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(54) **TECHNIQUE TO IMPROVE NAVIGATION PERFORMANCE THROUGH CAROUSELLING**

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(52) **U.S. Cl.**
    CPC *G01C 21/16* (2013.01); *G01C 21/165* (2013.01); *G01C 25/00* (2013.01)
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    USPC 701/505, 508, 509, 510, 1
    See application file for complete search history.

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(57)   **ABSTRACT**

A method to improve estimation and stabilization of heading in an inertial navigation system is provided. The method includes operating an inertial measurement unit oriented in a first orientation, forward-rotating the operational inertial measurement unit by a selected-rotation angle about a Z-body axis of the inertial navigation system, wherein the inertial measurement unit is oriented in a second orientation, operating the inertial measurement unit oriented in the second orientation, reverse-rotating the operational inertial measurement unit by the selected-rotation angle about the Z-body axis, wherein the inertial measurement unit is oriented in the first orientation, continuously receiving information indicative of an orientation of the inertial measurement unit at a rotational compensator, and continuously-rotationally compensating navigation module output at the rotational compensator, wherein output of the rotational compensator is independent of the rotating.

8 Claims, 5 Drawing Sheets
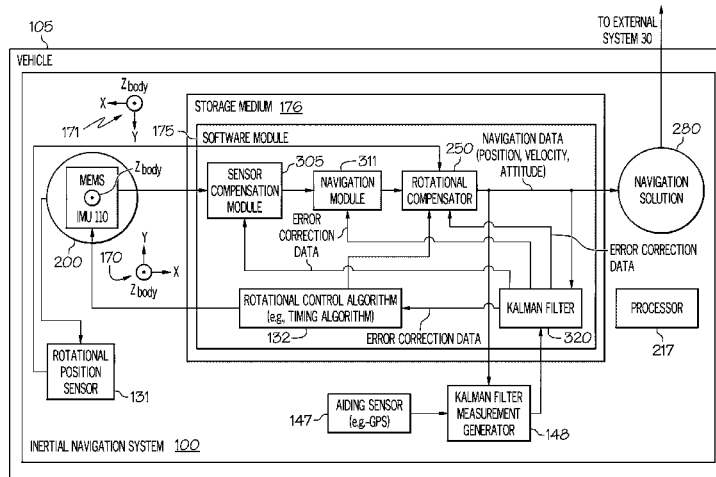
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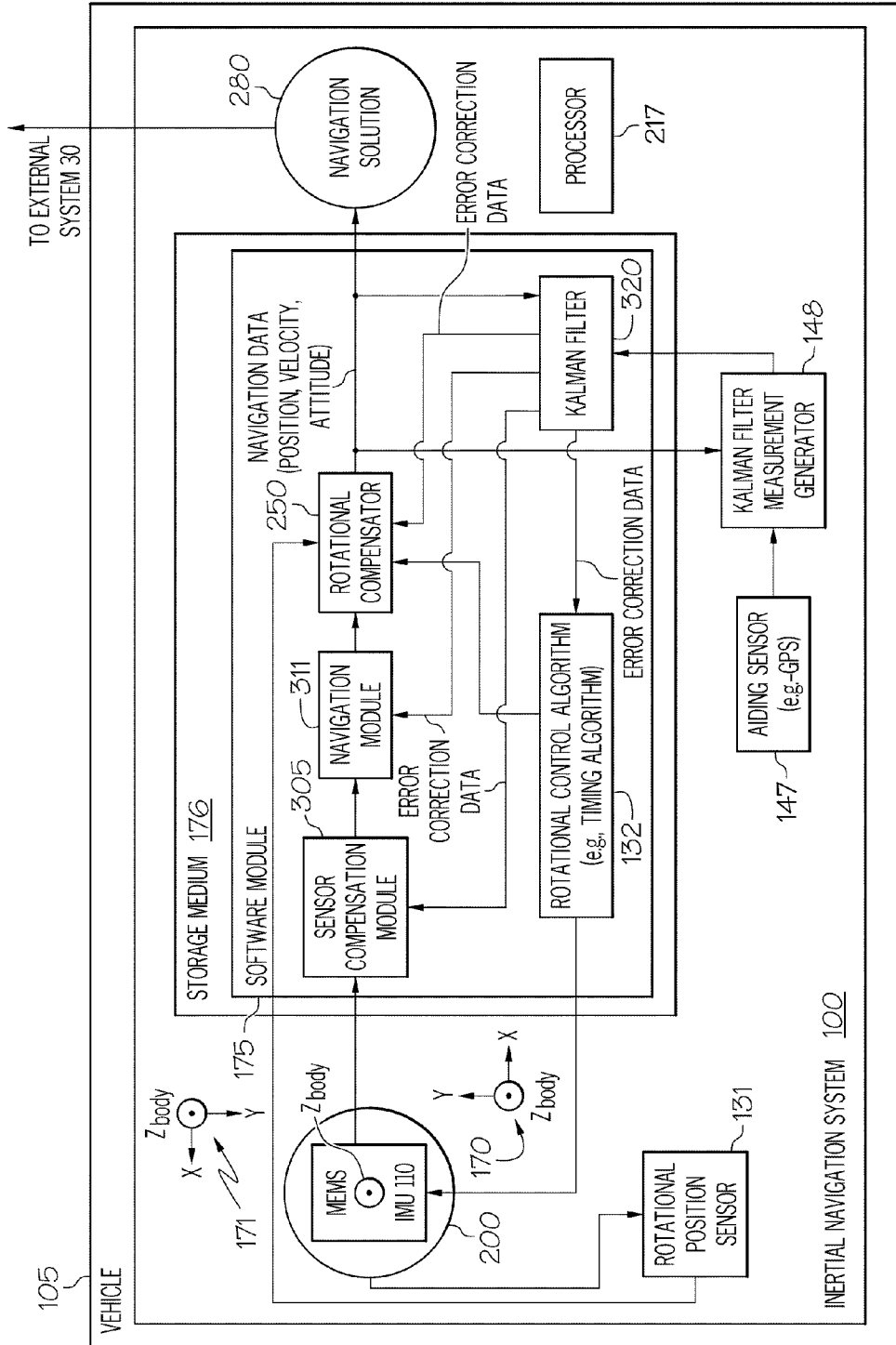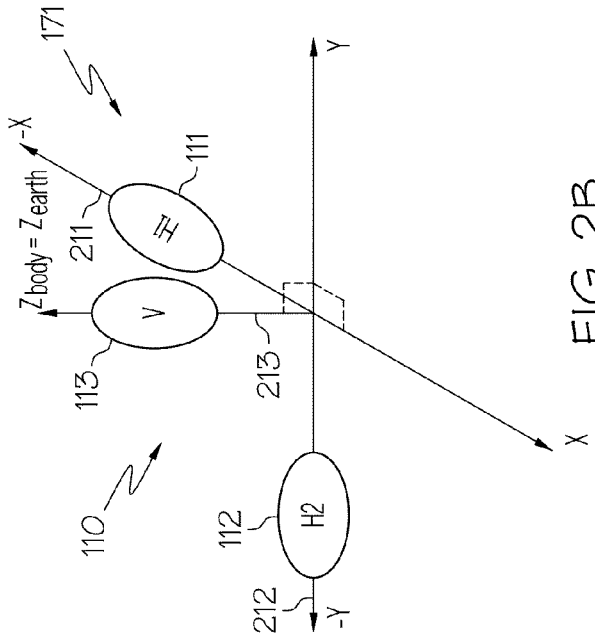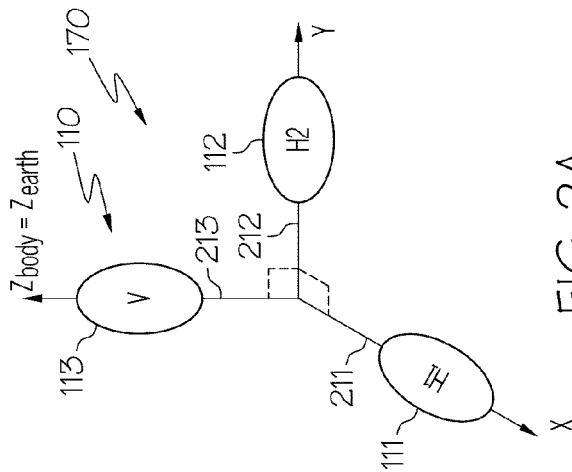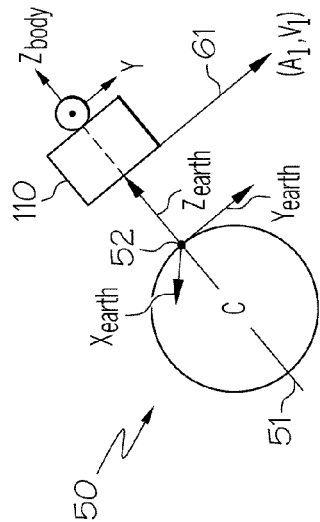
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FIG. 1

