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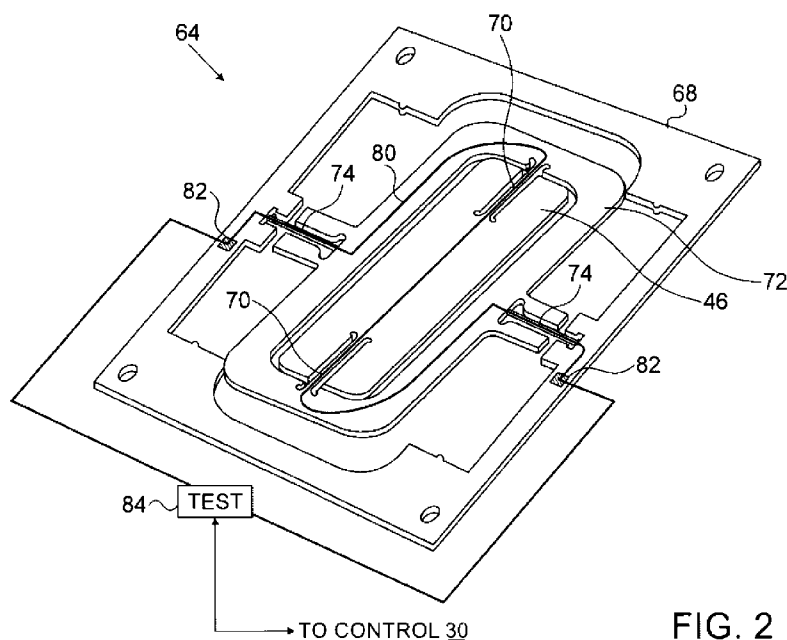


FIG. 2

(57) Abstract: A method for monitoring includes providing a device (64) including a first part (46) and a second part (72) and a movable joint (70) connecting the first part to the second part. An electrical characteristic of a conductive path (80) crossing the movable joint is measured, and a remedial action is initiated in response to detecting a change of the electrical characteristic.

DETECTING_FAILURE_OF_SCANNING_MIRROR**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims the benefit of U.S. Provisional Patent Application 61/736,551, filed December 5 13, 2012, which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to operational testing and verification of mechanical devices, and particularly to techniques for verifying the 10 integrity of micro-electro-mechanical systems (MEMS) devices.

BACKGROUND

MEMS devices are found in a wide range of applications, as diverse as optical scanners, automotive 15 pressure sensors and accelerometers, and gyroscopes used in computing and communication devices. MEMS-based optical scanners are described, for instance, in U.S. Patent 7,952,781 and in U.S. Patent Application Publication 2013/0207970, whose disclosures are 20 incorporated herein by reference.

Methods for monitoring the operation of a scanning mirror are known in the art. For example, U.S. Patent Application Publication 2013/0250387, whose disclosure is incorporated herein by reference, describes a 25 transmitter, which is configured to emit a beam comprising pulses of light, and a scanning mirror, which is configured to scan the beam over a scene. A receiver is configured to receive the light reflected from the scene and to generate an output indicative of the pulses 30 returned from the scene. A grating is formed on an

optical surface in the apparatus and is configured to diffract a portion of the beam at a predetermined angle, so as to cause the diffracted portion of the beam to be returned from the scanning mirror to the receiver. A
5 controller is coupled to process the output of the receiver so as to detect the diffracted portion and to monitor a scan of the mirror responsively thereto.

SUMMARY

Embodiments of the present invention that are
10 described herein provide methods and apparatus that can be used to test and verify the integrity of hinged mechanical devices.

There is therefore provided, in accordance with an embodiment of the present invention, a method for
15 monitoring, which includes providing a device including a first part and a second part and a movable joint connecting the first part to the second part. An electrical characteristic of a conductive path crossing the movable joint is measured. A remedial action is
20 initiated in response to detecting a change of the electrical characteristic.

In some embodiments, providing the device includes applying photolithographic processing to etch the first and second parts of the device and the joint from a
25 substrate and to deposit a metal trace so as to form the conductive path on a surface of the substrate. In a disclosed embodiment, the device includes a micro-electro-mechanical system (MEMS), and the substrate includes a semiconductor wafer.

