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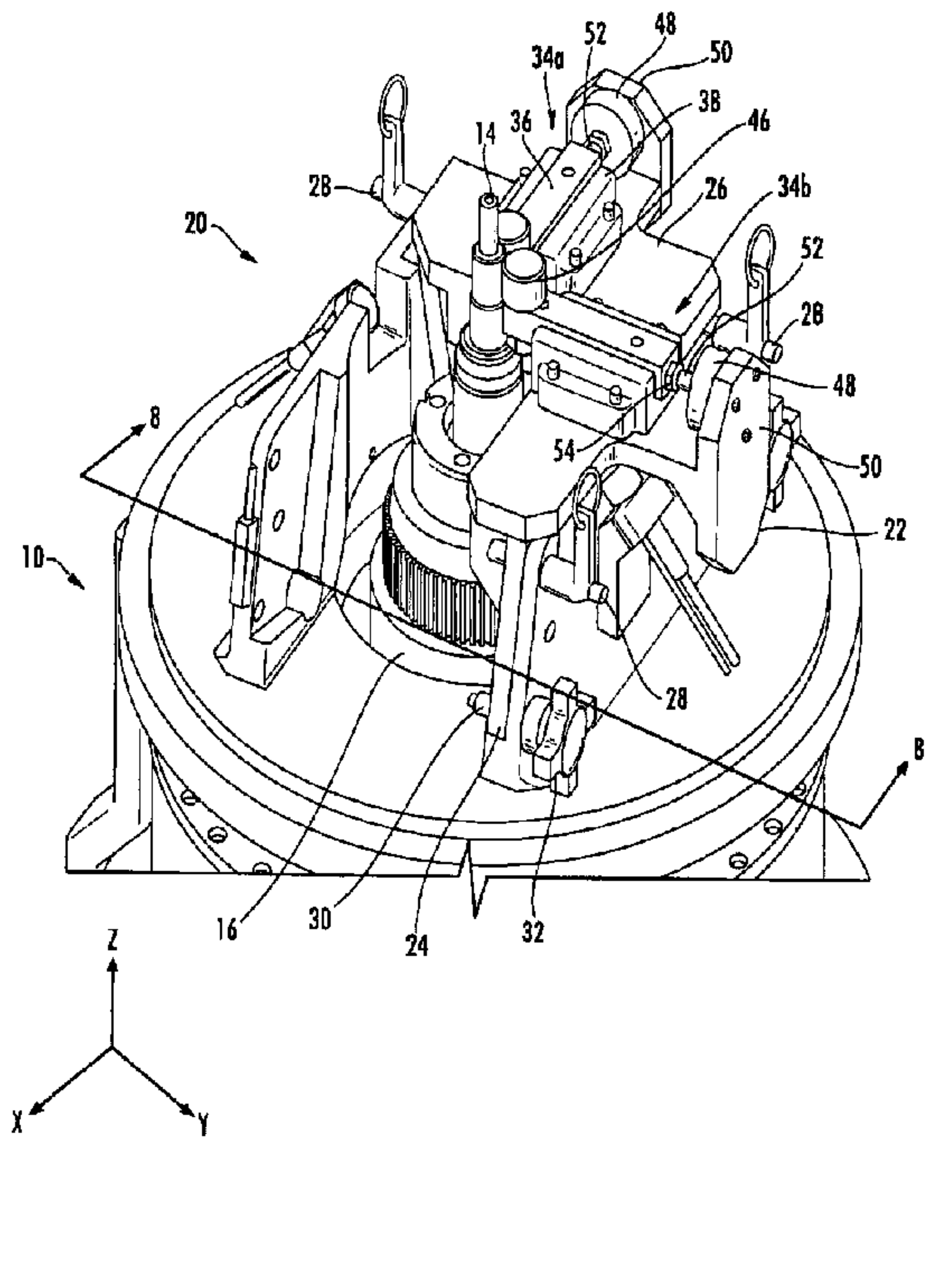
(54) **Titre** : APPAREIL ET PROCEDE DESTINES A MESURER LES CHARGES D'UN OUTIL DE SOUDAGE PAR FRICTION-MALAXAGE
(54) **Title**: APPARATUS AND METHOD FOR MEASURING LOADS ON A FRICTION STIR WELDING TOOL

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An apparatus (20) and method are provided for measuring loads on a rotating friction stir welding tool (14) of a friction stir welding machine (10). The apparatus (20) includes a frame (22) that can be connected to the friction stir welding machine (10), and rollers (46) rotatably connected to the frame (22) are structured to contact and rotate with the friction stir welding tool (14). Each roller (46) is adapted to adjust in a respective direction and communicate with a respective load cell (48) so that the load cells (48) detect a positional characteristic of the rollers (46) and measure loads applied to the rotating friction stir welding tool (14) during operation. The rollers (46) can- contact the rotating tool (14) directly during operation of the machine, such as while the rotating tools is being moved through a workpiece to form a friction stir weld joint, to measure the loads on the tool in the direction of movement of the tool and a direction normal to the movement, i.e., the path and path normal directions.

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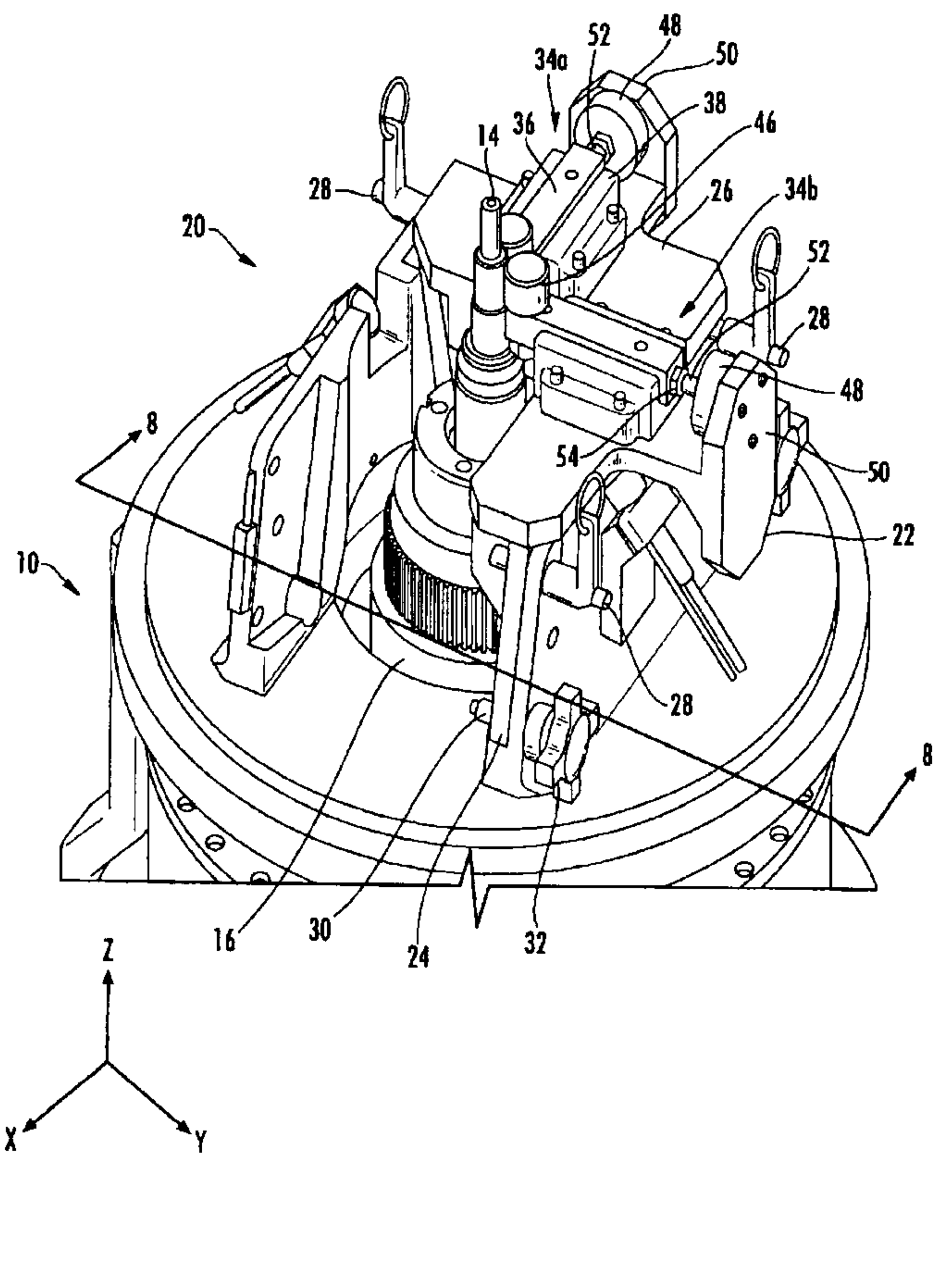


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# APPARATUS AND METHOD FOR MEASURING LOADS ON A FRICTION STIR WELDING TOOL

## Description

Embodiments of the present invention relate to apparatuses and methods for measuring loads on a friction stir welding tool of a friction stir welding machine and, in particular, for measuring the loads on the tool during operation of the machine.

Friction stir welding is a process in which a rotating tool is urged into and/or through a workpiece, e.g., to join multiple members of the workpiece in a solid state or to repair cracks in a workpiece. One conventional friction stir welding machine includes a spindle that holds the rotatable tool. The spindle rotates the tool and moves the tool along a desired path through the workpiece. The tool can define a shoulder that is urged against the workpiece during welding and a pin-like portion that extends from the shoulder into the workpiece. In some cases, the tool can also define threads or other contours on its outer surface. As the tool is urged through the workpiece, a continuous weld joint can be formed. For example, during one conventional friction stir welding process, the rotating tool is plunged into a workpiece or between two workpieces by a friction stir welding machine to produce the required resistance force to generate sufficient frictional heating to form a region of plasticized material. The longitudinal axis of the tool is typically held normal to the surface of the workpiece (or at a small angle relative to the normal direction so that the trailing edge of the shoulder is thrust into and consolidates the plasticized material). Upon solidification of the plasticized material, the members of the workpiece are joined along the weld joint. Friction stir welding is further described in U.S. Patent No. 5,460,317 to Thomas et al.