FIG. 2A

FIG. 2B

FIG. 2C

OPERATE AN IMU IS ORIENTED IN A FIRST ORIENTATION ~302

FORWARD-ROTATE THE OPERATIONAL IMU BY A SELECTED-ROTATION ANGLE ABOUT THE Z-BODY AXIS TO ORIENT THE IMU IN A SECOND ORIENTATION ~304

SENSE THE FORWARD-ROTATING AT A ROTATIONAL POSITION SENSOR ~306

OPERATE THE IMU ORIENTED IN THE SECOND ORIENTATION ~308

REVERSE-ROTATE THE OPERATIONAL IMU ABOUT THE Z-BODY AXIS BY THE SELECTED-ROTATION ANGLE TO REORIENT IMU IN THE FIRST ORIENTATION ~310

SENSE THE REVERSE-ROTATING AT THE ROTATIONAL POSITION SENSOR ~312

OPERATE THE IMU ORIENTED IN THE FIRST ORIENTATION ~314

CONTINUOUSLY RECEIVE INFORMATION INDICATIVE OF THE ORIENTATION OF THE IMU AT A SENSOR COMPENSATOR ~316

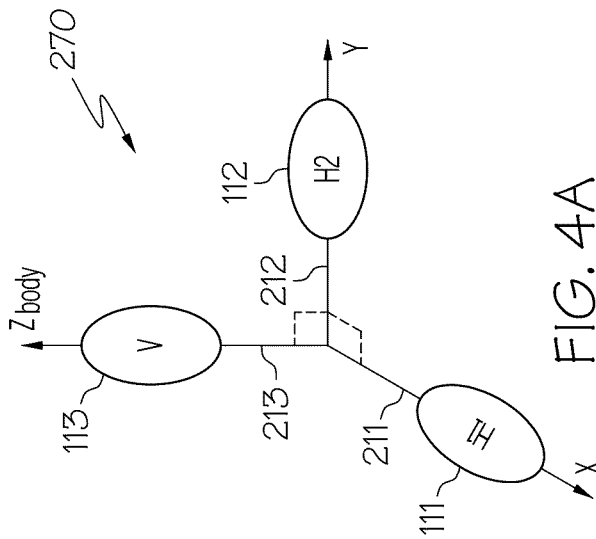CONTINUOUSLY-ROTATIONALLY COMPENSATE NAVIGATION MODULE OUTPUT AT A ROTATIONAL COMPENSATOR ~318
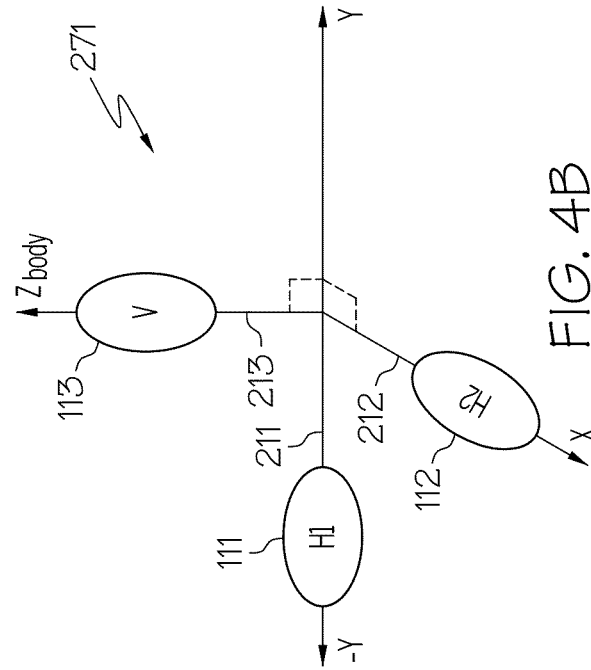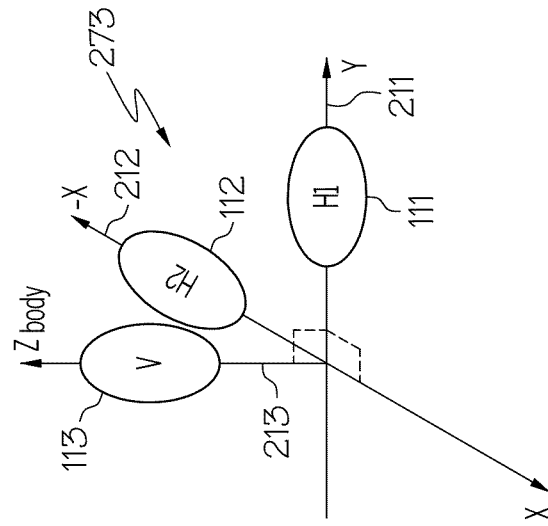
300

FIG. 3

FIG. 4B

FIG. 4A

FIG. 4D

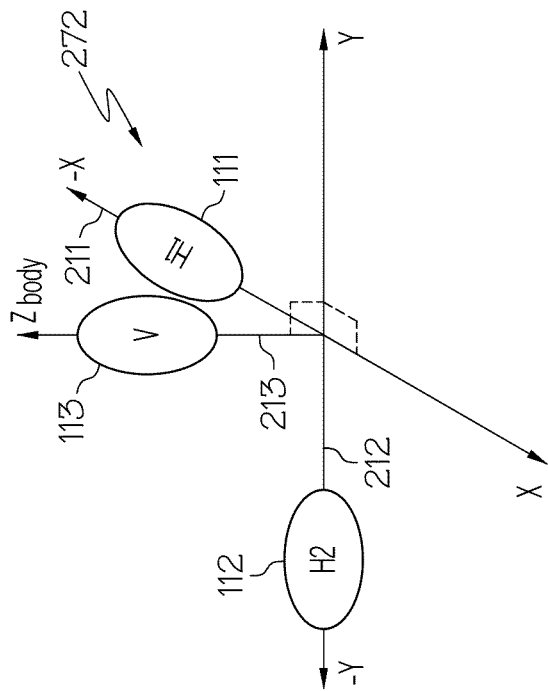FIG. 4C

TECHNIQUE TO IMPROVE NAVIGATION PERFORMANCE THROUGH CAROUSELLING

BACKGROUND

Navigation systems (such as, inertial navigation systems (INS), attitude heading reference systems (AHRS)) that use micro-electro-mechanical system (MEMS) sensors cannot gyrocompass, since MEMS sensors are low quality gyroscopes, typical greater than 2 degrees per hour bias stability for over periods, generally, greater than 10 minutes (long-term), but less than 2 degrees/hour bias for periods, generally, shorter than 10 minutes (short-term). Therefore navigation systems that include MEMS gyroscopes cannot gyro compass and display unacceptable heading drift during free inertial navigation. The inertial sensors (inertial measurement units) with performance better than 2 degrees per hour must be used in navigations system to enable gyro-compassing and prevent this unacceptable heading drift during free inertial navigation. These high performance inertial sensors are expensive and limit the application that can use low cost MEMS gyros.

SUMMARY

The present application relates to a method to improve estimation and stabilization of heading in an inertial navigation system. The method includes operating an inertial measurement unit oriented in a first orientation, forward-rotating the operational inertial measurement unit by a selected-rotation angle about a Z-body axis of the inertial navigation system, wherein the inertial measurement unit is oriented in a second orientation, operating the inertial measurement unit oriented in the second orientation, reverse-rotating the operational inertial measurement unit by the selected-rotation angle about the Z-body axis, wherein the inertial measurement unit is oriented in the first orientation, continuously receiving information indicative of an orientation of the inertial measurement unit at a rotational compensator, and continuously-rotationally compensating navigation module output at the rotational compensator, wherein output of the rotational compensator is independent of the rotating.

The details of various embodiments of the claimed invention are set forth in the accompanying drawings and the description below. Other features and advantages will become apparent from the description, the drawings, and the claims.

DRAWINGS

FIG. 1 is a block diagram of one embodiment of an inertial navigation system in accordance with the present invention;

FIGS. 2A-2B show an inertial measurement unit positioned in a first orientation and a second orientation, respectively, in accordance with the present invention.

FIG. 2C shows the inertial measurement unit of FIGS. 2A-2B with respect to earth-referenced axes in accordance with the present invention.

FIG. 3 is a flow diagram of one embodiment of a method to stabilize heading in an inertial navigation system in accordance with the present invention; and

FIGS. 4A-4D show an inertial measurement unit positioned in a first orientation, a second orientation, a third

orientation, and a fourth orientation, respectively, in accordance with the present invention.

Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

The inertial navigation system described herein enables inertial sensors with long-term biases worse than 2 degrees per hour to gyro compass when the short term (i.e., on the order of minutes) gyro bias stability is less than 2 degrees/hour. The physical act of rotating the inertial measurement unit, as described herein, physically distributes (and thereby reduces) the long-term bias error in the gyroscopes in the inertial measurement unit. The Kalman filter generates error correction data for both the rotational software and hardware; and the error correction data for the navigation module.

