Title of the Invention: Apparatus and method for calibration of a three axis vector field sensor

Abstract Title: Apparatus and methods for three axis vector field sensor calibration

Provided are apparatus and methods for the calibration of a three axis vector field sensor that provides options for simpler and less expensive calibration of offset and gain for all three axes X, Y, Z. Sensor readings are taken from a number of orientations of the sensor obtained by rotating the sensor around a single axis 100 perpendicular to the calibration field g. By appropriately orienting the sensor relative to the calibration field, so that each axis forms a non-zero angle relative to the axis of rotation, and adopting a set of selected orientations in which successive orientations are obtained by rotating the sensor through 1.0472 radians around the axis of rotation 100, the effect of measurement noise on each measurement axis can be made to be approximately equal, and the effect can be maximized.

The sensor readings taken during the calibration process are used to compute a gain and offset value for each axis of the three-axis vector field sensor.

The three axis vector field sensor may be used in a mounting plate onto which a torsion balance (240, figure 3), capable of measuring partial pressure of oxygen, may be mounted. Also, the sensor may be used on a hard disc drive (300,310, figure 4) to sense shock such as dropping of the hard disc drive.
FIG. 6

orient a three axis vector field sensor in an apparatus at a starting position such that each axis of said sensor forms a non-zero angle relative to an axis of rotation perpendicular to the calibration field (501)

rotate the sensor around the axis of rotation to a predefined position (502)

collect and store data from said vector field sensor in said position (503)

Sufficient Readings?

Yes

determine the offset and gain of each axis of the sensor from the data collected (504)

No
FIG. 7

500 Start of procedure

510 Orient the test system such that the X-axis of the vector field sensor is subjected to 0.8165 of the calibration field and the Y- and Z- axes are subjected to -0.4082 of the calibration field.

Store the output of the X, Y, and Z sensor axes as X₀, Y₀, and Z₀ respectively.

Set count = 1.

520 Rotate the test system through 1.0472 rad. Store the output of the X, Y, and Z axes as X_count, Y_count, and Z_count respectively. Increment count.

530 Determine the offset and gain for each axis as X_offset, Y_offset, Z_offset, X_gain, Y_gain, and Z_gain.

540 Store the values of X_offset, Y_offset, Z_offset, X_gain, Y_gain, and Z_gain in non-volatile memory.

550 End of procedure
APPARATUS AND METHOD FOR CALIBRATION OF A THREE-AXIS VECTOR FIELD SENSOR

FIELD OF INVENTION

The present invention relates to a calibration apparatus, and a method and controller for controlling a calibration apparatus. The invention provides apparatus and methods for calibrating a vector field sensor, such as a magnetic field sensor or an accelerometer.

BACKGROUND

Accelerometers are known to measure acceleration or orientation for a number of applications. The outputs may be a voltage, a current, a pulse width modulated pulse sequence, a numerical value, or an electric charge. Other output types also exist.

It is known in the art that a vector field sensor produces a measurement, \( M \), that is characterised by an offset, \( D \), and gain, \( G \), such that the measured field component, \( F \), is proportional to the output of the sensor axis after subtraction of \( D \), and where the constant of proportionality is \( G \). That is:

\[
F = G \times (M - D)
\]

A calibration method and apparatus is known in the art that comprises a mechanism for recording the output from a vector field sensor at two different orientations such that \( D \) and \( G \) may be determined.

EP0999449 describes a calibration solution that determines \( D \) and \( G \) in an electronic accelerometer, including a method of calibration in an accelerometer system using two single axis accelerometers. One of the accelerometers is fixed and one is movable between first and second positions such that its measurement axis is oriented parallel to
the earth's gravitational field. Measurements are obtained in a first position when the axes of both accelerometers are aligned, and in a second position when the axis of the movable accelerometer is aligned in an opposite orientation (180° away) from the axis of the fixed accelerometer. These measurements are used to calibrate the accelerometer system.

In US7350394, an approximate calibration is achieved by placing a system containing a three axis micro-electro-mechanical system (MEMS) accelerometer in an orientation such that two axes are perpendicular to the earth's gravitational field and the third axis is parallel to the earth's gravitational field. In this system, it is assumed that the characteristics of all three axes are similar and the offset and sensitivity is determined from the output of either of the axes perpendicular to the earth's gravitational field. However, where the three axes have dissimilar characteristics, the calibration determined using this technique will be inaccurate.

In JP9251031, the gain of a 3-axis accelerometer is calibrated by placing the accelerometer on an incline such that the output from each axis is exposed to an identical gravitational field strength, and then determining gain for each axis by multiplying the reading by a coefficient that depends on the mounting angle of the device. This technique does not allow for the determination of offset.

