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(54) **APPARATUS AND METHOD FOR CALIBRATING INERTIAL SENSOR**

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(71) Applicant: **DENSO CORPORATION**, Kariya-city (JP)

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(72) Inventors: **Suguru HOCHI**, Kariya-city (JP);
Katsuhiko MUTO, Kariya-city (JP);
Yuya HIGUCHI, Kariya-city (JP)

(57) **ABSTRACT**

In an apparatus for calibrating an inertial sensor configured to detect an angular velocity of a vehicle, an angular velocity estimator is configured to estimate a value for an angular velocity of the vehicle based on a value for an attitude of the vehicle and a value for a change in attitude of the vehicle estimated by the attitude estimator, and an error estimator is configured to estimate a value for an angular velocity error that is an error between the value for the angular velocity of the vehicle estimated by the angular velocity estimator and the value for the angular velocity of the vehicle detected by the inertial sensor. A calibrator is configured to calibrate the value for the angular velocity of the vehicle detected by the inertial sensor based on the value for the angular velocity error estimated by the error estimator.

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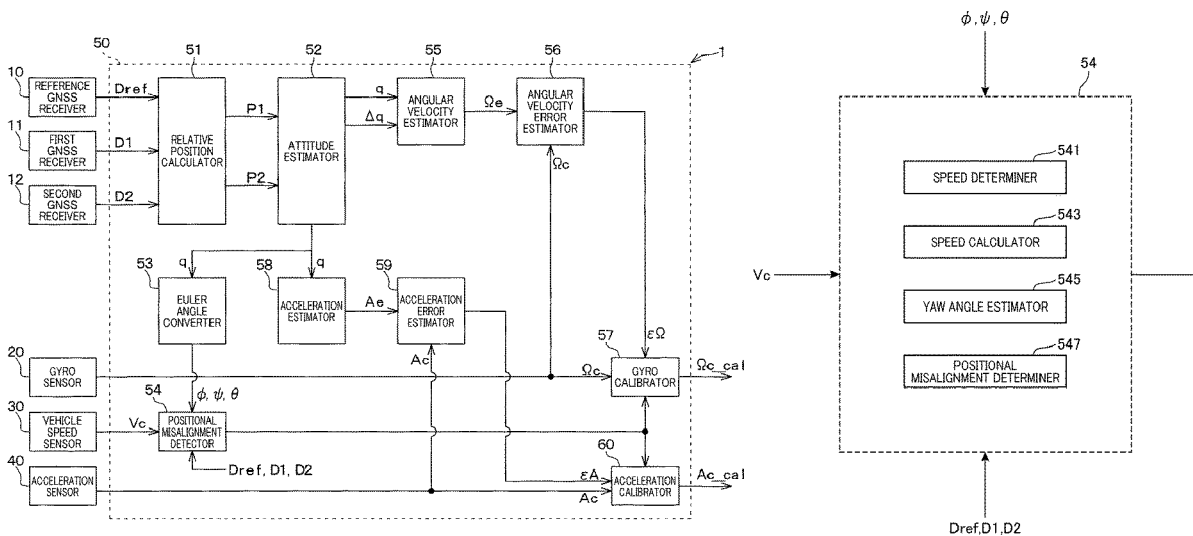
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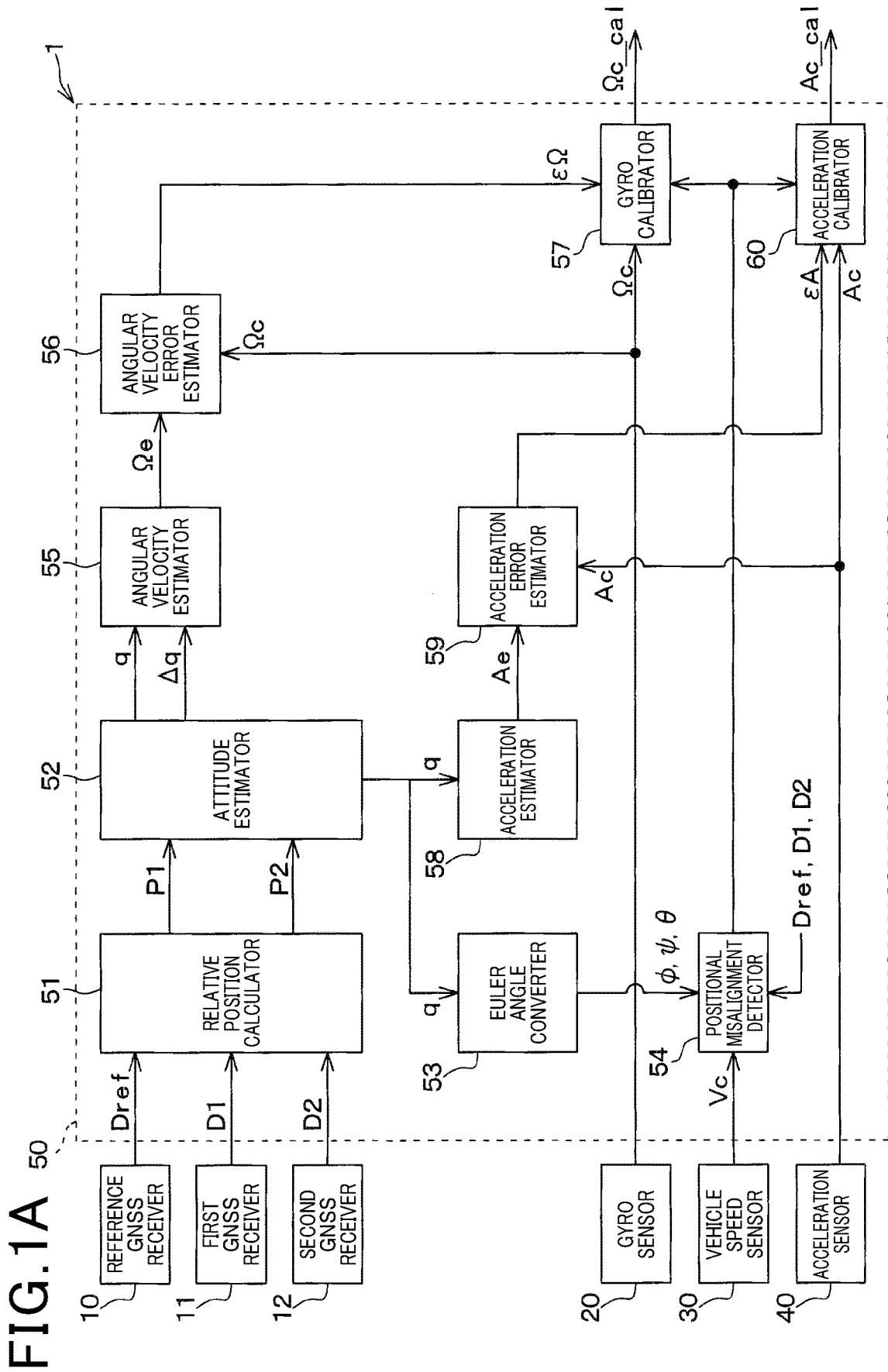