FIG. 1 is a block diagram of one embodiment of an inertial navigation system 100 in accordance with the present invention. The inertial navigation system 100 on a vehicle 105 includes an inertial measurement unit (MEMS IMU) 110 that includes three orthogonally mounted gyroscopes and three associated accelerometers. The inertial navigation system 100 also includes a rotational device 200 on which the inertial measurement unit 110 is positioned (fixedly attached). The rotational device 200 is configured to rotate the inertial measurement unit 110 about a Z-body axis Z_{body} of the inertial navigation system 100 from a first orientation 170 to a second orientation 171. The rotating of the inertial measurement unit 110 physically distributes the long-term bias error in the gyroscopes in the inertial measurement unit 110 and thereby reduces the long-term bias error in the gyroscopes.

As shown in FIG. 1, the basis vectors (X, Y, Z_{body}) of the first orientation 170 and the second orientation 171 are offset from the inertial measurement unit 110 and the rotational device 200, for ease of viewing, although the Z-body axis Z_{body} of the inertial navigation system 100 is the axis of rotation of the rotational device 200. The axis of rotation of the rotational device 200 can be any axis within the vehicle 105.

In one implementation of this embodiment, the input axis of one of the three gyroscopes in the inertial measurement unit 110 is aligned to be parallel to and overlapping the axis of rotation of the rotational device 200 (i.e., Z-body axis Z_{body}). In another implementation of this embodiment, none of the input axes of the gyroscopes the inertial measurement unit 110 are aligned with the Z-body axis Z_{body} about which the rotational device 200 rotates. In this case, the horizontal sensing and vertical sensor gyroscopes are virtual sensors and the generation of the virtual sensor is accomplished through mathematically rotating the sensor data into the body axes of the rotation device 200.

As shown in FIG. 1, the first orientation 170 is represented generally by the vectors (X, Y, Z_{body}) in which the Z axis is parallel to the Z-body axis Z_{body}. The second orientation 171 is represented by the same vectors (X, Y, Z) after a rotation of 180° about the Z-body axis Z_{body}. In this exemplary configuration, when the vehicle 105 is travelling in a plane parallel to a tangential plane of the earth, the Z-body axis Z_{body} is equal to the vertical-earth axis Z_{earth}. In this exemplary configuration, when the vehicle 105 is an airborne vehicle that is diving, the Z-body axis Z_{body} is not parallel to the vertical-earth axis Z_{earth} during the dive. The distribution and reduction of the long-term bias error in the inertial measurement unit 110 resultant from the rotating the inertial

measurement unit **110** is most effective (i.e., the reduction of long-term bias error is maximized) when the Z-body axis Z_{body} axis is parallel to the vertical-earth axis Z_{earth}.

As defined herein, the vertical-earth axis Z_{earth} is parallel to the gravitational force vector on the inertial measurement unit **110** and is perpendicular to the plane tangential to the earth's surface beneath the inertial measurement unit **110**. The plane tangential to the earth's surface is not a local surface but rather a smoothed surface in which variations in the altitude of the earth's surface (e.g., mountains and valleys) are averaged out.

The inertial navigation system **100** also includes a software module **175** and a rotational position sensor **131** to sense the orientation of the inertial measurement unit **110** and/or the rotational device **200**. The inertial navigation system **100** also includes a storage medium **176** in which the software module **175** is stored, an aiding sensor **147**, a Kalman filter measurement generator **148**, and at least one processor **217** to execute the software in the software module **175**.

The software module **175** includes a sensor compensation module **305**, a navigation module **311**, a rotational compensator **250**, a Kalman filter **320**, and a rotational control algorithm **132**. In embodiments, the inertial navigation system **100** includes a memory (not shown). The software module **175** is configured to remove the effect of the rotation of the inertial measurement unit **110**. This improves the ability of the inertial navigation system **100** to estimate the heading and to stabilize the heading. By physically rotating the rotational device **200** (and the fixedly attached inertial measurement unit **110**) about the Z-body axis Z_{body} and by removing the effect of the rotation of the inertial measurement unit **110** in the software module **175**, the heading error is less than it would be without the carouselling rotation of the inertial measurement unit **110** about the Z-body axis Z_{body}.

The rotational control algorithm **132** sends instructions to the rotational device **200** to control the rotation of the rotational device **200**. The rotational device **200** is configured to rotate the fixedly attached inertial measurement unit **110** by one hundred eighty (180) degrees from the first orientation **170** to the second orientation **171** in one or more rotation steps. Based on the input received from the rotational control algorithm **132**, the rotational device **200** rotates the inertial measurement unit **110**.

A mechanical system (not shown) drives the rotational device **200** to rotate to a specified orientation based on the instructions received form the rotational control algorithm **132**, and the fixedly attached inertial measurement unit **110** is likewise rotated to the specified orientation. The mechanical system can include motors, chains, belts, cogs, cams, and other mechanical devices to effect a rotation of the rotational device **200**. In one implementation of this embodiment, the mechanical system is part of the rotational device **200**.

The inertial measurement unit **110** sends output data to the sensor compensation module **305**. The sensor compensation module **305** receives the input from the inertial measurement unit **110** and compensates the inertial measurement unit **110** for errors modeled in the Kalman filter **320** or determined during initial calibration at the factory. The sensor compensation module **305** outputs information indicative of output from the inertial measurement unit **110** to the navigation module **311**. The sensor compensation module **305** receives the error correction data output from the Kalman filter **320**.

The navigation module **311** generates navigation data based on input received from the inertial measurement unit **110**. Specifically, the navigation module **311** calculates

velocity, position, and heading (also referred to herein as attitude or azimuth) based on information indicative of output of the inertial measurement unit **110** received from the sensor compensation module **305**. The navigation module **311** includes the software/firmware to function as the navigation processor for the inertial navigation system **100**. The navigation module **311** sends the information indicative of the position, velocity, and attitude of the vehicle **105** to the rotational compensator **250**.

