

US00RE44150E

(19) **United States**  
(12) **Reissued Patent**  
**Cramer et al.**

(10) **Patent Number:** **US RE44,150 E**  
(45) **Date of Reissued Patent:** **\*Apr. 16, 2013**

(54) **SELF-COMPENSATING LASER TRACKER**  
  
(75) Inventors: **Peter G. Cramer**, Coatesville, PA (US);  
**James K. West**, Landenberg, PA (US);  
**Robert E. Bridges**, Kennett Square, PA (US)  
  
(73) Assignee: **Faro Technologies, Inc.**, Lake Mary, FL (US)  
  
(\*) Notice: This patent is subject to a terminal disclaimer.  
  
(21) Appl. No.: **13/222,233**  
  
(22) Filed: **Aug. 31, 2011**

**Related U.S. Patent Documents**

Reissue of:

(64) Patent No.: **7,583,375**  
Issued: **Sep. 1, 2009**  
Appl. No.: **12/335,219**  
Filed: **Dec. 15, 2008**

U.S. Applications:

(60) Continuation-in-part of application No. 11/969,566, filed on Jan. 4, 2008, now Pat. No. 7,466,401, which is a division of application No. 10/935,459, filed on Sep. 7, 2004, now Pat. No. 7,327, 446.  
  
(60) Provisional application No. 60/500,775, filed on Sep. 5, 2003.  
  
(51) **Int. Cl.**  
**G01B 11/26** (2006.01)  
  
(52) **U.S. Cl.**  
USPC ..... **356/154**  
  
(58) **Field of Classification Search** ..... 356/154  
See application file for complete search history.

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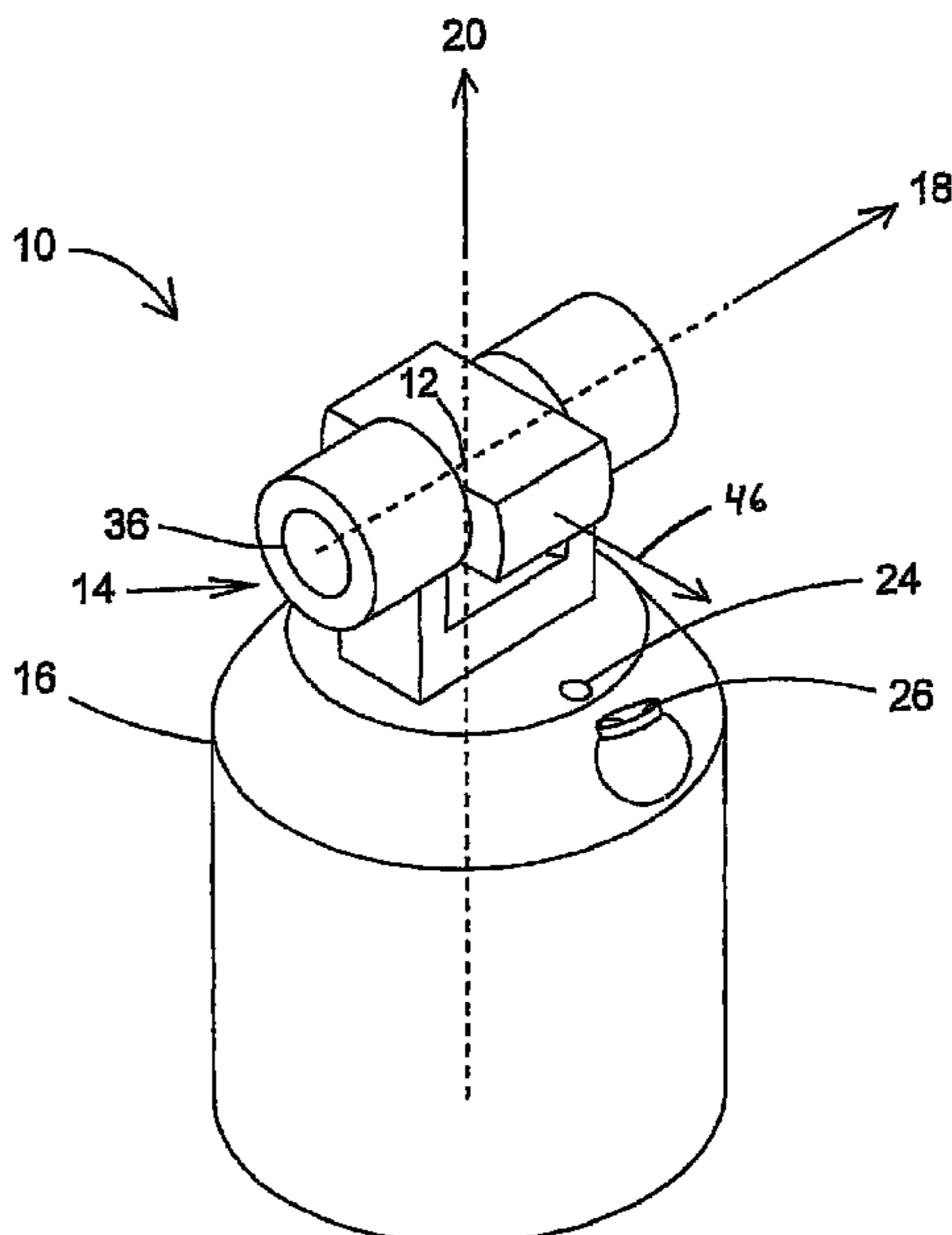
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*Primary Examiner* — Roy M Punnoose  
(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP

(57) **ABSTRACT**

A self-compensating laser tracker may include a frame assembly including a laser, and at least two-embedded, non-moveable, reflecting members; and a rotatable mirror. The laser and the mirror are arranged such that a laser beam emitted from the laser may be reflected by the mirror. One of the at least two reflecting members may be a cube corner retroreflector and a second of the at least two reflecting members may be a frame assembly mirror. The cube corner retroreflector and the frame assembly mirror may be fixed in position on the frame assembly relative to the rotatable payload and relative to each other, and are structured to reflect the laser beam in a front sight mode and a back sight mode.

