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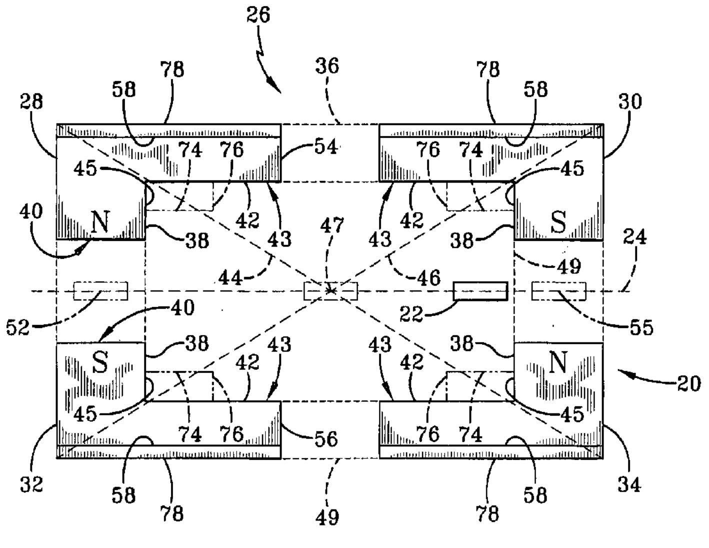
[Continued on next page]

(54) **Title:** LINEAR DISPLACEMENT SENSOR



(57) **Abstract:** A linear displacement sensor (20) uses four spaced apart magnets (28, 30, 32, 34) arranged in a rectangular array and has an axis of symmetry (24). Each magnet has a staircase shape of at least two steps (38, 42) ascending towards a centerline. Each magnet of the array has a single N-S with magnets arranged as mirror images about the axis of symmetry (24) having opposed poles, and magnets located on diagonals defined by the rectangular array having the same pole facing the axis of symmetry. The linear displacement sensor (20) employs a magnetic strength field sensor (22) such as a programmable Hall effect sensor that is mounted for movement relative to the magnetic array along the axis of symmetry (24). The height of the steps (38, 42) defining the staircase shape of the magnets (28, 30, 32, 34) is selected to produce a magnetic field of selected linearity along a selected portion of the axis of symmetry.

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LINEAR DISPLACEMENT SENSOR

The present invention relates to position measurement devices used to sense linear motion using magnetic fields.

It is often necessary to measure the position or displacement of two elements relative to each other. A particularly useful measurement is the linear displacement of a moving stage as it travels along a stationary base. This displacement can be measured with many different sensing technologies over a large range of accuracies, with different levels of complexity, and at a wide range of costs.

Some common apparatus for measuring linear displacement employ linear encoders, capacitive sensors, eddy current sensors, a linear variable differential transformer, photoelectric or fiber optic sensors, or magnetic field sensors. Linear encoders use a glass or metal ruler that is made of a high stability material so that changes in temperature do not affect measurement accuracy. These materials, such as quartz, steel, invar, glass or ceramics generally require special machining techniques to manufacture and thus are more expensive.

Capacitive sensors are used with both conductive and nonconductive target materials but are very sensitive to environmental variables that change the dielectric constant of the medium between the sensor and the target, usually air. Eddy current sensors contain two coils: an active coil that indicates the presence of a conducting target, and a secondary coil that completes a bridge circuit. A linear variable differential transformer (LVDT) sensor has a series of inductors in a hollow cylindrical shaft and a solid cylindrical core. The LVDT produces an electrical output that is proportional to the displacement of the core along the shaft. The size and mounting of these coils or cores and the sensitivity of measurement are competing design factors in the use of eddy current or LVDT sensors.

Photoelectric and fiber optic sensors use beams of light to measure distance or displacement. The photoelectric sensor uses free-space transmission of light while the fiber optic sensor uses a pair of adjacent fibers to carry light to a target and receive reflected light from the object. Alignment of the fibers and the complexity of the optics needed to maintain the light path are difficulties in using this technology.

