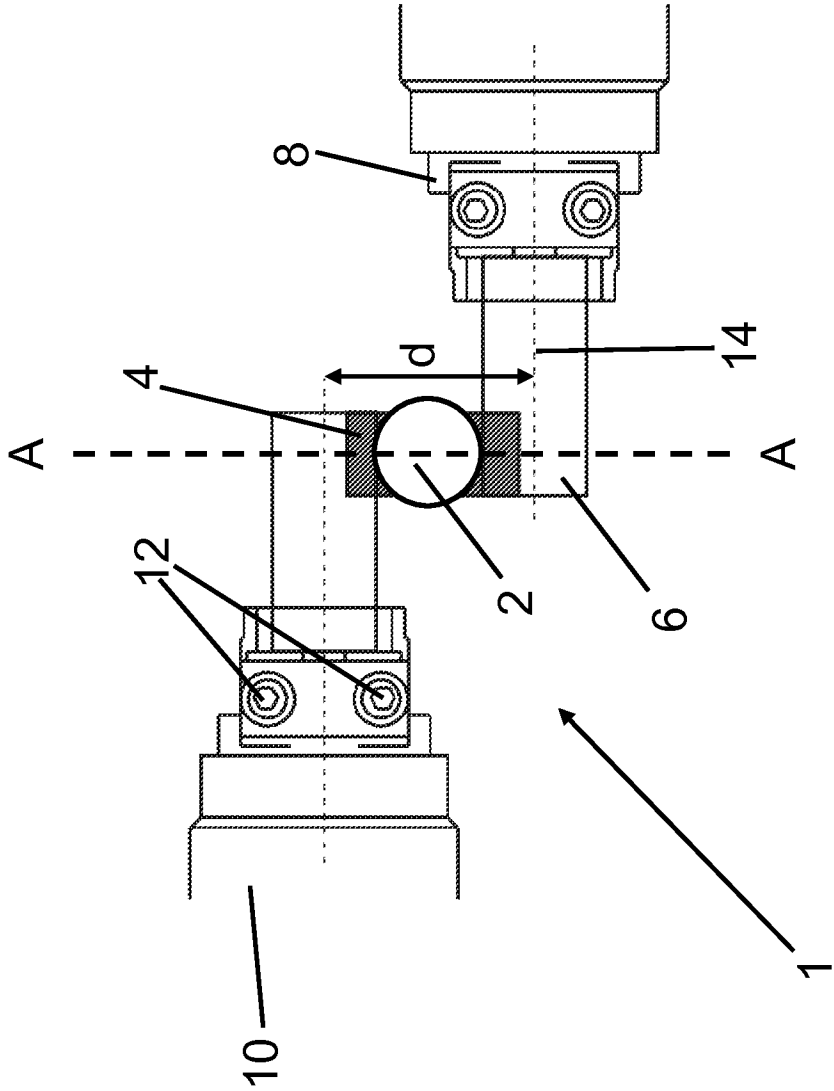


Fig. 1

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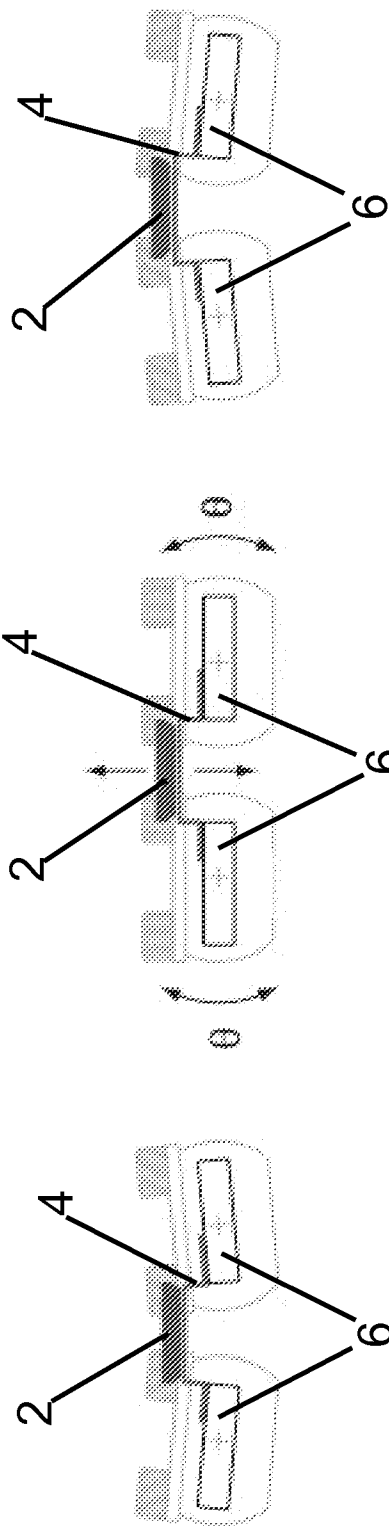