**7 Claims, 5 Drawing Sheets**



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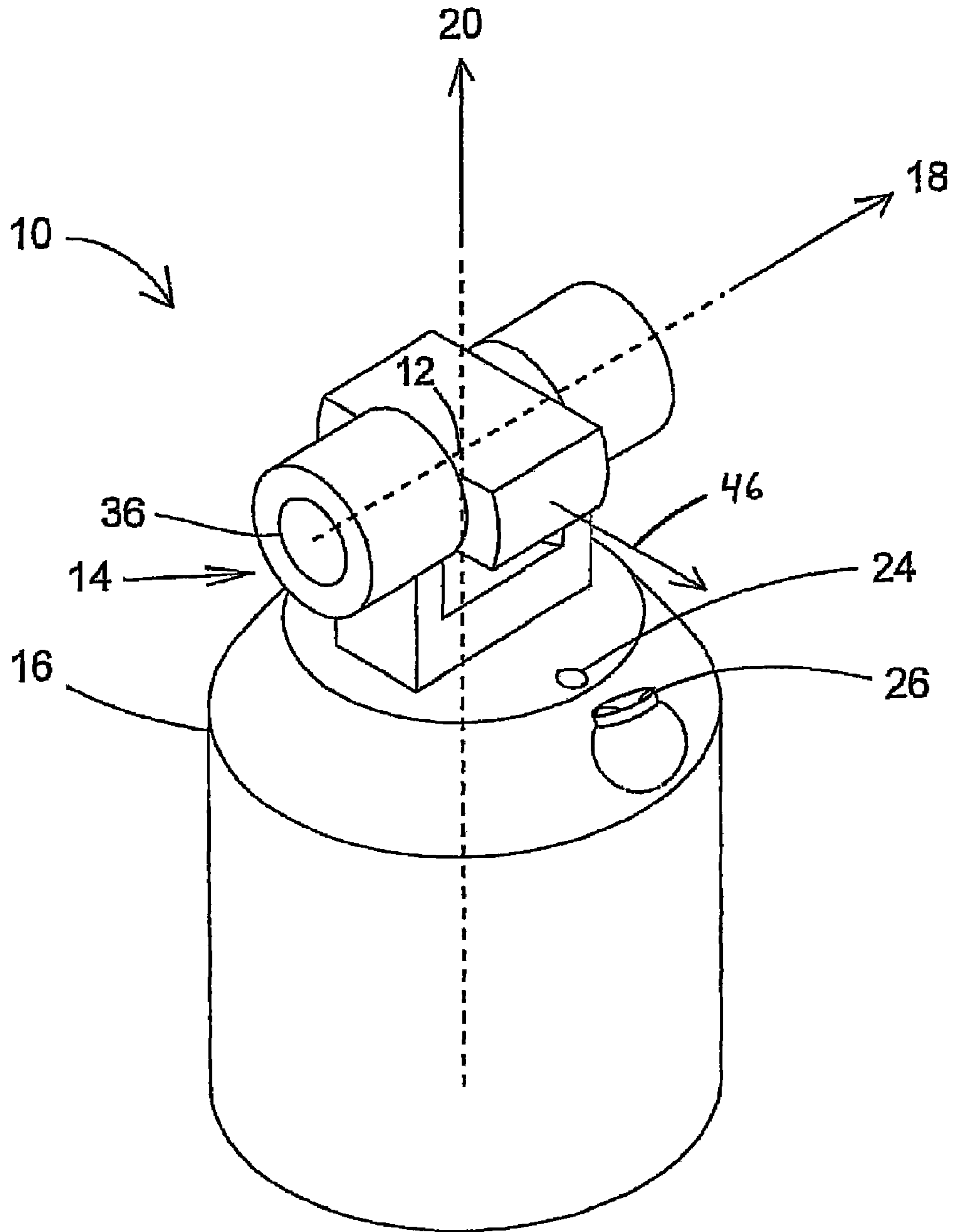