The loads or magnitude of forces exerted by the friction stir welding machine for moving the tool through the workpiece must be maintained above a prescribed minimum in order to generate the required frictional heating. The various loads provided between the tool and the workpiece can be affected by the rotational speed of the tool, the rate at which the tool is translated through the workpiece, the temperature of the tool and workpiece, the size and material properties of the workpiece, and the size and geometry of the tool. For example, threads or other contours provided on the outer surface of the tool can affect both the loads experienced between the tool and workpiece as well as the degree of mixing of the material of the workpiece during welding. In some cases, the forces on the welding tool can be significant, and deviations from optimal loading conditions can affect the quality of the resulting weld joints, the speed at which the joints are formed, and the longevity of the welding tool and welding machine.

In one typical welding operation, the welding machine includes an automated controller that moves the tool along a predetermined path through the workpiece. The controller is programmed to provide certain welding parameters, e.g., a predetermined radial load on the tool, a predetermined axial load on the tool, a predetermined rotational speed, and a predetermined speed of translation through the workpiece. That is, the machine can exert a load of a predetermined force (e.g., in pounds) on the tool in the axial direction of the tool toward the workpiece, rotate the tool at a predetermined speed (e.g., in RPM), and move the tool through the workpiece at a predetermined speed (e.g., in inches per second). Due to variations in welding conditions, such as variations in the thickness or material of the workpiece or geometric variations throughout the workpiece and the welding path, the loads that result between the tool and the workpiece can change significantly during a single welding operation. Thus, the optimum axial load, rotational speed, and translational speed may vary throughout the operation. In some cases, the controller can be programmed to change the welding parameters during the operation in an attempt to adjust for variations. Such welding programs can require complex determinations based on the characteristics of a specific workpiece.

In some cases, the machine can also include internal sensors that detect characteristics of the machine that are indicative of the loading on the tool. For example, the sensors may measure a hydraulic pressure in a hydraulic actuation system that moves the tool and attempt to use that pressure to determine a loading condition on the tool. In order to correlate the output of the sensor with the actual loads on the tool, a "static" calibration operation can be performed by urging the tool against a load measurement device so that the output of the sensor can be calibrated with the output of the load measurement device. Such "static" calibration operations are performed with the tool in a non-operational condition. That is, the tool is neither rotating nor welding when urged against the load measurement device. For a machine calibrated in this way, discrepancies generally exist between the true loads on the tool during operation and the loads determined by the machine's internal sensors.

Thus, there is a need for an improved apparatus and method for measuring loads on a friction stir welding tool of a friction stir welding machine. The apparatus should be capable of measuring the loads that are actually applied to the tool and should be capable of measuring the loads during operation of the machine, i.e., while the tool is rotating and/or the tool is being used to perform a welding operation.

Embodiments of the present invention provide an apparatus and method for measuring loads on a rotating friction stir welding tool of a friction stir welding machine. The apparatus is capable of contacting the tool to measure the loads that are applied at the tool. Further, the apparatus can be used during operation of the machine, i.e., while the tool is rotating and/or moving through a workpiece, to measure the loads applied in the direction of movement of the tool and a direction normal to the movement, i.e., the "path" and "path normal" directions.

According to one embodiment, the apparatus includes a frame configured to be connected to a friction stir welding machine. First and second rollers are rotatably connected to the frame and structured to contact and rotate with the friction stir welding tool. The first and second rollers are adapted to adjust in first and second directions, each direction being generally perpendicular to a longitudinal direction of the tool. For example, the first roller can be rotatably connected to a first rail that is slidably mounted to the frame and constrained to adjust in the first direction, and the second roller can be rotatably connected to a second rail that is slidably mounted to the frame and constrained to adjust in the second direction, so that loads applied to the tool in the first and second directions are transmitted by the rails to the first and second rollers, respectively. First and second load cells communicate with the rollers. Each load cell is adapted to detect a positional characteristic of a respective one of the rollers along a respective one of the first and second directions. Thus, the load cells are configured to measure loads applied to the rotating friction stir welding tool during operation. The first and second directions can be perpendicular so that the first load cell is configured to measure a load applied in a direction of movement of the tool through a workpiece (path direction) and the second load cell is configured to measure a load applied in a direction normal to the direction of movement (path normal direction).

According to one aspect of the present invention, each rail extends between first and second ends and is configured to slide in a track mounted to the frame, a respective one of the rollers being mounted to the first end of each rail and the second end of each rail configured to contact a respective one of the load cells. A first adjustment member can be configured to be adjusted to thereby adjust the position of the first roller along the first direction and the distance between the first roller and the first load cell, and a second adjustment member can be configured to be adjusted to thereby adjust the position of the second roller along the second direction and the distance between the second roller and the second load cell.

The frame can be removably connected to the machine by one or more releasable fasteners. Further, the friction stir welding machine can be provided to define one or more mounting features for releasable engagement with the frame. The friction stir welding machine, which includes the rotatable friction stir welding tool, can also have one or more sensors for detecting a load applied to the tool, such as internal, nonremovable sensors that can be calibrated with the measurements taken by the load cells.

According to another embodiment, a method is provided for measuring loads on a rotating friction stir welding tool of a friction stir welding machine during operation of the machine. The method includes connecting a frame to the friction stir welding machine so that first and second rotatable rollers are disposed against the tool. The friction stir welding machine is operated so that the friction stir welding tool rotates and thereby rotates the first and second rollers. For example, the rotating friction stir welding tool can be moved through a workpiece in a direction of movement to thereby friction stir weld the workpiece. A first load applied to the first roller in a first direction generally perpendicular to a longitudinal direction of the tool is measured, and a second load applied to the second roller in a second direction generally perpendicular to the longitudinal direction of the tool is measured, e.g., by measuring the loads applied to first and second load cells in the respective directions, one of which can be in the direction of movement of the tool through the workpiece and the other of which can be normal to the direction of movement.

The first and second rollers can be adjustable in the first and second directions, respectively, so that the first and second rollers are disposed against the tool. For example, each roller can be connected to a rail that is slidably adjusted relative to the tool, and each rail can be connected to a respective first or second load cell. That is, the first roller can be rotatably connected to a first rail that is constrained to adjust in the first direction so that loads applied to the tool in the first direction are transmitted via the first roller and the first rail to the first load cell. Similarly, the second roller can be rotatably connected to a second rail that is constrained to adjust in the second direction, the second roller rotatably connected to the second rail such that loads applied to the tool in the second direction are transmitted via the second roller and second rail to the second load cell. First and second adjustment members can also be configured to adjust the position of the first and second rollers in the first and second directions, respectively, relative to the load cells.

The frame of the apparatus can be releasably connected to the friction stir welding machine with one or more releasable fasteners and then removed from the friction stir welding machine after the measuring operation. In some cases, the friction stir welding machine can define one or more one sensors for detecting a load applied to the tool, and the method can include calibrating the sensor(s) of the friction stir welding machine according to the first and second loads that are applied to the rollers and measured by the apparatus, e.g., so that the sensors can be used to provide an accurate measurement after the apparatus is removed from the machine.

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a perspective view illustrating a friction stir welding machine with an apparatus mounted thereto for measuring the loads on the tool of the machine according to one embodiment of the present invention;

Figure 2 is a perspective view illustrating a portion of the friction stir welding machine of Figure 1 as indicated in Figure 1;

Figure 3 is another perspective view illustrating the friction stir welding machine of Figure 1;

Figure 4 is a perspective view illustrating a portion of the friction stir welding machine of Figure 1 as indicated in Figure 3;

Figure 5 and 6 are perspective views illustrating the apparatus of Figure 1 for measuring loads on the tool of a friction stir welding machine;

Figure 7 is a perspective view illustrating the apparatus of Figure 1 in a partially assembled condition;

Figure 8 is a partial cut-away view illustrating the apparatus of Figure 1 as generally seen in elevation along line 8-8 of Figure 4;

Figure 9 is a partial cut-away view illustrating the apparatus of Figure 1 as generally seen in elevation in a direction perpendicular to Figure 8;

Figure 10 is a perspective view schematically illustrating the friction stir welding machine and apparatus for measuring the loads on the tool of the machine of Figure 1 during a friction stir welding operation; and

Figure 11 is a plan view schematically illustrating the friction stir welding machine and apparatus of Figure 10.

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to the drawings and, in particular, to Figures 1-4, there is shown a friction stir welding machine **10** for friction stir welding a workpiece **12** (Figures 10 and 11). According to one embodiment of the present invention, an apparatus **20** is mounted to the friction stir welding machine **10** for measuring the forces or loads on a tool **14** of the machine **10**. The friction stir welding machine **10**, which can be a generally conventional device, includes a spindle **16** with multiple actuators for rotating the tool **14** and moving the tool **14** into and through a workpiece **12**. Further, the spindle **16** can be moved along the workpiece **12** by one or more additional actuation devices, such as a Computer Numerical Control (CNC) device. The machine **10** can be operated manually but is typically configured for automatic operation, i.e., with the spindle **16** and/or the CNC device controlled by a controller that operates the various actuators to move the tool **14** along a predetermined weld path according to a predetermined welding software program. As the spindle **16** is moved along the workpiece **12**, the tool **14**, which is secured to the spindle **16**, is also moved. In particular, the CNC device can move the spindle **16**, and hence the tool **14**, along the X-, Y-, and Z-axes. Further, the CNC device can rotate the tool **14** about the C-axis, i.e., as indicated by reference numeral **18a**. The spindle **16** can also include actuators for rotating about the A-axis, indicated by reference numeral **18b**, and the E-axis, indicated by reference numeral **18c**, in addition to rotating the tool **14** about the longitudinal axis of the tool **14**.

As shown, for example, in Figure 4, the apparatus **20** is mounted to the spindle **16** proximate to the rotatable tool **14** and configured to contact the tool **14**. The apparatus **20** is shown removed from the friction stir welding machine **10** in Figures 5-7. The apparatus **20** generally includes a frame or structure **22**, which corresponds to the configuration of the friction stir welding machine **10** near the tool **14**. In particular, the frame **22** includes a base portion **24** defining several leg-like supports that, when disposed against a face surface of the spindle **16** of the friction stir welding machine **10**, support a table-like portion **26** of the frame **22** at a position near the tool **14**.