Magnetic field strength sensor such as the Hall effect sensor, GMR sensor, or an AMR sensor can be used with a linear array of teeth or alternating magnetic poles to produce a sinusoidal output indicative of the sensor's linear motion, however the initial position must be determined and each tooth or magnetic pole must be counted and phase data analyzed for greatest accuracy. A sensor that outputs voltage that is directly proportional to linear position has advantages. One such sensor uses a pair of magnets with convex surfaces facing each other of the same magnetic pole. This type of sensor requires forming a nonlinear curve on the faces of the magnets, which can be costly.

What is needed is a linear displacement sensor that produces direct correspondence between position and magnetic field strength that can be constructed with simple magnet geometry. This problem is solved by a linear displacement sensor according to the present invention as disclosed herein.

FIG. 1 is a side elevation view of a four magnet array and linear displacement sensor of the invention.

FIG. 2 is an end elevation view of the four magnet array and linear displacement sensor of FIG. 1.

FIG. 3 is a graphic view of the magnetic field strength along the axis of an array of four magnets of the type shown in FIG. 1 at three different step heights.

FIG. 4 is an illustrative graphical view of off axis magnetic field strength variation for an array of two magnets versus the array of four magnets of FIG. 1.

A linear displacement sensor 20 is shown in FIG. 1. The linear displacement sensor 20 is comprised of a magnetic field strength sensor 22 which senses magnetic field strength and polarity which is moved along a symmetry axis 24 of an array 26 of four symmetrically arranged magnets 28, 30, 32, and 34. Each of the magnets is arranged in one of the four quadrant of a rectangle 36. Each magnet 28, 30, 32, and 34 is in the shape of a staircase having at least two steps, a proximal step 38 with a pole surface 40 closest to the line of symmetry 24, and a distal step 42 which is spaced further from the line of symmetry and has a pole surface 43. Axial spacing between the steps of each magnet defines a step side 45. The four step sides 45 together define a smaller rectangle 49 having a center coincident with the center point 47 of the larger rectangle 36 that lies on the line of symmetry 24. Each magnet of the array of magnets 26 is arranged with a single N-S or S-N pole, as shown in FIG. 1. Magnets 28, 34 which are which lie along a first diagonal 44 of the rectangle 36 are arranged with the north pole facing the line of symmetry 24. The magnets 32, 30 which lie along a second diagonal 46 of the rectangle 36 are arranged with the south pole facing the line of symmetry 24. The diagonals 44, 46 cross at the center 47 of the rectangle 36 and the symmetry axis 24 passes through the center 47 bisecting angles formed between the diagonals. Magnets 28, 32, which are arranged as mirror images with respect to the line of symmetry 24, are arranged with unlike poles facing each other. Furthermore, magnets 30, 34 which are also arranged as mirror images with respect to the line of symmetry 24, also are arranged with unlike poles facing each other; however, the arrangement of the polls N-S is reversed with respect to the poll arrangement S-N of the magnets 28, 32.

As shown in FIG. 1, the magnetic field strength sensor 22 is moved along the line of symmetry 24 by either motion of the sensor or of the magnetic array 26. The magnetic field strength sensor 22 is preferably a Hall effect sensor with onboard logic that can be programmed to adjust to the output of the Hall affect device according to an onboard program. A suitable device is, for example, an HAL 855 available from Micronas GmbH of Freiburg, Germany.

FIG.3 shows a graph 48 of a simulation of the output of the Hall effect sensor as it is moved along the axis of symmetry 24 from one side to the other of the rectangle 36 of the magnetic array 26. Also illustrated in FIG. 3 is a graph 50 of a simulation of the output of the Hall effect sensor as it moves along the axis of symmetry in an arrangement wherein the spacing of the magnets remains as illustrated in FIG. 1 but the lower steps 42 of each magnet are completely eliminated. The graph 50 shows how the field strength increases as the magnetic field strength sensor 22 approaches a point 52 of maximum field strength between opposed magnets 28, 32, and decreases as the sensor approaches the center 47 of the rectangle 36. As the magnetic field strength sensor 22 continues to move toward +a point 55 of maximum field strength between opposed magnets 30, 34, the magnetic field continues to decrease because the opposed poles of the second pair of magnets 30, 34 are reversed. The arrangement of magnets without a step illustrated by the graph 50 shows that such an arrangement is unsuitable for a linear transducer because the field strength remains essentially constant for a considerable distance on either side of the center 47 and thus magnetic field strength could not be used to accurately determine position along the axis of symmetry 24.