FIGURE 1

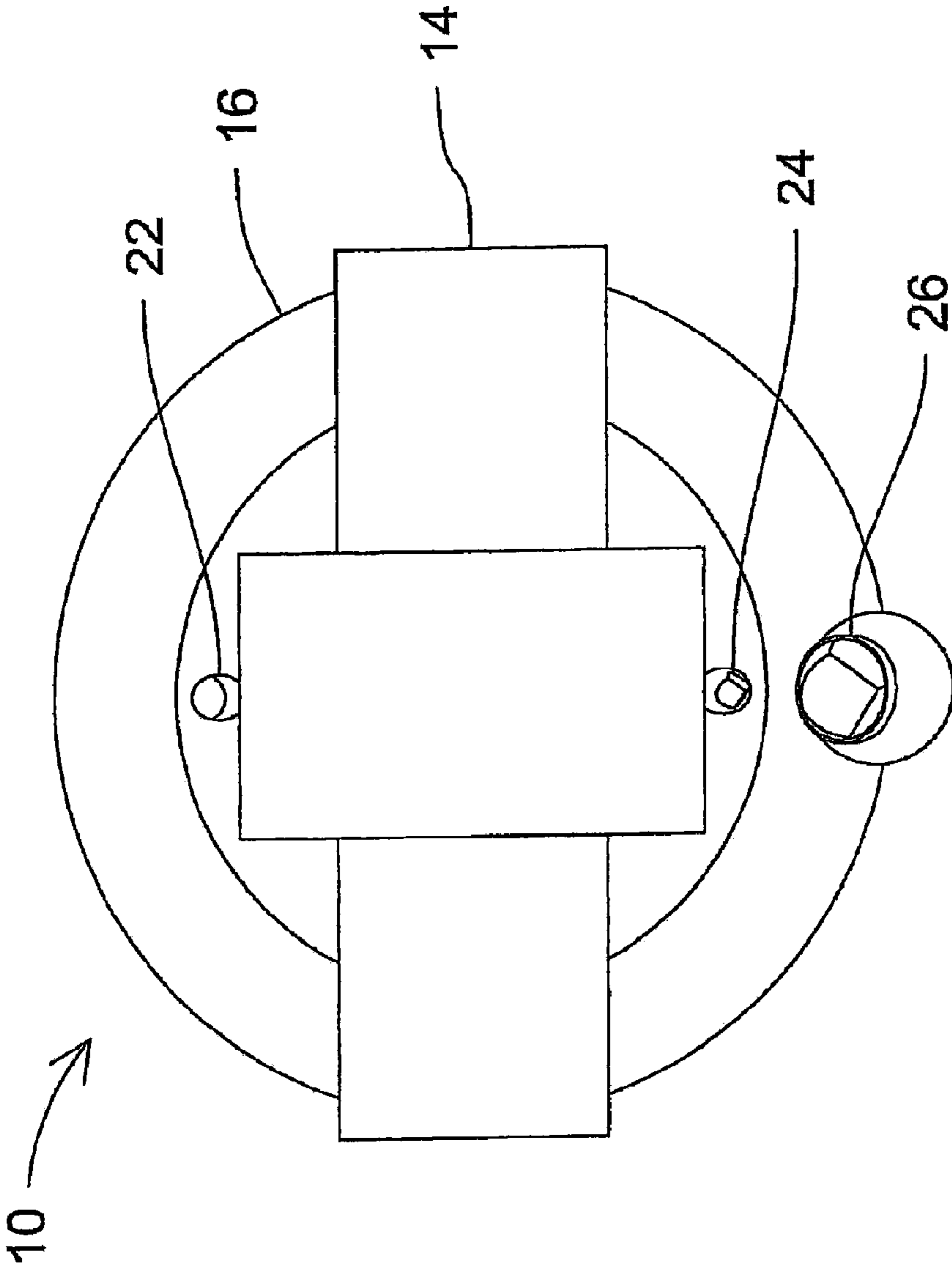


FIGURE 2

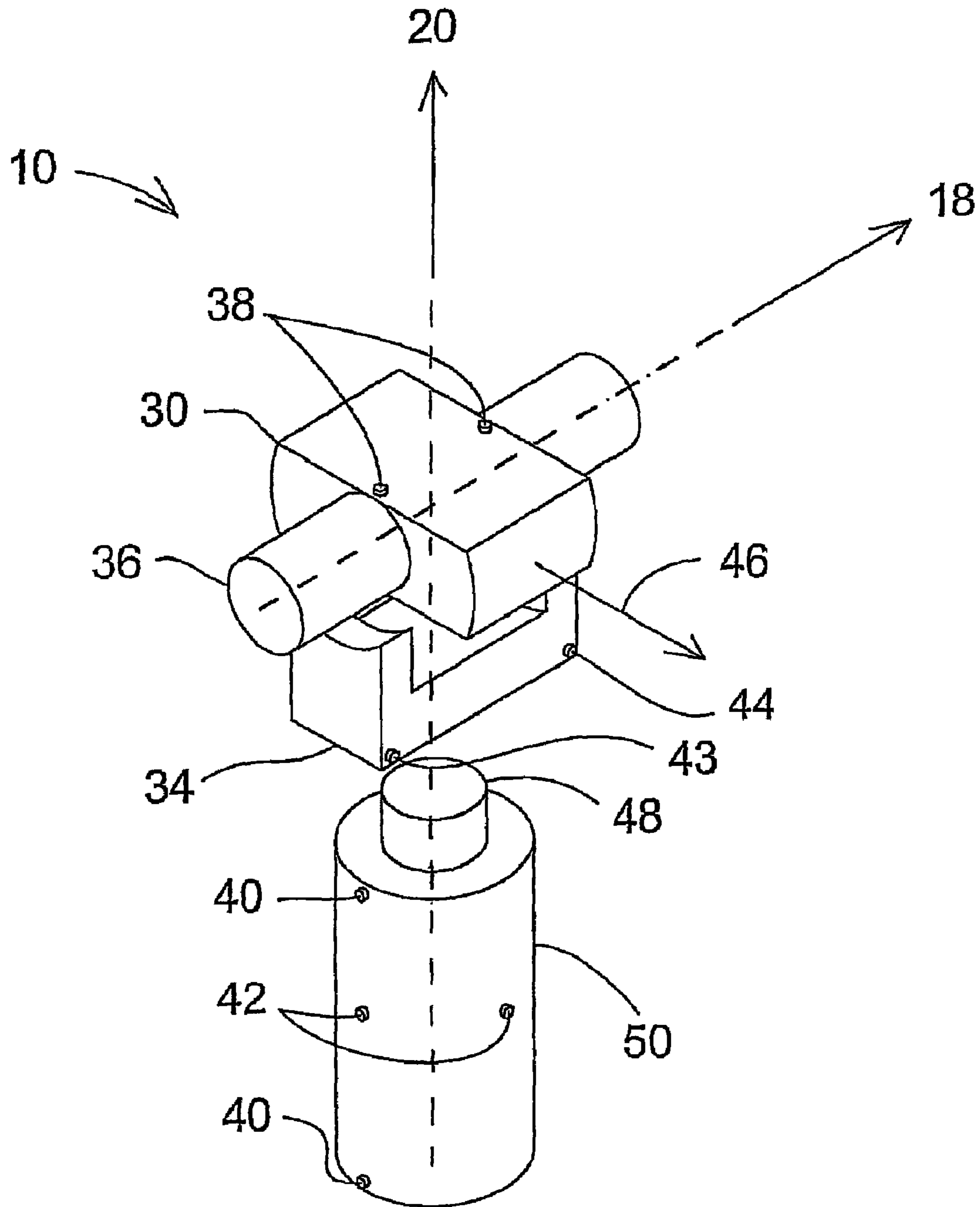


FIGURE 3

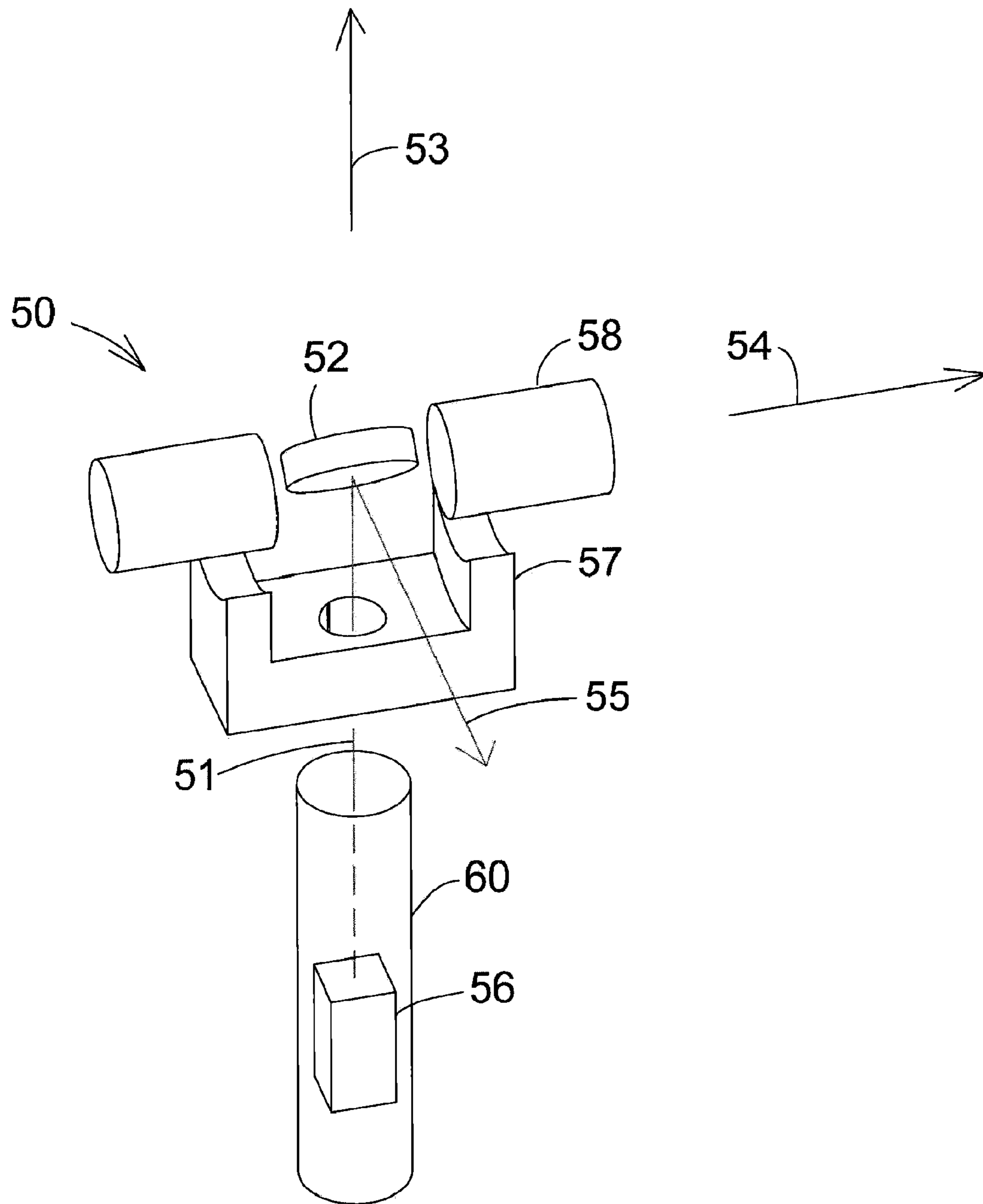


FIGURE 4

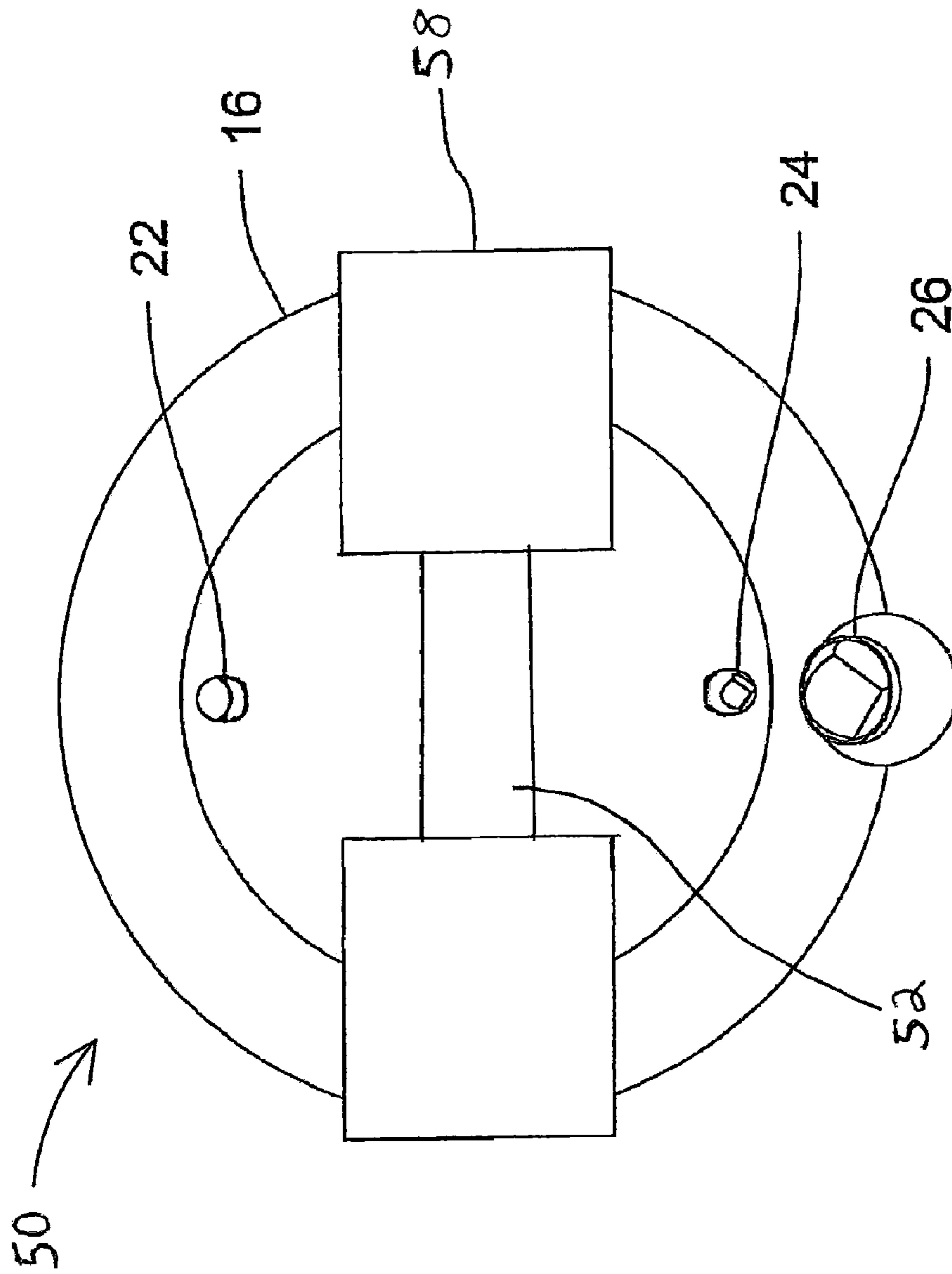


FIGURE 5

## SELF-COMPENSATING LASER TRACKER

**Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.**

## CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation in part (CIP) of U.S. application Ser. No. 11/969,566, filed Jan. 4, 2008, the contents of which are herein incorporated by reference and priority to which is hereby claimed. The Ser. No. 11/969,566 application is a divisional application of U.S. application Ser. No. 10/935,459, filed Sep. 7, 2004 which claimed the benefit of the date of earlier filed provisional application, U.S. Provisional Application No. 60/500,775, filed on Sep. 5, 2003, the contents of both of which are incorporated by reference herein, and priority to both which is hereby claimed.

## BACKGROUND

The present disclosure relates to a coordinate measuring device. One set of coordinate measurement devices belongs to a class of instruments that measure the coordinates of a point by sending a laser beam to the point. The laser beam may impinge directly on the point or may impinge on a retroreflector target that is in contact with the point. In either case, the instrument determines the coordinates of the point by measuring the distance and the two angles to the target. The distance is measured with a distance-measuring device such as an absolute distance meter or an interferometer. The angles are measured with an angle-measuring device such as an angular encoder. A gimbaled beam-steering mechanism within the instrument directs the laser beam to the point of interest. The laser beam may come from a source of laser light located within the gimbaled beam-steering mechanism. Alternatively, the laser beam may come from an external source of laser light and reflect off a mirror attached to the gimbaled beam-steering mechanism. Exemplary systems for determining coordinates of a point are described by U.S. Pat. No. 4,790,651 to Brown et al. and U.S. Pat. No. 4,714,339 to Lau et al.

The laser tracker is a particular type of coordinate-measuring device that tracks the retroreflector target with one or more laser beams it emits. A device that is closely related to the laser tracker is the laser scanner. The laser scanner steps one or more laser beams to points on a diffuse surface. The laser tracker and laser scanner are both coordinate-measuring devices. It is common practice today to use the term laser tracker to also refer to laser scanner devices having distance- and angle-measuring capability. This broad definition of laser tracker, which includes laser scanners, is used throughout this application.

