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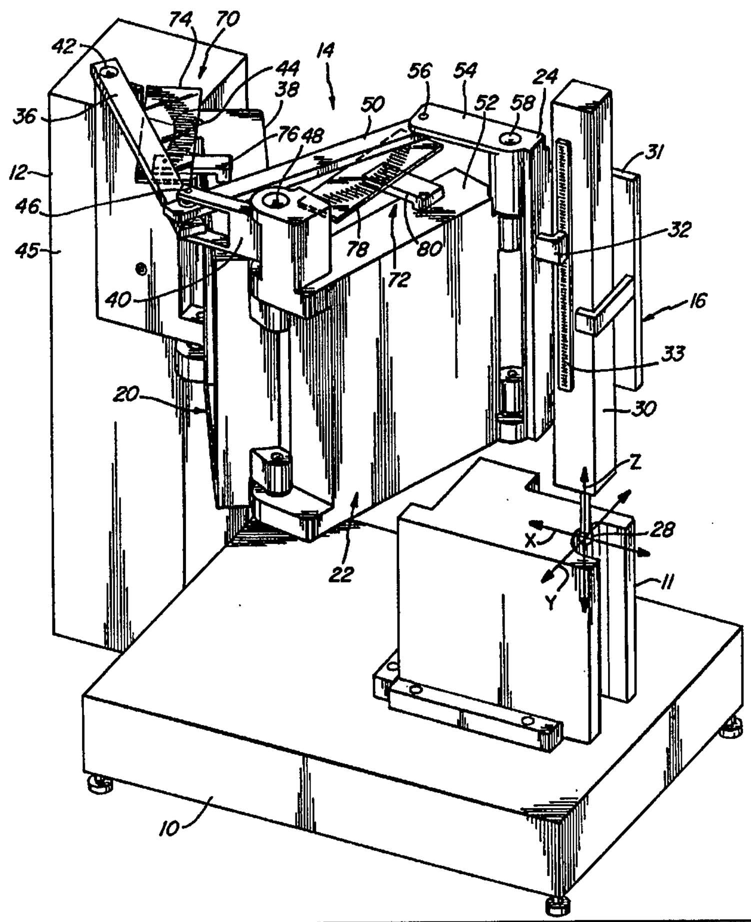
(54) Title: COORDINATE MEASURING MACHINE HAVING ARTICULATED ARM

(57) Abstract

A coordinate measuring machine includes a support structure (12), an articulated arm (14) having a first end pivotally connected to the support structure (12) and a second end that is movable in a horizontal plane. A Z-ram assembly (16) is mounted to the second end of the articulated arm (14). The Z-ram assembly (16) includes a Z-ram housing (31) and a probe (28) that is vertically movable with respect to the Z-ram housing (31). The probe (28) is movable within a measurement volume defined by the articulated arm (14) and the Z-ram assembly (16). The coordinate measuring machine further includes a measuring assembly for determining coordinates of the probe (28) in the measurement volume. The articulated arm (14) preferably includes first and second arm assemblies (20, 22) that have a parallelogram configuration to prevent substantial rotation of the Z-ram assembly (16) as the articulated arm (14) is moved in the horizontal plane. The angles of the arm (14) are preferably measured using a sensor which includes a pattern of parallel, straight grating lines.



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COORDINATE MEASURING MACHINE HAVING ARTICULATED ARM

Field of the Invention

This invention relates to coordinate measuring machines and, more particularly, to a coordinate measuring machine having an articulated arm that is pivotally movable in a horizontal plane and a probe that is vertically movable with respect to the articulated arm to provide movement in three dimensions.

Background of the Invention

Coordinate measuring machines are used for dimensional inspection of workpieces such as machined parts. A workpiece is typically secured to a table, and a measuring probe is movable within a measuring volume. Measuring scales monitor the position of the probe within the measuring volume. To measure the coordinates of a point on the workpiece, the probe is brought into contact with the point, and the X, Y and Z measuring scales of the machine are read. To measure a distance between two points, the points are contacted successively, the coordinates of both points are read and distance is calculated from the coordinates. State of the art coordinate measuring machines have refinements such as high resolution measuring systems, electrical contact probes, motor drives, computer control drives and computer acquisition and processing of data.

Conventional moving bridge coordinate measuring machines (CMM) include a bridge that moves in the Y direction along guideways on the table of the CMM. A carriage moves in the X direction along guideways on the bridge. A ram with a probe mounted to its lower end moves vertically through bearings in the carriage. Scale systems between the bridge and the table, between the carriage and the bridge, and between the ram and the carriage indicate the positions of the movable elements in three orthogonal directions. A moving bridge CMM is disclosed, for example, in U.S. Patent No. 4,939,678, issued July 3, 1990 to Beckwith, Jr. Another prior art coordinate measuring machine is the horizontal arm machine, wherein a horizontal ram is supported by a Z carriage on a Z rail.

Prior art coordinate measuring machines provide highly satisfactory performance, in terms of both accuracy and reliability. However, such systems are relatively costly because of their complexity and because of the need for precision mechanical parts, such as the guideways upon which precision air bearings carry a carriage or a ram. It is desirable to provide coordinate measuring machines which are highly accurate and reliable, yet are simple in construction and low in cost.

Various pivoting manipulators and articulated arms have been disclosed in the prior art. Japanese Document No. 3-100416, published April 25, 1991, discloses apparatus for determining the position of a detecting probe which utilizes a pivoting linkage. U.S. Patent No. 4,341,502, issued July 27, 1982 to Makino, discloses an assembly robot which includes a quadrilateral link mechanism for controlling the position and the attitude of a workpiece. U.S. Patent No. 5,180,955, issued January 19, 1993 to Karidis et al, discloses positioning apparatus which includes a multibar linkage drive mechanism. U.S. Patent No. 4,329,111, issued May 11, 1982 to Schmid, discloses a mechanical manipulator including an articulated arm having a first member pivotally connected to a first pivot axis and a second member pivotally connected at a second pivot axis to the first member. U.S. Patent No. 4,894,595, issued January 16, 1990 to Sogawa et al, discloses an industrial robot having a movable arm with a support element which maintains a parallelogram shape throughout the range of motion of the arm. U.S. Patent No. 3,703,968, issued November 28, 1972 to Uhrich et al, discloses a manipulator arm having two parallelogram linkages in combination with a trapezium linkage. Insofar as known to applicants, prior art coordinate measuring machines have not utilized pivoting mechanical structures for positioning a measuring probe.

Summary of the Invention

In accordance with the present invention, a coordinate measuring machine comprises a support structure, an articulated arm having a first end pivotally connected to the support structure and a second end that is movable in a horizontal plane, and a Z-ram assembly mounted to the second end of the articulated arm. The Z-ram assembly includes a Z-ram housing and a probe that is vertically movable with respect to the Z-ram housing. The probe is movable within a measurement volume defined by the articulated arm and the Z-ram assembly. The coordinate measuring machine further comprises a measuring assembly for determining coordinates of the probe in the measurement volume. The coordinate measuring machine may further include a table for supporting a workpiece for coordinate measurement. The table is fixed in position relative to the support structure.

The articulated arm preferably comprises a first arm assembly pivotally connected to the support structure for movement in the horizontal plane and a second arm assembly pivotally connected to the first arm assembly for movement in the horizontal plane.

The measuring assembly preferably comprises a first measuring device for measuring a first angle of the first arm assembly with respect to the support structure, a second measuring device for measuring a second angle of the second arm assembly with respect to the first arm assembly, a third measuring device for measuring the position of the probe relative to the Z-ram housing, and a processing device responsive to the first, second and third measuring devices for determining the coordinates of the probe in the measurement volume.

The articulated arm preferably includes means for moving the Z-ram assembly in the horizontal plane without substantial rotation of the Z-ram assembly. In a preferred embodiment, first, second, third, fourth, fifth and sixth vertical pivot axes are associated with the first and second arm assemblies. The first, second, third and fourth pivot axes define a first parallelogram, and the third, fourth, fifth and sixth pivot axes define a second parallelogram. The first arm assembly includes a first arm member connected between the first and third pivot axes, a second arm member connected between the second and fourth pivot axes and a first link member connected between the third and fourth pivot axes. The second arm assembly includes a third arm member connected between the third and fifth pivot axes, a fourth arm member connected between the fourth and sixth pivot axes and a second link member connected between the fifth and sixth pivot axes. The Z-ram assembly is connected to the second link member and moves in the horizontal plane without rotation.