FIG. 1B

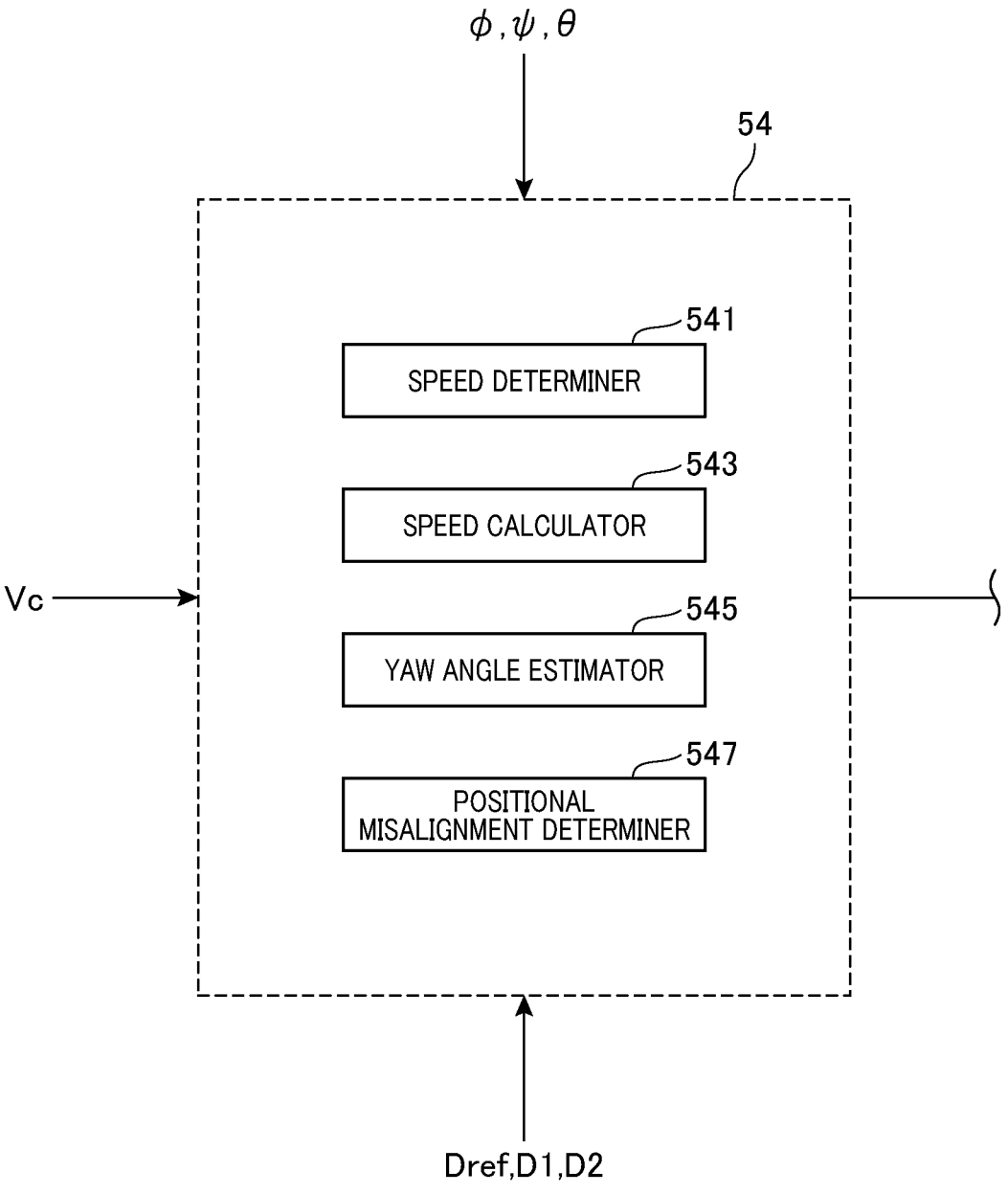


FIG. 2

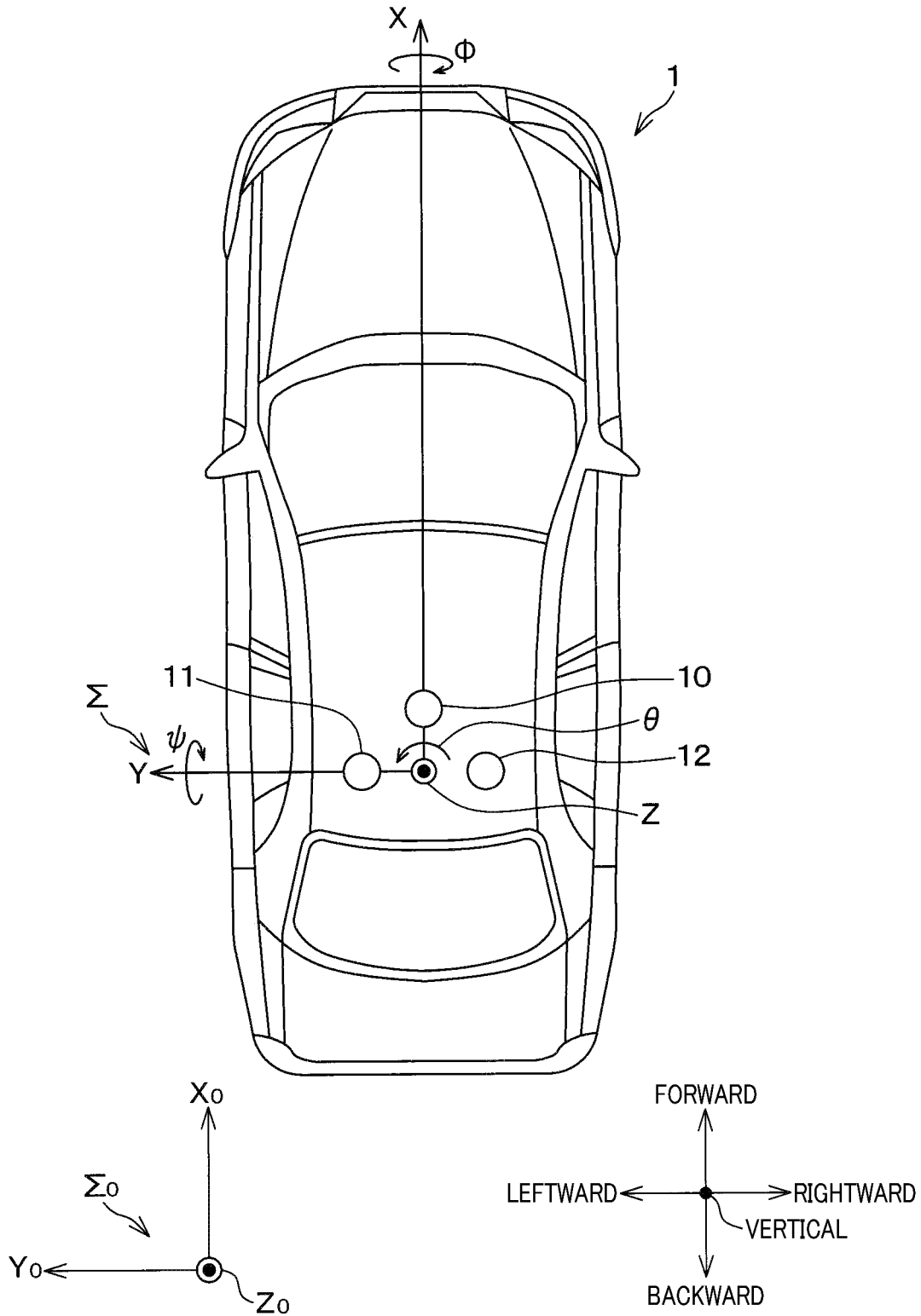


FIG. 3

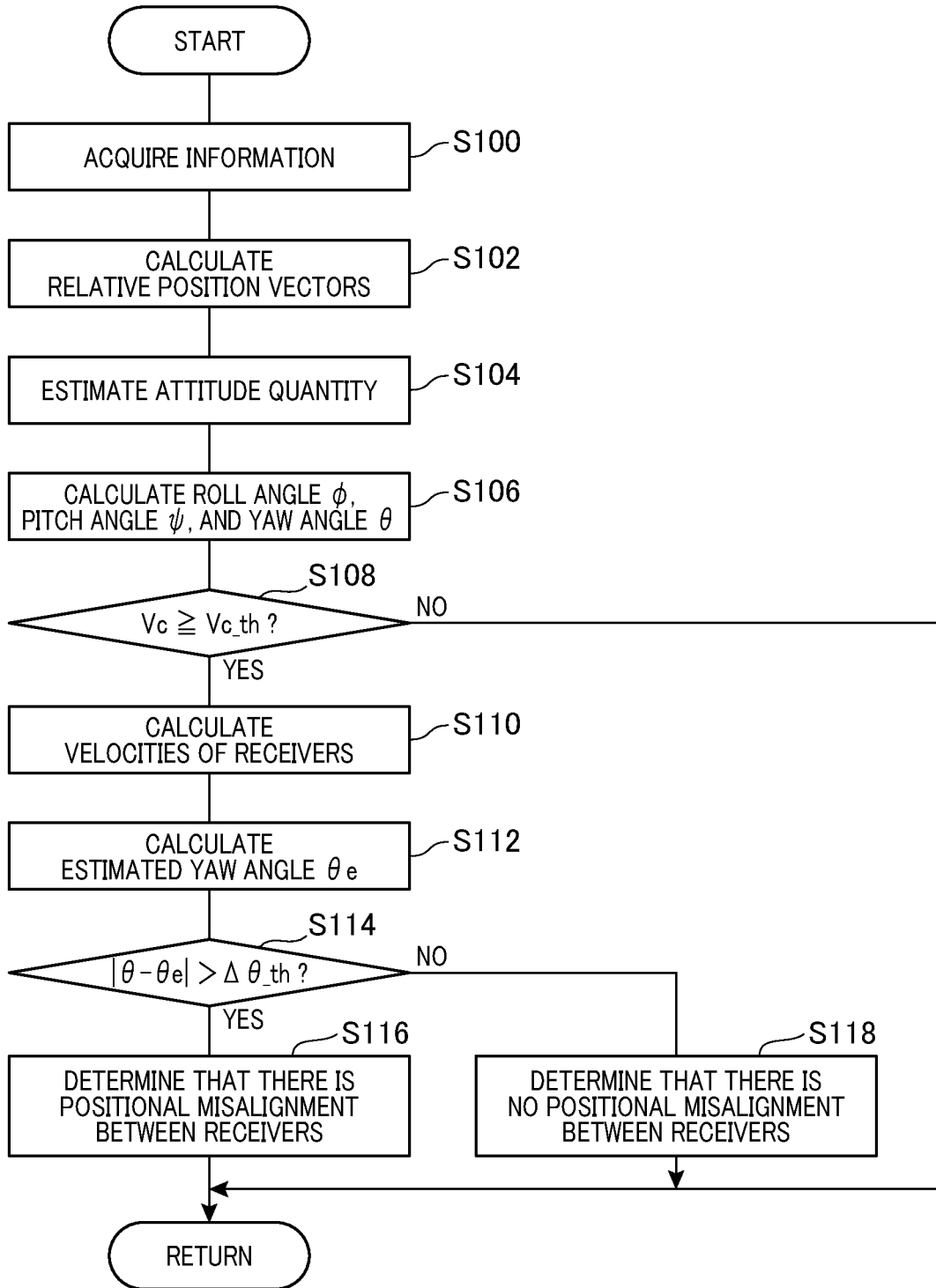


FIG. 4

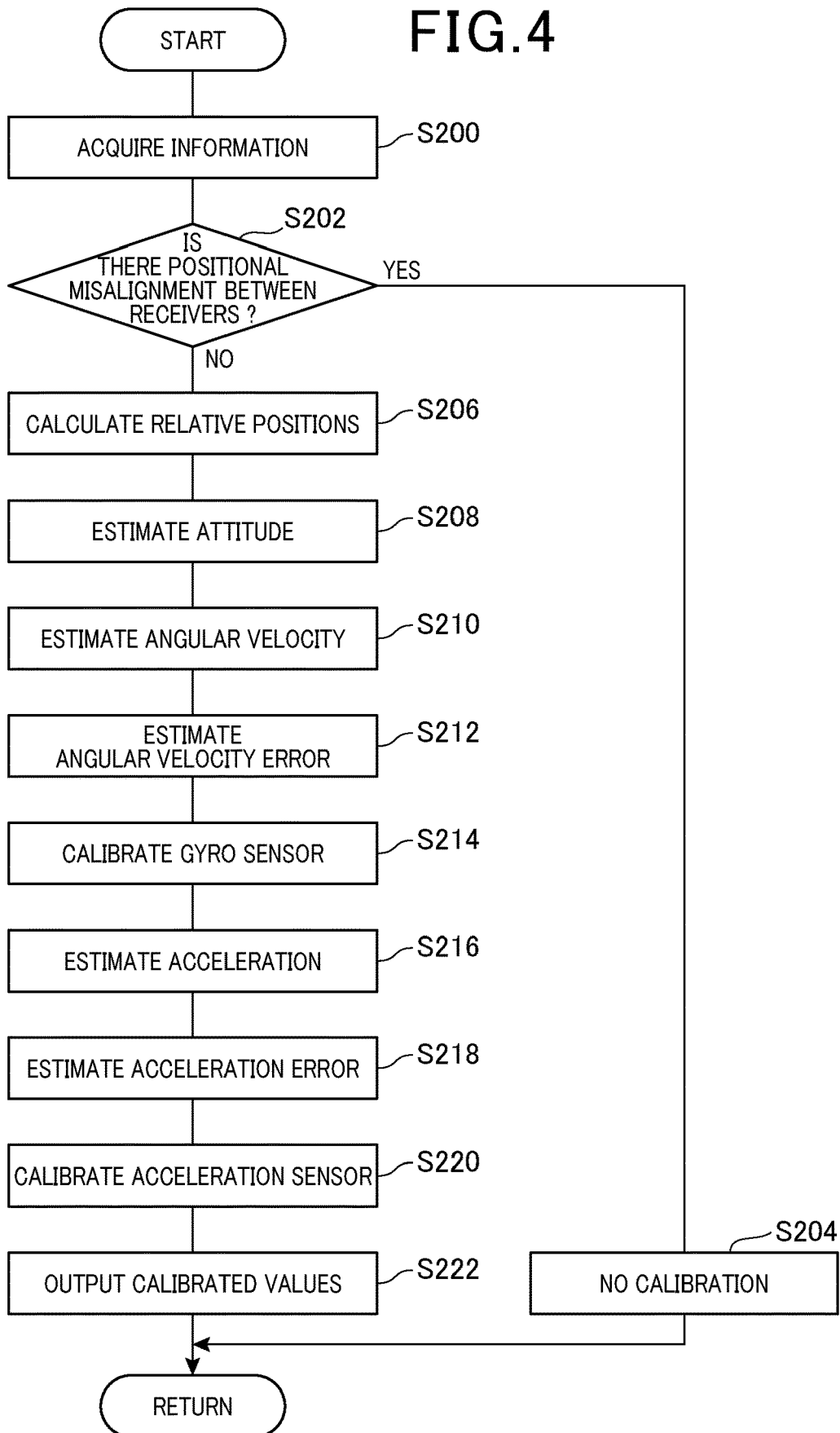


FIG. 5

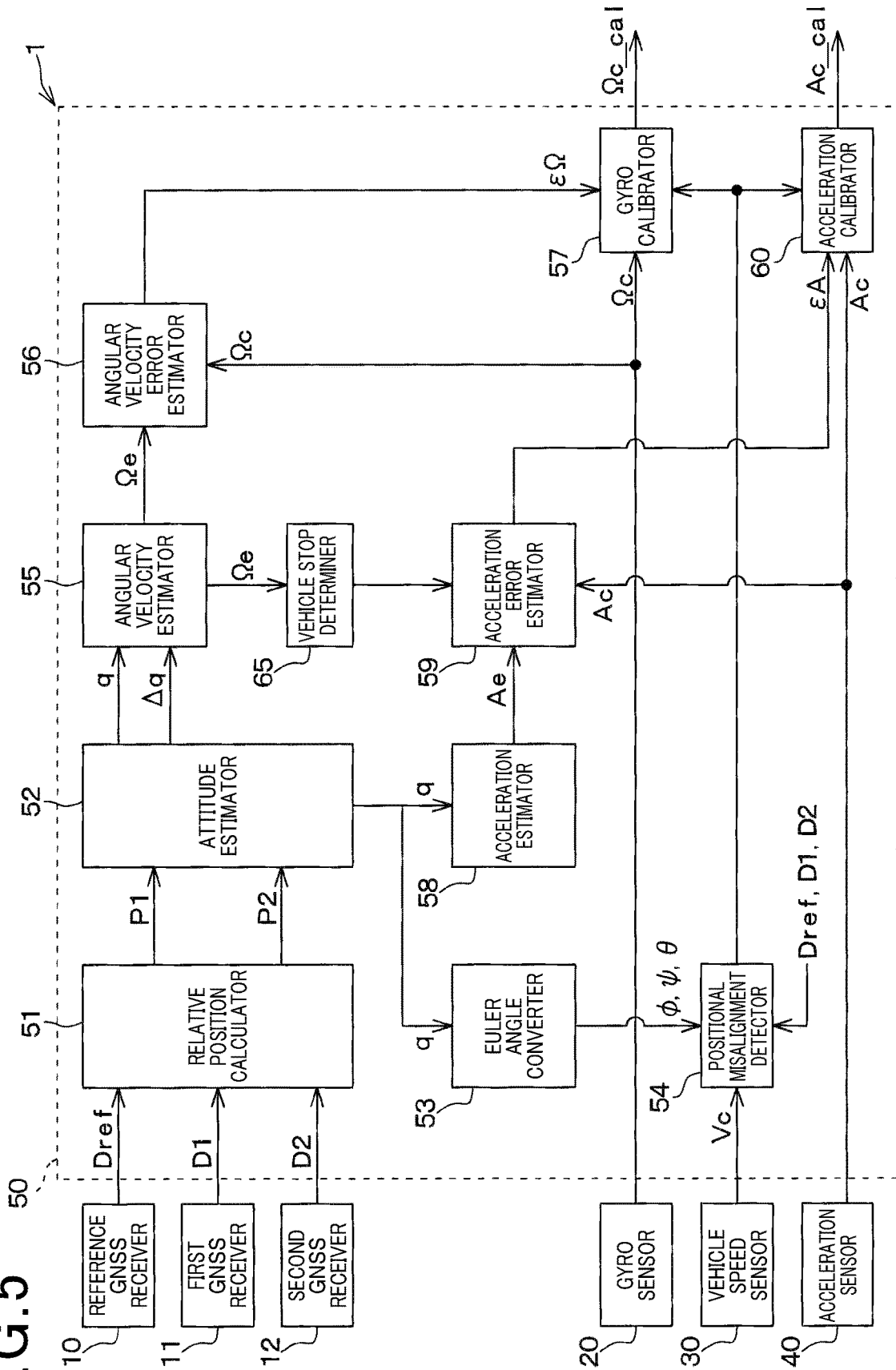
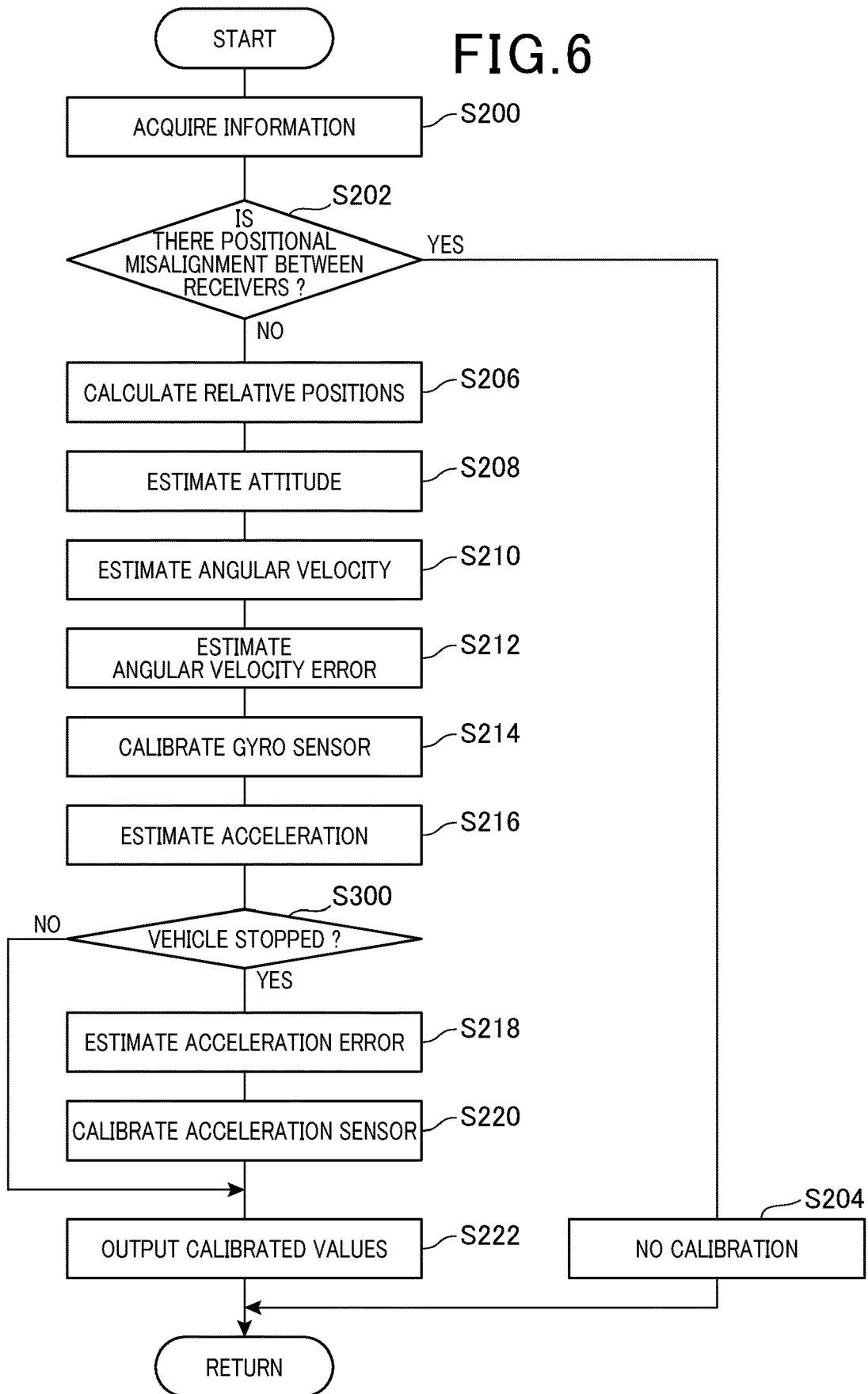


FIG. 6



APPARATUS AND METHOD FOR CALIBRATING INERTIAL SENSOR

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is based on and claims the benefit of priority from earlier Japanese Patent Application No. 2020-148868 on Sep. 4, 2020, the description of which is incorporated herein by reference.

BACKGROUND

Technical Field

[0002] This disclosure relates to an apparatus and a method for calibrating an inertial sensor.

Related Art

[0003] A calibration apparatus for calibrating an acceleration sensor mounted to a vehicle is known that calibrates the acceleration sensor when a reference location and a stopping location of the vehicle match and a reference orientation and a stopping orientation of the vehicle match.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] In the accompanying drawings:

[0005] FIG. 1A is a block diagram of a calibration apparatus according to one embodiment;

[0006] FIG. 1B is a functional block diagram of a positional misalignment detector of the calibration apparatus;

[0007] FIG. 2 is a top view of a vehicle carrying the calibration apparatus;

[0008] FIG. 3 is a flowchart of a positional misalignment detection process performed by the calibration apparatus;