Fig. 2a

Fig. 2b

Fig. 2c

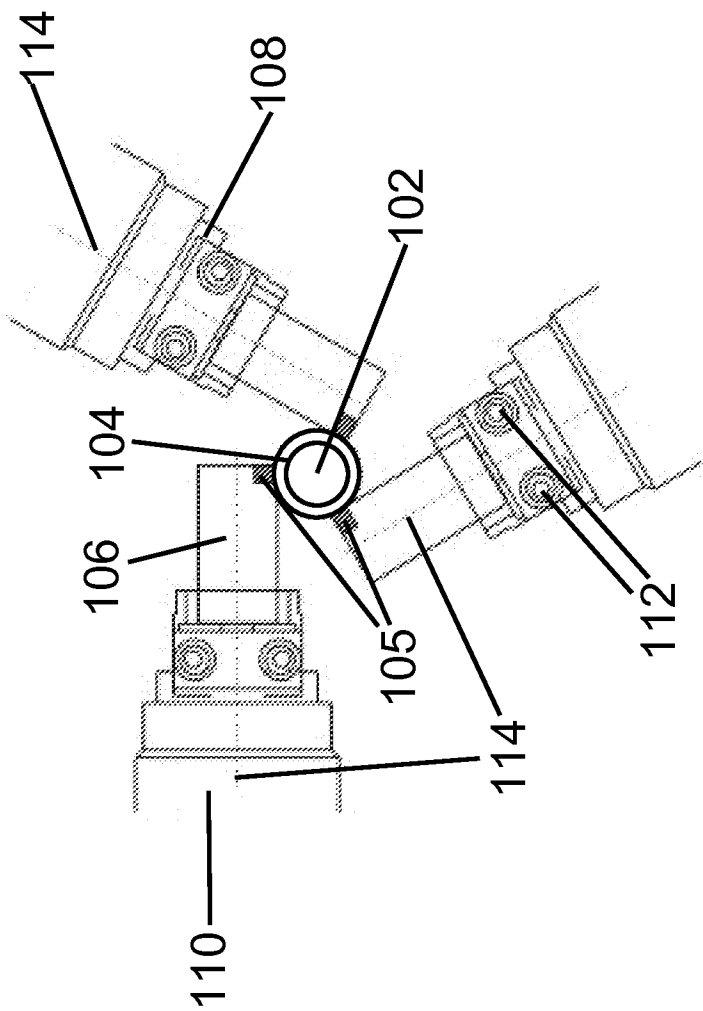


Fig. 3