According to a further aspect of the invention, the first measuring device preferably comprises a grating mounted in a fixed position with respect to the first arm member and a read head mounted in a fixed position with respect to the second arm member. The grating has a grating pattern comprising parallel, straight grating lines. The read head includes a sensor for sensing displacement of the grating lines relative to the read head as the first angle varies. The sensor generates a signal representative of the angular change of the first arm assembly with respect to a reference angle. Preferably, the second measuring device has the same structure as the first measuring device and is mounted on the third and fourth arm members of the second arm assembly.

In an alternative embodiment of the invention, a coordinate measuring machine comprises a support structure, first articulated arm having a first end pivotally connected to the support structure and a second end that is movable in a horizontal plane, a second articulated arm having a first end pivotally connected to the support structure and a second end that is movable in the horizontal plane, and a Z-ram assembly mounted to the second ends of the first and second articulated arms. The Z-ram assembly includes a Z-ram housing and a probe that is vertically movable with respect to the Z-ram housing. The coordinate measuring machine further comprises a measuring assembly for determining coordinates of the probe in the measurement volume.

Brief Description of the Drawings

For a better understanding of the present invention, reference is made to the accompanying drawings, which are incorporated herein by reference and in which:

FIG. 1 is a left, front, top perspective view of a coordinate measuring machine;

FIG. 2 is a right, front, top perspective view of the coordinate measuring machine of FIG. 1, showing use with an alternate probe fixture;

FIG. 3 is a top plan view of the coordinate measuring machine of FIG. 1;

FIG. 4 is an exploded perspective view of the coordinate measuring machine of FIG. 1;

FIG. 5 is a schematic top plan view of the coordinate measuring machine of FIG. 1, with the probe shown at an arbitrary point;

FIG. 6 is a schematic cross-sectional view of angle sensor 72, taken along line 6-6 of FIG. 5;

FIG. 7 is a schematic diagram of the angle measuring device used in the coordinate measuring machine;

FIG. 8 is a schematic diagram of an alternate embodiment of the angle measuring device;

FIG. 9 is a block diagram of the measuring assembly for determining probe coordinates in the coordinate measuring machine; and

FIG. 10 is a schematic top view of an alternate embodiment of the coordinate measuring machine.

Detailed Description

A coordinate measuring machine is illustrated in FIGS. 1-5. The major components of the coordinate measuring machine include an optional table 10 for holding workpiece 11 for measurement, a column, or support structure 12, an articulated arm 14 and a Z-ram assembly 16.

When table 10 is not utilized, the support structure 12 is mounted on or adjacent to a surface plate or other suitable surface for holding a workpiece. The coordinate measuring machine also includes a measuring assembly for determining coordinates as described below. The support structure 12 may be in the form of a vertical post and functions as a support for one end of the articulated arm 14. The support structure 12 is fixed in position relative to table 10 and may be attached to table 10. The articulated arm 14 is pivotally attached to support structure 12. More particularly, the articulated arm 14 includes a first arm assembly 20 pivotally connected to the support structure 12 and a second arm assembly 22 pivotally connected to the first arm assembly. The first and second arm assemblies 20 and 22 pivot about vertical axes so that end 24 of the articulated arm 14 is movable in a horizontal plane.

The Z-ram assembly 16 is shown schematically in FIGS. 1-5 for ease of understanding. The Z-ram assembly 16 is mounted to end 24 of articulated arm 14 and includes a Z-ram 30 that is vertically movable with respect to a Z-ram housing 31. The Z-ram housing 31 is securely mounted to end 24 of articulated arm 14. A probe 28 is removably attached to the Z-ram 30. Thus, by vertical movement of probe 28 with respect to Z-ram housing 31 and movement of articulated arm 14 in the horizontal plane, the probe 28 is movable within a three-dimensional measurement volume of the coordinate measuring machine. The X, Y and Z directions of probe movement are indicated in FIG. 1. The movement of probe 28 is typically manually controlled by the machine operator. The Z-ram assembly 16 preferably includes bearings 35 between the Z-ram 30 and the Z-ram housing 31 for permitting vertical movement of Z-ram 30 and a counterbalance (not shown) for maintaining the Z-ram 30 in a desired vertical position.

The dimensions of the measurement volume are defined in the horizontal plane by the range of movement of the articulated arm 14 and in the vertical direction by the range of movement of probe 28 with respect to Z-ram housing 31. By determining the angle of first arm assembly 20 with respect to support structure 12, the angle of second arm assembly 22 with respect to first arm assembly 20 and the vertical position of the probe 28 with respect to the housing 31, the measuring assembly determines the coordinates of the probe 28 in the measurement volume.

The first arm assembly 20 includes a first arm member 36, a second arm member 38 and a first link member 40. The first arm member 36 is pivotally connected to a bracket 45 at a first pivot axis 42, and the second arm member 38 is pivotally connected to bracket 45 at a second pivot axis 44. The bracket 45 is rigidly mounted to support structure 12. The first arm member

36 and the link member 40 are pivotally connected at a third pivot axis 46, and the second arm member 38 and the link member 40 are pivotally connected at a fourth pivot axis 48. Pivotal movement of arm assembly 20 is indicated by arrow 49 in FIG. 3. The range of motion of arm assembly 20 is indicated by arrow 47 in FIG. 5.

The second arm assembly 22 includes a third arm member 50, a fourth arm member 52 and a second link member 54. The third arm member 50 is pivotally connected to first arm member 36 and link member 40 at the third pivot axis 46. The fourth arm member 52 is pivotally connected to second arm member 38 and link member 40 at the fourth pivot axis 48. The third arm member 50 is pivotally connected to link member 54 at a fifth pivot axis 56, and the fourth arm member 52 is pivotally connected to link member 54 at a sixth pivot axis 58. Pivotal movement of arm assembly 22 is indicated by arrow 59 in FIG. 3. The range of motion of arm assembly 22 is indicated by arrow 57 in FIG. 5. The Z-ram assembly 16 is rigidly mounted to second link member 54. The pivot axes 42, 44, 46, 48, 56 and 58 are parallel to each other and are typically oriented vertically.

As shown in FIG. 3, the pivot axes 42, 44, 46, 48, 56 and 58 of articulated arm 14 define two interconnnected parallelograms. More specifically, pivot axes 42, 44, 46 and 48 define vertices of a first parallelogram 60 associated with first arm assembly 20, and pivot axes 46, 48, 56 and 58 define vertices of a second parallelogram 62 associated with the second arm assembly 22. Dashed lines are drawn in FIG. 3 between pivot axes 44 and 48 and between pivot axes 48 and 58 to clearly illustrate the parallelograms, because the shapes of arm members 38 and 52 are somewhat misleading. As the articulated arm 14 moves in the horizontal plane, the angles between intersecting sides of the parallelograms 60 and 62 vary. However, opposite sides remain parallel.

The parallelogram structure of the articulated arm has an important consequence in the operation of the coordinate measuring machine. As end 24 of the articulated arm 14 is moved in the horizontal plane, the Z-ram assembly 16 also moves in the horizontal plane but does not rotate substantially with respect to the support structure 12. The substantially non-rotational movement of Z-ram assembly 16 is important when the coordinate measuring machine is used with a probe extension. For example, a probe extension 29 (shown in FIGS. 2 and 4) may be attached to Z-ram 30 in place of probe 28. The probe extension 29 extends in an arbitrary direction from the vertical axis of Z-ram assembly 16. Probe extensions may be required for measuring side features of workpieces, such as side holes or the like. It can be seen that rotation of the Z-ram assembly 16 would cause the probe extension to rotate as the probe is moved through the measurement volume. Such probe rotation would require a relatively complex calculation to determine the coordinates of the probe extension. By ensuring that the probe extension 29 does not rotate substantially as it is moved through the measurement volume, the calculation of coordinates is simplified, and a fixed correction can be made for probe extensions. Various other probes and probe extensions can be attached to the Z-ram 30 and used for coordinate measurement.

As best shown in FIGS. 1 and 4, second arm member 38 and fourth arm member 52 are relatively rigid structural components of the articulated arm 14. The arm members 38 and 52 and the pivotal connections of these arm members are sufficiently rigid to move the Z-ram assembly 16 through the measurement volume with negligible bending, twisting or other distortion, which would introduce errors in the coordinate measurements. Furthermore, the pivotal connections between elements must not permit significant relative movement between the pivotally connected elements (other than rotation). By contrast, first arm member 36, first link member 40, third arm member 50 and second link member 54 are control elements which prevent substantial rotation of Z-ram assembly 16 and can be less structurally rigid than the arm members 38 and 52.