In US2009138224, a single axis accelerometer is placed in three different known orientations relative to a horizontal plane and the accelerometer readings from these positions are analysed in order to determine offset and gain values for the accelerometer. US 2009138224 fails to disclose an efficient mechanism for calibration of multiple axes.

The inventors of the present invention have determined that there remains a need for an improved solution for calibration of multiple axes of a vector field sensor.
SUMMARY OF INVENTION

In a first aspect, the invention provides an apparatus for calibrating a three axis vector field sensor in a static uniform calibration field, comprising:

- means for holding a three axis vector field sensor at a starting position such that each axis of said sensor forms a non-zero angle relative to an axis of rotation that is perpendicular to the direction of the calibration field;
- means for rotating the sensor around the axis of rotation;
- means for collecting and storing data from a plurality of different orientations obtained by rotating the sensor around the axis of rotation; and,
- means for determining the offset and gain of each axis of the sensor from the data collected.

In one embodiment, the means for rotating the sensor is controlled to rotate the sensor to a plurality of predetermined angular positions corresponding to a plurality of different orientations of each axis, by rotating around a single axis perpendicular to the calibration field. The rotation of the sensor is halted at these positions and data is collected by the means for collecting and storing data at each position.

The inventors of the present invention have implemented a method that enables calibration of offset and gain for a three-axis vector field sensor by orienting the sensor in only six distinct orientations, and achieving those orientations by rotating a suitably-oriented sensor around a single axis of rotation perpendicular to the calibration field. Such a solution is mechanically simpler than an alternative that requires rotation about multiple axes, and requires fewer fixed positions and fewer readings (reducing calibration time and data storage requirements) than alternatives. As noted above, known solutions for calibration of an accelerometer typically fail to effectively calibrate all three axes of the accelerometer for gain and offset.
Multiple three-axis vector field sensors may be simultaneously held, rotated and calibrated using an apparatus according to one embodiment of the invention, and data to determine the offset and gain for each such sensor is obtained using that apparatus.

In another embodiment, measurements are taken during rotation of the sensor, without halting at fixed positions. For example, sensor outputs can be monitored at a set of predefined positions or monitored continuously during a controlled rotation of the sensor or sensors, and used to calibrate offset and gain.

The three-axis vector field sensor may be an accelerometer, a magnetic field sensor, an electric field sensor or another transducer. Apparatus according to the invention may include means for holding and rotating one or many sensors of the same type, or holding and rotating a larger assembly that includes one or more sensors. The offset and gain can be determined for each such sensor.

The three axis vector field sensor gain and offset may be affected by environmental influences, including but not limited to temperature, pressure, electric or magnetic field strength. The three axis vector field sensor may be contained within a mechanism that also includes sensors able to measure such environmental factors. Apparatus implementing the invention may include a means for controlled variation of the environmental effects measured by the other sensors, and means for recording the data output by the other sensors. The captured environmental sensor data can then be used to calibrate the environmental sensors, and the results can be correlated with the data collected by the three axis vector field sensor, to numerically eliminate the effects of the environmental factors.

In one embodiment of the invention, the mechanism that contains the three-axis vector field sensor includes a temperature sensor as well as a three-axis accelerometer. Temperature is varied during the test using electrical heating and refrigeration, or other means, and the gain and offset of the accelerometer is determined at at least two different temperatures. A linear temperature compensation is determined for gain and offset of
each axis of the accelerometer. In such an embodiment of the invention, the equipment varies one or more sensor calibration parameters including, but not limited to, temperature, pressure, gas concentration, magnetic field strength, electric field strength, and flow rate.

In a further aspect, the invention provides a method for determining offset and gain for a three-axis vector field sensor in a static uniform calibration field, comprising the steps of:

(a) positioning a three axis vector field sensor at a starting position such that each axis of said sensor forms a non-zero angle relative to an axis of rotation perpendicular to the direction of the calibration field;

(b) rotating the sensor around the axis of rotation;

(c) collecting and storing data output by the sensor in a plurality of different orientations obtained by rotating the sensor around the axis of rotation; and

(d) determining the offset and gain of each axis of the sensor from the data collected in step (c).

In one application of the invention, a three-axis accelerometer in a paramagnetic oxygen sensor system can be calibrated. This measurement system uses a torsion balance which employs the paramagnetic property of oxygen. The torsion balance experiences a torque in the presence of a paramagnetic gas, such as oxygen or nitrogen dioxide, and may also experience a torque due to interaction of the earth’s gravitational field and mechanical imperfections in the torsion balance. By accurately measuring the earth’s gravitational field with an accelerometer, techniques exist to computationally compensate for the torque created by the interaction of the earth’s gravitational field and mechanical imperfections in the torsion balance. Because the characteristics of the accelerometer may be affected by normal assembly techniques, including soldering and mechanical assembly of compound structures, it is beneficial to calibrate the accelerometer after it has been assembled in the oxygen measurement transducer. This embodiment benefits from the single axis of rotation by using a single motor to rotate one or more paramagnetic oxygen sensors. Computational and storage elements incorporated in the
measurement system for oxygen partial pressure determination are programmed to implement the calibration algorithms and to store the resulting calibration coefficients.