[0009] FIG. 4 is a flowchart of an inertial sensor calibration process performed by the calibration apparatus;

[0010] FIG. 5 is a block diagram of a calibration apparatus according to one modification; and

[0011] FIG. 6 is a flowchart of an inertial sensor calibration process performed by the calibration apparatus according to the modification.

DESCRIPTION OF SPECIFIC EMBODIMENTS

[0012] The above known calibration apparatus, as disclosed in JP-A-2018-132378, calibrates the acceleration sensor when the vehicle is placed at a preset location and orientation. Thus, the calibration apparatus is unable to calibrate the acceleration sensor, for example, while the vehicle is traveling or moving. Besides the acceleration sensor, a gyro sensor for detecting an angular velocity of the vehicle may be calibrated. Since the above known calibration apparatus also calibrates the gyro sensor when the vehicle is placed at a preset location and orientation, the above known calibration apparatus is unable to calibrate the gyro sensor while the vehicle is traveling or moving.

[0013] In view of the above, it is desired to have an apparatus and a method for calibrating an inertial sensor that detects an acceleration and an angular velocity of a vehicle, capable of calibrating the inertial sensor whether while the vehicle is traveling or while the vehicle is stopped.

[0014] A first aspect of the present disclosure provides an apparatus for calibrating an inertial sensor configured to detect an angular velocity of a vehicle, the vehicle being

equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the apparatus including: a position calculator configured to calculate a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculate a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites; an attitude estimator configured to estimate a value for an attitude of the vehicle and a value for a change in attitude of the vehicle based on the first relative position and the second relative position; an angular velocity estimator configured to estimate a value for an angular velocity of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator and the value for the change in attitude of the vehicle estimated by the attitude estimator; an error estimator configured to, based on the value for the angular velocity of the vehicle estimated by the angular velocity estimator and a value for the angular velocity of the vehicle detected by the inertial sensor, estimate a value for an angular velocity error that is an error between the value for the angular velocity of the vehicle estimated by the angular velocity estimator and the value for the angular velocity of the vehicle detected by the inertial sensor; and a calibrator configured to calibrate the value for the angular velocity of the vehicle detected by the inertial sensor based on the value for the angular velocity error estimated by the error estimator.