An essential component of the coordinate measuring machine is the measuring assembly which determines the position of the probe 28 in the measurement volume. In order to determine the position of probe 28, it is necessary to determine the position of end 24 of articulated arm 14 in the horizontal plane and the position of the probe 28 relative to the Z-ram housing in the vertical direction. The vertical position of probe 28 relative to Z-ram housing 31 can be determined by a scale and sensor in accordance with well-known techniques. In particular, a scale 33 is affixed to the Z-ram 30, and a sensor 32 is affixed to the end 24 of articulated arm 14 or other element which does not move vertically. The sensor 32 reads the scale 33 and generates a signal representative of the vertical displacement of the probe 28 relative to articulated arm 14.

In order to determine the position of the Z-ram assembly 16 in the horizontal plane, it is necessary to determine the angle of first arm assembly 20 relative to the support structure 12 and the angle of the second arm assembly 22 relative to the first arm assembly 20. These angles may be determined by determining the angles between intersecting sides of the parallelograms 60 and 62 associated with the articulated arm 14. In general, any suitable angle measuring device may be utilized for measuring the angles of the articulated arm 14. For example, conventional rotary encoders may be utilized. However, available rotary encoders with acceptable accuracy are relatively expensive.

A preferred angle measuring device, or angle sensor, will now be described. The preferred device provides high accuracy angle measurement at low cost. A first angle measuring device 70 is used for determining the angle of first arm assembly 20 with respect to support structure 12. More specifically, angle measuring device 70 is used for measuring an angle ϕ_1 between a line through pivot axes 42 and 46 and a line through pivot axes 42 and 44. A second angle measuring device 72 is used for determining the angle between first arm assembly 20 and second arm assembly 22. More specifically, angle measuring device 72 is used for measuring an angle ϕ_2 between a line through pivot axes 46 and 56 and a line through pivot axes 46 and 48.

First angle measuring device 70 includes a grating 74 mounted to first arm member 36 and a read head 76 mounted to second arm member 38. As the articulated arm 14 is moved in the horizontal plane, the parallelogram 60 changes shape, and the read head 76 moves relative to grating 74. The second angle measuring device 72 includes a grating 78 mounted to third arm member 50 and a read head 80 mounted to fourth arm member 52. As the articulated arm 14 is moved in the horizontal plane, the parallelogram 62 changes shape, and the read head 80 moves relative to grating 78. The angle measuring devices 70 and 72 are described in detail below.

The angle measuring device 72 is illustrated schematically in FIG. 7. It will be understood that the angle measuring device 70 preferably has the same configuration. As indicated above, arm members 50 and 52 and link members 40 and 54 define parallelogram 62. Because the sides of the parallelogram are pivotally attached at axes 46, 48, 56 and 58, the angle ϕ between link member 40 and arm member 52 is variable as the articulated arm 14 is moved in the horizontal plane. As further indicated above, grating 78 is rigidly mounted to arm member 50, and read head 80 is rigidly mounted to arm member 52. As the parallelogram 62 changes shape, the angle ϕ changes and arm member 50 moves linearly with respect to arm member 52 (since opposite sides of the parallelogram remain parallel as the parallelogram changes shape).

The grating 78 is provided with a pattern 84 of parallel, straight grating lines 86 on a substrate 88 that may be light transmissive. The grating lines may, for example, be a metal, such as chromium. The width and spacing of lines 86 is selected to provide a desired angular measurement resolution. In an example of the angle measuring device, the width of each grating line 86 is 20 micrometers, the spacing between adjacent grating lines 86 is 20 micrometers, and link members 40 and 54 have lengths of 110 millimeters. In this example, an average angular measurement resolution of 0.3 arc-second is obtained. As shown in FIG. 7, the pattern 84 of grating lines 86 may be arc-shaped to ensure that the pattern 84 remains aligned with the read head 80 as the angle ϕ changes.

As shown in FIGS. 6 and 7, the read head 80 includes a sensor 90 rigidly attached to arm member 52 by a mounting bracket 92 or other suitable structure. The sensor 90 is preferably an electro-optical sensor, including a light source 89 and photodetector 91, for sensing displacement of grating lines 86 relative to read head 80.

As the arm member 50 moves linearly with respect to arm member 52, the sensor 90 senses displacement of grating lines 86 relative to read head 80. The angle measuring device 72 with a single grating pattern as shown in FIG. 7 can be used for determining the incremental angular change. In order to determine the absolute value of angle ϕ, it is necessary to determine a starting or reference angle from which the incremental angular change is measured. The reference angle can, for example, be the angle of a "home", or starting, position of the articulated arm 14. The scale reading of the sensor 90 is related to the angle ϕ by:

$$A = R \times \cos(\phi + \Upsilon) + A_0 \qquad (1)$$

where A is the scale reading at angle ϕ, R is the length of link members 40 and 54, Υ is the tilt angle between grating lines 86 and arm member 50, and A_0 is the scale reading at the reference angle. In this embodiment, the value of A_0 is determined by moving the articulated arm to the reference angle and recording the scale reading A_0 of the sensor 90. Then, for a scale reading A, the angle ϕ is determined from equation (1).

In other cases, it may be desirable to measure the absolute angle ϕ rather than the incremental angular change relative to a reference angle. The angle measuring device 72 can be configured to determine the absolute value of angle ϕ. As shown in FIG. 8, a second pattern 100 of parallel, straight grating lines 102 is formed on substrate 88 of grating 78. The grating lines 102 are perpendicular to grating lines 86 of pattern 84. In this embodiment, the read head 80 includes, in addition to sensor 90, a second sensor 104 attached to mounting bracket 92 and positioned for sensing displacement of grating lines 102 as the angle ϕ varies. The angle ϕ is determined from the scale readings of sensors 90 and 104 as follows. Assume that sensor 90 provides a scale reading A and that sensor 104 provides a scale reading B. The tilt angle between grating lines 102 and arm member 50 is Υ, and the length of link members 40 and 54 is

R. Then the scale readings A and B are related to angle ϕ by:

$$A = R \times \cos(\phi + \Upsilon) + A_o \qquad (2)$$

$$B = R \times \sin(\phi + \Upsilon) + B_o \qquad (3)$$

where A_o and B_o are scale readings at the home position. The sensitivity of the measuring device is determined by differentiating equations (2) and (3).

$$dA = -R \times \sin(\phi + \Upsilon) \times d\phi \qquad (4)$$

$$dB = R \times \cos(\phi + \Upsilon) \times d\phi \qquad (5)$$

Given a certain linear resolution dA and dB, the sensitivity for angle ϕ is best at and is symmetric for $\phi+\Upsilon = \pi/2$. In a specific application, the angle ϕ may not be symmetric about $\pi/2$. In this case, the tilt angle Υ can be used to make up the difference.

Each of the scale readings A and B is incremental and is not sufficient alone to solve for angle ϕ, given R, Υ and dA and dB, because $d\phi$ is also unknown. The combination of the scale readings, however, can be used to determine the absolute angle ϕ. For a small motion that yields a change in scale readings ΔA and ΔB, then equations (4) and (5) can be combined to yield:

$$\phi = \tan^{-1}(\Delta A/\Delta B) - \Upsilon \qquad (6)$$

Given ΔA, ΔB and Υ, the angle ϕ can be computed from equation (6). For the example of the articulated arm 14 shown in FIGS. 1-5 and described above, the angle ϕ is symmetric about 70°, and the angle Υ is preferably about 20°.

A second embodiment of the grating 78 for measuring the absolute value of angle ϕ is now described. In this embodiment, the second pattern 100 of grating lines is representative of position along grating pattern 84. Thus, for example, the spacing between grating lines or between groups of grating lines may vary along the length of the grating pattern. The readings of sensors 90 and 104 are processed to determine an absolute angle. The details of this approach are described in U.S. Patent No. 3,982,106, issued September 21, 1976 to Stutz, the disclosure of which is hereby incorporated by reference. The grating, or scale, includes a pattern having uniformly spaced marks (pattern 84) and a second pattern (pattern 100) parallel to the first having multiple absolute value marks, each of which is spaced from the next following mark by a distance characterizing the absolute value of its distance to a reference position.