30 Typically, measuring the electrical characteristic includes measuring an electrical continuity of the conductive path, and detecting the change includes

detecting a loss of the continuity in response to a failure of the joint.

In one embodiment, the first part of the device includes a mirror and the second part of the device includes a gimbal, and the movable joint includes rotatable hinges between the mirror and the gimbal, and the rotatable hinges are crossed by the conductive path. The mirror may include a conductive material, which forms a part of the conductive path. Additionally or alternatively the rotatable hinges between the mirror and the gimbal may include first hinges, and the device may include a base and second rotatable hinges between the gimbal and the base, wherein the conductive path crosses both the first and the second hinges. In a disclosed embodiment, providing the device includes directing a beam of light toward the mirror so as to scan the beam reflected from the mirror as the mirror rotates on the hinges, and initiating the remedial action includes interrupting the beam of the light.

Alternatively or additionally, initiating the remedial action includes issuing an indication of a failure of the device.

There is also provided, in accordance with an embodiment of the present invention, a mechanical device, including first and second parts and a movable joint connecting the first part to the second part. An electrical path crosses the movable joint. A control circuit is configured to measure an electrical characteristic of the conductive path and to initiate a remedial action in response to detecting a change of the electrical characteristic.

The present invention will be more fully understood from the following detailed description of the embodiments thereof, taken together with the drawings in which:

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic, pictorial illustration of an optical scanning head, in accordance with an embodiment of the present invention; and

10 Fig. 2 is a schematic, pictorial illustration of a scanning mirror with a test circuit, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In some cases, structural failure of a MEMS device has to be detected with minimal delay. This sort of rapid failure detection is needed, for example, in MEMS-based scanning projector systems, in which a beam of light is emitted by a laser source and is reflected by a scanning mirror onto an object or scene, which may contain one or more people. (Systems of this sort are described in the above-mentioned U.S. Patent Application Publication 2013/0207970, as well as in PCT Patent Application PCT/IB2013/056101, filed July 25, 2013, whose disclosure is incorporated herein by reference.) In such a system, if the mirror integrity is compromised and the laser beam no longer scans as intended, the light source should be shut down immediately, possibly within several microseconds or less, in order to avoid exceeding exposure limits dictated by eye safety standards.

25 As another example, if an accelerometer loses structural stability, it may fail to detect movement. In applications requiring immediate detection of motion,

such as safety applications, it is important to detect device malfunction and take prompt action.

Embodiments of the present invention that are described herein provide devices and methods that enable
5 real-time monitoring of the structural integrity of mechanical devices, and initiate immediate remedial action when the structural integrity is compromised. This sort of monitoring is particularly useful in detecting failure of a scanning mirror, as illustrated in
10 the embodiment described below, but it can also be used advantageously with other types of MEMS devices, as well as in small-scale mechanical devices of other sorts. The disclosed embodiments link structural integrity with a simple electrical characteristic, such as electrical
15 continuity (measured, for example, in terms of conductivity) of a certain path crossing the device. The device is configured and the monitored electrical characteristic is chosen so as to exhibit a sharp transition - such as loss of electrical continuity - when
20 the device fails. The transition is easily measured with low latency, using a simple monitoring circuit.

Generally stated, embodiments of the present invention are directed to devices comprising at least first and second mechanical parts, connected by a movable
25 joint (or multiple joints). A control circuit measures an electrical characteristic of a conductive path crossing the movable joint and initiates a remedial action in response to detecting a change of the electrical characteristic. In devices in which the first
30 and second parts of the device and the joint are etched from a substrate by a photolithographic process (such as etching of MEMS devices from a semiconductor wafer), a

metal trace may be deposited on the surface of the substrate as a part of the processing steps so as to form the conductive path on a surface of the substrate.