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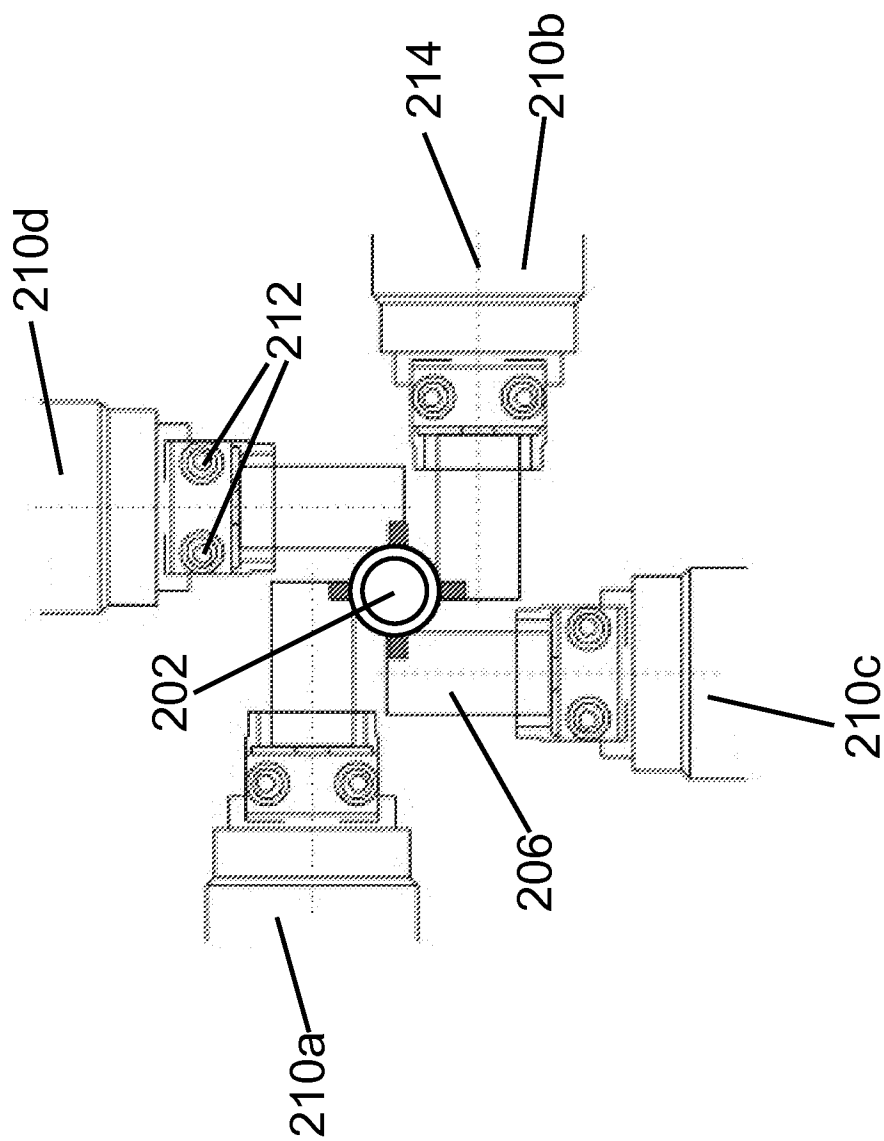