The angle measuring device 72 has been described in connection with measuring the angle ϕ between intersecting sides of a parallelogram. The grating or scale is fixed in position with respect to a first side of the parallelogram, and the read head is fixed in position with respect to a second side of the parallelogram that is parallel to the first side. It can be seen that the pivotally connected parallelogram converts angular motion of link member 40 with respect to arm member 52 to linear motion of arm member 50 with respect to arm member 52. More generally, the angle measuring device shown and described herein can be used for angle measurement in any situation where angular motion is converted to linear motion along a certain direction. The angle measuring device described herein has the advantage that it can be implemented at substantially lower cost than prior art angle measuring devices because of the use of parallel, straight line gratings.

A block diagram of the measuring assembly of the coordinate measuring machine is shown in FIG. 9. The measuring assembly is implemented with angle measuring devices that measure incremental angle from a home or reference angle. A sensor 110 of angle measuring device 70 corresponds to the sensor 90 shown in FIG. 7. A sensor 112 of angle measuring device 72 corresponds to the sensor 90 shown in FIG. 7. The probe position sensor 32 is shown in FIG. 1. The sensors 110, 112 and 32 provide scale readings to a coordinate processor 120. The coordinate processor 120 includes an angle calculator 122 which converts a scale reading ΔA_1 from sensor 110 and constants A_{01}, Υ_1 and R_1 to an angle ϕ_1 of the first arm assembly 20 with respect to support structure 12 using equation (1). An angle calculator 124 converts a scale reading ΔA_2 from sensor 110 and constants A_{02}, Υ_2 and R_2 to an angle ϕ_2 of second arm assembly 22 with respect to first arm assembly 20 using equation (1). The constants A_{01} and A_{02} represent scale readings at the home positions of sensors 110 and 112, respectively. The constants Υ_1 and Υ_2 represent the angles between the grating lines 86 and arm member 50 (see FIG. 7) for measuring devices 70 and 72, respectively. The constants R_1 and R_2 represent the lengths of the link members 40 and 54 of measuring devices 70 and 72, respectively. The angle ϕ_1 from angle calculator 122, the angle ϕ_2 from angle calculator 124 and the probe vertical position P from probe position sensor 32 are provided to a coordinate calculator 128. The coordinate calculator combines these values according to the following equations:

$$X = L_1 \bullet \cos(\phi_1 + \Upsilon_1) + L_2 \bullet \cos(\phi_2 + \Upsilon_2) \quad (7)$$

$$Y = -L_1 \bullet \sin(\phi_1 + \Upsilon_1) + L_2 \bullet \sin(\phi_2 + \Upsilon_2) \quad (8)$$

where X and Y represent the X and Y coordinates of probe 28, L_1 represents the distance between axes 44 and 48 (FIG. 3) and L_2 represents the distance between axes 48 and 58. Pivot axis 44 is preferably designated as the origin of the X-Y plane for coordinate measurements. The coordinate calculator 128 determines the X, Y and Z coordinates of the probe 20 in the measurement volume. The coordinate processor 120 may be implemented as a microprocessor that is programmed to solve the specified equations.

In an example of the coordinate measuring machine of the present invention, the measurement volume has dimensions of 300 millimeters on a side. The measurement accuracy within the measurement volume is about 0.02 millimeter. The disclosed coordinate measuring machine provides high accuracy measurement at relatively low cost. Since no air bearings are required for suspension of machine components such as carriages and rams, no supply air pump is required in the machine.

An alternative embodiment of the coordinate measuring machine is shown schematically in FIG. 10. The first end of articulated arm 14 is pivotally connected to support structure 12, and the second end of articulated arm 14 is movable in a horizontal plane, as shown and described above. Z-ram assembly 16 is mounted to the second end of articulated arm 14. As described above, articulated arm 14 includes first arm assembly 20 and second arm assembly 22. The coordinate measuring machine shown in FIG. 10 additionally includes a second articulated arm 14' having a first end pivotally connected to support structure 12 and a second end that is movable in the horizontal plane. The Z-ram assembly 16 is also mounted to the second end of articulated arm 14'. The articulated arm 14' is essentially a mirror image of the articulated arm 14. Thus, a first arm assembly 20' is a mirror image of first arm assembly 20, and a second arm assembly 22' is a mirror image of second arm assembly 22. The embodiment of FIG. 10 provides somewhat more rigid support of Z-ram assembly 16 than the embodiment shown in FIGS. 1-5 and described above.

While there have been shown and described what are at present considered the preferred embodiments of the present invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the scope of the invention as defined by the appended claims.

CLAIMS

What is claimed is:

1. A coordinate measuring machine comprising:

a support structure;

an articulated arm having a first end pivotally connected to said support structure and a second end that is movable in a horizontal plane;

a Z-ram assembly including a Z-ram housing mounted to the second end of said articulated arm and a probe that is vertically movable with respect to said Z-ram housing, whereby said probe is movable within a measurement volume defined by said articulated arm and said Z-ram assembly; and

a measuring assembly for determining coordinates of said probe in said measurement volume.

2. A coordinate measuring machine as defined in claim 1 wherein said articulated arm comprises:

a first arm assembly pivotally connected to said support structure for movement in said horizontal plane; and

a second arm assembly pivotally connected to said first arm assembly for movement in said horizontal plane.

3. A coordinate measuring machine as defined in claim 1 wherein said articulated arm includes means for moving said Z-ram assembly in said horizontal plane without substantial rotation of said probe assembly.

4. A coordinate measuring machine as defined in claim 2 wherein:

first, second, third, fourth, fifth and sixth vertical pivot axes are associated with said first and second arm assemblies, said first, second, third and fourth pivot axes define a first parallelogram, and said third, fourth, fifth and sixth pivot axes define a second parallelogram;

said first arm assembly includes a first arm member connected between said first and third pivot axes, a second arm member connected between said second and fourth pivot axes, and a first link member connected between said third and fourth pivot axes;

said second arm assembly includes a third arm member connected between said third and fifth pivot axes, a fourth arm member connected between said fourth and sixth pivot axes, and a second link member connected between said fifth and sixth pivot axes, said Z-ram assembly being connected to said second link member, whereby said Z-ram assembly moves in said horizontal plane without substantial rotation.

5. A coordinate measuring machine as defined in claim 4 wherein said measuring assembly comprises:

a first measuring device for measuring a first angle of said first arm assembly with respect to said support structure;

a second measuring device for measuring a second angle of said second arm assembly with respect to said first arm assembly;

a third measuring device for measuring a position of said probe relative to said Z-ram housing; and

a processing device responsive to said first, second and third measuring devices for determining the coordinates of said probe in said measurement volume.

6. A coordinate measuring machine as defined in claim 5 wherein said first measuring device comprises:

a grating having a grating pattern comprising a plurality of parallel, straight grating lines, said grating being mounted in a fixed position with respect to said first arm member; and

a read head mounted in a fixed position with respect to said second arm member, said read head including a sensor for sensing displacement of said grating lines relative to said read head as said first angle varies, said processing device being responsive to the sensed displacement of said grating lines for determining said first angle.

7. A coordinate measuring machine as defined in claim 5 wherein said second measuring device comprises:

a grating having a grating pattern comprising a plurality of parallel, straight grating lines, said grating being mounted in a fixed position with respect to said third arm member; and

a read head mounted in a fixed position with respect to said fourth arm member, said read head including a sensor for sensing displacement of said grating lines relative to said read head as said second angle varies, said processing device being responsive to the sensed displacement of said grating lines for determining said second angle.

8. A coordinate measuring machine as defined in claim 5 wherein said first measuring device comprises:

a grating having a first grating pattern and a second grating pattern formed on a substrate, said first grating pattern comprising a plurality of parallel, straight grating lines and said second grating pattern comprising a plurality of parallel, straight grating lines perpendicular to the grating lines of said first grating pattern, said grating being mounted in a fixed position with respect to said first arm member; and

a read head including first and second sensors for sensing displacement of the grating lines of said first and second grating patterns, respectively, relative to said read head as said first angle varies, said processing device being responsive to the sensed displacements of said first and second grating patterns for determining said first angle.