The frame **22** is typically removably connected to a weldment or structure that is connected (e.g., removably connected) to the spindle **16** of the machine **10** so that the apparatus **20** can be connected to the machine **10** for a calibration operation and then removed from the machine **10**. Thereafter, the machine **10** can be operated without the apparatus **20**, and the apparatus **20** can be used for calibrating another machine **10**. For example, the frame **22** of the apparatus **20** can be removably connected or mounted to the machine **10** using one or more releasable fasteners, such as pins, bolts, clamps, or the like. As illustrated, locating pins **28** are disposed through apertures defined by the frame **22** and through corresponding apertures defined by the friction stir welding machine **10**. Thus, the frame **22** can be arranged on the friction stir welding machine **10** as shown in Figure 4 and each pin **28** can be disposed through the corresponding holes of the frame **22** and machine **10** to secure the frame **22** to the machine **10** in the desired orientation. Further, additional fasteners provided for securing the frame **22** in place can include spring-loaded pins, or bolts **30** with handknobs **32** disposed in threaded holes of the frame **22** so that an operator can rotate the handknobs **32** to tighten the bolts **30** against the machine **10** or into corresponding threaded or unthreaded holes of the machine **10**. In some cases, the apparatus **20** can limit one or more of the various operational motions of the machine **10**, while in other cases the machine **10** can operate to move in any of its movements regardless of the apparatus **20** mounted thereon.

Alternatively, in other embodiments of the present invention, the apparatus **20** can be provided as a nonremovable, i.e., integral, part of the machine **10** that cannot be easily removed therefrom. For example, the apparatus **20** can be made nonremovable by welding or otherwise fixedly securing the frame **22** of the apparatus **20** to the machine **10**.

At least one load measurement mechanism **34a**, **34b** is mounted on the table-like portion **26** of the frame **22**. In the illustrated embodiment, two load measurement mechanisms **34a**, **34b** are provided, each including a member that is adjustably mounted on the frame **22**. In particular, each load measurement mechanism **34a**, **34b** includes a rail **36** that is slidably mounted in a track or guide **38**. The track **38** is mounted or otherwise secured to the frame **22**, e.g., by bolts **40** or otherwise, and defines a slot for receiving the rail **36**. The rail **36** is disposed in the slot such that the track **38** constrains the rail **36** to slide or otherwise adjust along one direction of motion. As shown in Figures 8 and 9, each rail **36** extends between first and second ends **42**, **44**. A rotatable roller **46** is mounted to the first end **42** of each rail **36** so that an outer surface of the roller **46** extends beyond the rail **36** to directly contact the tool **14**. At the second end **44** of the rail **36**, opposite the roller **46**, the rail **36** is connected to a respective load cell **48** that is secured to a flange **50** of the frame **22** and configured to measure loads transmitted by the tool **14** through the roller **46** and rail **36**. That is, with the rollers **46** disposed against the tool **14**, any loading of the tool **14** in the direction of the respective roller **46** is transmitted directly from the tool **14** to the roller **46** and via the respective rail **36** to the respective load cell **48** for measurement by the cell **48**. If the tool **14** is loaded in the directions of both rollers **46**, i.e., with a load directed in a direction that is not parallel to either of the first and second directions, each of the load cells **48** can detect the portion or component of the total loading on the tool **14** that is applied in the respective direction.

Each load roller **46** is mounted to the respective rail **36** rotatably so that the roller **46** can rotate against the tool **14**, i.e., against the same integral member that is rotated and urged into or along the workpiece **12** for welding. In this way, the roller **46** can be in direct contact with the tool **14** while the tool **14** is rotating so that the roller **46** is rotated by the tool **14**. Each roller **46** can include a bearing or other rotatable mount. Such direct contact or engagement between the tool **14** and the rollers **46** can facilitate a measurement of the loading on the tool **14** that is more accurate than other measurements in which the loads are determined based on correlations between the loading of the tool and the output of a sensor that is not directly connected to the tool **14**. Further, the measurement of the loading during operation of the machine **10** can facilitate a measurement of the loading on the tool **14** that is more accurate than other measurements in which the operating loads are determined based on measurements performed on a static tool.

The rails **36** can also be supported by bearings or other low-friction adjustment devices so that forces are transmitted efficiently between the tool **14** and the load cells **48**. That is, each track **38** can be a roller bearing that permits low-friction motion of the respective rail **36** only along a single direction of motion.

Various types of load cells **48** can be used. Typically, each load cell **48** is adapted to detect a positional characteristic of the roller to thereby detect a load or force on the respective roller **46** along the direction of the respective track **38** and rail **36**. For example, each load cell **48** can detect small changes in force, displacement, stress, strain, pressure, or the like and provide an output signal that is representative of the load, i.e., force, applied thereto. One exemplary load cell **48** that can be used in the present invention is the Model 53 load cell with readout, available from Sensotec - Lebow products, part of Honeywell Sensing and Control, Part No. 060-0239-08 with a range of 10,000 lbs.

An adjustment member can also be provided between the rail **36** and the load cell **48** to adjust the distance between each roller **46** and the associated load cell **48** so that the roller **46** is disposed in contact with the tool **14** but without significant compression of the roller **46** and rail **36** when the tool **14** is not loaded. For example, as shown in Figures 5-7, a screw or bolt **52** is disposed in a threaded aperture of each rail **36** at the second end **44** thereof. With the tool **14** stopped and unloaded, an operator can easily rotate the bolt **52** to adjust the length by which the bolt **52** extends from the rail **36**, so that the roller **46** contacts the tool **14** and the head of the bolt **52** contacts the load cell **48** without applying any significant load on the load cell **48** (e.g., about 1 lb or less). A nut **54** provided on the bolt **52** can be adjusted against the rail **36** to secure the bolt **52** in the adjusted configuration relative to the rail **36** and prevent the bolt **52** from rotating during operation.

In the illustrated embodiment, the apparatus **20** includes two load measurement mechanisms **34a, 34b**. The rails **36** of the two load measurement mechanisms **34a, 34b** are configured to slidably adjust in directions that are perpendicular to the axial or longitudinal direction of the tool **14**. Further, the rails **36**, and hence the rollers **46**, are configured to adjust in directions that are normal to one another. That is, as shown in Figure 4, the axial direction of the tool **14** extends in the direction of the Z-axis, and the rails **36** are configured to adjust relative to the frame **22** in the directions of the X- and Y-axes, respectively. Thus, the two load measurement mechanisms **34a, 34b** of the apparatus **20** can be used to determine the total load applied to the tool **14** as the tool **14** is moved through the workpiece **12**. For example, if the tool **14** is moved through a workpiece **12** in the direction **56** (Figure 8), the load cell **48** of one load measurement mechanism **34b** can determine the load applied to the tool **14** in the opposite, parallel direction. The load cell **48** of the other load measurement mechanism **34a** can further determine any loads applied in a direction normal to direction **56** (i.e., in a direction into the page in Figure 8). Thus, the apparatus **20** is capable of determining the loads applied both in a direction of movement of the tool **14** along the welding path and in a direction perpendicular thereto, i.e., the path and path normal directions.

Figures 10 and 11 illustrate the use of the apparatus **20** for measuring the loads on the rotating tool **14** of the friction stir welding machine **10** while the machine **10** is performing a friction stir welding operation to join two members **12a, 12b** of a workpiece **12**. As indicated in Figure 11, the tool **14** of the machine **10** rotates in direction **58**, and the tool **14** is moved in direction **60** through the workpiece **12** along an interface **62** of the two abutting members **12a, 12b** of the workpiece. As the tool **14** moves through the workpiece **12**, the rotating tool **14** generates friction with the workpiece, thereby plasticizing material of the workpiece. The plasticized material is mixed by the tool **14** and thereafter cools and solidifies to form a friction stir welded joint **64**. The workpiece **12** and the weld path can define various contours and configurations, including complex curves about multiple axes. The direction and orientation of the tool **14** can be modified accordingly while performing a welding operation, e.g., by changing the direction of the tool **14** through the workpiece **12** in the X- and Y-axes (Figure 11) and/or by changing the orientation of the tool **14**, e.g., by rotating the of the tool **14** to correspond to the curvature of the workpiece **12** (Figure 10).

As the tool **14** moves through the workpiece **12**, loads applied to the tool **14** are also applied via the rails **36** to the load cells **48**. For example, as the tool **14** moves in direction **60** in Figure 11, a load is applied to the tool **14**, and hence to the load cell **48** of mechanism **34b**, in the opposite parallel direction **66**. Some loading (typically of a smaller magnitude) can also occur in a path normal direction **68** toward the roller **46** of the other mechanism **34a** and is detected by the load cell **48** of the mechanism **34a**. Each load cell **34a**, **34b** is configured to generate load signals and communicate the load signals to a controller **70** and/or another interface such as a calibrated read-out that includes a digital LED display for displaying the load signals to a user.

The motion of the tool **14** through the workpiece **12** is controlled by a controller, which includes a processor and a memory, and which can be the same controller **70** that receives the load signals from the load cells **48** (as illustrated) or a separate control device. The controller **70** controls the motions and other operations of the machine **10**. In particular, the processor of the controller **70** can provide commands for controlling the actuators of the machine **10** according to a weld program, i.e., a predetermined list of computer program instructions, which can be stored in the memory of the controller **70** as software. In this way, the processor controls the tool **14** to move along a weld path that corresponds to the interface **62**. Further, the processor can control the tool **14** to move according to a variety of welding parameters such as the loads exerted by or on the tool **14**. For example, the weld program can include instructions for controlling the speed or other aspect of the movement of the tool **14** to maintain a particular load (or particular range of loads) on the tool **14**. In some cases, the load (or range of loads) can vary throughout the welding operation, e.g., according to the material or other characteristics of the workpiece **12**. In this regard, the controller **70** can receive the load data measured by the load cells **48** and adjust the motion of the tool **14** accordingly, e.g., by increasing the speed at which the tool **14** moves through the workpiece **12** to increase the load on the tool **14** or decreasing the speed at which the tool **14** moves through the workpiece **12** to decrease the load on the tool **14**. In some cases, the controller **70** can mathematically combine the loads determined by the different cells **48** to determine a single magnitude and direction that is representative of the total load applied to the tool **14**.

Further, the controller **70** can also receive load data provided by the friction stir welding machine **10**, e.g., data generated by sensors **72** provided within and integral to the machine **10**. Such sensors **72** can detect pressures, stresses, strains, and the like and thereby determine the loads on the tool **14**. The controller **70** can compare the signals provided by the load cells **48** with the machine's internal sensors **72**. Further, the controller **70** can calibrate (or provide an output that can be used by an operator to calibrate) one or more of the machine's internal sensor(s) **72**. In this way, the apparatus **20** can facilitate the calibration of the integral sensor(s) **72** of the machine **10** so that subsequent measurements by each integral sensor **72** of the machine **10** are sufficiently accurate. Such a calibration operation is typically performed on new friction stir welding machines and can also be performed periodically to maintain the accuracy of the machine's internal sensors **72**.