In the magnetic array 26 illustrated in FIG. 1, each magnet 28, 30, 32, 34 has a step height of 4 mm as measured from a rear face 58 of each magnet. These distal steps 42 on the upper magnets 28, 30 extend toward each other and define an upper gap 54 between magnets 28, 30 above the axis of symmetry 24, and centered above the center 47 of the rectangle 36. The distal steps 42 the lower magnets 32, 34 extend toward each other and define a lower gap 56 between the lower magnets 32, 34 that is positioned below the center 47 of the rectangle 36. As shown in FIG. 3, the graph 48 is very nearly linear between a point 60 between proximal steps 38 of the magnets 28, 32 of FIG. 1 and a point 62 between proximal steps 38 of magnets 30, 34. In particular, the slope of the magnetic field strength remains nearly constant as the magnetic field strength sensor 22 crosses the center 47 and is between the upper gap 54 and the lower gap 56. The magnet array 26 of FIG. 1 provides a relatively steeply sloped linear change in magnetic field strength over a range of approximately 15 mm between point 60 and point 62. A graph of magnetic field strength for a 2 mm step 64, and a 5 mm step 66 are also shown in FIG. 3 illustrating how step size can be varied to search for the most linear change in magnetic field strength within a magnet array similar to the array 26 shown in FIG. 1. Any remaining nonlinearity of the magnetic field strength slope can be corrected for by programming nonvolatile memory, which forms a part of the programmable Hall effect sensor 22. Thus the output of the Hall effect sensor 22 may be read directly as linear position. Of course inherent accuracy is lost if the slope of magnetic field strength at any point approaches zero.

The four magnet array 26 also provides nearly constant magnetic field strength for small deviations from the axis of symmetry 24. FIG. 4 shows a simulation of off-axis magnetic field strength for points on the graph 48 where the magnetic field strength is approximately 800 gauss. The graph 68 shows a slope of zero in the immediate vicinity of the axis of symmetry 24 that remains small for approximately 0.5 mm on either side of the axis of symmetry 24. This is in contrast to a two magnetic array comprising, for example the lower magnets 32, 34 of FIG. 1, where the graph 70 of the off axis change in magnetic field has a constant and relatively steep positive slope on either side of a line 72 in the same relative position as the axis of symmetry 24.

The individual magnets 28, 30, 32, 34 as shown in FIG.1 can employ pole pieces 78 which increase the strength of the magnetic fields generated by the magnets. Because high-strength magnets are often made from relatively rare elements, the cost of the magnets can be reduced by decreasing the size of the magnets while maintaining the field strength through the use of the pole pieces 78 which are constructed from magnetically permeable material typically a low cost soft ferrous alloy. The pole pieces may be plates affixed to the rear surfaces 58 of each of the magnets 28, 30, 32, 24 of the array 26. The addition of a pole piece reduces the amount of magnet material needed to form the magnetic array of a selected magnetic field strength.

An alternative embodiment linear displacement sensor 74 can be constructed where each magnet of the array has with three or more steps, as shown in phantom lines in FIG. 1. In the alternative embodiment, a third step 76 is situated intermediate in distance from the symmetry axis of symmetry 24 having a spacing between the proximal step 38 and the distal step 42. The use of a third step 76 is advantageous when a linear displacement sensor with a relatively long sensing distance is required, for example a sensor with a substantially linear change in magnetic field strength over a distance of 30 mm was constructed using an array of four three-step magnets.

In the design of the linear displacement sensor 20 the following design variables can be used to achieve a desired shape of a graph of magnetic field strength versus linear position: varying the size of the rectangle 36 which defines the position of the magnets; varying the number of steps formed in each magnet and the distance each step is spaced from the axis of symmetry; varying the width of the step along the axis of symmetry; varying the width of the gap 54, 56 formed between the magnets along the axis of symmetry; varying the type of magnetic material used in the size of the magnets; and employing pole pieces.