9. A coordinate measuring machine as defined in claim 5 wherein said second measuring device comprises a grating having a first grating pattern and a second grating pattern formed on a substrate, said first grating pattern comprising a plurality of parallel, straight grating lines and said second grating pattern comprising a plurality of parallel, straight grating lines perpendicular to the grating lines of said first grating pattern, said grating being mounted in a fixed position with respect to said third arm member; and

a read head mounted in a fixed position with respect to said fourth arm member, said read head including first and second sensors for sensing displacement of the grating lines of said first and second grating patterns, respectively, relative to said read head as said second angle varies, said processing device being responsive to the sensed displacements of said grating lines for determining said second angle.

10. A coordinate measuring machine as defined in claim 1 further comprising a table for supporting said workpiece for coordinate measurement, said table having a fixed position relative to said support structure.

11. A coordinate measuring machine as defined in claim 1 which does not require a source of pressurized air for suspension of machine components.

12. A coordinate measuring machine comprising:

a support structure;

a first articulated arm having a first end pivotally connected to said support structure and a second end that is movable in a horizontal plane;

a second articulated arm having a first end pivotally connected to said support structure and a second end that is movable in said horizontal plane;

a Z-ram assembly including a Z-ram housing mounted to the second ends of said first and second articulated arms and a probe that is vertically movable with respect to said Z-ram housing, whereby said probe is movable within a measurement volume defined by said first and second articulated arms and said Z-ram assembly; and

a measuring assembly for determining coordinates of said probe in said measurement volume.

13. A coordinate measuring machine as defined in claim 12 wherein said first and second articulated arms each comprise:

a first arm assembly pivotally connected to said support structure for movement in said horizontal plane; and

a second arm assembly pivotally connected to said first arm assembly for movement in said horizontal plane.

14. A coordinate measuring machine comprising:

a table for supporting a workpiece for coordinate measurement;

a support structure that is fixed in position relative to said table;

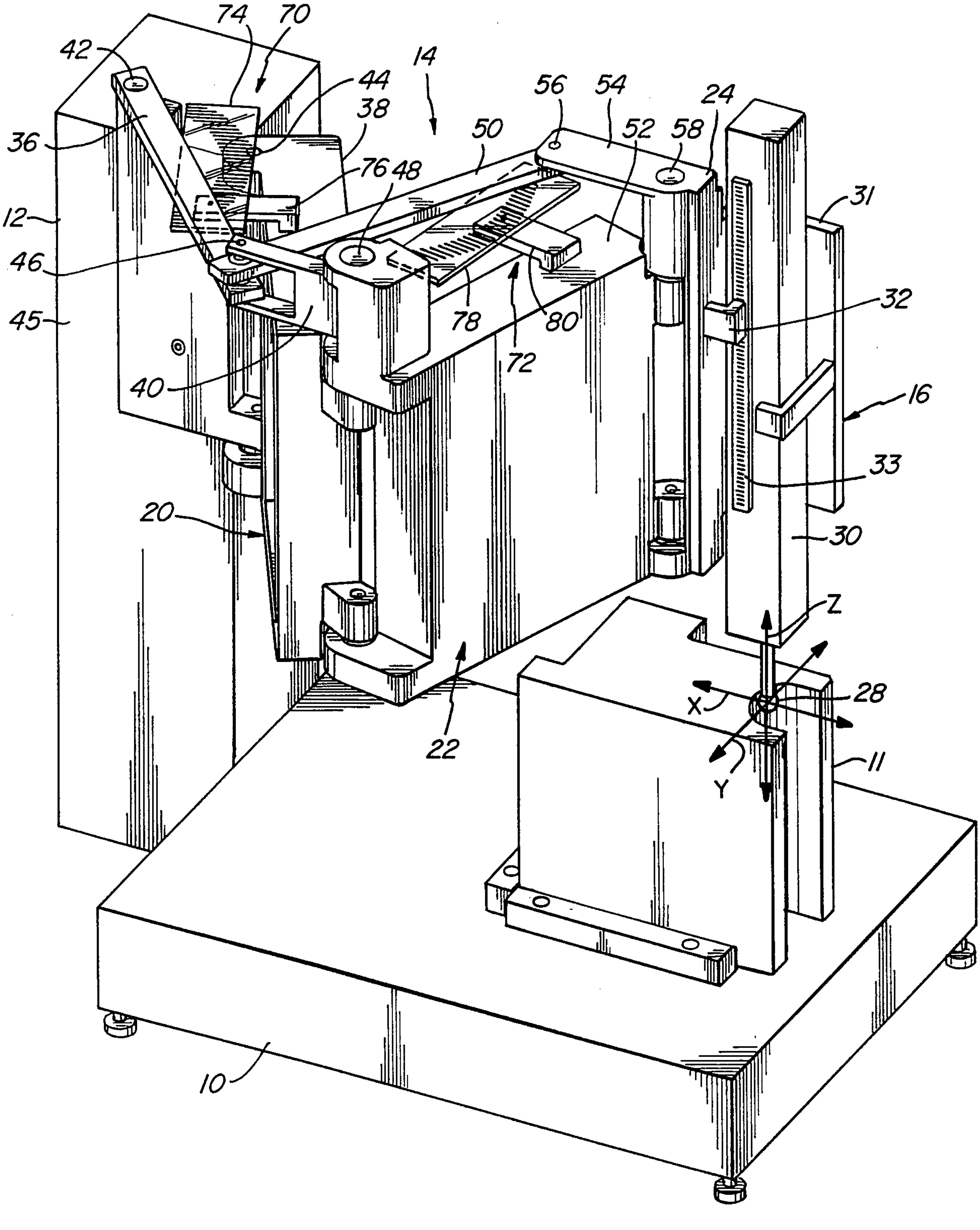
an articulated arm having a first end pivotally connected to said support structure and a second end that is movable in a horizontal plane;

a Z-ram assembly including a Z-ram housing mounted to the second end of said articulated arm and a probe that is vertically movable with respect to said Z-ram housing, whereby said probe is movable within a measurement volume defined by said articulated arm and said Z-ram assembly; and a measuring assembly for determining coordinates of said probe in said measurement volume.

15. A coordinate measuring machine as defined in claim 14 wherein said articulated arm comprises:

a first arm assembly pivotally connected to said support structure for movement in said horizontal plane; and

a second arm assembly pivotally connected to said first arm assembly for movement in said horizontal plane.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11
Y
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Fig. 1

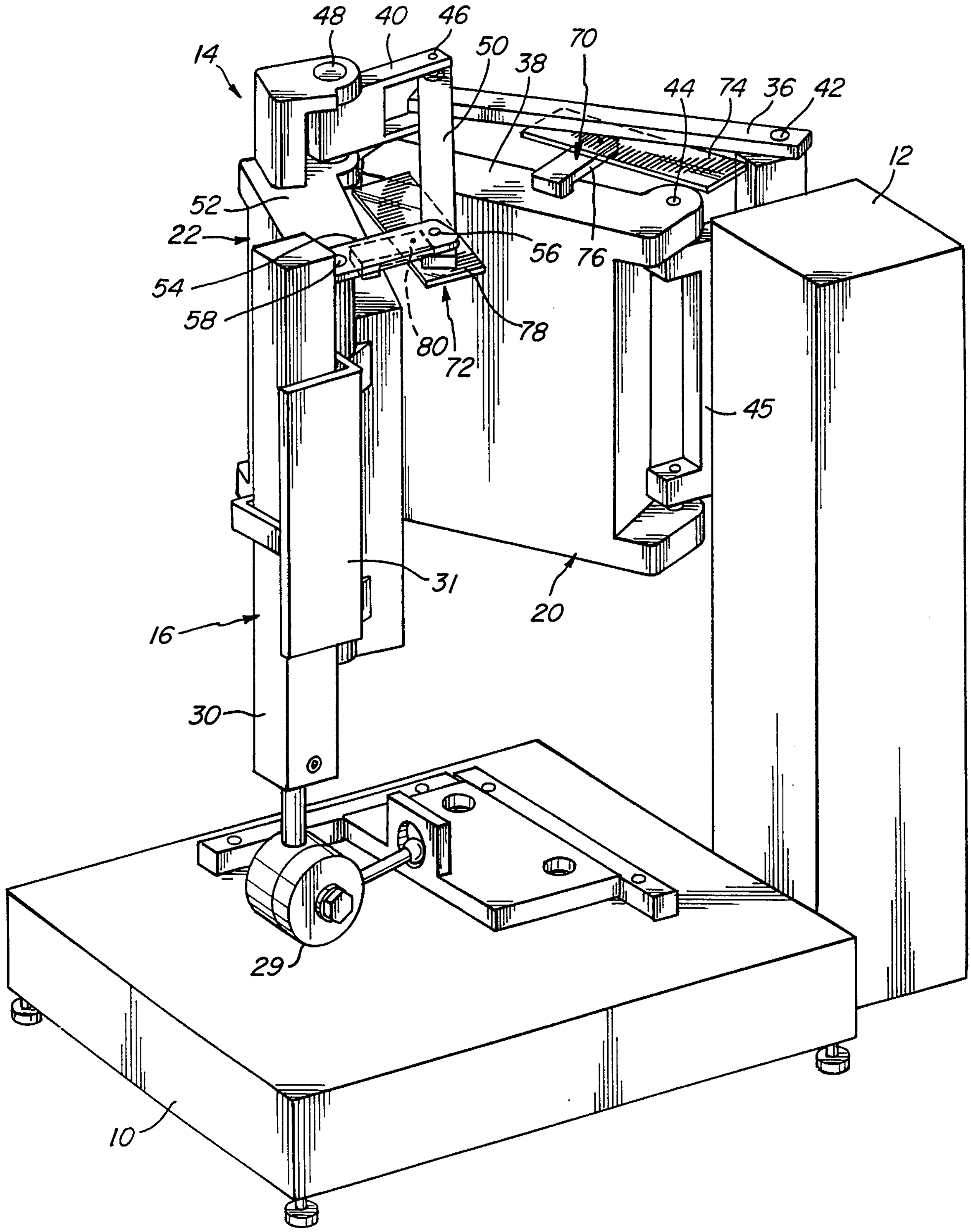
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Fig. 2