[0015] A second aspect of the present disclosure provides an apparatus for calibrating an inertial sensor configured to detect an acceleration of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the apparatus including: a position calculator configured to calculate a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculate a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites; a attitude estimator configured to estimate a value for an attitude of the vehicle based on the first relative position and the second relative position; an acceleration estimator configured to estimate a value for an acceleration of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator;

[0016] an error estimator configured to, based on the value for the acceleration of the vehicle estimated by the acceleration estimator and a value for the acceleration of the

vehicle detected by the inertial sensor, estimate a value for an acceleration error that is an error between the value for the acceleration of the vehicle estimated by the acceleration estimator and the value for the acceleration of the vehicle detected by the inertial sensor; and a calibrator configured to calibrate the value for the acceleration of the vehicle detected by the inertial sensor based on the value for the acceleration error estimated by the error estimator.

[0017] A third aspect of the present disclosure provides a method for calibrating an inertial sensor configured to detect an angular velocity of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the method including: calculating a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculate a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites; estimating a value for an attitude of the vehicle and a value for a change in attitude of the vehicle based on the first relative position and the second relative position; estimating a value for an angular velocity of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator and the value for the change in attitude of the vehicle estimated by the attitude estimator; based on the value for the angular velocity of the vehicle estimated and a value for the angular velocity of the vehicle detected by the inertial sensor, estimating a value for an angular velocity error that is an error between the value for the angular velocity of the vehicle estimated and the value for the angular velocity of the vehicle detected by the inertial sensor; and calibrating the value for the angular velocity of the vehicle detected by the inertial sensor based on the value for the angular velocity error estimated by the error estimator.

[0018] A fourth aspect of the present disclosure provides a method for calibrating an inertial sensor configured to detect an acceleration of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the method including: calculating a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculating a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites; estimating a value for an attitude of the vehicle based on the first relative position and the second relative position; estimating a value for an accelera-

tion of the vehicle based on the value for the attitude of the vehicle estimated; based on the value for the acceleration of the vehicle estimated and a value for the acceleration of the vehicle detected by the inertial sensor, estimating a value for an acceleration error that is an error between the value for the acceleration of the vehicle estimated and the value for the acceleration of the vehicle detected by the inertial sensor; and calibrating the value for the acceleration of the vehicle detected by the inertial sensor based on the value for the acceleration error estimated.

[0019] The first relative position is a relative position of the first receiver to the reference receiver disposed in the vehicle. The second relative position is a relative position of the second receiver to the reference receiver disposed in the vehicle. Therefore, the first relative position and the second relative position do not change whether the vehicle is stopped or traveling. This allows the calibration apparatus to estimate the value for the attitude of the vehicle based on the first relative position and the second relative position, regardless of whether the vehicle is stopped or traveling. Therefore, whether the vehicle is stopped or traveling, that is, whether the vehicle is stationary or moving, the calibration apparatus can calibrate the inertial sensor based on the estimated value for the attitude of the vehicle.

[0020] Hereinafter, exemplary embodiments of the present disclosure will be described in detail with reference to the accompanying drawings, in which like reference numerals refer to similar elements and duplicated description thereof will be omitted.

[0021] A calibration apparatus **50** is an inertial sensor calibration apparatus and is used in, for example, a vehicle **1**. The vehicle **1** will now be described.

[0022] As illustrated in FIG. 1A, the vehicle **1** includes a reference Global Navigation Satellite System (GNSS) receiver **10**, a first GNSS receiver **11**, a second GNSS receiver **12**, a gyro sensor **20**, a vehicle speed sensor **30**, an acceleration sensor **40**, and a calibration apparatus **50**.

[0023] The reference GNSS receiver **10** corresponds to a reference receiver. As illustrated in FIG. 2, the reference GNSS receiver **10** is disposed in the vehicle **1**. The reference GNSS receiver **10** receives signals from a plurality of positioning satellites (not shown). As illustrated in FIG. 1A, the reference GNSS receiver **10** transmits reference data Dref to the calibration apparatus **50** based on the received signals. The calibration apparatus **50** will be described later. The reference data Dref includes, for example, a wavenumber and a phase of a carrier wave, ephemeris and the like, from each positioning satellite with respect to time. The ephemeris is orbital information of the positioning satellite.

[0024] The first GNSS receiver **11** corresponds to a first receiver. The first GNSS receiver **11** is mounted to the vehicle **1** and disposed to the left of and behind the reference GNSS receiver **10** as illustrated in FIG. 2. Like the reference GNSS receiver **10**, the first GNSS receiver **11** receives signals from the plurality of positioning satellites (not shown). As illustrated in FIG. 1A, the first GNSS receiver **11** transmits first data D1 to the calibration apparatus **50** based on the received signals. The first data D1 includes, for example, a wavenumber and a phase of a carrier wave, ephemeris and the like, from each positioning satellite with respect to time.

[0025] The second GNSS receiver **12** corresponds to a second receiver. The second GNSS receiver **12** is mounted to the vehicle **1** and disposed to the right of and behind the

reference GNSS receiver **10** as illustrated in FIG. 2. Like the reference GNSS receiver **10** and the first GNSS receiver **11**, the second GNSS receiver **12** receives signals from the plurality of positioning satellites (not shown). As illustrated in FIG. 1A, the second GNSS receiver **12** transmits second data **D2** to the calibration apparatus **50** based on the received signals. The second data **D2** includes, for example, a wavenumber and a phase of a carrier wave, ephemeris and the like, from each positioning satellite with respect to time. The positioning satellites used for the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12** may include Global Positioning System (GPS) satellites, Global Navigation Satellite System (GLONASS) satellites, Galileo satellites, quasi-zenith satellites, and other satellites.

[0026] The gyro sensor **20** corresponds to an inertial sensor. As illustrated in FIG. 1A, the gyro sensor **20** transmits, to the calibration apparatus **50** (described later), a signal corresponding to a detected angular velocity Ω_c of the vehicle **1**.

[0027] The vehicle speed sensor **30** transmits, to the calibration apparatus **50**, a signal corresponding to a vehicle speed V_c , where the vehicle speed V_c is the magnitude of speed of the vehicle **1**.

[0028] The acceleration sensor **40** corresponds to an inertial sensor. As illustrated in FIG. 1A, the acceleration sensor **40** transmits, to the calibration apparatus **50** (described later), a signal corresponding to a detected acceleration A_c of the vehicle **1**.

[0029] The calibration apparatus **50** is configured around at least one microcomputer formed of a central processing unit (CPU), non-transitory tangible storage media, such as a read-only memory (ROM), a random-access memory (RAM), a flash memory and the like, and an input-output interface. The CPU executes programs stored in the ROM or the flash memory, where the RAM is used as a workspace. In addition, the calibration apparatus **50** calibrates the gyro sensor **20** and the acceleration sensor **40** by the CPU executing a calibration program. In addition, as described later, the calibration apparatus **50** executes another program than the calibration program to detect a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**. The positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12** means a deviation in predetermined positional relationship between the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12**.

[0030] The calibration apparatus **50** includes, as functional blocks, a relative position calculator **51**, an attitude estimator **52**, an Euler angle converter **53**, and a positional misalignment detector **54**. The calibration apparatus **50** further includes, as functional blocks, an angular velocity estimator **55**, an angular velocity error estimator **56**, a gyro calibrator **57**, an acceleration estimator **58**, an acceleration error estimator **59**, and an acceleration calibrator **60**.

[0031] The relative position calculator **51** calculates a first relative position vector **P1** based on the reference data D_{ref} from the reference GNSS receiver **10** and the first data **D1** from the first GNSS receiver **11**. The relative position calculator **51** calculates a second relative position vector **P2** based on the reference data D_{ref} from the reference GNSS receiver **10** and the second data **D2** from the second GNSS

receiver **12**. The first relative position vector **P1** is a vector representing a relative position of the first GNSS receiver **11** to the reference GNSS receiver **10** in the absolute coordinate system Σ_o . The second relative position vector **P2** is a vector representing a relative position of the second GNSS receiver **12** to the reference GNSS receiver **10** in the absolute coordinate system Σ_o . As illustrated in FIG. 2, the absolute coordinate system Σ_o is a coordinate system fixed in the space outside the vehicle **1**. X_o , Y_o , and Z_o axes of the absolute coordinate system Σ_o are orthogonal to each other. This absolute coordinate system Σ_o is represented in a right-handed system. The relative position calculator **51** is responsible for execution of step **S206** described later.