Generally the most linear graph of field strength versus distance is desired for uniform position sensing resolution, a magnetic field graph can vary significantly from the linear and still, by means of the programmable logic in the sensor, provide a linear output. In this arrangement, where the slope of the graph of magnetic field strength with respect to linear position is not constant, the variation in slope affects the inherent accuracy, which variation can be used to improve accuracy over a specific range by optimizing the magnets to have greater slope where greater resolution of linear position is desired, at the expense of somewhat lesser accuracy whether slope is less.

In a practical application employing the displacement sensor 20, the four magnets 28, 30, 32, 34 are mounted in a housing which is mounted for linear motion, and the Hall effect sensor 22 is fixedly mounted to a circuit board. Typically the housing containing the four magnets is mounted to travel on rails or some similar arrangement which constrains the axis of symmetry 24 to move over the Hall effect sensor 22.

The programmable magnetic field strength sensor 22 includes a Hall effect device or sensor element 80 within the sensor package. The device or sensor element 80 is arranged parallel to the axis of symmetry and parallel to the magnetic pole surfaces 40 such that the magnetic field lines between the magnets of the array 26 are perpendicular to the Hall effect device. The sensing direction of the Hall effect device or sensor element 80 is perpendicular to its sensor element, and thus it is sensitive to magnetic field strength in a direction perpendicular to the axis of symmetry 24.

The processing of the signal from the Hall effect device 80 may be done outside the package that houses the Hall effect device. Furthermore, it should be understood that other types of magnetic field sensors such as, for example, giant magnetoresistive (GMR) or Anisotropic Magneto-Resistive (AMR) sensors, with or without on-chip programmability could be used. In order to minimize the effect of external magnetic fields on the sensing system 20, the magnetic field used by the sensor should be maximized because by utilizing the entire measurement range of the magnetic sensor, variation in the output of the sensor due to external magnetic noise is minimized. To minimize package size, magnets of high magnetic field strength may be used such as alnico (an aluminum-nickel-cobalt alloy),or samarium-cobalt (SmCo), and neodymium-iron-boron (NdFeB). Each magnet 28, 30, 32, 34 may be formed as a single piece or may be formed by combining magnets of simpler shape by, for example, bonding one rectangular magnet on to another. The pole surfaces 40, 43, while generally planar and parallel to each other and the axis of symmetry 24, may incorporate such slight variations as do not substantially affect the benefits described.

It should be understood that in the claims terms like "substantially parallel", "substantially aligned", etc., are meant to encompass such minor variations from a parallel state, alignment, etc. which still preserve the functionality of the device.

The linear displacement sensor 20 is designed to allow slight misalignments in the magnets in the sensor without introducing substantial errors in the output of the sensor. Furthermore, using the onboard logic it is possible to calibrate each linear displacement sensor by controlled actuation accompanied by programming of onboard logic to linearize the output of the magnetic field strength sensor 22, taking into account the measured deviance from linearity due to geometry misalignment or variations in the magnetic fields of the magnets.

The arrangement of four similar or identical magnets at the corners of a rectangle, wherein magnets positioned across from each other along the line of symmetry have opposed poles and magnets connected by a diagonal have the same pole facing the axis of symmetry, need not be limited to magnets having a staircase shape facing the line of symmetry. The profile of the magnets, rather than having a staircase shape of two or more steps, can be a completely free variable that is optimized according to desired criteria of magnetic field strength along the axis of symmetry.

The present invention provides a linear displacement sensor with a uniform linearly sloping magnetic field along the axis of displacement, utilizing magnets of simple geometry, and that is less sensitive to displacement of the magnetic sensor off the sensing axis.