The scope of the claims should not be limited by the preferred embodiments set forth above, but should be given the broadest interpretation consistent with the description as a whole.

**What is claimed is:**

1. An apparatus for measuring loads on a rotating friction stir welding tool of a friction stir welding machine during operation of the friction stir welding machine, the apparatus comprising:

a frame configured to be connected to the friction stir welding machine;

first and second rollers rotatably connected to the frame and structured to contact and rotate with the friction stir welding tool, the first roller adapted to adjust in a first direction generally perpendicular to a longitudinal direction of the friction stir welding tool, and the second roller adapted to adjust in a second direction generally perpendicular to the longitudinal direction of the friction stir welding tool; and

first and second load cells in communication with the first and second rollers, the first load cell adapted to detect a positional characteristic of the first roller along the first direction and the second load cell adapted to detect a positional characteristic of the second roller along the second direction such that the load cells are configured to measure loads applied to the rotating friction stir welding tool during operation.

2. An apparatus according to claim 1 further comprising:

a first rail slidably mounted to the frame, the first rail connected to the first load cell and constrained to adjust in the first direction, and the first roller rotatably connected to the first rail such that loads applied to the friction stir welding tool in the first direction are transmitted via the first roller and first rail to the first load cell; and

a second rail slidably mounted to the frame, the second rail connected to the second load cell and constrained to adjust in the second direction, and the second roller rotatably connected to the second rail such that loads applied to the friction stir welding tool in the second direction are transmitted via the second roller and second rail to the second load cell.

3. An apparatus according to claim 1 wherein the first and second directions are perpendicular such that the first load cell is configured to measure a load applied in a direction of movement of the friction stir welding tool through a workpiece and the second load cell is configured to measure a load applied in a direction normal to the direction of movement.

4. An apparatus according to any one of claims 1 to 3 wherein the frame is removably connected to the friction stir welding machine by one or more releasable fasteners.

5. An apparatus according to claim 2 wherein each rail extends between first and second ends and is configured to slide in a track mounted to the frame, a respective one of the first and second rollers being mounted to the first end of each rail and the second end of each rail configured to contact a respective one of the first and second load cells.

6. An apparatus according to any one of claims 1 to 5 further comprising a first adjustment member configured to be adjusted to thereby adjust the position of the first roller in the first direction and the distance between the first roller and the first load cell, and a second adjustment member configured to be adjusted to thereby adjust the position of the second roller in the second direction and the distance between the second roller and the second load cell.

7. An apparatus according to any one of claims 1 to 6 further comprising a processor configured to adjust a speed of the motion of the friction stir welding tool through a workpiece according to the loads.

8. A friction stir welding machine comprising an apparatus for measuring load on a rotating friction stir welding tool according to any one of claims 1 to 7 and a rotatable friction stir welding tool, the friction stir welding machine defining at least one mounting feature for releasable engagement with the frame of the apparatus for measuring loads on the rotating friction stir welding tool.

9. A friction stir welding machine according to claim 8 further comprising at least one sensor for detecting a load applied to the friction stir welding tool.

10. A method for measuring loads on a rotating friction stir welding tool of a friction stir welding machine during operation of the friction stir welding machine, the method comprising:

connecting a frame to the friction stir welding machine such that first and second rotatable rollers are disposed against the friction stir welding tool;

operating the friction stir welding machine such that the friction stir welding tool rotates and thereby rotates the first and second rollers; and

during said operating step, measuring a first load applied to the first roller in a first direction generally perpendicular to a longitudinal direction of the friction stir welding tool and a second load applied to the second roller in a second direction generally perpendicular to the longitudinal direction of the friction stir welding tool.

11. A method according to claim 10 further comprising adjusting the first roller in the first direction and the second roller in the second direction such that the first and second rollers are disposed against the friction stir welding tool.

12. A method according to claim 11 wherein said adjusting step comprises adjusting a first adjustment member configured to adjust the position of the first roller in the first direction, and adjusting a second adjustment member configured to adjust the position of the second roller in the second direction.

13. A method according to claim 11 wherein said adjusting step comprises slidably adjusting first and second rails relative to the friction stir welding tool, the first rail connected to a first load cell and constrained to adjust in the first direction, the first roller rotatably connected to the first rail such that loads applied to the friction stir welding tool in the first direction are transmitted via the first roller and first rail to the first load cell, and the second rail connected to a second load cell and constrained to adjust in the second direction, the second roller rotatably connected to the second rail such that loads applied to the friction stir welding tool in the second direction are transmitted via the second roller and the second rail to the second load cell.

14. A method according to claim 13 wherein said measuring step comprises measuring the first load applied to the first load cell in the first direction and the second load applied to the second load cell in the second direction.

15. A method according to any one of claims 10 to 12 wherein said measuring step comprises measuring the first load applied to a first load cell in the first direction and the second load applied to a second load cell in the second direction, the first and second load cells being in communication with the first and second rollers, respectively.

16. A method according to any one of claims 10 to 15 wherein said connecting step comprises releasably connecting the frame to the friction stir welding machine with one or more releasable fasteners and further comprising removing the frame from the friction stir welding machine after said measuring step.

17. A method according to any one of claims 10 to 12 wherein said operating step comprises moving the rotating friction stir welding tool through a workpiece in a direction of movement thereby to friction stir weld the workpiece.

18. A method according to claim 17 wherein said measuring step comprises measuring the first load in the direction of movement and measuring the second load in a direction normal to the direction of movement.

19. A method according to claim 17 wherein said operating step comprises adjusting a speed of the friction stir welding tool through the workpiece according to the first and second loads.

20. A method according to any one of claims 10 to 19 wherein the friction stir welding machine defines at least one sensor for detecting a load applied to the friction stir welding tool and further comprising calibrating the at least one sensor of the friction stir welding machine according to the first and second loads applied to the first and second rollers and measured during said measuring step.