In a second application of the invention, a hard disk drive (HDD) incorporates an accelerometer that is used for free-fall detection, and the accelerometer requires calibration of offset and gain. This is carried out using the apparatus of the present invention. The hard disk drive incorporates rotating magnetic media and a readout device mounted on a cantilever moved by a motor. When the hard disk drive is subjected to shock while the readout device is located over the media, damage can occur to both. Damage is avoided by pre-emptively locating the readout device in a safe position in which it is unable to cause damage to, or be damaged by, the rotating media. Shock is most commonly caused when portable equipment incorporating the hard disk drive is dropped, and which then subsequently experiences an impact with a solid horizontal surface. At the instant the equipment is dropped, assuming it is subject to no forces other than gravity, the gravitational field measured by the accelerometer incorporated in the equipment is zero, and remains at zero until the moment of impact with the horizontal surface. By measuring the gravitational field strength, the accelerometer determines that the equipment has been dropped, and a mechanism moves the readout device to the safe position. The accelerometer must be accurately calibrated, otherwise it may not detect when the equipment has been dropped, or may incorrectly determine that it has, resulting in temporary loss of functionality of the hard disk drive. This embodiment benefits from the single axis of rotation by using a single motor to rotate multiple hard disk drives, each of which incorporates electronic systems capable of implementing the calibration computations and data storage. Because the characteristics of the accelerometer may be affected by normal assembly techniques, including soldering and mechanical assembly of compound structures, it is beneficial to calibrate the accelerometer after it has been assembled in the hard disk drive.
BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the invention are described below in more detail, by way of example, with reference to the accompanying drawings in which:

Figure 1 depicts a three-axis vector field sensor as a rectangular prism oriented at a known angle $\phi$ relative to the calibration field;

Figure 2 is a schematic representation of an apparatus including the three-axis vector field sensor connected to measurement circuits.

Figure 3 is a schematic representation of a paramagnetic oxygen sensor incorporating a three-axis accelerometer;

Figure 4 is a schematic representation of a hard disk drive incorporating a three-axis accelerometer;

Figure 5 is a schematic representation of a system for rotating a plurality of suitably-oriented three-axis vector sensors after being installed within a larger assembly such as a paramagnetic oxygen sensor, according to an embodiment of the present invention;

Figure 6 is a flow chart describing a sequence of operations for calibrating a three-axis vector field sensor, according to an embodiment of the present invention; and

Figure 7 is a flow chart describing the sequence of operations as given in Figure 6, when the sensor is initially oriented at an angle of $0.9553$ radians relative to the axis of rotation that is perpendicular to a calibration field, and is rotated through $6.2832$ radians, stopping at a predefined set of positions to take readings.
DETAILED DESCRIPTION OF EMBODIMENTS

Three-axis vector field sensors comprise three orthogonal measurement axes, each axis producing a measurement \( M \) that is characterised by an offset, \( D \), and gain or sensitivity, \( G \). Figure 1 depicts a three axis vector field sensor, represented as a rectangular prism, with the three orthogonal measurement axes labelled \( X \), \( Y \), and \( Z \). (Of course, sensors having different external shapes can also be used.) In the reference orientation shown, the lower plane face of the sensor forms a non-zero acute angle, \( \varphi \), with the direction of the calibration field, designated \( g \), the calibration field being a static uniform calibration field. For this sensor, measurement axes \( X \) and \( Y \) lie parallel to the plane of the lower planar surface and, in the reference orientation shown, both \( X \) and \( Y \) axes experience an equal field strength. The \( Z \) axis lies at a different angle to the calibration field. The sensor is mounted on a spindle for rotating the sensor about an axis 100, using a controlled single motor. The mechanism for holding the sensor to enable rotation is not required to be a spindle and other mechanisms are equally possible, including a rotating drum in which one or many sensors can be placed, or in which a larger assembly including a sensor can be placed. More generally, the invention provides a means for holding the sensor in an orientation such that each axis forms a non-zero angle relative to the axis of rotation provided by the apparatus; and a control mechanism is provided for controlled rotation of the sensor within the calibration field about the axis of rotation.