CLAIMS

1. A linear displacement sensor (20; 74) comprising:

four spaced apart magnets (28, 30, 32, 34) arranged symmetrically positioned to form four corners of a rectangle, which rectangle defines two diagonals, which meet to define a center point, and an axis of symmetry (24) passing through the center point and bisecting angles defined by the diagonals, each magnet (28, 30, 32, 34) having portions facing the axis of symmetry (24);

each magnet (28, 30, 32, 34) having a pole facing the axis of symmetry (24), wherein magnets lying on the same diagonal have identical poles facing the axis of symmetry (24), and magnets symmetrically positioned with respect to the axis of symmetry (24) have opposed poles; and

a magnetic field strength sensor (22) arranged for relative movement substantially along the axis of symmetry (24) with respect to the four magnets (28, 30, 32, 34).

2. A linear displacement sensor (20; 74) according to claim 1 wherein the first magnet, the second magnet, the third magnet, and the fourth magnet (28, 30, 32, 34) each have portions facing the axis of symmetry (24) which form in the shape of a staircase having at least two steps, the first step (38) spaced from the axis of symmetry (24), and the second step (42) spaced further from the axis of symmetry (24) than the first step (38).

3. A linear displacement sensor (20; 74) according to claim 1 wherein the magnetic field strength sensor (22) comprises a programmable Hall-effect sensor (80).

4. A linear displacement sensor (20) according to claim 2 wherein the first magnet, the second magnet, the third magnet, and the fourth magnet (28, 30, 32, 34) each have only two steps (38, 42).

5. A linear displacement sensor (74) according to claim 2 wherein the first magnet, the second magnet, the third magnet, and the fourth magnet (28, 30, 32, 34) each have three steps (38, 42, 76).

6. A linear displacement sensor (20; 74) according to any one of claims 1 through 5 wherein the first magnet, the second magnet, the third magnet, and the fourth magnet (28, 30, 32, 34) are mounted for motion with respect to the magnetic field strength sensor (22).

7. A linear displacement sensor (20; 74) according to any one of claims 1 through 5 wherein the first magnet, the second magnet, the third magnet, and the fourth magnet (28, 30, 32, 34) are arranged to maximize a rate of change of magnetic field strength with respect to distance along the axis of symmetry (24) and over a selected portion of the axis of symmetry .