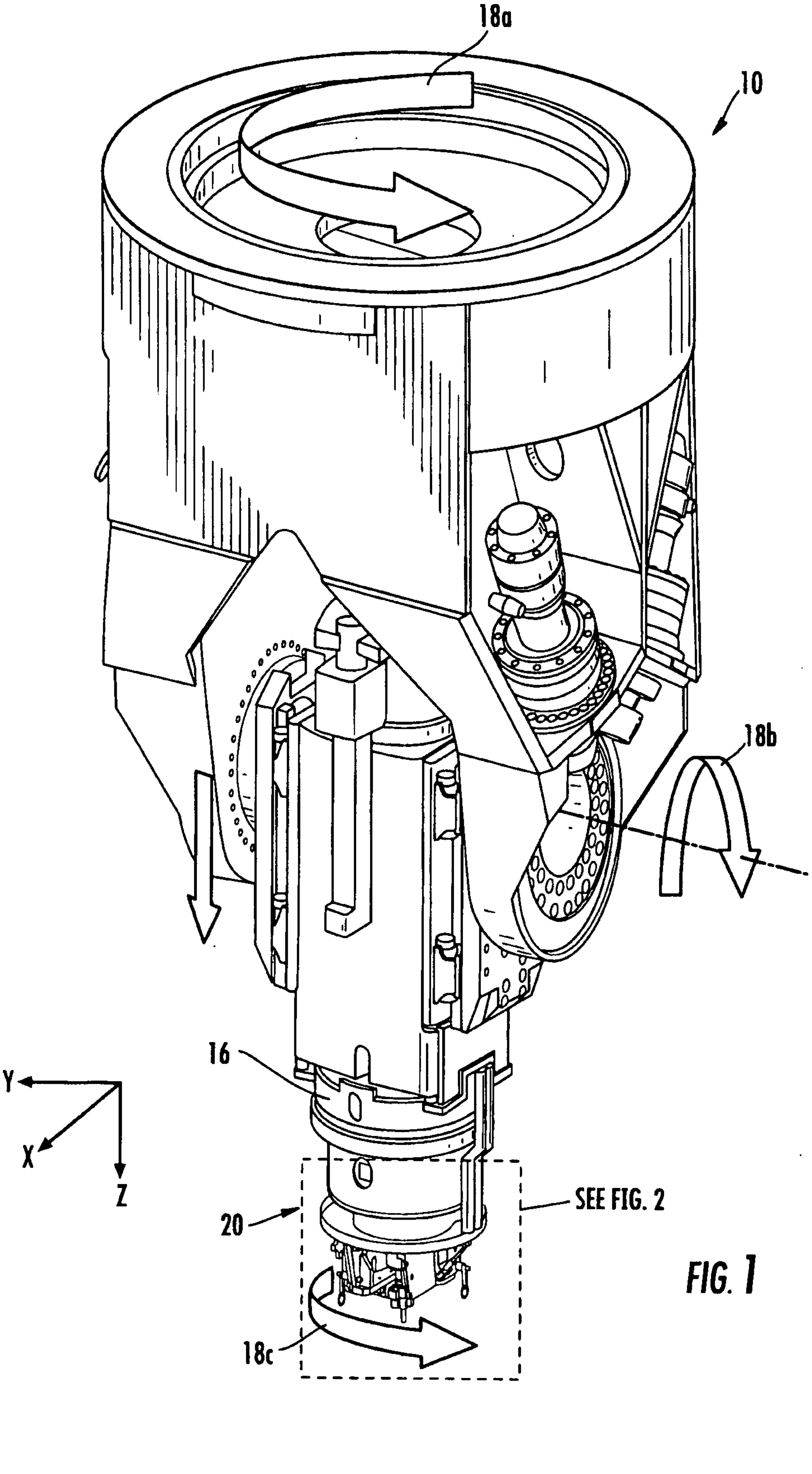


FIG. 1

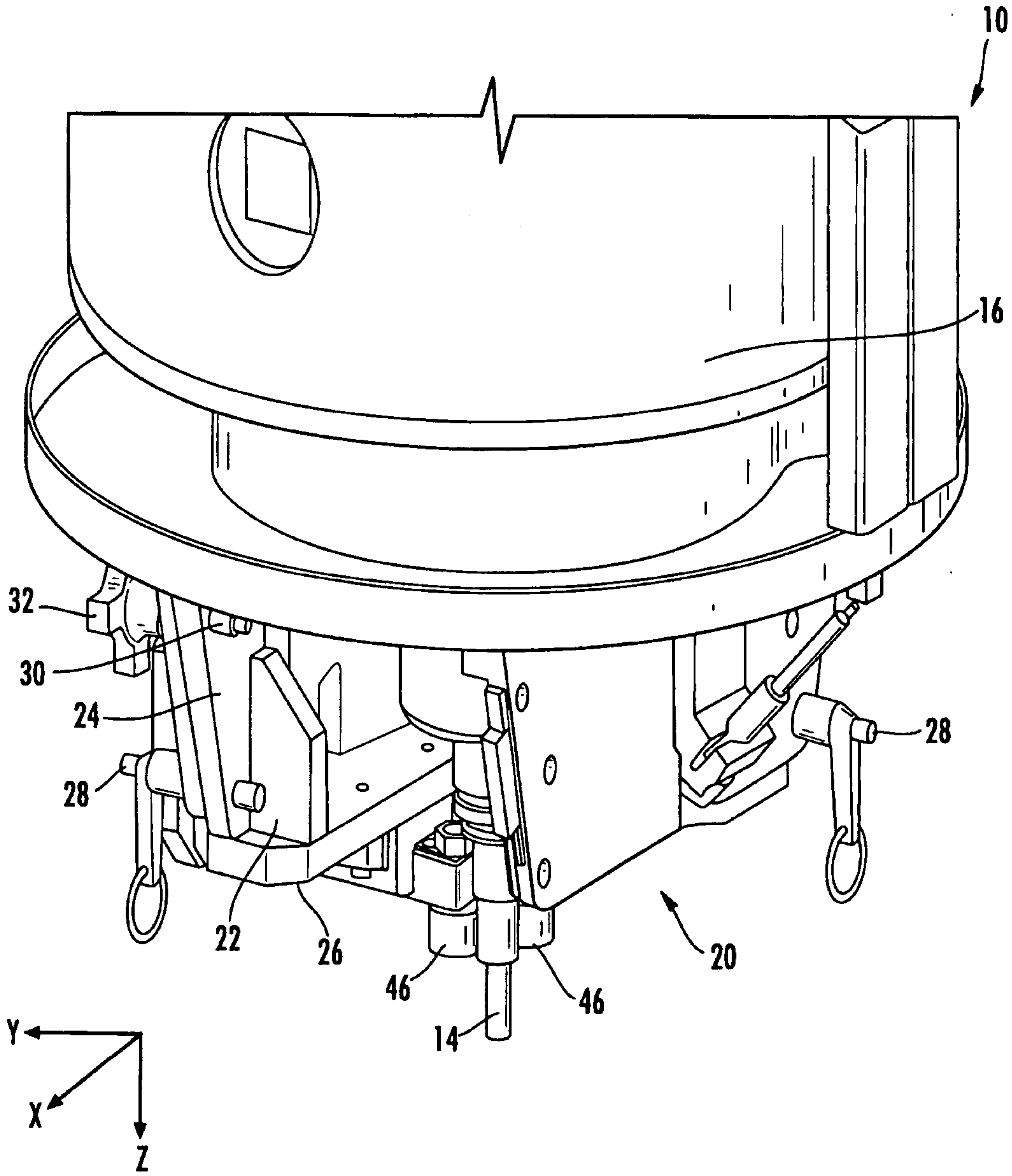


FIG. 2

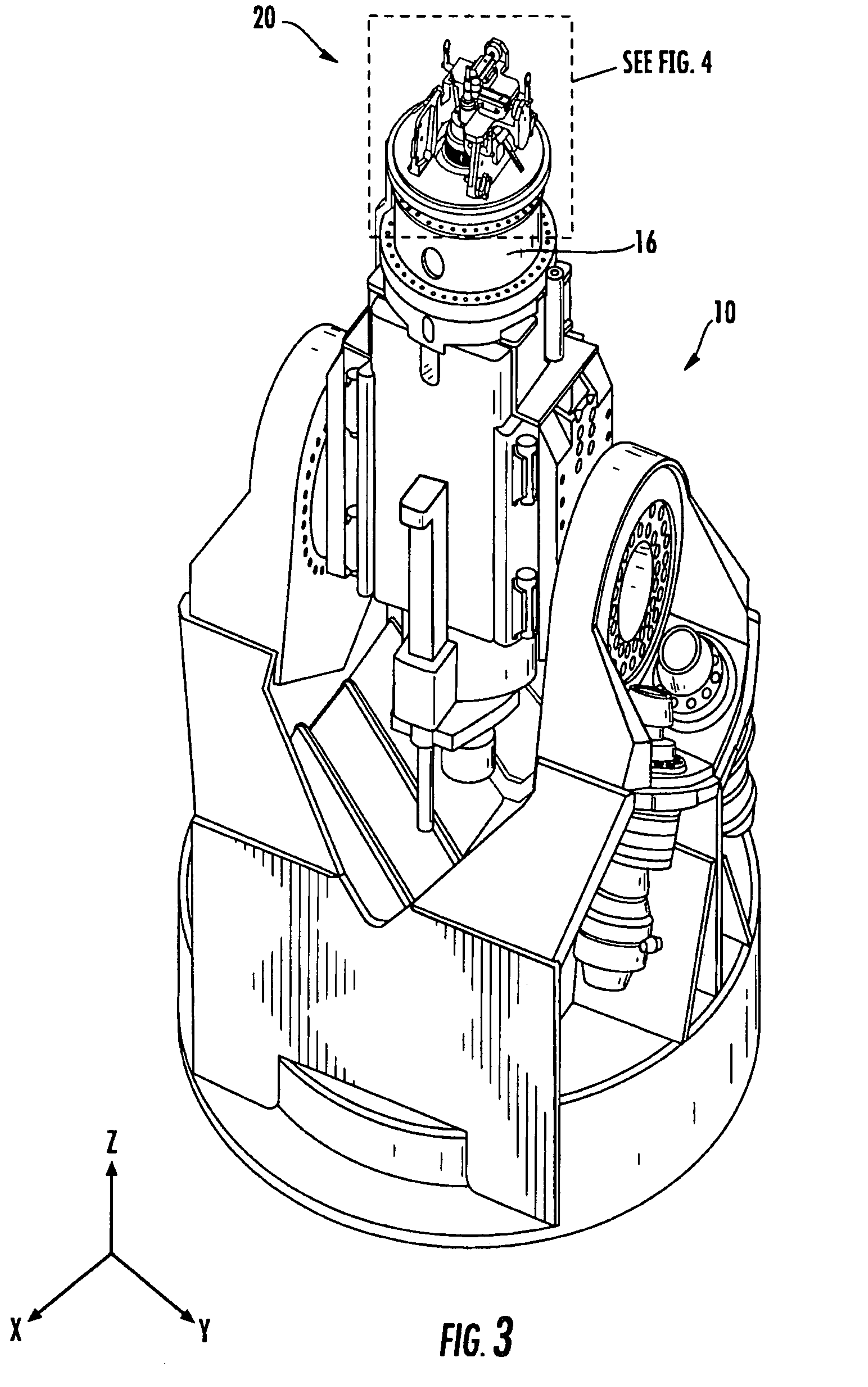


FIG. 3

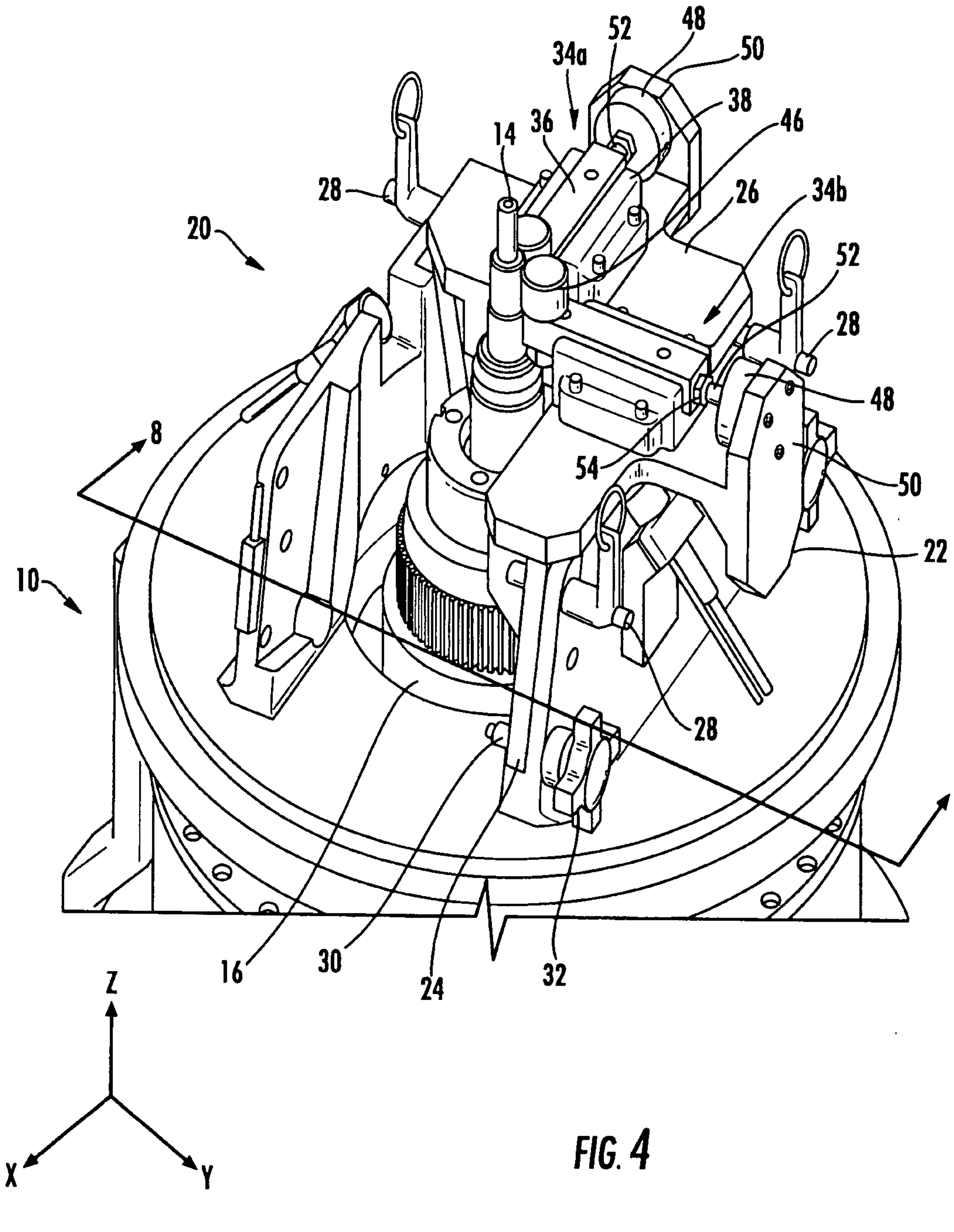
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FIG. 4