Fig. 4

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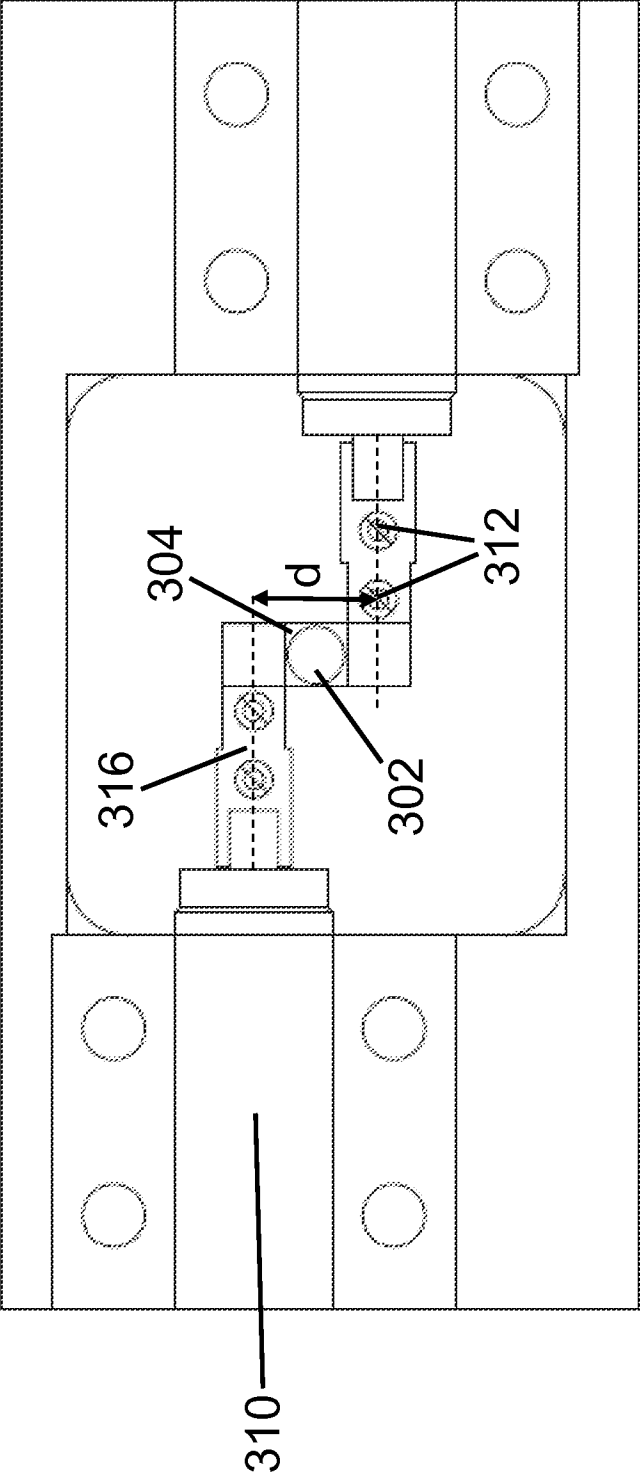


Fig. 5

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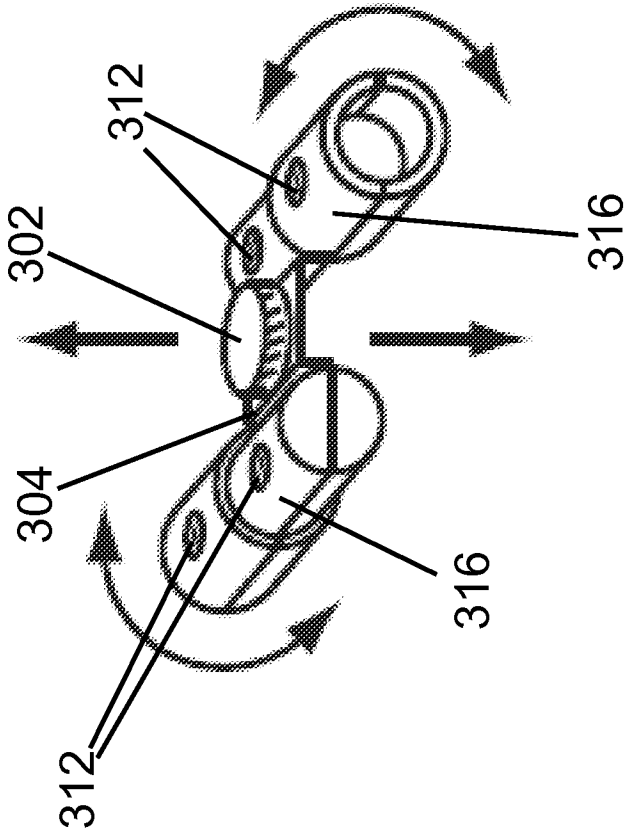