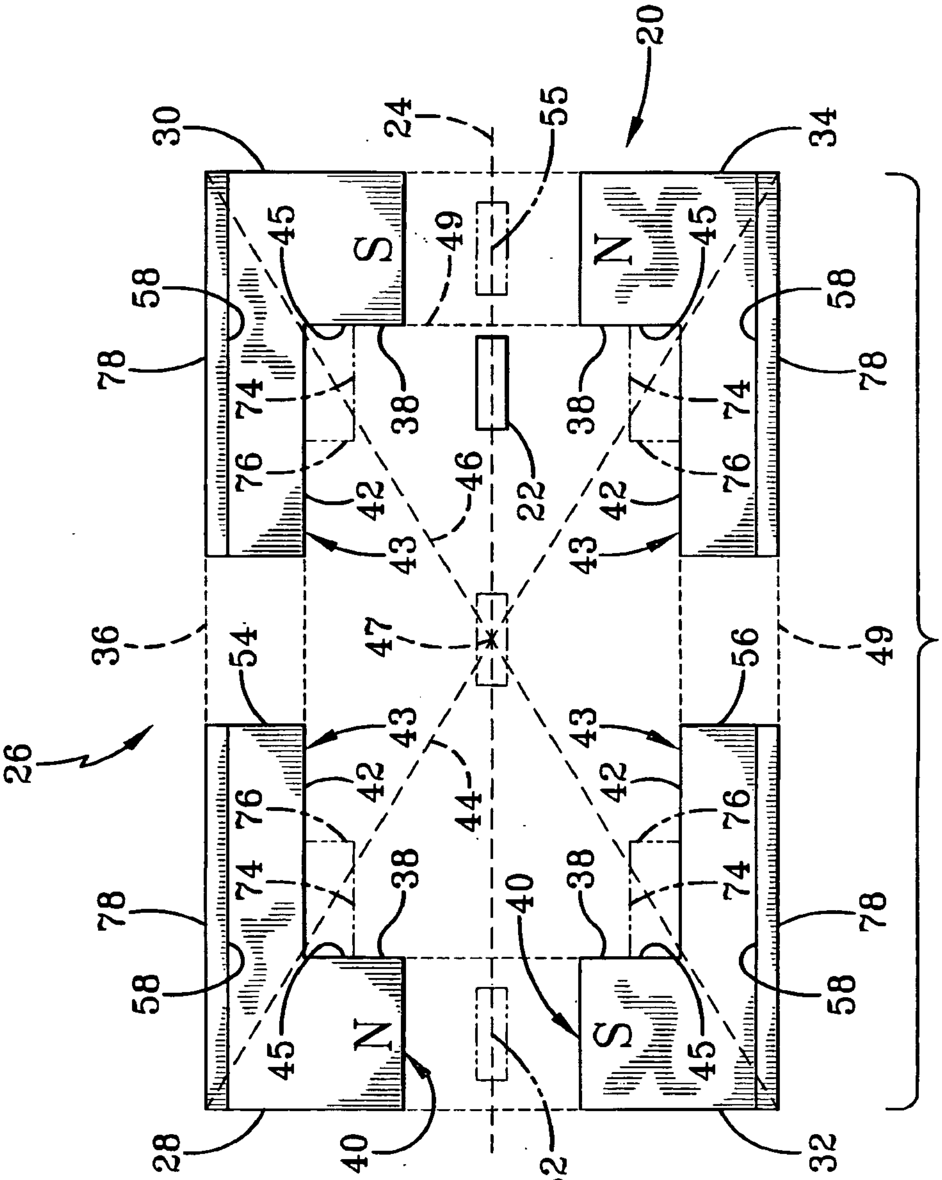
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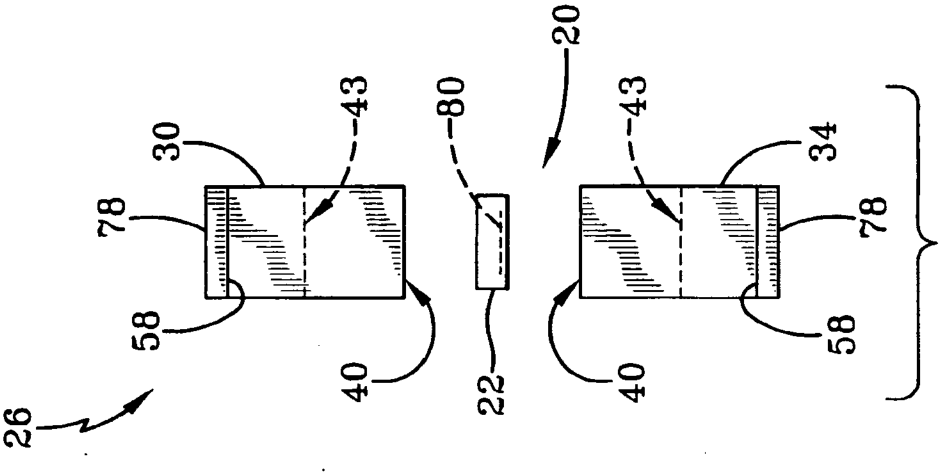