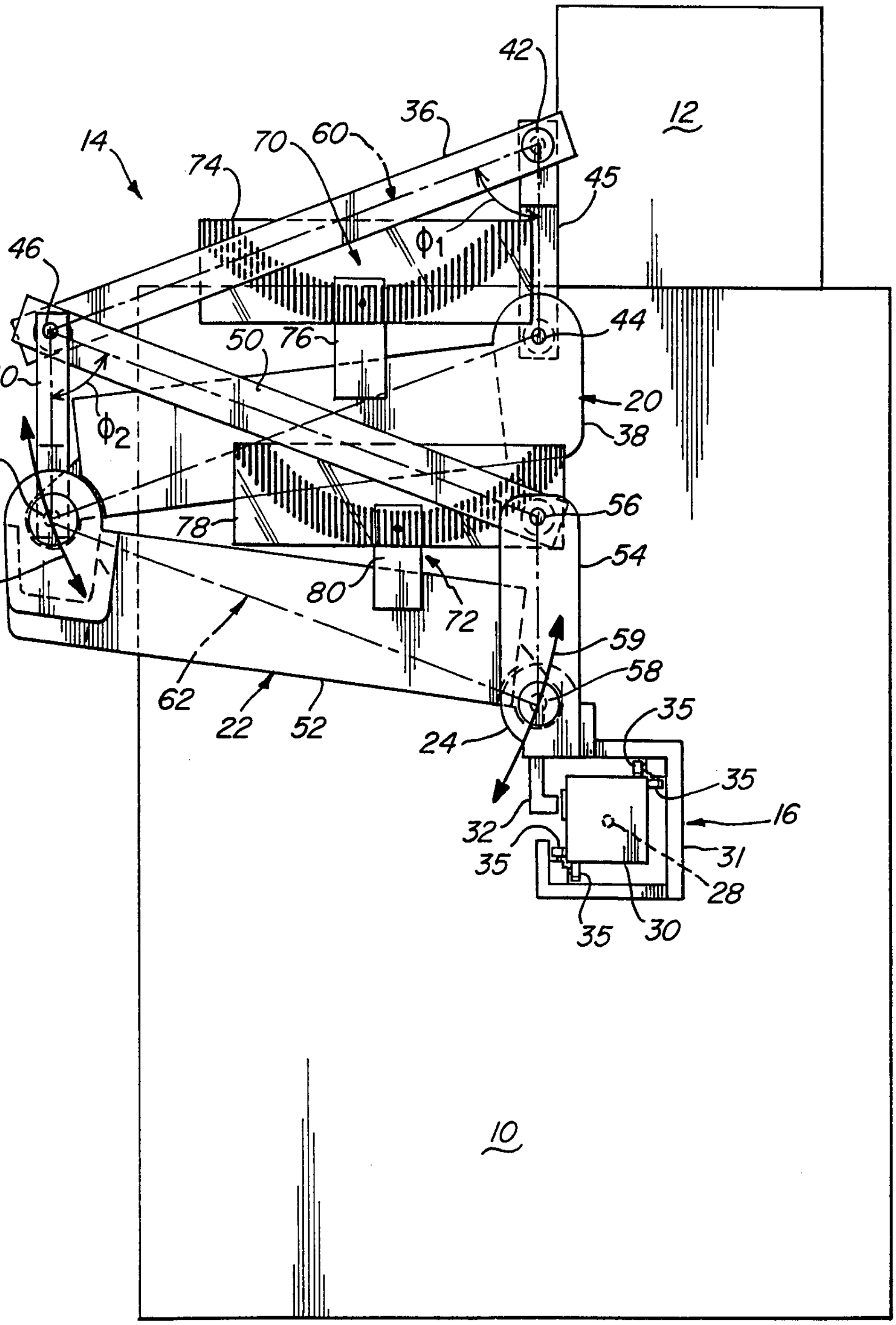
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Fig. 3

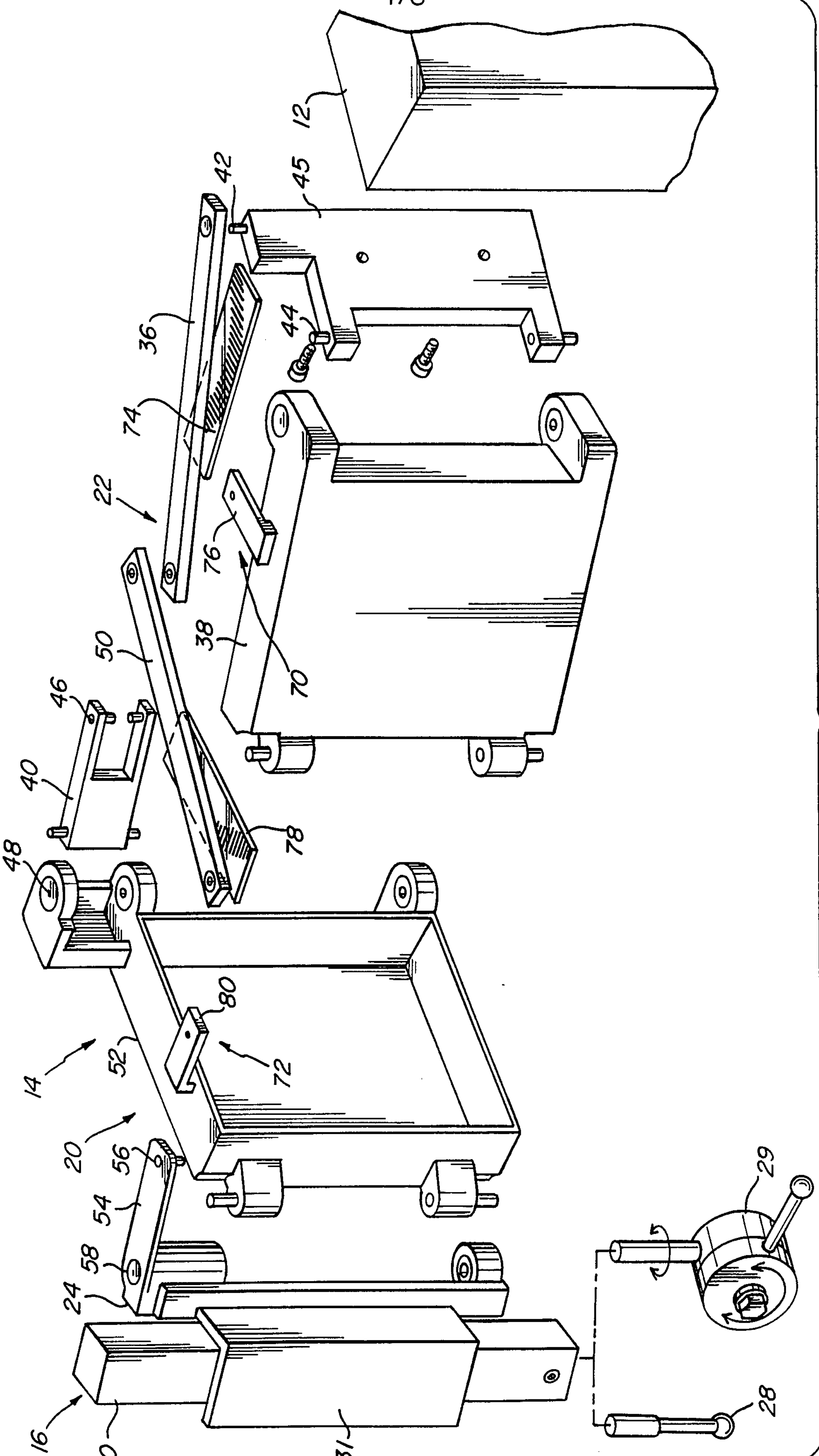
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Fig. 4