The rotational position sensor **131** sends the information indicative of the orientation of the inertial measurement unit **110** to the rotational compensator **250**. The rotational compensator **250** continuously receives information indicative of the orientation of the inertial measurement unit **110** in the data output from the rotational position sensor **131**. The rotational compensator **250** continuously-rotationally compensates the input received from navigation module **311** so that the output of the rotational compensator **250** is independent of the rotating. The rotational compensator **250** outputs information indicative of the position, velocity, and attitude (referred to as a navigation solution **280**), which is independent of the orientation of the inertial measurement unit **110** to Kalman filter **320** and an external system **30**.

The aiding sensor **147** inputs aiding information (such as a position of the vehicle **105**) to the Kalman filter measurement generator **148**. The Kalman filter measurement generator **148** generates measurement data that is sent to the Kalman filter **320**.

The Kalman filter **320** receives the navigation solution **280** from the rotational compensator **250** and the aiding information from the aiding sensor **147**. The Kalman filter **320** compares the aiding information received from aiding sensor **147** via the Kalman filter measurement generator **148** and the calculated position data received from the navigation module **311** (after compensation for rotation by the rotational compensator **250**) and continuously estimates errors in the rotation generation algorithm **132**, the rotation position sensor **131**, the inertial measurement unit **110**, the sensor compensation module **305**, the navigation module **311**, and the rotational compensator **250**.

The Kalman filter **320** sends the generated error-correction data to the rotation generation algorithm **132**, the sensor compensation module **305**, the navigation module **311**, and the rotational compensator **250**. Specifically, if there is a difference between the reference position and the calculated position, the Kalman filter **320** determines if there is an error in the inertial measurement unit **110** and/or the rotational position sensor **131** and sends error-correction data to the rotational control algorithm **132**, the sensor compensation module **305**, the navigation module **311**, and the rotational compensator **250**. In one implementation of this embodiment, the navigation module **311** writes the error-correction data generated by the Kalman filter **320** into a non-volatile memory (not shown). The error correction data generated by the Kalman filter **320** is stored in the non-volatile memory for use the next time the system is turned on. In this manner, the navigation solution **280** is corrected for any inertial measurement unit **110** or rotational position sensor **131** errors. The navigation solution **280** is output from the rotational compensator **250** to the external system **30** and to the Kalman filter **320**.

The inertial navigation system **100** shown in FIG. **1** is located on the vehicle **105**. The external system **30** is another system located on the vehicle **105**. In one implementation of this embodiment, the external system **30** is a system in a ground station that is communicatively coupled to the vehicle **105**.

In one implementation of this embodiment, the aiding sensor 147 is a global positioning system receiver 147 to input information related to a position of the vehicle 105 to the Kalman filter 148. In another implementation of this embodiment, the inertial measurement unit 110 is a MEMS inertial measurement unit 110 with greater than 2 degrees per hour long-term bias. In this case, the inertial navigation system 100 is a lower cost inertial navigation system 110. The vehicle 105 can be any type of vehicle, including a marine vehicle, a ground vehicle, a missile, an unmanned aircraft, or a manned aircraft, such as a jet, airplane, or helicopter.

FIGS. 2A-2B show an inertial measurement unit 110 positioned in a first orientation 170 and a second orientation 171. FIG. 2C shows the inertial measurement unit 110 of FIG. 1 with respect to earth-referenced axes (X_{earth}, Y_{earth}, Z_{earth}). As shown in FIG. 2C, the line 51 extending through the center "c" of the earth 50 to the inertial measurement unit 110 intersects the surface of the earth 50 at the point 52. The plane spanned by the x_{earth} axis and the y_{earth} axis is the plane tangential to the earth's surface beneath the inertial measurement unit 110. The plane spanned by the x_{earth} axis and the y_{earth} axis is perpendicular to the vertical-earth axis Z_{earth}. In the embodiment shown in FIG. 2C, the vertical-earth axis Z_{earth} is parallel to the Z-body axis Z_{body}. The vertical-earth axis Z_{earth} does not have to be parallel to the Z-body axis Z_{body}, however, as described above, the reduction of long-term bias error in the inertial measurement unit 110 is maximized when the inertial measurement unit 110 is rotated about a Z-body axis Z_{body} axis that is parallel to the vertical-earth axis Z_{earth}.

The inertial measurement unit 110 includes a first-horizontal-sensing gyroscope 111, a second-horizontal-sensing gyroscope 112, and a vertical-sensing gyroscope 113 that are orthogonally mounted with respect to each other. The inertial measurement unit 110 includes accelerometers associated with each of the gyroscopes 111-113 (not shown). The rotational device 200 (FIG. 1) is configured to rotate the inertial measurement unit 110 about the Z-body axis Z_{body} of the inertial navigation system 100 from a first orientation 170 (FIG. 2A) to a second orientation 171 (FIG. 2B). The input axis 211 of the first-horizontal-sensing gyroscope 111 is in the positive X direction (in the IMU basis) in the first orientation 170. After the rotation of 180 degrees in a first (single) rotation step, the input axis 211 of the first-horizontal-sensing gyroscope 111 is in the negative X direction in the second orientation 170. The input axis 212 of the second-horizontal-sensing gyroscope 112 is in the positive Y direction in the first orientation 170. After the rotation of 180 degrees in a first (single) rotation step, the input axis 212 of the second-horizontal-sensing gyroscope 112 is in the negative Y direction in the second orientation 170.

In one implementation of this embodiment, the vehicle 105 (shown in FIG. 2C to be above the earth's surface) travels in the direction 61 in the (x_e, y_e, z_e) space at a constant velocity V_1, while the methods of improving navigation performance of the vehicle 105 described herein are being implemented. In another implementation of this embodiment, the vehicle 105 is stationary, while the methods of improving navigation performance of the vehicle 105 described herein are being implemented. In yet another implementation of this embodiment, the vehicle 105 is accelerating at an acceleration A_1 in the (x_e, y_e, z_e) space, while the methods of improving navigation performance of the vehicle 105 described herein are being implemented.