In the present embodiment axis 100 is perpendicular to the calibration field \( g \), and a starting position involves holding the sensor in an orientation such that a first axis of the sensor is oriented at an angle \( \varphi \) of 0.9553 radian to the axis of rotation. This first axis is the \( Z \) axis in Figure 1. Angles are not represented accurately in Figure 1, which is merely schematic. This initial orientation enables the first axis to experience 0.8165 times the field strength of the calibration field. Meanwhile, the \( X \) and \( Y \) axes experience 0.4082 times the field strength. The apparatus can rotate the sensor from this initial position such that all three axes experience \( \pm 0.8165 \) times the field strength at predefined positions in the course of a 6.283 radian rotation.
A range of other starting orientations may be employed. However, in the preferred embodiment of the invention, a small number of predefined orientations are used and in each of those orientations, one axis experiences $\pm 0.8165$ times the field strength while the other axes experience $\pm 0.4082$ times the field strength. Thus, readings can be taken at a small number of predefined positions obtained by rotating the sensor about a single axis, and a simple set of equations can be applied to determine offset and gain for each axis. If limiting to the same small number of readings but not using the preferred starting orientation or not using equally spaced orientations, the variation in readings from each axis's output will be reduced for two of the axes over the course of the calibration process. For those two axes, the magnitude of any error caused by fixed measurement noise will be larger. Using an angle of orientation of 0.9553 radian between a sensor axis and the axis of rotation that is perpendicular to the calibration field as a starting orientation of the sensor and rotating the sensor through a series of orientations separated by 1.0472 radians maximizes the proportion of the field strength which exerts an influence on each of the axes, causing each sensor axis to experience $\pm 0.8165$ times the field strength at a respective position despite rotating about only a single axis of rotation.

The three-axis vector field sensor that is calibrated according to this invention can be of any type that can measure a time-invariant field. Each of the three orthogonal measurement axes produces an independent measurement that is recorded by the apparatus. Examples of the type of output that are suitable include; but are not limited to: numerical value from a digital output; voltage; current. The steps followed to calibrate the offset and gain values for each axis of the sensor 210 according to one embodiment of the invention are depicted in Figure 6.

In an embodiment of the invention, the three axis vector field sensor being calibrated is mounted in a rotation apparatus, by any known means for mounting (see Figure 6 step 501), at a starting orientation in which a first axis has a specific angle relative to the calibration field. In this embodiment, the sensor is mounted on a spindle arranged with its longitudinal axis perpendicular to the calibration field (see Figure 6 step 502). A motor rotates the spindle through a plurality of positions in order to effect the characterisation
process, as described below. A stepper motor is used in the present embodiment, for effective stop-start control with repeatable positioning, but simpler motors can be used in other embodiments.

Figure 2 shows a simplified electrical schematic of a system designed to employ an electronic three axis vector field sensor, 210. The output from the sensor takes the form of three voltage outputs. These are connected to an analogue to digital converter, 260, which is under the control of microcontroller 280 that incorporates non-volatile memory (see Figure 6 step 503). Microcontroller 280 is programmed with algorithms that calculate and store, and subsequently use, calibration coefficients relating to sensor 210 (see Figure 6 step 504). Results from the calibration process or subsequent measurements can be communicated to other equipment using media interface 230.

The apparatus records the values reported from each axis in the first orientation. X, Y, and Z axis values from the first orientation are recorded, and designated here as \( X_0 \), \( Y_0 \), and \( Z_0 \).

The apparatus then rotates the sensor around the axis denoted 100 in Figure 1 (by turning the spindle), stopping at a plurality of positions during its rotation to iteratively capture sets of unique measurements for each axis at each position, and to record sensor output values.

A set of sensor output values is captured and recorded for predetermined positions having an angular spacing between adjacent positions of 1.0472 radian. This produces six distinct sets of readings that can be solved for offset and gain for each axis of the sensor. The sensor outputs may also be taken for more than six positions by configuring the rotation means to stop and capture data at more than six positions during rotation, but one advantage of the present embodiment is that the six selected predetermined positions provide sufficient unique sets of data to enable calibration via a simple set of equations. Thus, the single-axis rotation mechanism and data processing operations are simple, and a relatively small amount of data needs to be captured, stored and processed.
A specific method for capturing sensor outputs at a plurality of positions is described below. The method is set out below using the optimum starting angle of one sensor axis at 0.9553 radian to the axis of rotation which is perpendicular to the calibration field, with readings taken at six different orientations. This process is depicted in Figure 7 of the attached drawings. However, as mentioned above, different starting angles and more than six positions may also used.