Compensation parameters are numerical values that are stored in software or firmware accessible to the tracker. These numerical values are applied to raw tracker data to improve tracker accuracy. Initially, the manufacturer of the tracker finds the compensation parameters by performing measurements called compensation procedures. Later, the tracker will be used at the customer's site to make measurements. Periodically, the tracker will be checked for accuracy by performing interim tests. If the accuracy is substandard, the tracker operator will perform one or more compensation procedures on the factory floor. These can take from a few minutes to an

hour or more, depending on the particular tracker and on the tests that are required. In most cases, the main cause of reduced tracker accuracy is thermal drift, although mechanical shock can also be important. New methods for compensating coordinate measuring devices such as laser trackers are needed to improve accuracy and speed testing.

## SUMMARY

At least an embodiment of a self-compensating laser tracker may include a frame assembly including a laser, and at least two-embedded, non-moveable, reflecting members; and a rotatable mirror. The laser and the mirror are arranged such that a laser beam emitted from the laser may be reflected by the mirror. One of the at least two reflecting members may be a cube corner retroreflector and a second of the at least two reflecting members may be a frame assembly mirror. The cube corner retroreflector and the frame assembly mirror may be fixed in position on the frame assembly relative to the rotatable payload and relative to each other, and are structured to reflect the laser beam in a front sight mode and a back sight mode.

The above-discussed and other deficiencies of the art are overcome or alleviated by the present apparatus and method for compensating a coordinate measurement machine, which may be a laser-based coordinate measurement machine, laser tracker, or other coordinate measurement device. In one exemplary method, such compensation comprises self-compensation of payload parameters by means of embedded tracker targets.

In another exemplary embodiment, such compensation comprises self-compensation of payload, azimuth-post, axis non-squareness, or R0 parameters by means of embedded temperature sensors.

Both methods may be referred to as self-compensation because they are compensation procedures that are performed without human intervention and without the need for external targets. The exemplary methods provide a fast, worry free way to maintain high tracker accuracy, even when temperature changes are large within the tracker's environment.

The above-discussed and other features and advantages of the apparatus and method for a self-compensating laser tracker will be appreciated and understood by those skilled in the art from the following detailed description and drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will now be described, by way of example only, with reference to the accompanying drawings which are meant to be exemplary, not limiting, and wherein like elements are numbered alike in several Figures, in which:

FIG. 1 illustrates a perspective view of an exemplary gimbaled beam-steering mechanism incorporating self-compensating elements; and

FIG. 2 illustrates a top plan view of the exemplary gimbaled beam-steering mechanism of FIG. 1;

FIG. 3 illustrates a perspective view of temperature sensors placed on internal components of the exemplary gimbaled beam-steering mechanism of FIG. 1; and

FIG. 4 illustrates an exemplary gimbaled beam-steering mechanism based on reflection off a mirror.

FIG. 5 illustrates a top plan view of an exemplary gimbaled beam-steering mechanism based on reflection off a mirror.

## DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

Reference will now be made in detail to exemplary embodiments, examples of which are illustrated in the accompanying drawings.



An exemplary gimballed beam-steering mechanism **12** of a laser tracker **10** illustrated in FIG. **1** comprises a zenith carriage **14** that is mounted on an azimuth base **16**. The zenith and azimuth mechanical axes **36, 48** internal to the tracker, as shown in FIG. **3**, are turned to point the laser beam **46** in the desired direction. The zenith and azimuth mechanical axes **36, 48** are illustrated as extending at least partially along illustrated axes **18, 20**, respectively. For the sake of clarity and simplicity, this sort of gimbal mechanism **12** is assumed in the following discussion. However, other types of gimbal mechanisms are possible, and the techniques described here may also be applicable to these other types.

For example, as shown in FIG. **4**, gimballed beam steering mechanism **50** comprises frame assembly **60**, yoke assembly **57**, zenith assembly **58**, and mirror **52**. In at least one embodiment, the yoke assembly **57**, zenith assembly **58**, and mirror **52** can be referred to as a rotatable payload. Laser **56** located within frame assembly **60** emits laser beam **51** that travels through hole in yoke assembly **57** and is reflected off mirror **52** to become laser beam **55**. Zenith assembly **58** causes mirror **52** to rotate about zenith axis **54**. Yoke assembly **57**, which is attached to zenith assembly **58**, rotates about azimuth axis **53**. In this way, mirror **52** can be steered in azimuth and zenith angular directions.

Self-Compensation by Means of Embedded Tracker Targets

An exemplary self-compensation method provides a way to determine four payload parameters—TX, TY, RX, and RY—that describe the position and orientation of the laser beam with respect to the gimbal point of the tracker. The gimbal point is defined as the mechanical pivot point of the tracker. In an ideal tracker, the gimbal point is fixed in space, and the laser beam (or beams) passes through this point. In a real tracker, the laser beam does not pass exactly through the gimbal point but is offset slightly with respect to it. This offset, defined as the perpendicular distance from the gimbal point to the laser beam, is accounted for by the two parameters TX and TY. Here y is along the zenith axis and x is perpendicular to y and to the laser beam.

Also, in an ideal laser tracker, the laser beam is perpendicular to the zenith and azimuth mechanical axes **36, 48** when the zenith angle is set to 90 degrees. In a real laser tracker, the angular departure of the laser beam from this ideal condition is described by the RX and RY parameters. The direction of RX is along the fingers when the thumb of the right hand points in the x direction. The direction of RY is along the fingers when the thumb of the right hand points in the y direction.

In the current exemplary method, two embedded targets **22, 24** are placed on the azimuth base **16** of the laser tracker as shown in FIGS. **1** and **2**. One of these targets **24** is a retroreflector, which may be a cube-corner, a retrosphere, or any type of device that sends the return beam back on itself. The second target **22** is a mirror, which is positioned in such a way that it can also serve as a retroreflector when the laser light is sent to the proper location on the mirror.

To determine the four parameters, measurements on each of these two targets may be performed in front sight and back sight modes. Front sight mode may be defined as the ordinary mode of operation of the tracker. Back sight mode may be obtained by starting in front sight mode and then doing the following: (1) rotate the azimuth axis **20** by 180 degrees; (2) rotate the zenith axis **18** to have the negative of the original zenith angle; and (3) turn on tracking. The last step will cause the laser beam to move to the proper position on the cube-corner or mirror so that the retrace condition is established. In other words, the laser beam that passes back into the tracker follows, or retraces, the path of the outgoing laser beam. In an

ideal laser tracker, the angular measurement of the embedded targets in front sight and in back sight will be the same. In a real tracker, these angles will not be exactly the same, and the discrepancy can be used to calculate the four parameters.

For the technique described here to be applicable, two conditions must be met: (1) the mechanical structure must be stable and (2) the returning laser beam must accurately retrace the outgoing laser beam.