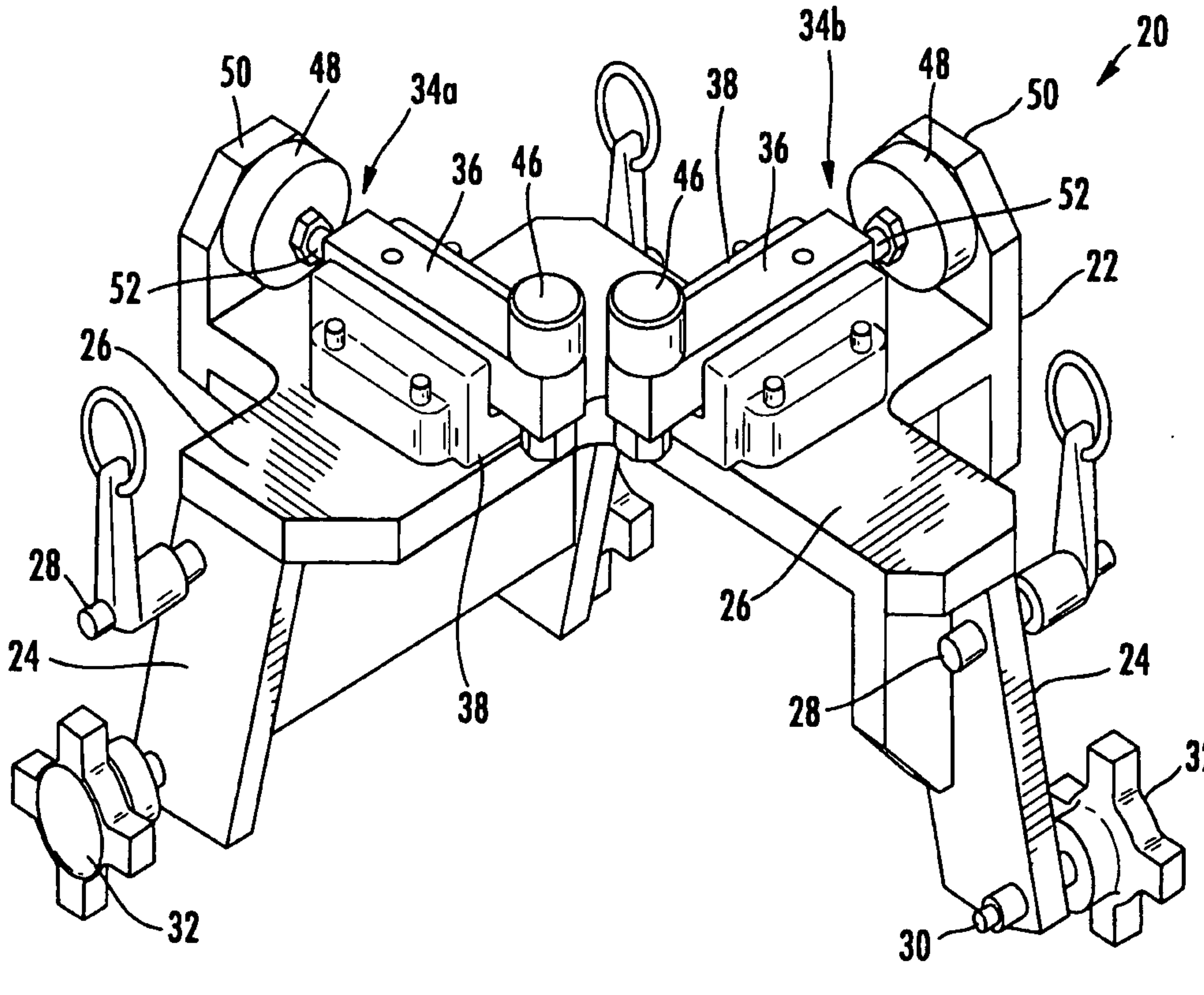
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FIG. 5

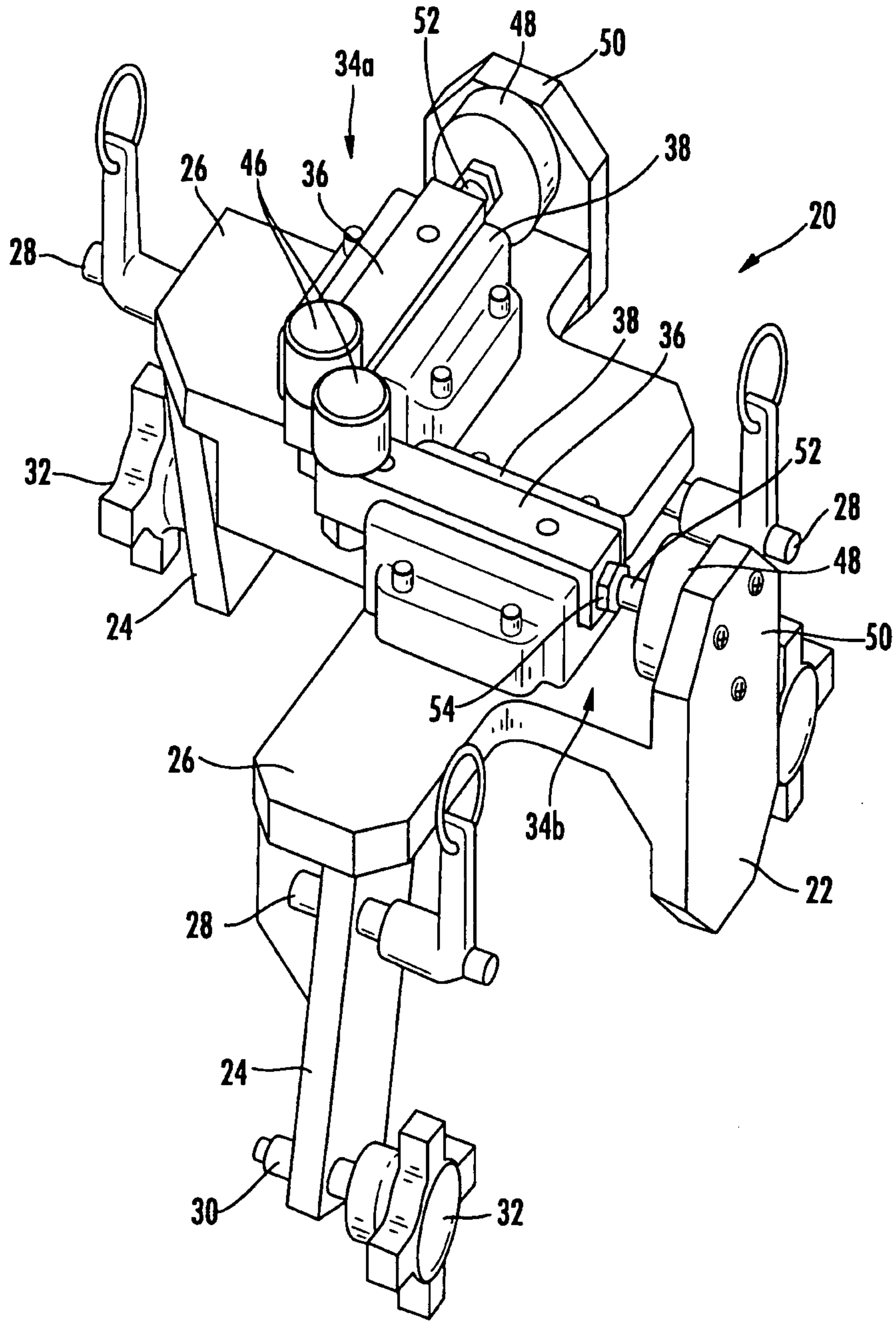
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FIG. 6

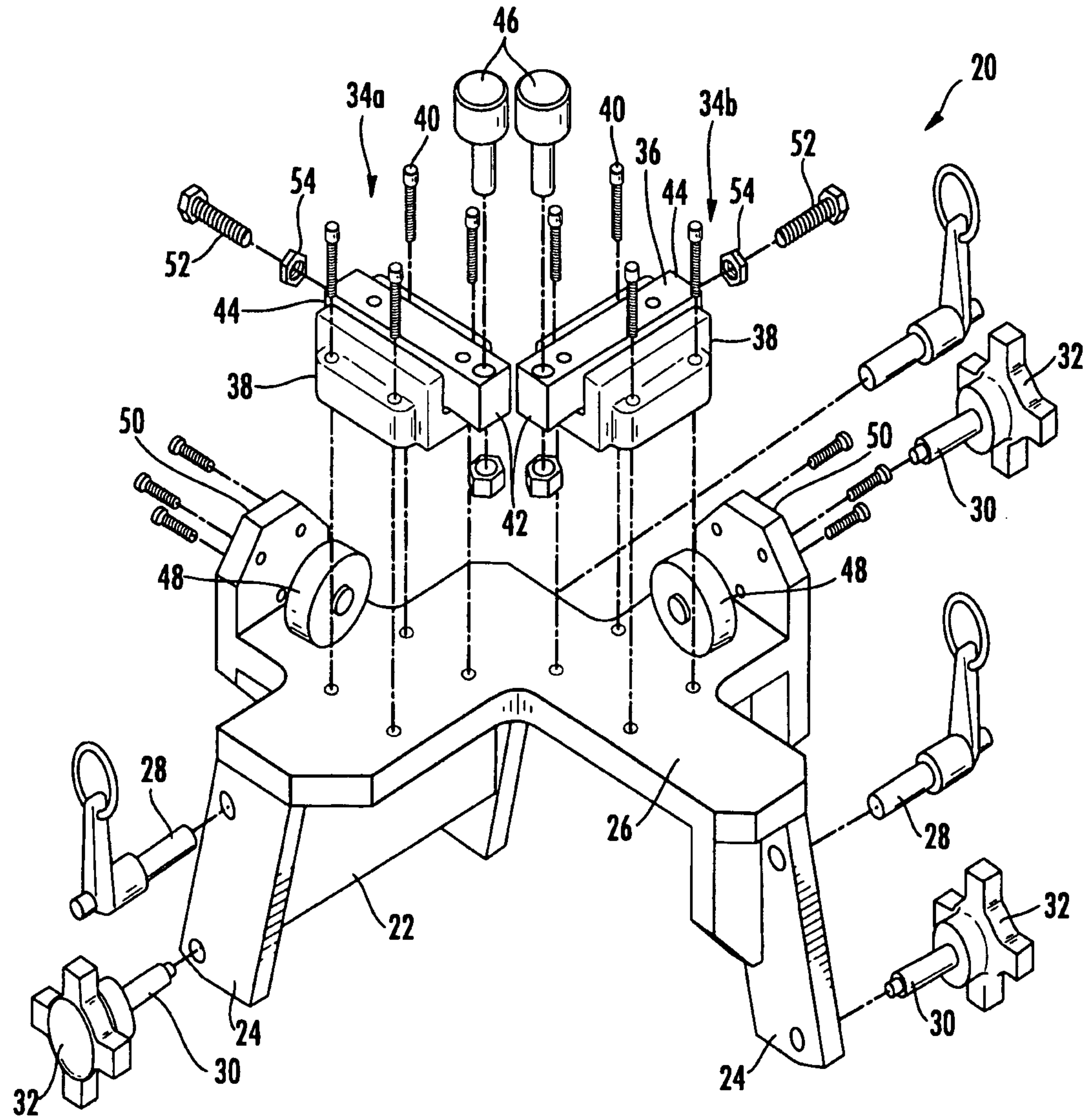
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FIG. 7