The steps taken to capture the unique sensor outputs in the apparatus of the present invention are as follows:

1. The sensor to be tested is mounted in an apparatus with a first axis at an angle of 0.9553 radians to the axis of rotation. The sensor mount is rotatable by a rotating means (e.g. including a motor-driven spindle) about an axis perpendicular to the calibration field. For example, the sensor may initially be oriented such that the X-axis is subjected to 0.8165 of the calibration field strength and the Y- and Z- axes are subjected to -0.4082 of the calibration field strength.

2. The output of the X, Y, and Z sensor axes in this initial position are recorded as $X_0$, $Y_0$, and $Z_0$ respectively (see Figure 7, step 510).

3. An iterative counter is configured so that count = 1

4. The sensor is then rotated through 1.0472 radians and stopped in a second position. In this position, the Y-axis of the sensor experiences -0.8165 of the calibration field strength. Unique measurements are obtained from the sensor axes at this position. The output of the X, Y, and Z axes are recorded as $X_{\text{count}}$, $Y_{\text{count}}$, and $Z_{\text{count}}$ respectively (see Figure 7, step 520)

5. Increment the counter by 1 so that count = count + 1.
6. If the value of count is less than 6 then steps 4 and 5 are repeated, and in each position one of the three sensor axes experiences 0.8165 or -0.8165 times the calibration field strength. If count=6 continue to the next step.

7. The offset for each axis is determined using the formulae (see fig 7 step 530):

$$X_{offset} = \frac{1}{6} \times \sum_{count=0}^{5} X_{count}$$
$$Y_{offset} = \frac{1}{6} \times \sum_{count=0}^{5} Y_{count}$$
$$Z_{offset} = \frac{1}{6} \times \sum_{count=0}^{5} Z_{count}$$

10. The gain for each axis is determined using the formulae:

$$X_{gain} = \frac{2 \times 0.8165}{X_0 - X_3}$$
$$Y_{gain} = \frac{2 \times 0.8165}{Y_4 - Y_1}$$
$$Z_{gain} = \frac{2 \times 0.8165}{Z_2 - Z_5}$$

15. The values for $X_{offset}$, $Y_{offset}$, $Z_{offset}$, $X_{gain}$, $Y_{gain}$, and $Z_{gain}$ are stored (see Figure 7 step 540).

20. Alternatively, once the values for X, Y and Z axes are obtained after step 6, the offset and gain for each axis may be determined in step 7 by solving the following set of simultaneous equations:

$$((X_{gain}(X_0-X_{offset}))^2+(Y_{gain}(Y_0-Y_{offset}))^2+(Z_{gain}(Z_0-Z_{offset}))^2)^{0.5}=g \quad \text{equation 1}$$
$$((X_{gain}(X_1-X_{offset}))^2+(Y_{gain}(Y_1-Y_{offset}))^2+(Z_{gain}(Z_1-Z_{offset}))^2)^{0.5}=g \quad \text{equation 2}$$
\[(X_{\text{gain}}(X_2-\text{Xoffset}))^2+(Y_{\text{gain}}(Y_2-\text{Yoffset}))^2+(Z_{\text{gain}}(Z_2-\text{Zoffset}))^2)^{0.5}=g\]  

\[(X_{\text{gain}}(X_3-\text{Xoffset}))^2+(Y_{\text{gain}}(Y_3-\text{Yoffset}))^2+(Z_{\text{gain}}(Z_3-\text{Zoffset}))^2)^{0.5}=g\]  

\[(X_{\text{gain}}(X_4-\text{Xoffset}))^2+(Y_{\text{gain}}(Y_4-\text{Yoffset}))^2+(Z_{\text{gain}}(Z_4-\text{Zoffset}))^2)^{0.5}=g\]  

\[(X_{\text{gain}}(X_5-\text{Xoffset}))^2+(Y_{\text{gain}}(Y_5-\text{Yoffset}))^2+(Z_{\text{gain}}(Z_5-\text{Zoffset}))^2)^{0.5}=g\]  

The above six equations are solved to find the offset and gain values, enabling calibration of subsequent measurements.

In an embodiment of the invention, a solution is determined using the Newton-Raphson method for non-linear systems of equations. Other numerical solution techniques can also be employed, but the availability of analytic partial derivatives of equations 1 to 6 to give the Jacobian matrix makes the Newton-Raphson technique simple to apply.

Therefore, by orienting the sensor in the apparatus of the present invention as described in the above method, every possible position that can be adopted during the calibration process provides a unique set of information, limited only by the measurement resolution. Thus, the set of simultaneous equations developed will be soluble.

In an application of the invention, depicted in Figure 3, a three axis electronic accelerometer 210 is soldered onto a printed circuit board 220 that is rigidly connected to a mounting plate 200 onto which a torsion balance, 240, capable of measuring partial pressure of oxygen, is mounted.