In a particular embodiment that is described below,
5 the movable joints comprise rotatable hinges between a scanning mirror and a gimbal, and the conductive path crosses the rotatable hinges. Since the mirror itself typically comprises a conductive coating on the substrate, this coating may be a part of the conductive
10 path. If a hinge breaks in operation, the control circuit will detect the loss of electrical continuity and may then interrupt the beam of light scanned by the mirror and/or issue an indication of a failure of the device.

15 The approach adopted by the disclosed embodiments is thus advantageous, *inter alia*, in that it requires only minimal additional circuitry to be added to an existing MEMS design. The conductive path itself may be deposited in the same process steps as are used to form other metal
20 structures (such as the reflective mirror surface) in the MEMS device. Failure detection using the disclosed techniques is fast and reliable, since structural integrity can be measured directly by a circuit built into the MEMS device; and the measurement does not depend
25 on any control loop of the scanning system, which may typically be much slower. Embodiments of the present invention thus enhance the safety and robustness of optical scanning engines, particularly for applications such as optical projection and 3D mapping, and may also
30 be applied to other types of small-scale mechanical devices.

Fig. 1 is a schematic, pictorial illustration of an optical scanning head 40 with a scanning integrity monitor, in accordance with an embodiment of the present invention. With the exception of this monitor itself,
5 optical scanning head 40 is similar to an optical scanning head that is described in the above-mentioned U.S. Patent Application Publication 2013/0207970. Head 40 is described here, for the sake of completeness, as an example of a device in which an embodiment of the present
10 invention may be implemented, but without in any way limiting the application of the present invention to this specific sort of device.

A transmitter 44, typically comprising a laser diode, emits pulses of light toward a polarizing
15 beamsplitter 60. The light from transmitter 44 reflects off beamsplitter 60 and then a folding mirror 62 toward a scanning micromirror 46. A MEMS scanner 64 scans the micromirror in X- and Y-directions with the desired scan frequency and amplitude, causing the beam of light to
20 scan over a scene. (The term "micromirror" is used in the present context simply to denote a small mirror, typically no more than about 10 mm across, and possibly smaller. Details of the present micromirror and scanner are shown in Fig. 2.) Light pulses reflected back from
25 the scene strike micromirror 46, which reflects the light via folding mirror 62 through beamsplitter 60. A receiver 48 senses the returned light pulses and generates corresponding electrical pulses.

A controller 30 drives transmitter 44 and scanner 64
30 and analyzes the time delay between the transmitted pulses and the corresponding pulses from receiver 48 in order to measure the time of flight of each pulse. Based

on this time of flight, the controller computes the depth coordinate (Z) of each point (X,Y) in the scene that is scanned by scanning head 40 and thus generates a depth map of the scene. Alternatively or additionally, the reflected light may be measured and processed in order to extract other scene characteristics. Further alternatively or additionally, controller 30 may drive transmitter and scanner in order to project an image onto the scene.

In any case, controller 30 also monitors the mechanical operation of scanner 64, as described hereinbelow. Upon receiving an indication of a malfunction, controller 30 will typically take remedial action, such as interrupting the beam from transmitter 44 (possibly by simply turning off power to the transmitter) and/or issuing an alert.

The specific mechanical and optical designs of the optical head shown in Fig. 1 are described here solely by way of example. Alternative device designs that incorporate monitoring schemes of the sort described herein are also considered to be within the scope of the present invention.

Fig. 2 is a schematic, pictorial illustration of mirror 46 and elements of MEMS scanner 64, in accordance with an embodiment of the present invention. This scanner is produced and operates on principles similar to those described in the above-mentioned U.S. Patent 7,952,781, but enables two-dimensional scanning of a single micromirror, as in the above-mentioned U.S. Patent Application Publication 2013/0207970 and PCT Patent Application PCT/IB2013/056101. Alternative methods that may be used in production of scanner 64 are described in

PCT Patent Application PCT/IB2013/059531, filed October 22, 2013, whose disclosure is incorporated herein by reference. Alternatively, the principles of the present invention may be applied to other sorts of scanning mirrors, such as the one described by Awtar, et al., in "Two-axis Optical MEMS Scanner," Proceedings of the ASPE 2005 Annual Meeting (Norfolk, Virginia, Paper No. 1800, 2005). Further alternatively, the methods of integrity monitoring that are described hereinbelow may be used with mirrors that scan only in a single direction.