[0032] The attitude estimator **52** uses the Kalman filter to estimate an attitude quantity q of the vehicle **1** based on the first relative position vector **P1** and the second relative position vector **P2** calculated by the relative position calculator **51**. The attitude estimator **52** estimates a change in attitude quantity Δq based on the estimated attitude quantity q . Details of estimation of the attitude quantity q and the change in attitude quantity Δq of the vehicle **1** will be described later. The attitude estimator **52** is responsible for execution of step **S208** described later.

[0033] The Euler angle converter **53** calculates a roll angle φ , a pitch angle ψ , and a yaw angle θ of the vehicle **1** based on the attitude quantity q estimated by the attitude estimator **52**. The Euler angle converter **53** is responsible for execution of step **S106** described later.

[0034] As illustrated in FIG. 2, a coordinate system with a given position in the vehicle **1** as the origin is referred to as a vehicle coordinate system Σ . For example, the given position in the vehicle is the center of gravity of the vehicle **1**. The forward direction of the vehicle **1** is the positive direction of the X-axis in the vehicle coordinate system Σ . The leftward direction of the vehicle **1** is the positive direction of the Y-axis in the vehicle coordinate system Σ . The upward direction of the vehicle **1** is the positive direction of the Z-axis in the vehicle coordinate system Σ . The vehicle coordinate system Σ is represented as a right-handed system.

[0035] A roll angle φ is a rotation angle about the X-axis in the vehicle coordinate system Σ . The positive direction of the roll angle φ is the clockwise direction as the positive direction of the X-axis is viewed from the origin of the vehicle coordinate system Σ . A pitch angle ψ is a rotation angle about the Y-axis in the vehicle coordinate system Σ . The positive direction of the pitch angle ψ is the clockwise direction as the positive direction of the Y-axis is viewed from the origin of the vehicle coordinate system Σ . A yaw angle θ is a rotation angle about the Z-axis in the vehicle coordinate system Σ . The positive direction of the yaw angle θ is the clockwise direction as the positive direction of the Z-axis is viewed from the origin of the vehicle coordinate system Σ . The roll angle φ , the pitch angle ψ , and the yaw angle θ are synonymous with ZYX Euler angles, that is, angles by which the vehicle coordinate system Σ is rotated about the Z-axis, the Y-axis, and the X-axis in this order. Details of calculation of the roll angle φ , the pitch angle ψ , and the yaw angle θ will be described later.

[0036] The positional misalignment detector **54** detects whether there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, based on the yaw angle θ calculated by the Euler angle converter **53** and the vehicle

speed V_c detected by the vehicle speed sensor 30. Details of detection of the positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11 or the second GNSS receiver 12 will be described later.

[0037] As illustrated in FIG. 1B, the positional misalignment detector 54 includes, as functional blocks, a speed determiner 541, a speed calculator 543, a yaw angle estimator 545, and a positional misalignment determiner 547.

[0038] The angular velocity estimator 55 calculates an estimated angular velocity Ω_e of the vehicle 1 based on the attitude quantity q and the change in attitude quantity Δq estimated by the attitude estimator 52. Details of estimation of the estimated angular velocity Ω_e will be described later. The angular velocity estimator 55 is responsible for execution of step S210 described later.

[0039] The angular velocity error estimator 56 estimates an angular velocity error ϵ_Ω of the vehicle 1 based on the estimated angular velocity Ω_e estimated by the angular velocity estimator 55 and the detected angular velocity Ω_c detected by the gyro sensor 20. The angular velocity error ϵ_Ω is an error between the estimated angular velocity Ω_e estimated by the angular velocity estimator 55 and the detected angular velocity Ω_c detected by the gyro sensor 20. As described later, the angular velocity error ϵ_Ω includes a value for a change in detected angular velocity Ω_c detected by the gyro sensor 20 when the angular velocity of the vehicle 1 changes or a value for the detected angular velocity Ω_c detected by the gyro sensor 20 when the vehicle 1 is stopped. Details of estimation of the angular velocity error ϵ_Ω will be described later. The angular velocity error estimator 56 is responsible for execution of step S212 described later.

[0040] The gyro calibrator 57 calibrates the detected angular velocity Ω_c detected by the gyro sensor 20 based on the angular velocity error ϵ_Ω estimated by the angular velocity error estimator 56. Details of calibration of the detected angular velocity Ω_c will be described later. The gyro calibrator 57 is responsible for execution of step S214 described later.

[0041] The acceleration estimator 58 calculates an estimated acceleration A_e of the vehicle 1 based on the attitude quantity q estimated by the attitude estimator 52. Details of estimation of the estimated acceleration A_e will be described later. The acceleration estimator 58 is responsible for execution of step S216 described later.

[0042] The acceleration error estimator 59 estimates an acceleration error ϵ_A of the vehicle 1 based on the estimated acceleration A_e estimated by the acceleration estimator 58 and the detected acceleration A_c detected by the acceleration sensor 40. The acceleration error ϵ_A is an error between the estimated acceleration A_e estimated by the acceleration estimator 58 and the detected acceleration A_c detected by the acceleration sensor 40. The acceleration error ϵ_A includes, as described below, a value for a change in detected acceleration A_c detected by the acceleration sensor 40 when the acceleration of the vehicle 1 changes or a value for the detected acceleration A_c detected by the acceleration sensor 40 when the vehicle 1 is stopped. Details of estimation of the acceleration error ϵ_A will be described below. The acceleration error estimator 59 is responsible for execution of step S218 described later.

[0043] The acceleration calibrator 60 calibrates the detected acceleration A_c detected by the acceleration sensor 40 based on the acceleration error ϵ_A estimated by the

acceleration error estimator 59. Details of calibration of the detected acceleration A_c will be described later. The acceleration calibrator 60 is responsible for execution of step S220 described later.

[0044] The vehicle 1 is configured as described above. The calibration apparatus 50 mounted to the vehicle 1 calibrates the gyro sensor 20 and the acceleration sensor 40. The calibration apparatus 50 detects a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12.

[0045] A positional misalignment detection process of detecting a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12 performed by the calibration apparatus 50 executing a positional misalignment detection program will be described with reference to the flowchart of FIG. 3. For example, this positional misalignment detection program is executed when the ignition is turned on in the vehicle 1. In the following, a period of a series of operations from the start of step S100 to the return to step S100 is defined as a control cycle of the positional misalignment detection process performed by the calibration apparatus 50.

[0046] At step S100, the calibration apparatus 50 acquires various information.

[0047] More specifically, the calibration apparatus 50 acquires the reference data D_{ref} from the reference GNSS receiver 10. The calibration apparatus 50 acquires the first data D_1 from the first GNSS receiver 11. The calibration apparatus 50 acquires the second data D_2 from the second GNSS receiver 12. The calibration apparatus 50 further acquires a vehicle speed V_c from the vehicle speed sensor 30.

[0048] At step S102, the calibration apparatus 50 calculates a first relative position vector P_1 and a second relative position vector P_2 .

[0049] For example, the calibration apparatus 50 uses a wavenumber and a phase of the contemporaneous carrier wave in each of the reference data D_{ref} and the first data D_1 acquired at step S100 to calculate the first relative position vector P_1 using the Moving Baseline RTK method. The calibration apparatus 50 uses a wavenumber and a phase of the contemporaneous carrier wave in each of the data for reference D_{ref} and the second data D_2 acquired at step S100 to calculate the second relative position vector P_2 using the Moving Baseline RTK method. RTK is an abbreviation for Real Time Kinematic.

[0050] At step S104, the calibration apparatus 50 estimates an attitude quantity q and a change in attitude quantity Δq of the vehicle 1 based on the first relative position vector P_1 and the second relative position vector P_2 calculated at step S102. details of estimation of the attitude quantity q and the change in attitude quantity Δq of the vehicle 1 will be described later.