Fig. 6

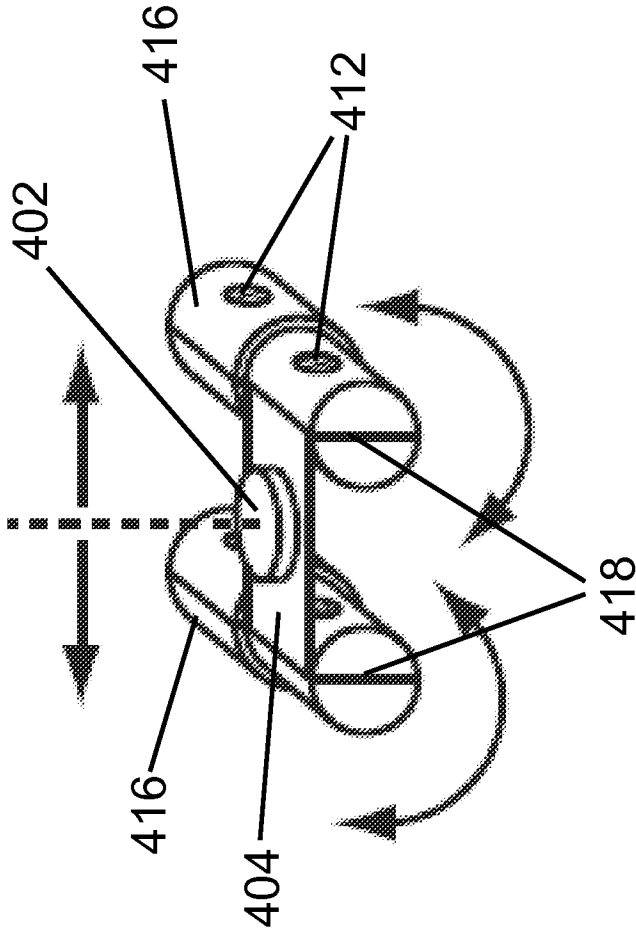


Fig. 7



## INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2011/050089

## A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B26/08 G02B26/10  
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)  
G02B

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

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                   | Relevant to claim No.       |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| X         | US 7 295 726 B1 (MILANOVIC VELJKO [US] ET AL) 13 November 2007 (2007-11-13)<br>page 6, line 16 - line 4; claim 3; figures 1,3,4<br>page 9, line 22 - line 23<br>-----                                                                | 1-3,5-27                    |
| X         | WO 2005/086858 A2 (UNIV COMMUNITY COLLEGE SYS NEV [US]; SUTKO JOHN LEONARD [US]; PUBLICOV) 22 September 2005 (2005-09-22)<br>column 12, line 59 - column 13, line 8; figures 11A,11B,12A,12B<br>column 11, line 42 - line 4<br>----- | 1-7,9,<br>10,12-26          |
| X         | GB 936 402 A (ELECTRICITE DE FRANCE)<br>11 September 1963 (1963-09-11)<br><br>page 2, line 37 - line 52; figure 1<br>-----<br>-/-                                                                                                    | 1-3,5-7,<br>12-17,<br>22,27 |



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

21 April 2011

Date of mailing of the international search report

29/04/2011

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                            | Relevant to claim No. |
|-----------|-----------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| A         | WO 2008/100310 A1 (OPTOELECTRONICS CO LTD<br>[JP]; OPTICON INC [US]; TAKAHASHI TORU<br>[JP]) 21 August 2008 (2008-08-21)<br>figure 2<br>----- | 1                     |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2011/050089

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s) | Publication<br>date                                                                        |
|-------------------------------------------|---------------------|----------------------------|--------------------------------------------------------------------------------------------|
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| WO 2005086858                             | A2                  | 22-09-2005                 | US 2008123169 A1 29-05-2008                                                                |
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