Micromirror 46 is produced by applying a suitable photolithographic process to a semiconductor substrate 68 and then etching the substrate to separate the micromirror from a gimbal 72, and to separate the gimbal from the remaining substrate 68. After etching, micromirror 46 (to which a suitable reflective coating is applied) is able to rotate about one axis relative to gimbal 72 on hinges 70, while gimbal 72 rotates in an orthogonal direction relative to substrate 68 on hinges 74. Scanner 64 may be driven by an electromagnetic scan drive, such as the type of drive that is described in the above-mentioned PCT Patent Application PCT/IB2013/056101.

In a typical MEMS implementation, hinges 70 and 74 are no more than 150 μm wide. The hinges may break or tear during operation due to manufacturing defects, drive circuit malfunction, physical abuse (drops, crashes), or material fatigue. These sorts of failures of one or more of the hinges will compromise or halt entirely the scan of micromirror 46, with the result that the beam reflected from the micromirror may remain fixed at the angle at which the scan ceased. The method of failure

detection described herein is applicable regardless of the type of and reason for the failure.

To detect failure of any of hinges 70 and 74, a conductive trace 80 is formed across micromirror 46, gimbal 72, and substrate 68, crossing all of hinges 70 and 74 as shown. (Alternatively, if desired, the trace may be formed only across certain hinges, such as hinges 74.) Trace 80 may be deposited on substrate 68 (including all the parts etched from the substrate) using methods of printed circuit and/or microelectronics production that are known in the art. For example, when metal is deposited to form a reflective coating on the surface of micromirror 46, the trace can be part of the same metal mask as the micromirror and can be made at the same time as the as the micromirror, using the same semiconductor process steps (such as photoresist patterning, shadow mask, sputtering or electroplating). Although trace 80 is shown in Fig. 2, for the sake of clarity, as running across micromirror 46, the metal coating on the micromirror may itself serve as a part of the conductive path of the trace.

Since silicon itself is not an insulator, it will conduct some current around trace 80. Therefore it may be beneficial to introduce an insulating layer, such as silicon dioxide or silicon nitride (possibly selectively patterned), between the silicon wafer and the trace. This insulating layer may be produced using manufacturing techniques that are known in the art, such as LPCVD/PECVD or thermal growth with subsequent patterning.

Alternatively, the trace may be created by patterned doping of the silicon wafer itself, as is known in the

art, or using other techniques that create a conductive path embedded in or connected to the silicon structure.

To monitor the structural integrity of scanner 64, a test circuit 84 measures the electrical continuity
5 between test pads 82. Test circuit 84 may be mounted on substrate 68, or it may be in a separate, off-board unit. Typically, test circuit 84 measures the conductivity (or equivalently, the resistance) between pads 82. Should any of hinges 70 or 74 break or tear, the continuity of
10 trace 80 crossing that hinge will be interrupted, breaking the electrical connection between test pads 82 and resulting in an immediate, marked decrease in conductivity (or increase of resistance). Alternatively, the test circuit may measure other electrical
15 characteristics that may be indicative of changes in the continuity of the conductive trace.

Controller 30 receives signals from test circuit 84 that are indicative of the measured trace continuity. Alternatively, the functionality of test circuit 84 may
20 be integrated into controller 30 itself (and for generality, the controller and test circuit are collectively referred to herein as a "control circuit"). Upon detecting a discontinuity, controller 30 initiates the appropriate remedial action, such as shutting off
25 transmitter 44 and/or raising a malfunction alarm.

Although a conductive path with a particular topology is shown in Fig. 2, in alternative embodiments other trace patterns may be used, depending on the MEMS design and monitoring needs. The trace may be formed not
30 only by deposition on the semiconductor substrate (on either the front or the back side), but alternatively as a conductive layer created by any other suitable

electronics production technique that is known in the art. The advantages of the monitoring approach described above are thus not limited to the specific device architecture that is shown in Fig. 1, and may be realized
5 in other sorts of MEMS devices, as well as miniature mechanical devices of other types.