The torsion balance experiences a torque in the presence of a paramagnetic gas, such as oxygen or nitrogen dioxide, and may also experience a torque due to interaction of the earth’s gravitational field and mechanical imperfections in the torsion balance. By accurately measuring the earth’s gravitational field, techniques exist to computationally
compensate for the torque created by the interaction of the earth's gravitational field and mechanical imperfections in the torsion balance. Because the characteristics of the accelerometer may be affected by normal assembly techniques, including soldering and mechanical assembly of compound structures, it is beneficial to calibrate the accelerometer after it has been assembled in the oxygen measurement transducer.

This embodiment benefits from the simple mechanism for rotating about a single axis of rotation, using a single motor to rotate one or more paramagnetic oxygen sensors. Furthermore, computational and storage elements are incorporated in the oxygen sensor apparatus so that calibration coefficients calculated according to the invention are stored.

During soldering and assembly to produce the apparatus of Figure 3, stresses induced in accelerometer 210 may cause parametric changes. It can therefore be beneficial to calibrate the accelerometer in situ after assembly of the paramagnetic sensor apparatus.

The complete paramagnetic sensor has mass and volume considerably greater than the mass and volume of the accelerometer 210, so a system capable of rotating it around a single axis for calibration purposes is especially beneficial. A system for rotating a larger assembly about multiple axes, such as a robot arm or a system comprising two motors, would be larger and more complex, and would require more power to operate, than the embodiment of the invention described here.

By correctly orienting the complete paramagnetic sensor as described in this invention, a simple, low power mechanism calibrates the accelerometer while fitted in the paramagnetic sensor. Media access connector 230 provides a means by which the complete sensor can be controlled in order to initiate calibration operations and to report measurements once the calibration process is complete.

In another application of the invention, depicted in Figure 4, a three axis electronic accelerometer 210 is soldered onto a printed circuit board 310 that forms part of a hard disk drive. The hard disk drive incorporates rotating magnetic media and a readout device mounted on a cantilever moved by a motor. When the hard disk drive is subjected to
shock while the readout device is located over the media, damage can occur to both. Damage is avoided by pre-emptively locating the readout device in a safe position in which it is unable to cause damage to, or be damaged by, the rotating media. Shock is most commonly caused when portable equipment incorporating the hard disk drive is dropped, and which then subsequently experiences an impact with a solid horizontal surface. At the instant the equipment is dropped, assuming it is subject to no forces other than gravity, the gravitational field measured by the accelerometer incorporated in the equipment is zero, and remains at zero until the moment of impact with the horizontal surface. By measuring the gravitational field strength, the accelerometer determines that the equipment has been dropped, and a mechanism moves the readout device to the safe position. The accelerometer must be accurately calibrated, otherwise it may not detect when the equipment has been dropped, or may incorrectly determine that it has, resulting in temporary loss of functionality of the hard disk drive. This embodiment benefits from the single axis of rotation by using a single motor to rotate multiple hard disk drives, each of which incorporates electronic systems capable of implementing the calibration computations and data storage. Because the characteristics of the accelerometer may be affected by normal assembly techniques, including soldering and mechanical assembly of compound structures, it is beneficial to calibrate the accelerometer after it has been assembled in the hard disk drive.

In Figure 4, readout mechanism 350 is mounted on a motor 360 that moves the readout mechanism across the surface of a disk 300 coated with magnetic material. The readout mechanism normally sits above the coated disk while the unit is operating. When the readout mechanism is located above the disk, damage may be caused when the unit is subjected to shock. To prevent damage, and while the unit is not in use, the readout mechanism can be moved so that it locates at safe position 320. Shock is commonly caused as a result of the hard disk drive being dropped. After the hard disk drive has been dropped, accelerometer 210 will detect no acceleration from the moment the hard disk drive is dropped until it hits a solid surface with a horizontal component. Whenever accelerometer 210 detects that acceleration is zero, the readout mechanism 350 can be moved to the safe area 320.
To ensure that zero acceleration is correctly detected, accelerometer 210 must be calibrated. When accelerometer 210 has poor accuracy, a zero acceleration may not be detected, with the result that the readout mechanism is not located to the safe position 320 when the hard disk drive is dropped. Alternatively, a wide margin of safety may be placed on the detection threshold, with the result that the readout mechanism is located in safe area 320 when it need not be, preventing data access from the hard disk drive.

By correctly orienting the complete hard disk drive as described in this invention, a simple, low power mechanism calibrates the accelerometer while fitted in the hard disk drive. Media access connector 340 provides a means by which the complete sensor can be controlled in order to initiate calibration operations and to access stored data once the calibration process is complete.