[0051] At step S106, the calibration apparatus 50 calculates a roll angle φ , a pitch angle ψ , and a yaw angle θ of the vehicle 1 based on the attitude quantity q estimated at step S104. details of calculation of the roll angle φ , the pitch angle ψ , and the yaw angle θ of the vehicle 1 will be described later. Step S106 is performed by the Euler angle converter 53 that corresponds to a converter.

[0052] The reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12 are disposed in the vehicle 1. Therefore, as the vehicle speed V_c increases, the velocity of the reference GNSS receiver 10,

the velocity of the first GNSS receiver **11**, and the velocity of the second GNSS receiver **12** increase. As these velocities become higher, values of these velocities become more stable, and thus the accuracy of calculating these velocities becomes higher. Furthermore, this improves the accuracy of calculating the estimated yaw angle θ_e described later.

[0053] At step **S108** subsequent to step **S106**, the calibration apparatus **50** determines whether the vehicle speed V_c acquired at step **S100** is equal to or higher than a vehicle speed threshold V_{c_th} . The calibration apparatus **50** thereby determines whether the accuracy of calculation of the velocity and the estimated yaw angle θ_e , which will be described later, is high. The vehicle speed threshold V_{c_th} is set by experiment, simulation, or the like. As described above, the vehicle speed V_c is a magnitude of the speed of the vehicle **1**. Step **S108** is performed by the speed determiner **541** of the positional misalignment detector **54**.

[0054] If the vehicle speed V_c is equal to or higher than the vehicle speed threshold V_{c_th} , the process flow proceeds to step **S110**. If the vehicle speed V_c is less than the vehicle speed threshold V_{c_th} , the above calculation accuracy is low. For this reason, the calibration apparatus **50** does not detect the positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, and the process flow then returns to step **S100**.

[0055] At step **S110** subsequent to step **S108**, the calibration apparatus **50** calculates the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ since the calculation accuracy is high. For example, the calibration apparatus **50** calculates the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ using the Doppler effect of the carrier waves from the positioning satellites (not shown). The reference receiver velocity V_{ref} is a velocity vector of the reference GNSS receiver **10** in the absolute coordinate system Σ_o . The first receiver velocity $V1$ is a velocity vector of the first GNSS receiver **11** in the absolute coordinate system Σ_o . The second receiver velocity $V2$ is a velocity vector of the second GNSS receiver **12** in the absolute coordinate system Σ_o . Step **S110** is performed by the speed calculator **543** of the positional misalignment detector **54**.

[0056] More specifically, the calibration apparatus **50** calculates, based on the wavenumber of the carrier wave received from each positioning satellite included in the reference data D_{ref} acquired at step **S100**, a wavelength and a frequency of this carrier wave. In addition, the calibration apparatus **50** calculates the velocity of each positioning satellite based on the ephemeris included in the reference data D_{ref} acquired at step **S100**. The calibration apparatus **50** calculates the reference receiver velocity V_{ref} based on the calculated frequency of the carrier wave, the calculated velocity of the positioning satellite, the frequency of the carrier wave transmitted from the positioning satellite, and the velocity of light. The calibration apparatus **50** also calculates the first receiver velocity $V1$ in the same manner as described above. Further, the calibration apparatus **50** calculates the second receiver velocity $V2$ in the same manner as described above. As described above, the ephemeris is orbital information of the positioning satellite. The frequency of the carrier wave transmitted from the positioning satellite is set according to the positioning satellite.

[0057] Then, at step **S112**, the calibration apparatus **50** calculates an average of the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ calculated at step **S110**. The calibration apparatus **50** thereby calculates an average speed V_{c_ave} of the vehicle **1** in the absolute coordinate system Σ_o . Calculating these average values allows noise included in the average speed V_{c_ave} to be smoothed out. Therefore, the noise included in the average speed V_{c_ave} is reduced as compared to cases where one of the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ is representative of the estimated speed of the vehicle **1**.

[0058] Further, the calibration apparatus **50**, for example, substitutes an X_o -axis directional component and a Y_o -axis directional component of this calculated average speed V_{c_ave} into the following relational expression (1). The calibration apparatus **50** thereby estimates the estimated yaw angle θ_e of the vehicle **1**. In the following relational expression (1), $V_{c_ave_Xo}$ is the X_o -axis directional component of the average speed V_{c_ave} in the absolute coordinate system Σ_o . $V_{c_ave_Yo}$ is the Y_o -axis directional component of the average speed V_{c_ave} in the absolute coordinate system Σ_o . Step **S112** is performed by the yaw angle estimator **545** of the positional misalignment detector **54**.

$$\theta_e = \arctan \left[\frac{V_{c_ave_Yo}}{V_{c_ave_Xo}} \right] \quad (1)$$

[0059] Subsequently, at step **S114**, the calibration apparatus **50** calculates an absolute value of a difference between the yaw angle θ calculated at step **S106** and the estimated yaw angle θ_e calculated at step **S112**, which is denoted by $|\theta - \theta_e|$.

[0060] In cases where there is no positional misalignment between the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12**, the yaw angle θ calculated at step **S106** and the estimated yaw angle θ_e calculated at step **S112** should be equal.

[0061] As described above, the yaw angle θ calculated at step **S106** is calculated based on the attitude quantity q of the vehicle **1** estimated at step **S104**. Further, this attitude quantity q of the vehicle **1** is calculated based on the first relative position vector $P1$ and the second relative position vector $P2$ calculated at step **S102**. As described above, the first relative position vector $P1$ is a vector representing a relative position of the first GNSS receiver **11** to the position of the reference GNSS receiver **10** in the absolute coordinate system Σ_o . The second relative position vector $P2$ is a vector representing a relative position of the second GNSS receiver **12** to the position of the reference GNSS receiver **10** in the absolute coordinate system Σ_o .

[0062] The yaw angle θ calculated at step **S106** is therefore calculated based on the first relative position vector $P1$ and the second relative position vector $P2$ calculated at step **S102**. In cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, values of the first relative position vector $P1$ and the second relative position vector $P2$ change as data of the misaligned receiver changes.

[0063] Therefore, in cases where there is a positional misalignment between the positions of the reference GNSS

receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12** with the vehicle **1** in the same attitude, the value of the yaw angle θ calculated at step **S106** is different from the value of the yaw angle θ in cases where there is no positional misalignment between the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12**.

[0064] As described above, the estimated yaw angle θ_e calculated at step **S112** is calculated using the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 . Since the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12** are located in the vehicle **1**, the reference receiver velocity V_{ref} , the first receiver velocity V_1 and the second receiver velocity V_2 vary with the vehicle speed V_c .

[0065] The estimated yaw angle θ_e calculated at step **S112** thus varies with the vehicle speed V_c . Even in cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, the vehicle speed V_c does not change.

[0066] Therefore, even in cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, the estimated yaw angle θ_e calculated at step **S112** does not change.

[0067] From the above, in cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**, the values of the yaw angle θ calculated at step **S106** and the estimated yaw angle θ_e calculated at step **S112** are not the same but different. Thus, the above absolute value $|\theta - \theta_e|$ increases as compared to cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**.

[0068] Therefore, at step **S114**, the calibration apparatus **50** determines whether the calculated absolute value $|\theta - \theta_e|$ is greater than a positional misalignment threshold $\Delta\theta_{th}$. The calibration apparatus **50** thereby detects a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**. The positional misalignment threshold $\Delta\theta_{th}$ is set by experiment, simulation, or the like.

[0069] If the absolute value $|\theta - \theta_e|$ is greater than the positional misalignment threshold $\Delta\theta_{th}$, the process flow proceeds to step **S116**. If the absolute value $|\theta - \theta_e|$ is equal to or less than the positional misalignment threshold $\Delta\theta_{th}$, the process flow proceeds to step **S118**.

[0070] At step **S116** subsequent to step **S114**, as the absolute value $|\theta - \theta_e|$ is greater than the positional misalignment threshold $\Delta\theta_{th}$, the calibration apparatus **50** determines that there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**. This determination is stored, for example, in the RAM of the calibration apparatus **50**. Thereafter, the process flow returns to step **S100**.

[0071] At step **S118** subsequent to step **S114**, as the absolute value $|\theta - \theta_e|$ is equal to or less than the positional misalignment threshold $\Delta\theta_{th}$, the calibration apparatus **50** determines that there is no positional misalignment between the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12**. This determination is stored, for example, in the RAM of the calibration apparatus **50**. Thereafter, the process flow returns to step **S100**. Steps

S114, **S116**, and **S118** are performed by the positional misalignment determiner **547** of the positional misalignment detector **54**.