FIG-1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80
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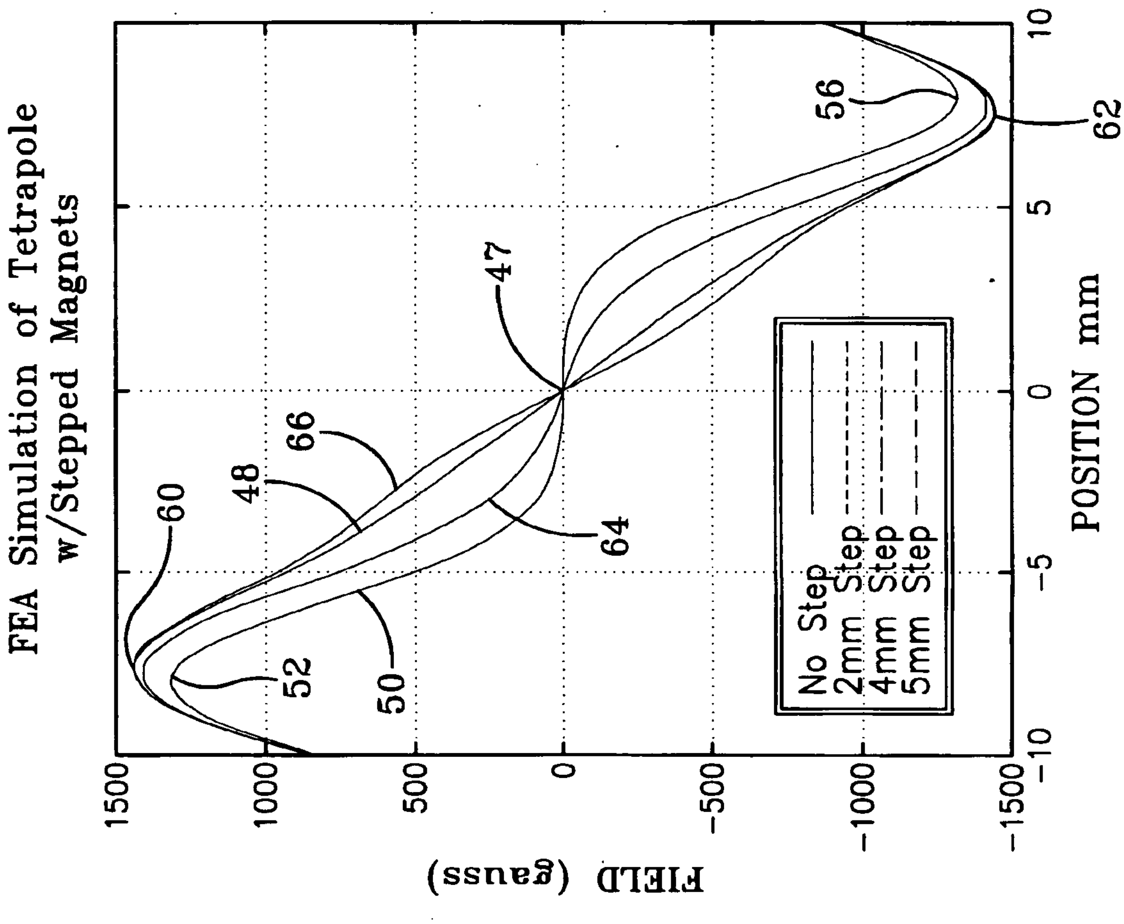
FIG-2