Referring to the first condition, the stability of the tracker structure is determined by the stability of two parameters: axis non-squareness (AXNS) and axis offset (AXOF). In an ideal tracker, the zenith mechanical axis is exactly perpendicular to the azimuth mechanical axis and the two mechanical axes are coplanar. In a real tracker, AXNS is the angular deviation from perpendicularity, and AXOF is the perpendicular distance between the two mechanical axes. For the mechanical structure to be stable, the AXNS and AXOF parameters must be stable, or at least predictable, over time.

Referring to the second condition, the accuracy of the returning laser beam will depend on the stability and proper compensation of the tracking system. Part of the returning laser light that enters the tracker splits off and strikes the position detector. The position detector gives an electrical signal that indicates where the centroid of the laser beam is located on the two-dimensional surface of the detector. If the returning laser beam exactly retraces the outgoing laser beam, it will strike a particular location, called the retrace location, on the position detector. The rest of the tracking system, which includes the angular encoders, the motors, the control electronics, and the control software, holds the laser beam near the retrace position when the tracker is in tracking mode. For the returning laser beam to accurately retrace the outgoing laser beam, the retrace location must be accurately known.

The RX and RY parameters are found by performing a back sight measurement on the embedded mirror **22**. If the zenith angle in front sight is  $ZE_{FS}$  and the zenith angle in back sight is  $ZE_{BS}$ , then the back sight angle will approximately equal the negative of the front sight measurement, and the sum of the two angles will be a small value,

$$\Delta ZE = ZE_{BS} + ZE_{FS} \quad (1)$$

The RY parameter is given by

$$RY = -\Delta ZE / 2 \quad (2)$$

If the azimuth angle in front sight is  $AZ_{FS}$  and the azimuth angle in back sight is  $AZ_{BS}$ , then the back sight angle will be bigger than the front sight angle by approximately pi radians. The change in the azimuth angle is a small number,

$$\Delta AZ = AZ_{BS} - \pi - AZ_{FS} \quad (3)$$

The RX parameter is given by

$$RX = \frac{1}{2} \sin(ZE) \cdot \Delta AZ - \cos(ZE) \cdot \sin(AXNS) \quad (4)$$

The TX and TY parameters are found by performing a back sight measurement on the embedded cube-corner. If d is the distance from the gimbal point to the embedded retroreflector, the TX and TY parameters can be found from

$$TX = \frac{1}{2} \Delta ZE \cdot d - AXOF \cdot \cos(ZE) - d \cdot RY \quad (5)$$

$$TY = d \cdot [\frac{1}{2} \Delta AZ / \sin(ZE) + RX + AXNS \cdot \cos(ZE)] \quad (6)$$

For the case shown in FIG. **4**, the center of the front surface of mirror **52** would, in the ideal case, be located at the gimbal point. In addition, emitted laser beam **51** would pass through the gimbal point, and reflected laser beam **55** would reflect perpendicular to the plane of azimuth axis **53** and zenith axis **54**. In at least one embodiment of a tracker, these conditions

are not met. The resulting errors can be reduced by making  
frontsight and backsight measurements using both a retro-  
reflector and a mirror to find compensation parameters. By  
putting the retroreflector and mirror on the body of the  
tracker, as shown in FIGS. 1-3, these compensation param-  
eters can be found automatically and quickly, without user  
intervention. In other words, it will be understood that the  
retroreflector and mirror structure shown in FIGS. 1-3, or  
other suitable arrangement, can also be used with the embodi-  
ment shown in FIG. 4. For example, FIG. 5 shows at least one  
embodiment of a tracker which includes mirror 52 and a  
frame assembly mirror 22 and retroreflector 24. This proce-  
dure helps ensure that the tracker performs well, even when  
exposed to temperature changes and mechanical shocks.

For the case of a gimbal mechanism that contains a mirror,  
as shown in FIG. 4, the kinematic model parameters that  
describe the characteristics of the system are somewhat more  
complicated than in the case in which the laser beam is  
launched directly from the payload. For example, in a non-  
ideal mirror-based tracker, the laser beam intersects the mir-  
ror at a position that varies with azimuth and zenith angle.  
Consequently, offset and angular deviation of the laser beam  
vary correspondingly.

Frontsight and backsight data collected from measure-  
ments of fixed retroreflector and fixed mirror are processed to  
optimize the parameters within the kinematic model. This is  
done by first writing a set of equations, ordinarily referred to  
as kinematic model equations, that describe the behavior of  
the specific device in question—in this case, the mirror-based  
tracker. The compensation parameters are explicitly included  
in the kinematic model equations. If the current values for the  
compensation parameters are incorrect, frontsight and back-  
sight data give inconsistent results, resulting in residual  
errors. The sum of squared errors is minimized using math-  
ematical optimization methods. Methods of optimization are  
well known in the field of metrology and are not discussed  
further here.

#### Self-Compensation by Means of Embedded Temperature Sensors

Most of the changes in tracker parameters result from the  
thermal expansion or contraction of components within the  
tracker. In an exemplary embodiment, temperature sensors  
embedded at multiple locations within the laser-tracker struc-  
ture monitor the temperature changes. The collected tempera-  
ture data enable the compensation parameters to be adjusted  
in real time. Temperature related adjustments are made to the  
following parameters: (1) payload, (2) azimuth-post, (3) axis  
non-squareness, and (4) R0.

#### Compensation of Payload Parameters by Means of Tempera- ture Sensors

With reference to FIG. 3, the payload 30 is the physical  
structure within the tracker that is rotated by the zenith  
mechanical axis 36. In one exemplary embodiment, one or  
more temperature sensors 38 embedded within the payload  
provide information on the temperature of components  
within the payload. These components include optical com-  
ponents such as beam splitters and lenses and mechanical  
components on which the optical components are mounted.

Expansions or contractions of the elements within the pay-  
load can cause a slight shifting in the four offset and angle  
parameters, RX, RY, TX, and TY. In a carefully constructed  
tracker, the slight changes in these parameters are propor-  
tional to the change in the payload temperature.