In an embodiment of the invention depicted in Figure 5, a plurality of paramagnetic oxygen sensors, each containing an accelerometer, are mounted in a drum 470 that sits on motor driven rollers, 450. Each oxygen sensor 400 has a gas exchange port 410 on an exposed face of the oxygen sensor. Palettes, 420, hold sensors in a planar array. Each palette 420 provides electrical connections to the sensors mounted on it, and the electrical signals from all the sensors are marshalled at the edge of the palette. Each palette mounts in a connection fixture 430 on backplane 440. Connection fixture 430 correctly orients the palette so that the accelerometer in each oxygen sensor is optimally oriented for calibration. Backplane 440 marshals the connections from the palettes and feeds them to a slip ring 460. The electrical signals are connected via slip ring 460 and cable 490 to a controller 480.

Each sensor station on palette 420 is fitted with a retention mechanism that allows oxygen sensors 400 to be installed and removed quickly. Further, the connection mechanism 430 on backplane 440 allows each palette to be installed and removed quickly.
When all oxygen sensors 400 are fitted in drum 470, this embodiment of the invention begins a calibration cycle under the direction of controller 480. In an embodiment of the invention controller 480 rotates rollers 450 such that drum 470 adopts six distinct positions, the first of which orients the accelerometer in each sensor 400 such that the accelerometer axes are located according to the requirements of 510 in Figure 6. Rollers 450 are then rotated, data is collected, and calculations are performed such that the algorithm shown in Figure 6 is completed. After completion, calibration coefficients relating to the accelerometer mounted in each sensor 400 are stored to non-volatile memory within the sensor. Subsequently, when employed as paramagnetic oxygen sensors, the data from the accelerometers is used with the calibration coefficients to provide accurate acceleration or gravitational field readings.

In Figure 5, connecting medium 490 carries both electrical signals and gases, interface 460 provides a means by which electrical signals and gases can be transferred into and out of drum 470, controller 480 generates and stores electrical signals and heats, cools, mixes and pressurises gases, and drum 470 can be sealed after sensors 400 have been located within it. In this aspect of the invention, sensors measuring acceleration, temperature, and pressure are also calibrated during the operating cycle, which is extended to incorporate additional steps. Further, the primary oxygen reading is also calibrated in the course of the process.

In the embodiment described above, the axis of rotation is arranged perpendicular to the calibration field and the chosen starting position for readings to be taken involves orienting the vector field sensor such that an axis of the sensor is at 0.9553 radians to the axis of rotation, and the sensor is rotated between six selected positions that are each separate by 1.0472 radians. As noted above, a number of alternative embodiments are also within the scope of the present invention. In alternative embodiments, variations on these orientations are possible, including an embodiment that has its axis of rotation at a non-zero angle to the calibration field but which is not perpendicular to that field. However, such an alternative embodiment tends to result in the different axes of the sensor being calibrated with different levels of accuracy. Alternative embodiments
involve taking readings at a larger number of orientations, either during rotation of the sensor or while the rotation has been halted.
CLAIMS

1. An apparatus for calibrating a three axis vector field sensor in a static uniform calibration field, comprising:
   means for positioning a three axis vector field sensor (210) at a starting position such that each axis of said sensor forms a non-zero angle relative to an axis of rotation that is perpendicular to the calibration field;
   means for rotating the sensor around the axis of rotation;
   means for collecting and storing sensor output data for a plurality of orientations of the sensor, which orientations are obtained by rotating the sensor around the axis of rotation; and
   means (280) for determining the offset and gain of each axis of the sensor from the data collected.

2. The apparatus of claim 1, wherein the means for rotating includes a controller for controlling rotation of the sensor around the axis of rotation between a plurality of predefined orientations.

3. The apparatus of claim 2, wherein the plurality of predefined orientations comprise six orientations, each orientation being obtained by rotating the sensor through approximately 1.0472 radians from the previous orientation.

4. The apparatus of any of the preceding claims, wherein said starting position orients a first axis of the sensor at an angle of approximately 0.9553 radians to the axis of rotation that is perpendicular to the direction of the calibration field.

5. The apparatus of claim 4, wherein the plurality of orientations include an orientation in which a second axis of the sensor is oriented at an angle of 0.9553 radians to the axis of rotation that is perpendicular to the direction of the calibration field and an
orientation in which the third axis of the sensor is oriented at an angle of 0.9553 radians
to the axis of rotation that is perpendicular to the direction of the calibration field.

6. The apparatus of any one of the preceding claims, wherein the means for
positioning is adapted to simultaneously hold, and the means for rotating is adapted to
simultaneously rotate, a plurality of three-axis vector field sensors.

7. The apparatus of any of the preceding claims, wherein the means for positioning
is adapted to hold an assembly including an installed three-axis vector field sensor, and
the means for rotating is adapted to rotate the assembly.