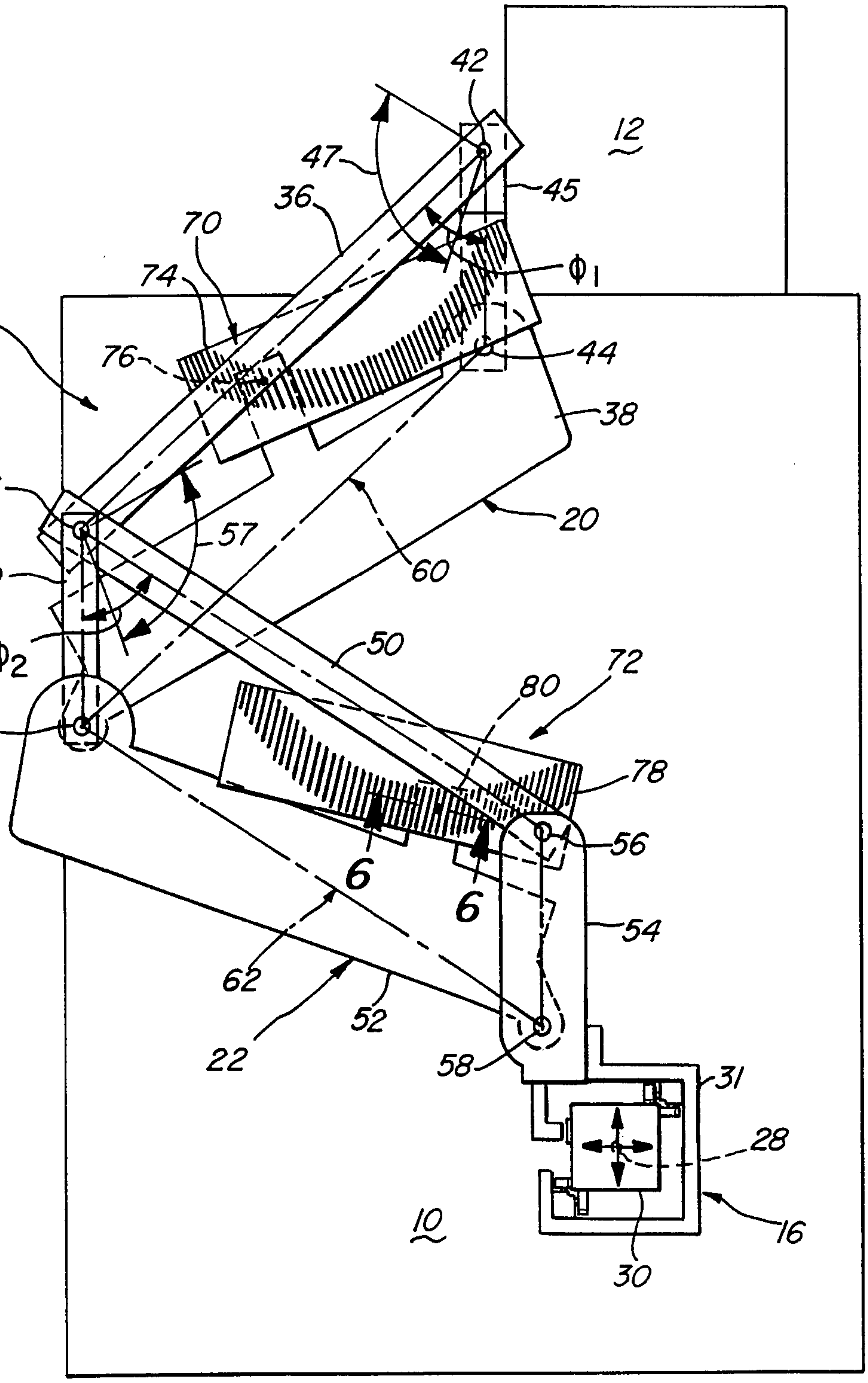
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Fig. 5

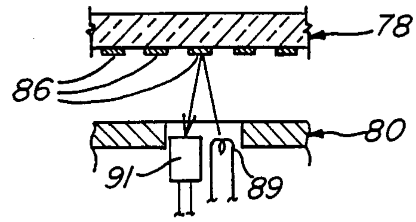
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Fig. 6