It will thus be appreciated that the embodiments described above are cited by way of example, and that the present invention is not limited to what has been
10 particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof which would occur to persons
15 skilled in the art upon reading the foregoing description and which are not disclosed in the prior art.

CLAIMS

1. A method for monitoring, comprising:

providing a device comprising a first part and a second part and a movable joint connecting the first part to the second part;

measuring an electrical characteristic of a conductive path crossing the movable joint; and

initiating a remedial action in response to detecting a change of the electrical characteristic.

2. The method according to claim 1, wherein providing the device comprises applying photolithographic processing to etch the first and second parts of the device and the joint from a substrate and to deposit a metal trace so as to form the conductive path on a surface of the substrate.

3. The method according to claim 2, wherein the device comprises a micro-electro-mechanical system (MEMS), and wherein the substrate comprises a semiconductor wafer.

4. The method according to any of claims 1-3, wherein measuring the electrical characteristic comprises measuring an electrical continuity of the conductive path, and wherein detecting the change comprises detecting a loss of the continuity in response to a failure of the joint.

5. The method according to any of claims 1-4, wherein the first part of the device comprises a mirror and the second part of the device comprises a gimbal, and wherein the movable joint comprises rotatable hinges between the mirror and the gimbal, and the rotatable hinges are crossed by the conductive path.

6. The method according to claim 5, wherein the mirror comprises a conductive material, which forms a part of the conductive path.

7. The method according to claim 5 or 6, wherein the rotatable hinges between the mirror and the gimbal comprise first hinges, and wherein the device comprises a base and second rotatable hinges between the gimbal and the base, and wherein the conductive path crosses both the first and the second hinges.

8. The method according to any of claims 5-7, wherein providing the device comprises directing a beam of light toward the mirror so as to scan the beam reflected from the mirror as the mirror rotates on the hinges, and wherein initiating the remedial action comprises interrupting the beam of the light.

9. The method according to any of claims 1-8, wherein initiating the remedial action comprises issuing an indication of a failure of the device.

10. A mechanical device, comprising:

first and second parts and a movable joint connecting the first part to the second part;

an electrical path crossing the movable joint; and

a control circuit, configured to measure an electrical characteristic of the conductive path and to initiate a remedial action in response to detecting a change of the electrical characteristic.

11. The device according to claim 10, wherein the first and second parts of the device and the joint are etched from a substrate, and wherein the electrical path

comprises a metal trace that is deposited on a surface of the substrate.

12. The device according to claim 11, wherein the first and second parts and the moveable joint constitute a micro-electro-mechanical system (MEMS), and wherein the substrate comprises a semiconductor wafer.

13. The device according to any of claims 10-12, wherein the electrical characteristic measured by the control circuit comprises an electrical continuity of the conductive path, and wherein the detected change comprises a loss of the continuity in response to a failure of the joint.

14. The device according to any of claims 10-13, wherein the first part of the device comprises a mirror and the second part of the device comprises a gimbal, and wherein the movable joint comprises rotatable hinges between the mirror and the gimbal, and the rotatable hinges are crossed by the conductive path.

15. The device according to claim 14, wherein the mirror comprises a conductive material, which forms a part of the conductive path.

16. The device according to claim 14 or 15, wherein the rotatable hinges between the mirror and the gimbal comprise first hinges, and wherein the device comprises a base and second rotatable hinges between the gimbal and the base, and wherein the conductive path crosses both the first and the second hinges.

17. The device according to any of claims 14-16, and comprising a light transmitter, which is configured to direct a beam of light toward the mirror so as to scan

the beam reflected from the mirror as the mirror rotates on the hinges, and wherein the remedial action comprises interrupting the beam of the light.

18. The device according to any of claims 10-17, wherein
5 the remedial action comprises issuing an indication of a failure of the device.