Initially the four angle parameters may be determined in  
either of two ways: by a pointing compensation or by a  
self-compensation with the embedded mirror and embedded  
cube-corner. The self-compensation method with the embed-

ded mirror and cube-corner was discussed above. The point-  
ing compensation is a measurement procedure that is carried  
out at the factory and that can also be carried out at the  
customer site, if desired. In this procedure, a spherically  
mounted retroreflector (SMR) 26 is measured in frontsight  
and backsight at a small number of locations. The spherically  
mounted retroreflector is a metal sphere into which a cube-  
corner retroreflector is mounted with the apex of the cube-  
corner at the center of the sphere. At the time of the compen-  
sation, the values of the parameters are recorded as  $RX_0$ ,  $RY_0$ ,  
 $TX_0$ , and  $TY_0$  along with the initial temperature of the pay-  
load as  $T_{PAYLOAD\_0}$ . The temperature of the payload is mea-  
sured with temperature sensors 38. Later, as the temperature  
of the payload changes to  $T_{PAYLOAD}$ , the change in payload  
temperature is defined as

$$\Delta T_{PAYLOAD} = T_{PAYLOAD} - T_{PAYLOAD\_0} \quad (7)$$

The values of the four parameters as corrected in real time  
are

$$RX = RX_0 + k_{RX} \cdot \Delta T_{PAYLOAD} \quad (8)$$

$$RY = RY_0 + k_{RY} \cdot \Delta T_{PAYLOAD} \quad (9)$$

$$TX = TX_0 + k_{TX} \cdot \Delta T_{PAYLOAD} \quad (10)$$

$$TY = TY_0 + k_{TY} \cdot \Delta T_{PAYLOAD} \quad (11)$$

The proportionality constants  $k_{RX}$ ,  $k_{RY}$ ,  $k_{TX}$ , and  $k_{TY}$  may  
be determined by placing a representative tracker within an  
enclosure and then varying the temperature while simulta-  
neously measuring the embedded mirror and cube-corner  
targets in frontsight and backsight modes to monitor the val-  
ues in RX, RY, TX, and TY. The proportionality constants are  
found by taking the change in parameter value divided by the  
change in temperature.

#### Compensation of Azimuth-Post Parameters by Means of Temperature Sensors

As illustrated by the exemplary tracker of FIG. 3, the  
tracker rotates in the azimuth direction about azimuth  
mechanical axis 48. This mechanical axis rotates on bearings  
that are mounted on the azimuth post 50. The exemplary  
tracker is mounted at the bottom of azimuth post 50. In one  
embodiment, the tracker is mounted in an upright position, so  
an expansion of the azimuth post causes the gimbal point to  
increase in height.

Temperature sensors 40, 42 attached to azimuth post 50  
monitor the temperature of the post. At the start of a measure-  
ment session, the temperature of the azimuth post is  $T_{AZ\_POST\_0}$ .  
As the measurement proceeds, the change in tempera-  
ture from the initial value is

$$\Delta T_{AZ\_POST} = T_{AZ\_POST} - T_{AZ\_POST\_0} \quad (12)$$

In response to the change in temperature, the height of the  
gimbal point will change by

$$\Delta Z_{GIMBAL} = k_{AZ\_POST} \cdot \Delta T_{AZ\_POST} \quad (13)$$

In the exemplary tracker, electronics along the side of the  
tracker may heat the azimuth post unevenly. In this case,  
temperature gradients within the azimuth post may cause the  
post to bend. This bending will have two effects. First, it will  
cause the gimbal point to move by  $\Delta X_{GIMBAL}$  and  $\Delta Y_{GIMBAL}$   
in the plane perpendicular to azimuth axis. Note that the  
directions X and Y do not generally correspond to the direc-  
tions x and y discussed previously. Second, the temperature  
gradients will cause the end of the azimuth post to change  
direction. The yoke 34 that supports the zenith mechanical  
axis is mounted on the end of the azimuth post, so the bending  
of the azimuth post will cause a change in the direction of the

laser beam leaving the tracker. The changes in the angular directions of the end of the azimuth post are referred to as  $\Delta\text{Ang}X_{AZ\_POST}$  and  $\Delta\text{Ang}Y_{AZ\_POST}$ . Here  $\Delta\text{Ang}X_{AZ\_POST}$  and  $\Delta\text{Ang}Y_{AZ\_POST}$  are the angular directions given by the curl of the fingers when the thumb of the right hand is pointed in the X or Y direction, respectively. The parameters associated with the bending of the azimuth post are associated with the change in temperature on the opposite sides of the azimuth post. These temperature differences can be measured by four temperature sensors **42** located every 90 degrees around the azimuth post **50**. If the representative temperature differences between the two sides of the azimuth post as measured by sensors **42** in the X and Y directions are  $\Delta T_{AZ\_POST\_X}$  and  $\Delta T_{AZ\_POST\_Y}$ , then the changes caused by post bending are given by

$$\Delta Y_{GIMBAL} = k_{AZ\_POST\_X\_GIMBAL} \cdot \Delta T_{AZ\_POST\_X} \quad (14)$$

$$\Delta Y_{GIMBAL} = k_{AZ\_POST\_Y\_GIMBAL} \cdot \Delta T_{AZ\_POST\_Y} \quad (15)$$

$$\Delta\text{Ang}X_{AZ\_POST} = k_{AZ\_POST\_X\_ANGLE} \cdot \Delta T_{AZ\_POST\_Y} \quad (16)$$

$$\Delta\text{Ang}Y_{AZ\_POST} = k_{AZ\_POST\_Y\_ANGLE} \cdot \Delta T_{AZ\_POST\_X} \quad (17)$$

Note that these four quantities are in the frame of reference of the overall tracker structure, which is fixed relative to the laboratory. By contrast, the quantities TX, TY, RX, and RY are in the payload frame of reference, which rotates in the azimuth and zenith directions and is not fixed relative to the laboratory. These different compensation effects are combined by first performing a mathematical transformation from one frame of reference to the other.

The constants of proportionality in the equations (14)-(17) are found by varying the temperature of the ambient environment while the tracker makes repeated measurements of four SMR targets. All four SMRs are located in approximately the same horizontal plane. Two of the SMRs are relatively close to the tracker and have an angular separation, as measured from the tracker, of approximately 90 degrees. The other two SMRs are farther from the tracker and have the same angular separation. As the gimbal points move, the indicated position of the four targets will change. The nearer targets will be affected relatively more by the change in the direction of the end of the azimuth post and relatively less by the movement in the gimbal  $\Delta X$  and  $\Delta Y$  than the targets farther from the tracker. This difference in sensitivity allows the four constants of proportionality to be extracted from the equations.

Compensation of the Axis Non-Squareness Parameter by Means of Temperature Sensors