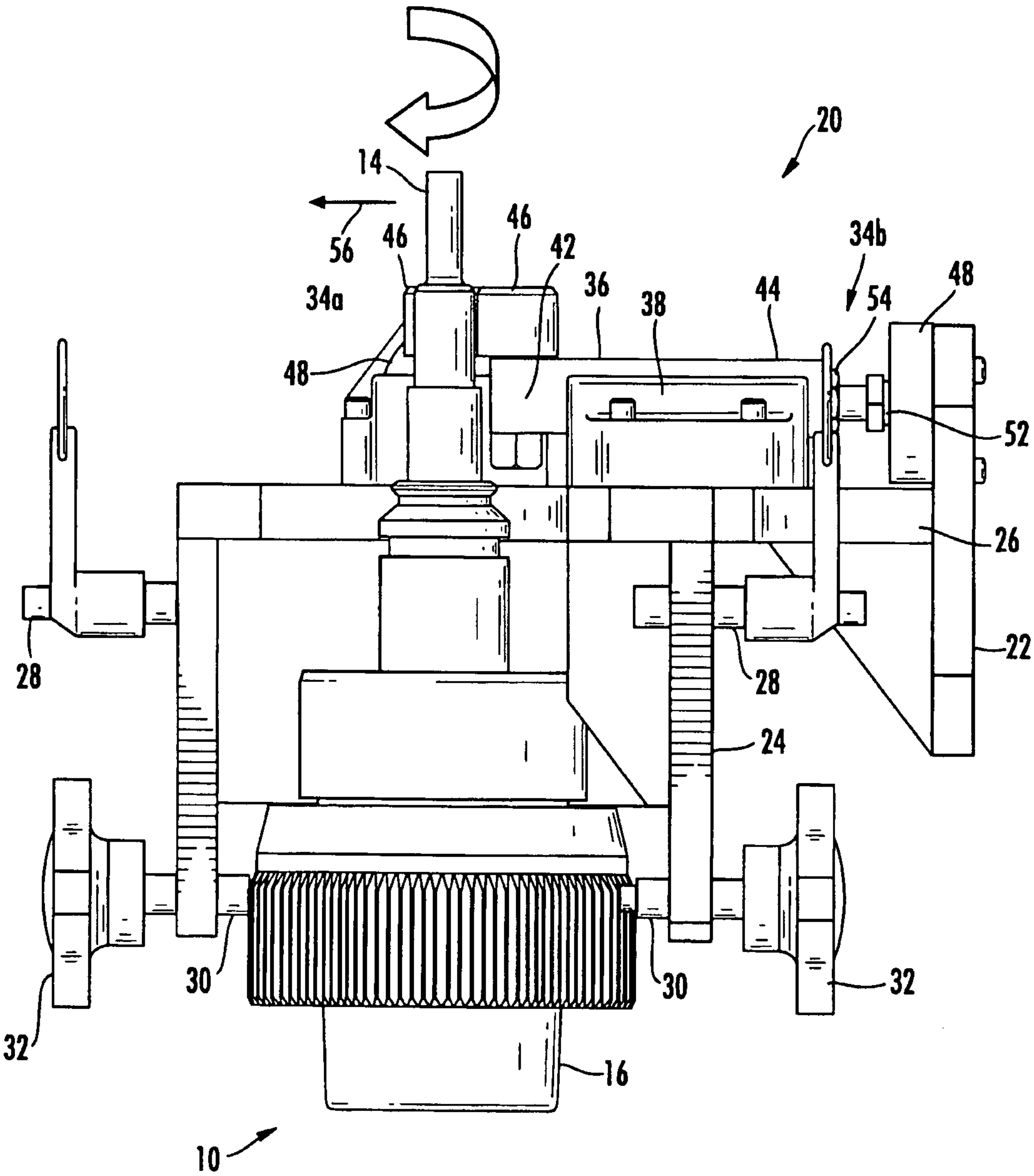
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FIG. 8

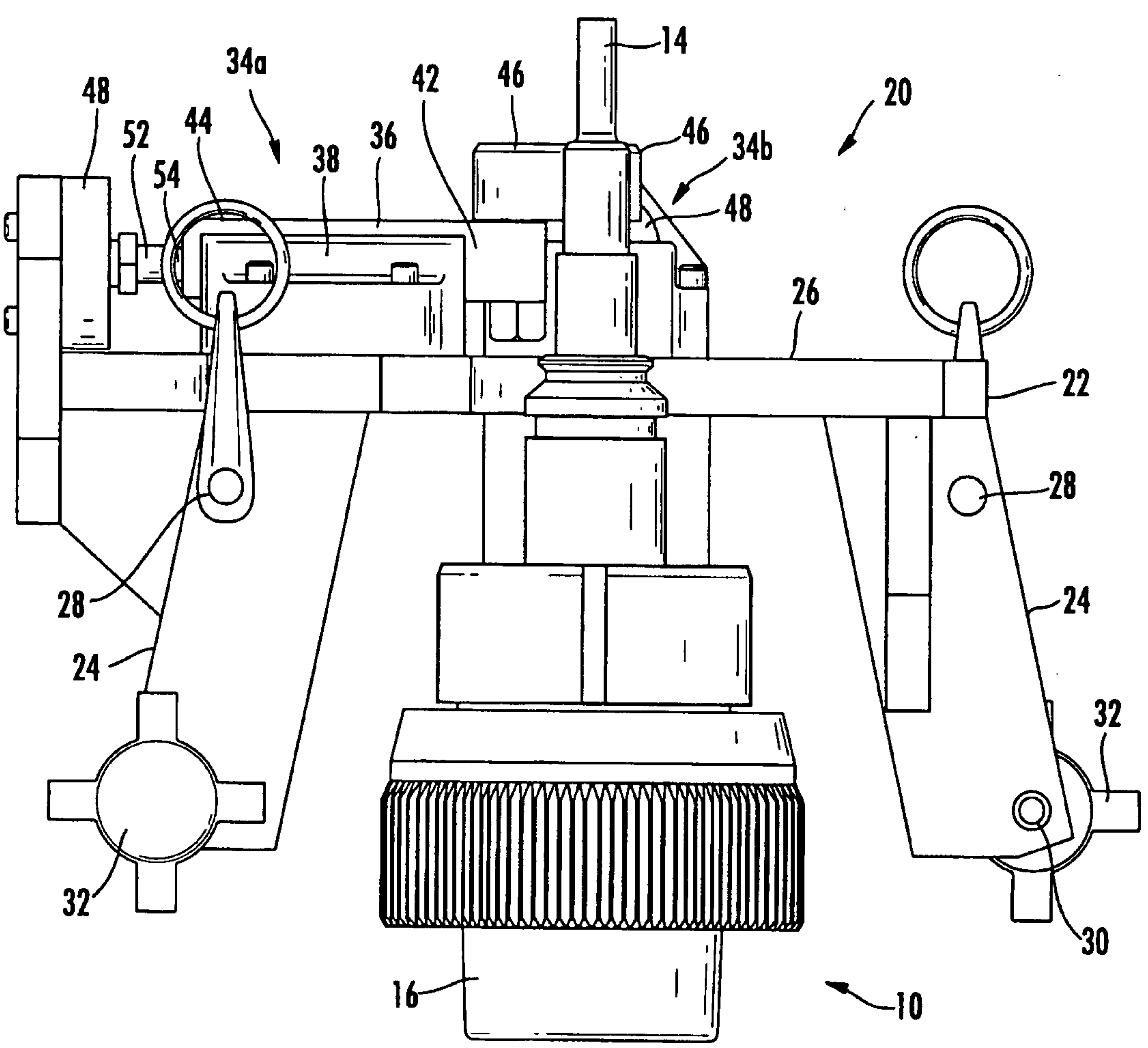
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FIG. 9