The method described herein is implemented by a rotation of the inertial measurement unit 110 about the Z-body axis

Z_{body}. The rotation of the inertial measurement unit 110 about the Z-body axis Z_{body}, while the Kalman filter 320 is detecting errors, serves to distribute the error so that it is cancelled out during a rotation cycle from the first orientation 170 to the second orientation 170 and back to the first orientation 170. The gyro biases (long term) are physically canceled during consecutive operations is the first orientation 170 for a pre-selected time duration and in the second orientation 171 for the same pre-selected time duration. This enables the navigation state (e.g., heading) to be estimated using sensors of reduced quality to an accuracy not achievable without implementing the method described herein. The vehicle 105 can include inexpensive MEMS inertial measurement units 110 with low quality gyroscopes and not experience heading drift during free inertial navigation.

FIG. 3 is a flow diagram of one embodiment of a method 300 to stabilize heading in an inertial navigation system in accordance with the present invention. The implementation of method 300 is described with reference to the inertial measurement unit 110 in the inertial navigation system 100 of FIGS. 1, 2A, and 2B. It is to be understood that method 300 can be implemented with other inertial navigation systems.

The three-orthogonally-mounted gyroscopes (the first-horizontal-sensing gyroscope 111, the second-horizontal-sensing gyroscope 112, and the vertical-sensing gyroscope 113) in the inertial measurement unit 110 are operated while the vehicle 105 is moving or stationary and the inertial measurement unit 110 is oriented in a first orientation 170 (block 302). The inertial measurement unit 110 is held in the first orientation 171 for a pre-selected time duration. The pre-selected time duration is selected based on a design decision regarding how fast the rotational device 200 can be rotated and how long the designer wants the inertial measurement unit 110 to be in motion. In one implementation of this embodiment, the pre-selected time duration is 1 minute. In another implementation of this embodiment, the pre-selected time duration is 15 seconds.

The Kalman filter 320 receives position input for the vehicle 105 from the aiding sensor 147 and a navigation solution 280 from the rotational compensator 250 during this time. The Kalman filter 148 estimates and corrects for the heading error of the inertial measurement unit 110 when the inertial measurement unit 110 is in the first orientation 170 based on the input from the aiding sensor 147 and the rotational compensator 250.

While the inertial measurement unit 110 continues to operate, the inertial measurement unit 110 is forward-rotated about the Z-body axis Z_{body} by a selected-rotation angle so that the inertial measurement unit 110 is orientated in the second orientation 171 (block 304). The time taken to rotate from the first orientation 170 to the second orientation 172 is referred to herein as the duration-of-rotation. The selected-rotation angle is one hundred eighty (180) degrees when there is a single rotational step. When the rotation step is completed, the inertial measurement unit 110 is oriented in a second orientation 171 as shown in FIG. 2B. The forward-rotating is sensed at the rotational position sensor 131 (block 306). Information indicative of the angular orientation of the rotational device 200 is sent to the sensor compensation module 305. In one implementation of this embodiment, the pre-selected time duration is 2 minutes and the duration-of-rotation is about 2 seconds.

The rotational control algorithm 132 controls the forward-rotating. The rotational control algorithm 132 sends instructions to the rotational device 200 to start and stop the rotation. The rotational device 200 responds to the rotation-

instructions from the rotational control algorithm 132 by rotating about the Z-body axis Z_{body}. The inertial measurement unit 110 is attached to the rotational device 200 and rotates by an associated amount about the Z-body axis Z_{body}. In one implementation of this embodiment, the rotational device 200 is positioned in a fixture (not shown) that permits an axis of the rotational device 200 to align to the earth's gravitational field. In such an embodiment, the fixedly attached inertial measurement unit 110 can be affixed to the rotational device 200 in which the Z-body axis Z_{body} is always parallel to the vertical-earth axis Z_{earth}.

During the rotation step (forward-rotation step), the Kalman filter 320 receives position input for the vehicle 105 from the aiding sensor 147 and the rotational compensator 250. When the inertial measurement unit 110 is being forward-rotated, the Kalman filter 148 estimates and corrects for the heading error of inertial measurement unit 110 based on the input from the aiding sensor 147 and the rotational compensator 250. The rotational compensator 250 corrects for the rotational motion (about the Z-body axis Z_{body}) of the rotating inertial measurement unit 110, so that the output of the navigation module 311, after it is processed by the rotational compensator 250, appears as though the inertial measurement unit 110 is not rotating about the Z-body axis Z_{body}. The Kalman filter 320 processing estimate the errors generated by navigation module 311, rotational control algorithm 132, and rotational device 200.

In one implementation of this embodiment, the rotational control algorithm 132 is a timing algorithm 132. In that case, the timing algorithm indicates a start-time of the forward-rotating, a stop time of the forward-rotating, and a forward-direction of rotation (e.g., clockwise (CW) or counter-clockwise (CCW) about the Z-body axis Z_{body}). The inertial measurement unit 110 is reoriented from the first orientation 170 to the second orientation 171 between the start-time and the stop-time of the forward-rotating.

The first-horizontal-sensing gyroscope 111, the second-horizontal-sensing gyroscope 112, and the vertical-sensing gyroscope 113 in the inertial measurement unit 110 continue to operate while the inertial measurement unit 110 is oriented in the second orientation 171 for the pre-selected time duration (block 308). The Kalman filter 320 receives position input for the vehicle 105 from the aiding sensor 147 and a navigation solution 280 from the navigation module 311 during this time. The Kalman filter 148 estimates and corrects for the heading error of the navigation solution when the inertial measurement unit 110 is in the first orientation 170 based on the input from the aiding sensor 147 and the rotational compensator 250.