8. The apparatus of claim 7, wherein the means for rotating is adapted to
simultaneously rotate a plurality of assemblies that each include an installed three-axis
vector field sensor.

9. The apparatus of claim 7 or claim 8, wherein the means for positioning is adapted
to hold an assembly comprising a paramagnetic oxygen sensor.

10. The apparatus of claim 7 or claim 8, wherein the means for positioning is adapted
to hold an assembly comprising a hard disk drive.

11. The apparatus of any of the preceding claims, wherein said three-axis vector field
sensor is an accelerometer, a magnetic field sensor or an electric field sensor.

12. The apparatus of any of the preceding claims, wherein said means for positioning
comprises a sensor holder mounted on a rotatable spindle.

13. The apparatus of any of claims 1 to 11, wherein said means for positioning is a
sensor holder within a rotatable drum.
14. The apparatus of any of the preceding claims, wherein said means for rotating comprises a motor-driven rotatable sensor holder.

15. The apparatus of claim 14, wherein said motor is arranged to drive one or more rollers on which a sensor-container drum is located, such that the drum rotates freely.

16. The apparatus of any of the preceding claims, wherein said means for determining the offset and gain comprises a programmed microcontroller having an associated input memory into which sensor output data can be saved for processing.

17. The apparatus of any of the preceding claims, further comprising:
   means for varying a sensor calibration parameter selected from the group consisting of temperature, pressure, gas concentration, magnetic field strength and electric field strength; and
   a sensor for measuring the varied sensor calibration parameter.

18. A hard disk drive comprising a read/write mechanism 350, means for moving said read/write mechanism to a safe position 320 in response to detection of free-fall and a three-axis accelerometer 210 for detecting free-fall; and further comprising a memory for storing offset and gain calibration coefficients, and a processor for calibrating output data from the three axes of said accelerometer 210 using the stored offset and gain calibration coefficients.

19. A paramagnetic oxygen sensor system comprising: a three-axis accelerometer 210 installed therein for measuring an orientation of the system; a memory for storing offset and gain calibration coefficients, and a processor for calibrating output data from the three axes of said accelerometer 210 using the stored offset and gain calibration coefficients.

20. A method for determining offset and gain for a three-axis vector field sensor in a static uniform calibration field, comprising the steps of:
(a) positioning a three-axis vector field sensor at a starting position such that each axis of said sensor forms a non-zero angle relative to an axis of rotation perpendicular to the direction of the calibration field;
(b) rotating the sensor around the axis of rotation;
(c) collecting and storing data output by the sensor in a plurality of different orientations obtained by rotating the sensor around the axis of rotation; and
(d) determining the offset and gain for each axis of the sensor from the data collected in step (c).

21. The method of claim 20, wherein the rotating step comprises controlling rotation of the sensor around the axis of rotation between a plurality of predefined orientations.

22. The method of claim 21, wherein the plurality of predefined orientations comprise six orientations, each orientation being obtained by rotating the sensor through approximately 1.0472 radians from the previous orientation.

23. The method of any one of claims 20 to 22, wherein a first axis of the sensor is oriented at an angle of approximately 0.9553 radians to the axis of rotation that is perpendicular to the direction of the calibration field when in the starting position.

24. The method of claim 23, wherein the plurality of orientations include an orientation in which a second axis of the sensor is oriented at an angle of approximately 0.9553 radians to the axis of rotation that is perpendicular to the direction of the calibration field and an orientation in which the third axis of the sensor is oriented at an angle of approximately 0.9553 radians to the axis of rotation that is perpendicular to the direction of the calibration field.

25. The method of any one of claims 20 to 24, comprising simultaneously rotating a plurality of three-axis vector field sensors to a set of predefined orientations, and collecting output data for each axis of each sensor at each orientation.
26. The method as claimed in any of claims 20 to 25, wherein in step (d) the offset of each sensor axis is computed by taking the mean of the two extrema for each sensor axis, and the gain of each sensor axis is computed by taking the reciprocal of the magnitude of the difference between the two extrema and multiplying by 1.633.

27. The method as claimed in claim 22, wherein in step (d) the offset of each sensor axis is computed by taking the mean of the six values reported from each sensor axis.
**Patents Act 1977: Search Report under Section 17**

**Documents considered to be relevant:**

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<td>US6871411 B1 (KANG) see abstract; fig.5 at least</td>
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<td>6, 17, 25</td>
<td>US6209383 A (MUELLER) figure 1; col.2, l.51 to col.4,l.14</td>
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**Field of Search:**
Search of GB, EP, WO & US patent documents classified in the following areas of the UKC¹:

Worldwide search of patent documents classified in the following areas of the IPC

G01C; G01P

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

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