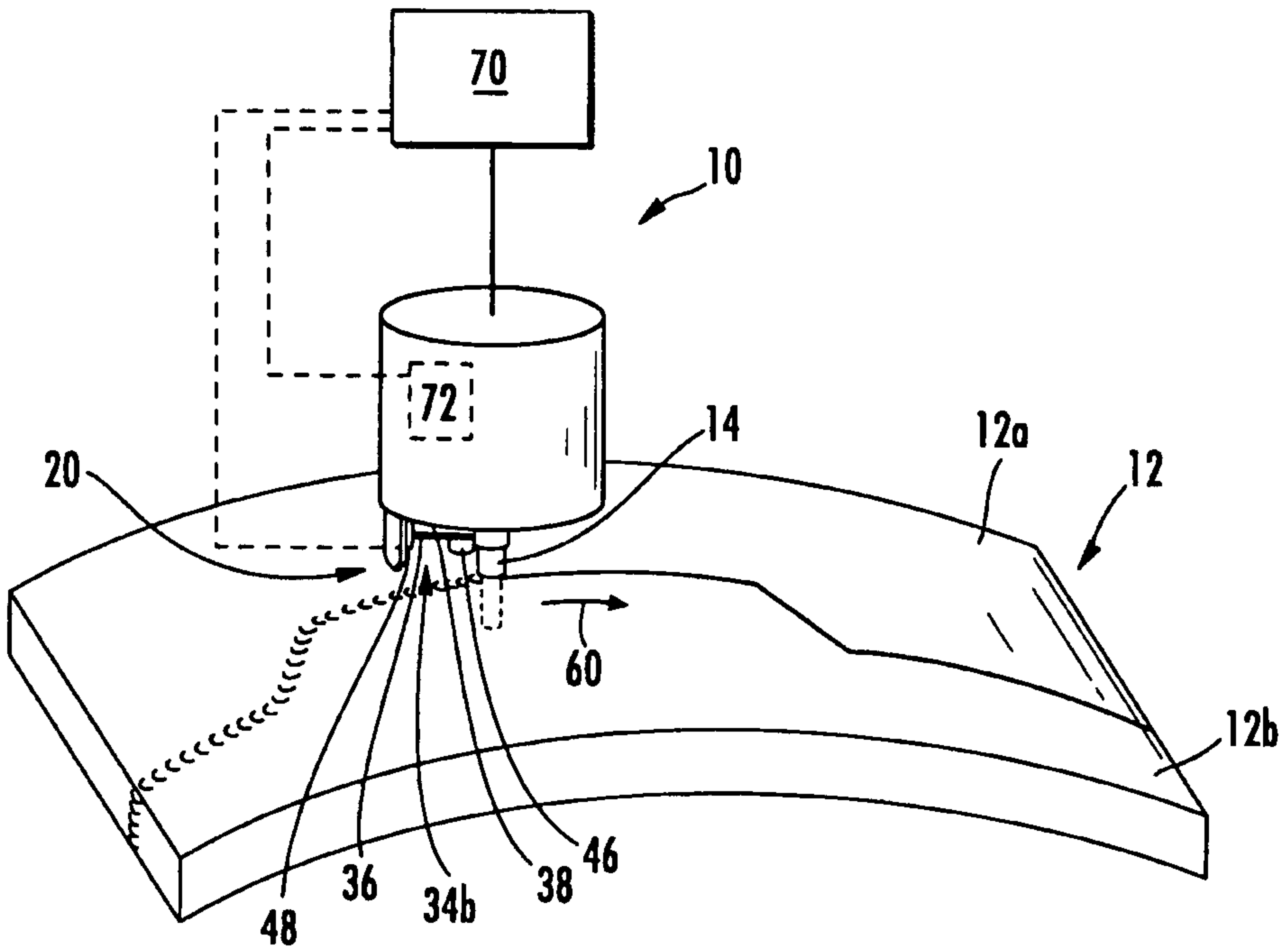



FIG. 10

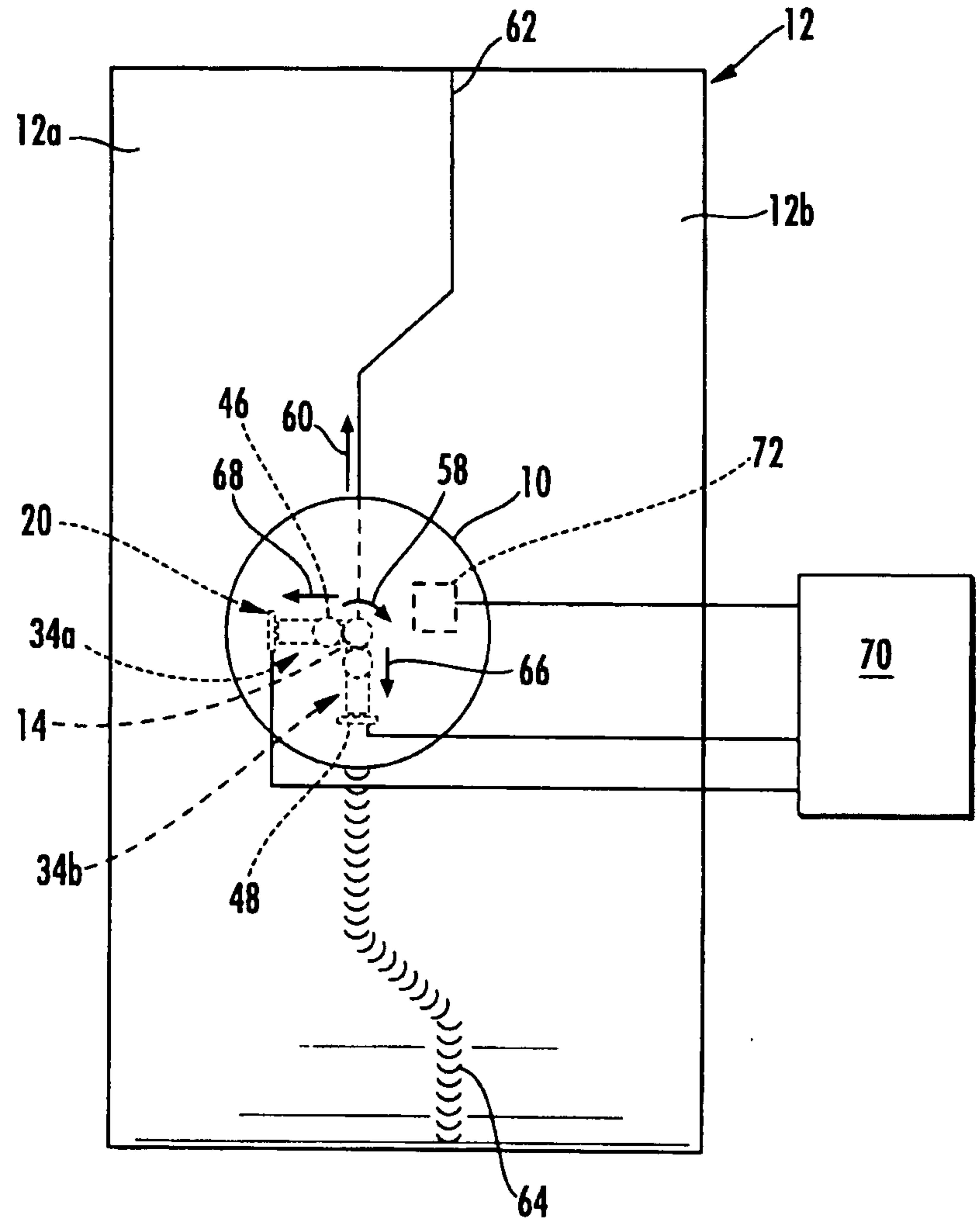
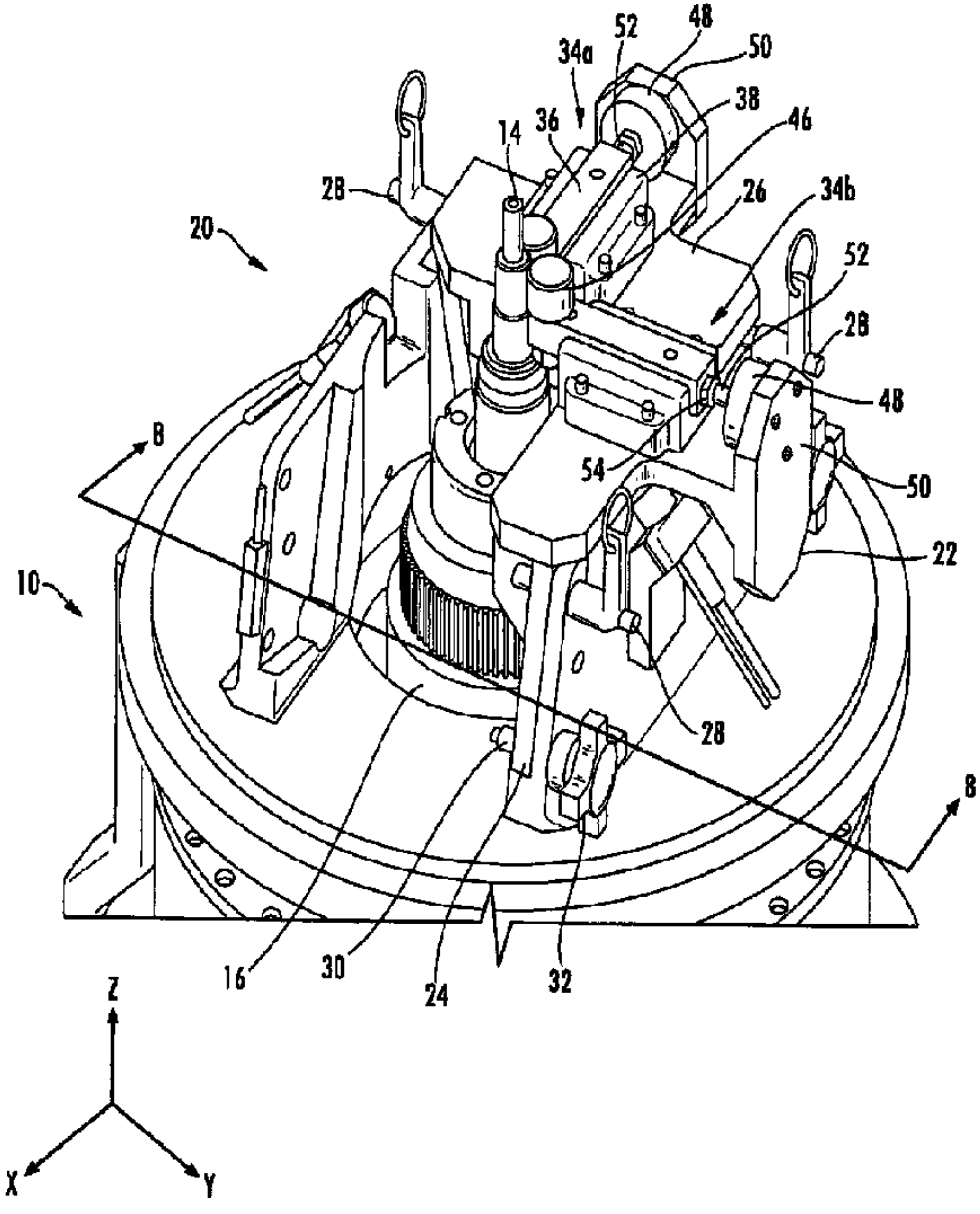



FIG. 11



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