While the inertial measurement unit 110 continues to operate, the inertial measurement unit 110 is reverse-rotated about the Z-body axis Z_{body} by the selected-rotation angle (block 310) so that the inertial measurement unit 110 is reoriented in the first orientation 170. The reverse-rotating is sensed at the rotational position sensor 131 (block 312). The time taken to rotate in the reverse direction (e.g., CCW or CW, whichever is opposite the direction of the forward-rotation) during block 213 equals the time taken to rotate in the forward direction during block 304. The Kalman filter 320 receives input and corrects for the heading error as described above during the reverse-rotation. The rotation allows the turn-on to turn-on biases to be physically distributed. By having the inertial measurement unit 110 oriented in two positions the error is distributed (half of the time the error is positive and half of the time the error is negative).

The rotational control algorithm 132 controls the reverse-rotating. The rotational control algorithm 132 sends instruc-

tions to the rotational device 200 to start and stop the reverse-rotation. The rotational device 200 responds to the rotation-instructions from the rotational control algorithm 132 by rotating about the Z-body axis Z_{body} as described above, but the direction of rotation is the reverse of that of block 304. When the reverse-rotation step is completed, the inertial measurement unit 110 is reoriented in a first orientation 171 as shown in FIG. 2A. The rotating of the inertial measurement unit 110 back and forth is referred to herein as carouselling.

In one implementation of this embodiment, the forward-rotation step and the reverse-rotation step are each 10 seconds in duration. In another implementation of this embodiment, the forward-rotation step and the reverse-rotation step are each 2 seconds in duration.

In embodiments in which the rotational control algorithm 132 is a timing algorithm 132, the timing algorithm indicates a start-time of the reverse-rotating, a stop time of the reverse-rotating, and a reverse-direction of rotation (e.g., CW or CCW). The inertial measurement unit 110 moves from the first orientation 170 to the second orientation 171 between the start-time and the stop-time of the reverse-rotating.

The three-orthogonally-mounted gyroscopes (the first-horizontal-sensing gyroscope 111, the second-horizontal-sensing gyroscope 112, and the vertical-sensing gyroscope 113) in the inertial measurement unit 110 are operated while the vehicle 105 is moving or stationary and the inertial measurement unit 110 is reoriented in the first orientation 170 (block 314). The inertial measurement unit 110 is held in the first orientation 170 for the pre-selected time duration. In all embodiments, the inertial measurement unit 110 is in the first orientation 170 fifty percent of the time and the second orientation 171 the other fifty percent of the time (given the rotation time is negligible with reference to the pre-selected time duration). The Kalman filter 320 receives position input for the vehicle 105 from the aiding sensor 147 and a navigation solution 280 from the rotational compensator 250 during this time. The Kalman filter 148 estimates and corrects for the heading error of the navigation module 311 when the inertial measurement unit 110 is re-oriented in the first orientation 170 based on the input from the aiding sensor 147 and the rotational compensator 250.

The rotational compensator 250 continuously receives information indicative of the orientation of the inertial measurement unit 110 (block 316) from the rotational position sensor 131. The rotational compensator 250 continuously-rotationally compensates the navigation module output received from the navigation module 311 (block 318). Thus, the output of the rotational compensator 250 is independent of the rotating. Specifically, the rotational compensator 250 removes the rotational effects from the generated navigation data output of the navigation module 311 while the inertial measurement unit 110 is operating in the first orientation 270 or the second orientation 271, or while the inertial measurement unit 110 is forward-rotating (e.g., CW) or reverse-rotating (e.g., CCW). The output of rotational compensator 250 is a navigation solution 280. The navigation solution 280 is sent to the Kalman filter 320 and the external system 30.

The Kalman filter 320 applies an attitude correction to the navigation solution 280, based on the operations while in the first orientation 170, during the forward-rotating, while in the second orientation 171, and during the reverse-rotating. By operating the inertial measurement unit 110 while in the first orientation 171 and the second orientation 172 for equal time durations and while forward-rotating and reverse-

rotating for equal time durations, the heading error is physi-
cally cancelled at the navigation module **311**.

FIGS. 4A-4D show an inertial measurement unit **110**
positioned in a first orientation **270**, a second orientation
271, a third orientation **272**, and a fourth orientation **273**,
respectively, in accordance with the present invention. From
the fourth orientation, the inertial measurement unit **110** is
forward-rotated to a fifth orientation that is identical to the
first orientation **270**. The rotational device **200** (FIG. **1**) is
configured to forward-rotate the inertial measurement unit
110 about the vertical-Z-body axis Z_{body} from the first
orientation **270** (FIG. **4A**) to the second orientation **271**
(FIG. **4B**) to the third orientation **272** (FIG. **4C**) to the fourth
orientation **273** (FIG. **4D**) and to the fifth orientation **270**.
Then the rotational device **200** (FIG. **1**) is configured to
reverse-rotate the inertial measurement unit **110** about the
vertical-Z-body axis Z_{body} from the fifth orientation **270** to
the fourth orientation **273** to the third orientation **272** to the
second orientation **271** and back to the first orientation **270**.
In the embodiments shown in FIGS. **4A-4D**, there are 4
rotational steps to rotate the inertial measurement unit **110**
through a selected-rotation angle of 90 degrees.

The physical act of forward rotating the inertial measure-
ment unit **110** by 360 degrees about the Z-body axis Z_{body}
and then reverse rotating the inertial measurement unit **110**
about the Z-body axis Z_{body} by 360 degrees physically
distributes (and thereby reduces) the long-term bias error in
the gyroscopes **111-113** in the inertial measurement unit **110**.
The orientations must be in sets, e.g., (0°, 180° or (90°, 180°,
270°, 360°). In one implementation of this embodiment, the
inertial measurement unit **110** is continuously rotated for-
ward and then backward (reverse) about the Z-body axis
Z_{body}.