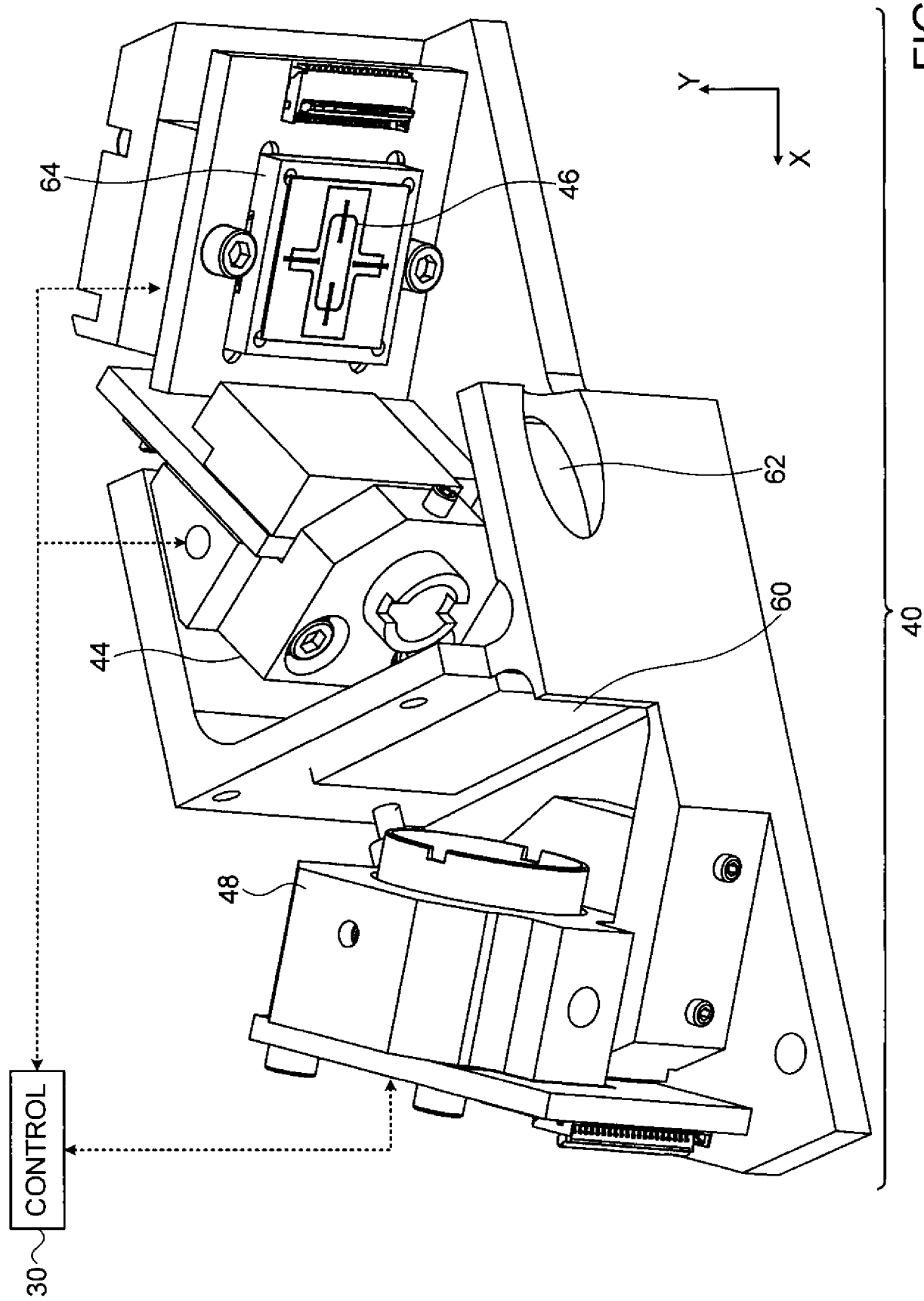
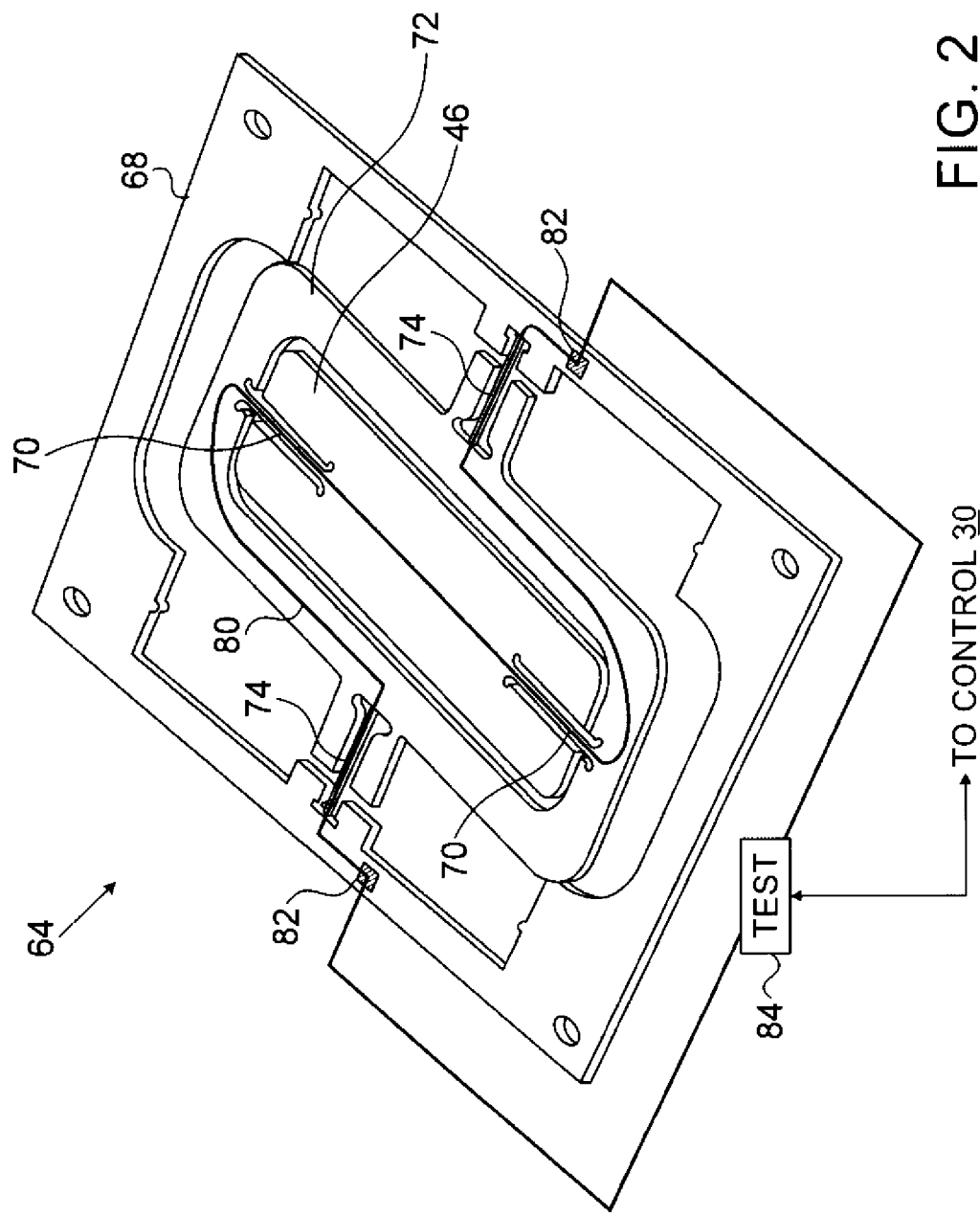


FIG. 1



INTERNATIONAL SEARCH REPORT

International application No.

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A. CLASSIFICATION OF SUBJECT MATTER IPC (2014.01) G02B 26/08, B81C 99/00 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) IPC (2014.01) G02B 26/08, B81C 99/00, B81B 5/00 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) Databases consulted: THOMSON INNOVATION, Esp@cenet, Google Patents, FamPat database Search terms used: MEMS, check, verification, test, electrical continuity, probe, failure, malfunction, fault, disconnection, QA, hinge, axis, joint, pivot, torsion, arm		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "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 24 Apr 2014		Date of mailing of the international search report 24 Apr 2014
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