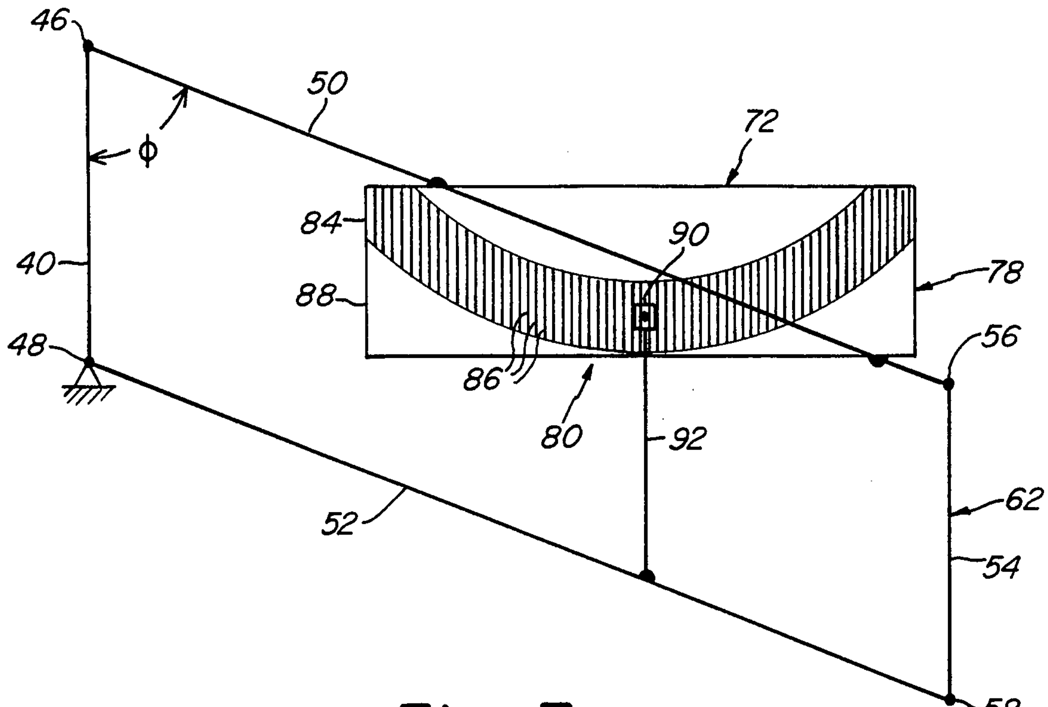
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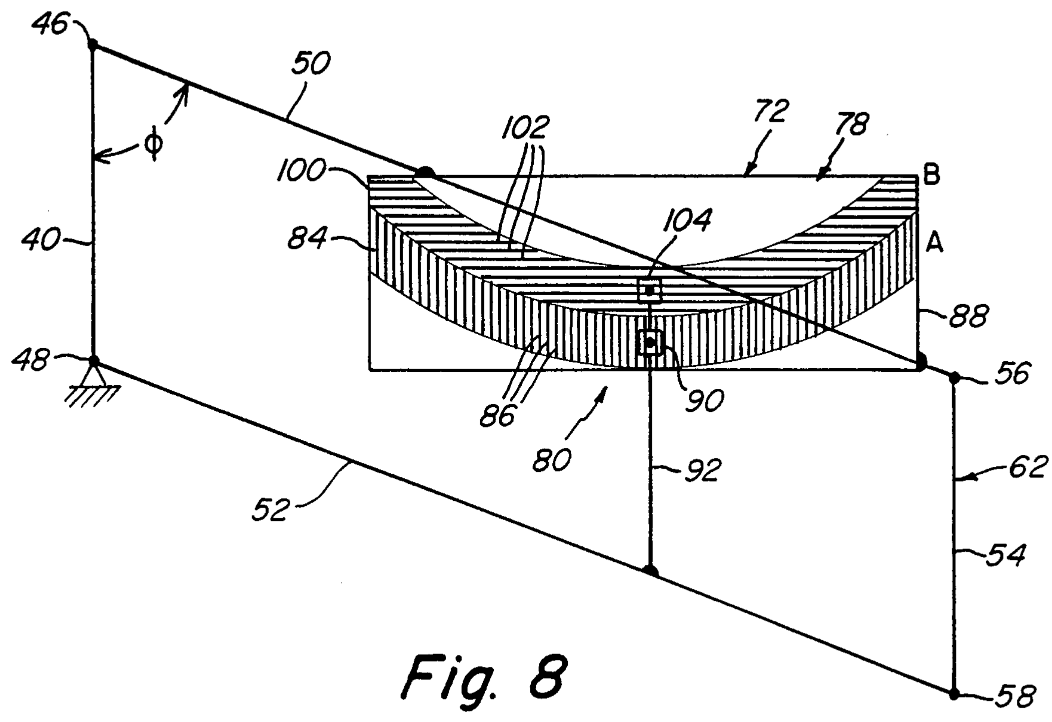
Fig. 7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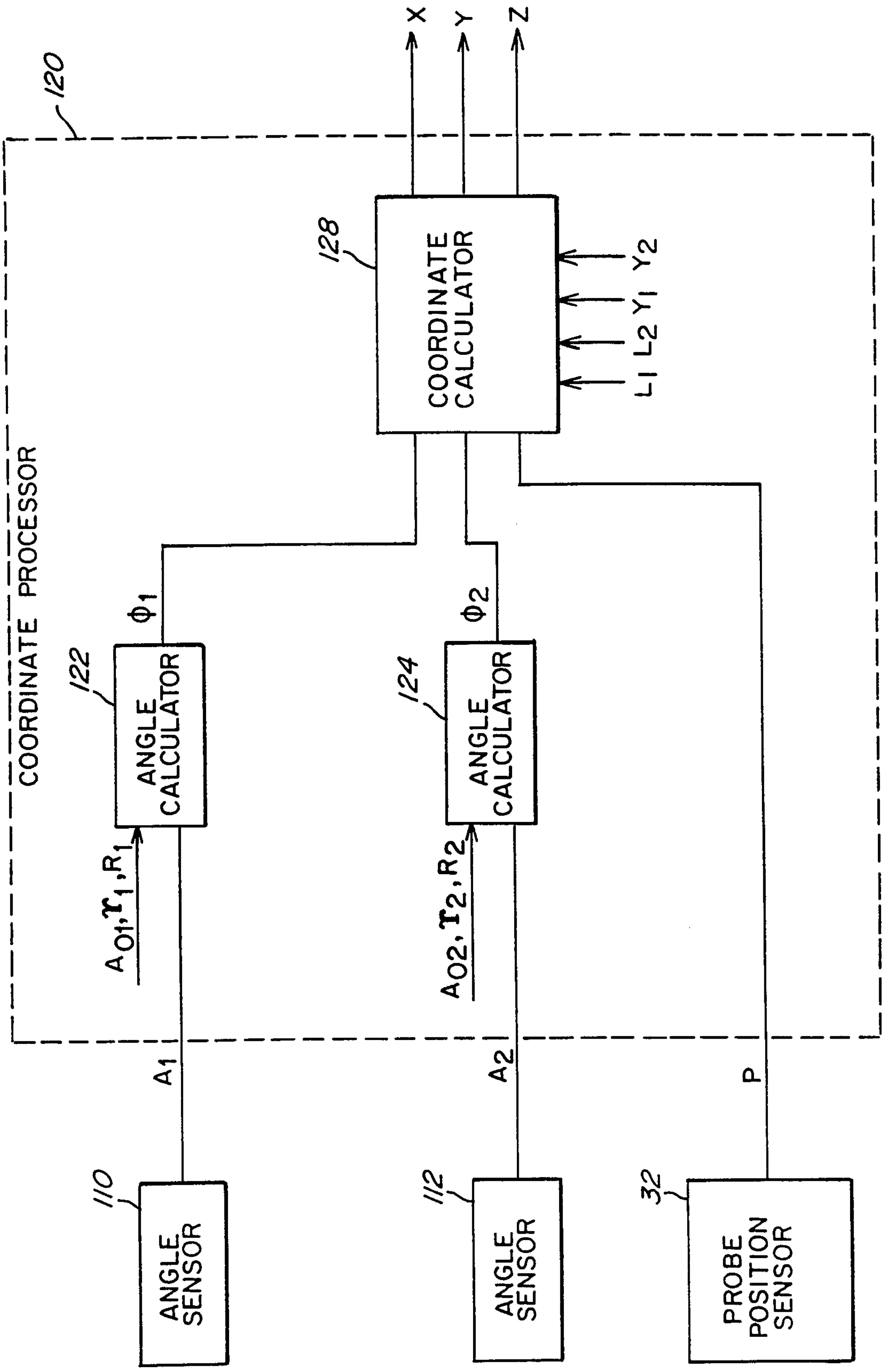
58

Fig. 8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Y
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φ1
φ2
A01, r1, R1
A02, r2, R2
A1
A2
P
110
ANGLE SENSOR
112
ANGLE SENSOR
32
PROBE POSITION SENSOR

Fig. 9

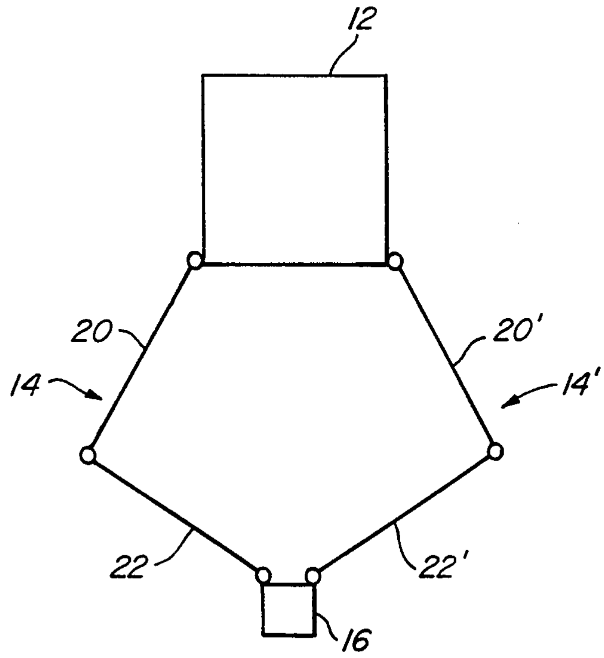

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/06913

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01B 5/008
US CL : 33/503, 556
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)

U.S. : 33/503, 556

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)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP, A, 6-241,766 (Hirayama) 02 September 1994, Figure 1	1-3, 10, 11, 14, 15
X	US, A, 5,396,712 (HERZOG) 14 March 1995, col.2, lines28-64	1-3, 10, 11, 14, 15
X ----- Y	US, A, 4,961,267 (HERZOG) 9 October 1990, col. 5 line 56 - col. 13 line 11	1-3, 10, 11, 12, 14, 15 ------- 13
A	US, A, 5,134,782 (BREYER ET AL.) 4 August 1992	None
A	US, A, 4,703,443 (MORIYASU) 27 October 1987	None
A	US, A, 4,679,331 (KOONTZ) 14 July 1987	None

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

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"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: 01 JULY 1996

Date of mailing of the international search report: 25 JUL 1996

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/06913

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,676,002 (SLOCUM) 30 June 1987	None
A	DL, A, 141,061 (KRIEG) 09 April 1980	None