The Kalman filter **320** applies an attitude, position, and
velocity corrections to the navigation solution **280** based on
the operations in the first orientation **270**, the second orien-
tation **271**, the third orientation **272**, the fourth orientation
273 and the fifth orientation **270**, while the inertial mea-
surement unit **110** is forward-rotating and reverse-rotating
through 90 degree forward-rotational steps and reverse-
rotational steps. By operating the inertial measurement unit
110 while in the first orientation **270**, the second orientation
271, the third orientation **272**, the fourth orientation **273**, and
the fifth orientation **270** for equal time durations and while
forward-rotating and reverse-rotating for equal time dura-
tions, the heading error is physically cancelled.

The sensor compensation module **305** receives informa-
tion indicative of the sensor errors in the inertial measure-
ment unit **110** as estimated by the Kalman filter **320** during
the 360° forward-rotations and reverse-rotations. The sensor
compensation module **305** removes the inertial measure-
ment unit errors estimated by the Kalman filter **320**. The
rotational compensator **250** continuously-rotationally com-
pensates the navigation module output using data from the
rotational position sensor **131**. The rotational compensator
250 also receives information indicative of the rotational
errors in the rotational device **200** or the rotational position
sensor **131** from the Kalman filter **320**. The output of the
rotational compensator **250** is independent of the rotating of
the inertial measurement unit **110**.

In this manner, the inertial navigation system **100** is able
to include an inertial measurement unit **110** that has low-
quality inexpensive gyroscopes, such as micro-electro-me-
chanical system (MEMS) sensors with greater than 2
degrees per hour long-term bias with reduced heading drift
during free inertial navigation.

In one implementation of this embodiment, the correc-
tions are applied when the inertial measurement unit **110** is
in the first orientation **170**. In this case, the system is left to
drift in the other orientations (e.g., **171-173**). The Kalman
filter **320** computes errors in the non-rotating navigation
solution **280** and applies those corrections to the navigation
module **311** and the sensor compensation module **305**. The
Kalman filer **320** also sends corrections to the rotation
control algorithm **132** and the rotational compensator **250** to
improve the ability of the rotation control algorithm **132** to
cause a symmetric evenly distributed rotation and to
improve the ability of the rotational compensator **250** to
remove motion caused by the rotation device **200**.

A number of embodiments of the invention defined by the
following claims have been described. Nevertheless, it will
be understood that various modifications to the described
embodiments may be made without departing from the spirit
and scope of the claimed invention. Accordingly, other
embodiments are within the scope of the following claims.

What is claimed is:

1. An inertial navigation system, comprising:
an inertial measurement unit including at least three
sensors including at least one gyroscope and at least
two accelerometers;
a rotational device on which the inertial measurement unit
including the at least three sensors is positioned, the
rotational device configured to simultaneously rotate
the at least three sensors positioned on the rotational
device about a Z-body axis of the inertial navigation
system from a first orientation to a second orientation;
a rotational position sensor to sense:
a forward-rotation of the inertial measurement unit first
from the first orientation to the second orientation
and then a reverse-rotation of the inertial measure-
ment unit from the second orientation to the first
orientation; or
a forward-rotation of the inertial measurement unit first
from the first orientation through the second orien-
tation to first orientation and then a reverse-rotation
of the inertial measurement unit from the first ori-
entation through the second orientation to the first
orientation,
wherein the inertial measurement unit operates first while
forward-rotating and then while reverse-rotating;
a software module stored in a non-transitory storage
medium including:
a rotational control algorithm configured, when
executed by a processor, to control the rotation of the
rotational device;
a rotational compensator;
a sensor compensation module configured to receive
input from the inertial measurement unit;
a navigation module configured, when executed by the
processor, to receive input from the sensor compen-
sation module; and
a Kalman filter communicatively coupled to send error
correction data to the navigation module, the sensor
compensation module, the rotational control algo-
rithm, and the rotational compensator; and
the processor configured to execute the software module,
wherein the rotational compensator receives information
indicative of an orientation of the inertial measurement
unit from the rotational position sensor and from the
rotational control algorithm, and, when executed by the
processor, the rotational compensator compensates for
the rotation of the inertial measurement unit about the
Z-body axis, wherein navigational data output from the

rotational compensator is compensated for the forward-rotation and the subsequent reverse-rotation of the inertial measurement unit,

wherein the software module is configured, when executed:

    to remove the effect of the forward-rotation and the subsequent reverse-rotation of the inertial measurement unit; and

    to generate error correction data based on the operation of the inertial measurement unit first while forward-rotating and then while reverse-rotating, and

wherein gyroscope bias errors are distributed based on consecutive operations of the inertial measurement unit in the first orientation and the second orientation, and wherein a heading error of the inertial navigation system is reduced by the distribution of the gyroscope bias errors.

2. The inertial navigation system of claim 1, further comprising an aiding sensor to input information to the Kalman filter.

3. The inertial navigation system of claim 1, wherein at least three sensors of the inertial measurement unit include a first-horizontal-sensing gyroscope, a second-horizontal-sensing gyroscope, and a vertical-sensing gyroscope, the gyroscopes being orthogonally mounted.

4. The inertial navigation system of claim 1, wherein the rotational device is configured to rotate the inertial measure-

ment unit by one hundred eighty degrees from the first orientation to the second orientation in at least one rotation step.

5. The inertial navigation system of claim 1, wherein the inertial measurement unit is a micro-electro-mechanical system (MEMS) inertial measurement unit.

6. The inertial navigation system of claim 3, wherein the Z-body axis of the inertial navigation system is parallel to an input axis of the vertical-sensing gyroscope.

7. The inertial navigation system of claim 6, further comprising:

    a fixture in which the rotational device is fixedly attached, wherein the fixture permits the input axis of the vertical-sensing gyroscope to align to a gravitational field of the earth, wherein the Z-body axis is parallel to a vertical-earth axis while the rotational position sensor rotates about the Z-body axis.

8. The inertial navigation system of claim 3, further comprising:

    a fixture in which the rotational device is fixedly attached, wherein the fixture permits an axis of the rotational device to align to a gravitational field of the earth, wherein the Z-body axis Z_{body} is parallel to a vertical-earth axis while the rotational position sensor rotates about the Z-body axis.

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