FEA Simulation of Tetrapole
w/Stepped Magnets
FIELD (gauss)
POSITION mm
1500
1000
500
0
−500
−1000
−1500
−10
−5
0
5
10
No Step
2mm Step
4mm Step
5mm Step
60
52
50
48
66
64
47
56
62

FIG–3

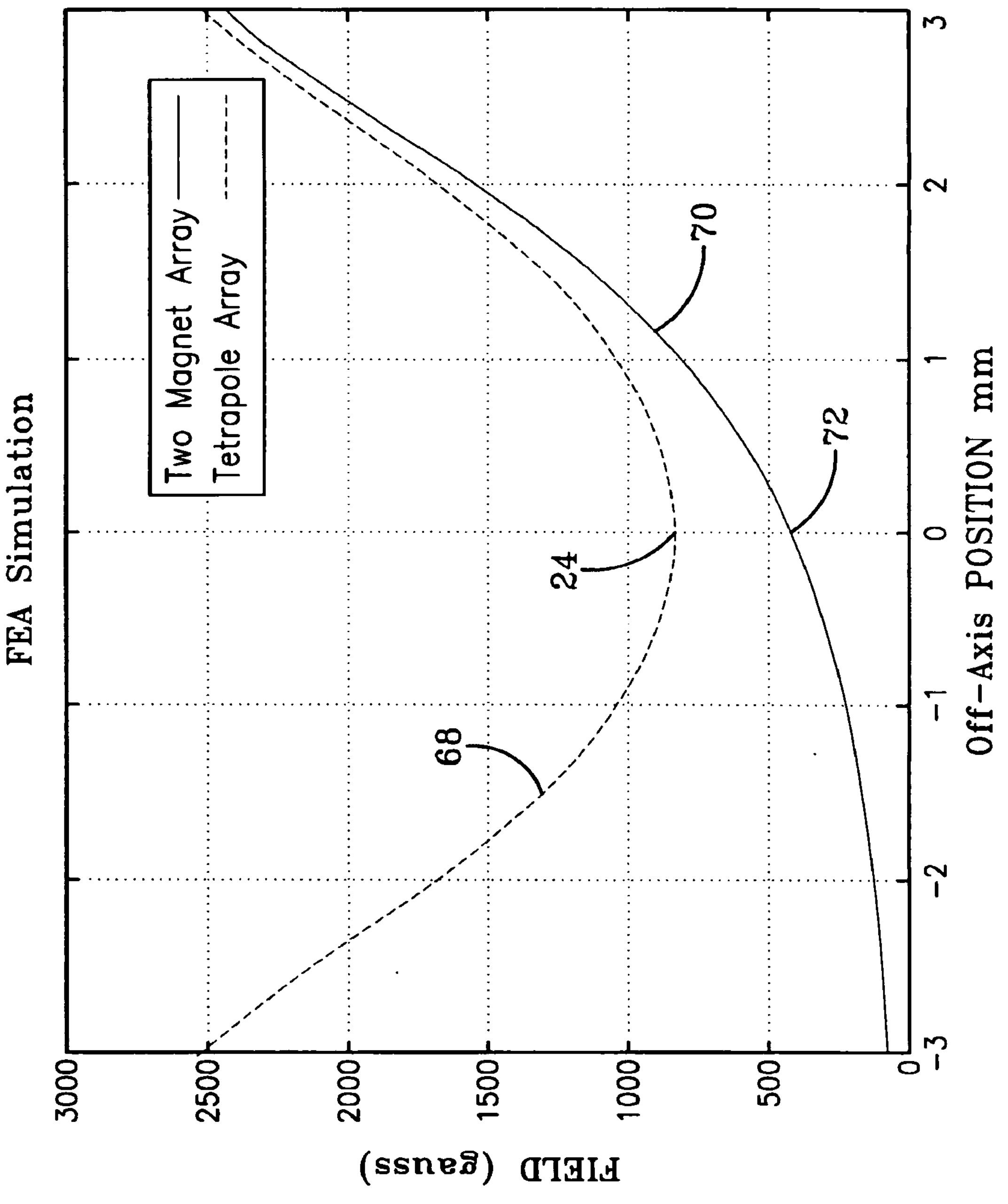

FEA Simulation
Two Magnet Array
Tetrapole Array
68
24
70
72
FIELD (gauss)
3000
2500
2000
1500
1000
500
0
-3
-2
-1
0
1
2
3
Off-Axis POSITION mm

FIG-4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2007/014269

A. CLASSIFICATION OF SUBJECT MATTER

G01D 5/12(2006.01)i, G01B 7/00(2006.01)i

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 8: G01L 9/12, G01B 7/00, G01B 7/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models since 1975
Japanese utility models and applications for utility models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKIPASS (KIPO internal) & Keywords: linear & displacement & sensor & magnet and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6553840 B2 (JOHN A. FOURNIER et al.) 29 APRIL 2003 see column 2, line 14 - column 3, line 38.	1-7
A	US 7088095 B1 (NICHOLAS F. BUSCH) 08 AUGUST 2006 see column 2, line 42 - column 5, line47 and figure 2A.	1-7
A	US 5475304 A (GARY A. PRINZ) 12 DECEMBER 1995 see column 2, line 42 - column 4, line 26.	1-7
A	US 5936400 A (IGOR TCHERTKOV et al.) 10 AUGUST 1999 see column 3, line 35 - column 5, line 22.	1-7

☐ 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
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"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
10 JANUARY 2008 (10.01.2008)

Date of mailing of the international search report
10 JANUARY 2008 (10.01.2008)

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2007/014269

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