Previously it was explained that in an ideal tracker the zenith mechanical axis is exactly perpendicular to the azimuth mechanical axis. In a real tracker, the angular deviation from perpendicularity is called the axis non-squareness. In calculations of target position, the effect of axis non-squareness is removed by the axis non-squareness (AXNS) parameter. In a carefully constructed laser tracker, the axis non-squareness will be stable and relatively unaffected by ambient air temperature. However, a relatively large motor may be needed to obtain fast zenith movements. This motor is mounted on the zenith mechanical axis and may generate considerable heat if rapid movements are performed for an extended period. This heat may cause a thermal expansion near one end of the azimuth axis. This can result in a movement of the zenith mechanical axis, with the result that the AXNS parameter is changed. To account for the change in the AXNS parameter in real time, temperature sensors **43**, **44** monitor the temperature of the yoke **34**, which is the structure that supports the zenith axis. The difference in the tempera-

tures of sensor **43** and **44** at a given time is called  $\Delta T_{ZE\_AXIS}$  and the corresponding change in the AXNS parameter is

$$\Delta\text{AXNS} = k_{AXNS} \cdot \Delta T_{ZE\_AXIS} \quad (18)$$

To find the constant of proportionality  $k_{AXNS}$  in this equation, the temperature difference  $\Delta T_{ZE\_AXIS}$  is monitored while the change in the AXNS parameter is also measured. If the payload parameters RX, RY, TX, and TY are accurately known, then the AXNS parameter can be easily determined by simply measuring SMRs or spherically mounted mirrors at three different zenith angles from the tracker in front sight and back sight modes. For example, the SMRs may be placed in magnetic nests that are glued to the floor at distances of 2, 4, and 6 meters from the tracker. As discussed previously, the payload parameters can be accurately determined by means of the on-tracker mirror and cube-corner, so the three-target approach is a good one. An even more-accurate approach to determining the AXNS parameter is to construct a fixture to hold SMRs equidistant from the tracker in a semicircular pattern within a vertical plane. The targets would then be measured in front sight and back sight modes. The advantage of this approach is that it enables calculation of the AXNS parameter independently of RX, RY, TX, and TY. However, because the AXNS parameter can be accurately determined without this special fixture, the approach that uses three floor targets is usually preferable.

A parameter that is closely related to the AXNS parameter is the AXOF parameter. As discussed previously, in an ideal tracker the azimuth and zenith mechanical axes are coplanar. In a real tracker, the AXOF is the perpendicular distance between the two mechanical axes. It is possible to compensate AXOF to account in real time for temperature changes. However, in a carefully constructed tracker, the AXOF parameter is small, perhaps 10 micrometers, and the change in the parameter is relatively insensitive to the change in temperature. For this reason, it is usually not necessary to compensate for the AXOF parameter in real time.

Compensation of the R0 Parameter by Means of Temperature Sensors

The parameter R0 is defined as the distance from the gimbal point to the home position of the tracker. The home position is located at the center of SMR **26** when the SMR is placed on the magnetic nest rigidly affixed to the tracker structure. FIGS. **1** and **2** show the SMR mounted in this magnetic nest at the home position. In the exemplary tracker, the magnetic nest is located near the lower portion of the tracker so that the angular range of the tracker is not obstructed. The value of the R0 parameter is determined at the factory, or at the customer site, by a compensation procedure. In this procedure, two magnetic nests are glued to instrument stands, and the instrument stands are adjusted so that the centers of SMRs placed within these nests are at the same height as that of the gimbal point of the tracker. First, the tracker is placed directly in line with, but outside of, the two instrument stands. The tracker measures the distance to an SMR placed in the first nest and also to an SMR placed in the second nest. The difference in distance between these two SMR locations is the true distance between the two SMRs. Next the tracker is moved in line with, but between, the two instrument stands. Again the tracker measures the distance to an SMR placed in each of the two nests. In an ideal tracker the sum of the distances as measured with the tracker between instrument stands is exactly equal to the distance measured with the tracker outside of the two instrument stands. The discrepancy between these two values is used to correct the R0 value.

At the time that the R0 compensation procedure is performed, the initial R0 value,  $R0_0$ , and the initial temperature representative of the path between the gimbal and home points,  $T_{R0_0}$ , are recorded from at least one temperature sensor. The temperature sensor may be located in the vicinity of the home position, gimbal point, or at any other location where the recorded temperature change correlates well with the change in R0. To correct R0 in real time, the initial temperature is subtracted from the current temperature  $T_{R0}$  to get the temperature difference:

$$\Delta T_{R0} = T_{R0} - T_{R0_0} \quad (19)$$

The change in the R0 parameter is given by

$$\Delta R0 = k_{R0} \cdot \Delta T_{R0} \quad (20)$$

The constant of proportionality  $k_{R0}$  is found at the factory by placing an SMR in the home position and using the interferometer or the absolute distance meter within the tracker to monitor the change in the distance to the SMR as a function of the temperature  $T_{R0}$ .

While reference is made to exemplary placement of temperature sensors, it should be noted that any placement within or on the tracker effective to provide indications of temperature change relevant to the parameter to be measured are contemplated herein.

It will be understood by those skilled in the art that the invention is not limited to a laser, but can be practiced by any source of electromagnetic radiation producing a beam.

While the description above refers to particular embodiments of the present invention, it will be understood that many modifications may be made without departing from the spirit thereof. The accompanying claims are intended to cover such modifications as would fall within the true scope and spirit of the present invention. The presently disclosed embodiments are therefore to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims, rather than the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. A self-compensating laser tracker comprising:

a frame assembly comprising:

a laser; and

at least two-embedded, non-moveable, reflecting members; and

a rotatable mirror;

wherein the laser and the mirror are arranged such that a laser beam emitted from the laser is reflected by the mirror;

one of the at least two reflecting members is a cube corner retroreflector and a second of the at least two reflecting members is a frame assembly mirror; and

wherein the cube corner retroreflector and the frame assembly mirror are fixed in position *relative to each other* on a *stationary portion* of the frame assembly [relative to the rotatable payload and relative to each other], and are structured to reflect the laser beam in a *frontsight mode* and a *backsight mode*.

2. A self-compensating laser tracker in accordance with claim 1, wherein the frame assembly comprises a gimbaled mechanism.

3. A self-compensating laser tracker in accordance with claim 2, wherein the gimbaled mechanism produces motion in [the] azimuth and zenith directions.

4. A self-compensating laser tracker comprising:  
a frame assembly comprising:

a laser; and

at least two-embedded, non-moveable, reflecting members; and

a rotatable structure comprising at least one mirror;

wherein the laser and the mirror are arranged such that a laser beam emitted from the laser is reflected by the mirror;

one of the at least two reflecting members is a cube corner retroreflector and a second of the at least two reflecting members is a frame assembly mirror; and

wherein the cube corner retroreflector and the frame assembly mirror are fixed in position *relative to each other* on a *stationary portion* of the frame assembly [relative to the rotatable payload and relative to each other], and are structured to reflect the laser beam in a *frontsight mode* and a *backsight mode*.

5. A self-compensating laser tracker that emits a laser beam, comprising:

a rotatable payload from which the laser beam is emitted; at least two embedded, non-moveable, reflecting members provided on a support for the payload;

wherein one of said at least two reflecting members is a cube corner retroreflector and a second of said at least two reflecting members is a mirror and wherein the cube corner retroreflector and the mirror are fixed in position on the support relative to each other and are structured to reflect the laser beam in a *frontsight mode* and a *backsight mode* when the payload is rotated accordingly in order to determine and then self-compensate for deviations in desired payload parameters where the payload parameters describe position and orientation of the laser beam.

6. A self-compensating laser tracker in accordance with claim 5, wherein said support comprises a gimbaled mechanism.

7. A self-compensating laser tracker in accordance with claim 6, wherein said gimbaled mechanism produces motion in azimuth and zenith directions.

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