[0072] As described above, the calibration apparatus **50** detects the presence or absence of a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**.

[0073] How to estimate the attitude quantity q of the vehicle **1** at step **S104** in the calibration apparatus **50** will now be described.

[0074] To describe how to estimate the attitude quantity q , some terms are defined as follows.

[0075] Position coordinates of the reference GNSS receiver **10** in the vehicle coordinate system Σ are represented by Ant_{ref} . Position coordinates of the first GNSS receiver **11** in the vehicle coordinate system Σ are represented by Ant_1 . Position coordinates of the second GNSS receiver **12** in the vehicle coordinate system Σ are represented by Ant_2 . For example, the X coordinate of Ant_{ref} in the vehicle coordinate system Σ is set to 1. The Y coordinate of Ant_{ref} in the vehicle coordinate system Σ is set to 0. The Z coordinate of Ant_{ref} in the vehicle coordinate system Σ is set to 0. The X coordinate of Ant_1 in the vehicle coordinate system Σ is set to 0. The Y-coordinate of Ant_1 in the vehicle coordinate system Σ is set to 1. The Z-coordinate of Ant_1 in the vehicle coordinate system Σ is set to 0. The X-coordinate of Ant_2 in the vehicle coordinate system Σ is set to 0. The Y-coordinate of Ant_2 in the vehicle coordinate system Σ is set to -1. The Z-coordinate of Ant_2 in the vehicle coordinate system Σ is set to 0.

[0076] Ant_{ref} is expressed as in the following relational expression (2-1). Ant_1 is expressed as the following relational expression (2-2). Ant_2 is expressed as the following relational expression (2-3). In the relational expressions (2-1) to (2-3), the superscript 'T' is the matrix transpose operator.

$$Ant_{ref}=[100]^T \quad (2-1)$$

$$Ant_1=[010]^T \quad (2-2)$$

$$Ant_2=[0-10]^T \quad (2-3)$$

[0077] The attitude quantity q of the vehicle **1** is represented by a quaternion. The quaternion represents a rotation of the vehicle **1** in the three-dimensional space. four components of the attitude quantity q are denoted as q_0 , q_1 , q_2 , and q_3 . These components q_0 , q_1 , q_2 , and q_3 include information about the attitude of the vehicle **1**.

[0078] In such a quaternion representation, the attitude quantity q is expressed as shown in the following relational expressions (3-1) and (3-2). The coordinate transformation matrix E , which transforms position coordinates in the vehicle coordinate system Σ into position coordinates in the absolute coordinate system Σ_0 , is expressed using the attitude quantity q as shown in the following relational expression (3-3). In the following relational expression (3-1), i , j , and k are basis elements of quaternions. In the following relational expression (3-2), the superscript 'T' is the matrix transpose operator.

$$q = q^0 + q^1 \times i + q^2 \times j + q^3 \times k \quad (3-1)$$

$$q = [q^0 \quad q^1 \quad q^2 \quad q^3]^T \quad (3-2)$$

$$E = \begin{bmatrix} q^0^2 + q^1^2 - q^2^2 - q^3^2 & 2 \times (q^1 \times q^2 + q^0 \times q^3) & 2 \times (q^1 \times q^3 - q^0 \times q^2) \\ 2 \times (q^1 \times q^2 - q^0 \times q^3) & q^0^2 - q^1^2 + q^2^2 - q^3^2 & 2 \times (q^2 \times q^3 + q^0 \times q^1) \\ 2 \times (q^1 \times q^3 + q^0 \times q^2) & 2 \times (q^2 \times q^3 - q^0 \times q^1) & q^0^2 - q^1^2 - q^2^2 + q^3^2 \end{bmatrix} \quad (3-3)$$

[0079] Let us denote the position coordinates of the reference GNSS receiver **10** in the absolute coordinate system Σ_0 as Ant_ref_abs. Let us denote the position coordinates of the first GNSS receiver **11** in the absolute coordinate system Σ_0 as Ant1_abs. Let us denote the position coordinates of the second GNSS receiver **12** in the absolute coordinate system Σ_0 as Ant2_abs.

[0080] Ant_ref_abs is calculated by multiplying Ant_ref by the above coordinate transformation matrix E, as shown in the following relational expression (4-1). Ant1_abs is calculated by multiplying Ant1 by the above coordinate transformation matrix E, as shown in the following relational expression (4-2). Ant2_abs is calculated by multiplying Ant2 by the above coordinate transformation matrix E, as shown in the following relational expression (4-3). As described above, Ant_ref represents position coordinates of the reference GNSS receiver **10** in the vehicle coordinate system Σ . Ant1 represents position coordinates of the first GNSS receiver **11** in the vehicle coordinate system Σ . Ant2 represents position coordinates of the second GNSS receiver **12** in the vehicle coordinate system Σ .

$$\text{Ant_ref_abs} = E \times \text{Ant_ref} \quad (4-1)$$

$$= \begin{bmatrix} q^0^2 + q^1^2 - q^2^2 - q^3^2 \\ 2 \times (q^1 \times q^2 - q^0 \times q^3) \\ 2 \times (q^1 \times q^3 + q^0 \times q^2) \end{bmatrix}$$

$$\text{Ant1_abs} = E \times \text{Ant1} \quad (4-2)$$

$$= \begin{bmatrix} 2 \times (q^1 \times q^2 + q^0 \times q^3) \\ q^0^2 - q^1^2 + q^2^2 - q^3^2 \\ 2 \times (q^2 \times q^3 - q^0 \times q^1) \end{bmatrix}$$

$$\text{Ant2_abs} = E \times \text{Ant2} \quad (4-3)$$

$$= \begin{bmatrix} -2 \times (q^1 \times q^2 + q^0 \times q^3) \\ -(q^0^2 - q^1^2 + q^2^2 - q^3^2) \\ -2 \times (q^2 \times q^3 - q^0 \times q^1) \end{bmatrix}$$

[0081] Further, a six-dimensional number vector having f11, f12, f13, f21, f22 and f23 as components is defined as shown in the following relational expression (5).

[0082] f11 is represented by subtracting the Xo-axis directional component of the Ant_ref_abs from the Xo-axis directional component of the Ant1_abs. Therefore, f11 is an Xo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing a relative position of the first GNSS receiver **11** to the position of the reference GNSS receiver **10**.

[0083] f12 is represented by subtracting the Yo-axis directional component of Ant_ref_abs from the Yo-axis directional component of Ant1_abs. Therefore, f12 is a Yo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing a relative position of the first GNSS receiver **11** to the position of the reference GNSS receiver **10**.

[0084] f13 is represented by subtracting the Zo-axis directional component of Ant_ref_abs from the Zo-axis directional component of Ant1_abs. Therefore, f13 is a Zo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing the relative position of the first GNSS receiver **11** to the position of the reference GNSS receiver **10**.

[0085] f21 is represented by subtracting the Xo-axis directional component of Ant_ref_abs from the Xo-axis directional component of Ant2_abs. Therefore, f21 is a Xo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing the relative position of the second GNSS receiver **12** to the position of the reference GNSS receiver **10**.

[0086] f22 is represented by subtracting the Yo-axis directional component of Ant_ref_abs from the Yo-axis directional component of Ant2_abs. Therefore, f22 is a Yo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing the relative position of the second GNSS receiver **12** to the position of the reference GNSS receiver **10**.

[0087] f23 is represented by subtracting the Zo-axis directional component of Ant_ref_abs from the Zo-axis directional component of Ant2_abs. Therefore, f23 is a Zo-axis directional component of a vector, in the absolute coordinate system Σ_0 , representing the relative position of the second GNSS receiver **12** with respect to the position of the reference GNSS receiver **10**.

[0088] f11, f12, f13, f21, f22, and f23 are values based on the positions of the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12** that are preset in the vehicle coordinate system Σ .

$$\begin{bmatrix} f11 \\ f12 \\ f13 \\ f21 \\ f22 \\ f23 \end{bmatrix} = \begin{bmatrix} 2 \times (q^1 \times q^2 + q^0 \times q^3) - (q^0^2 + q^1^2 - q^2^2 - q^3^2) \\ (q^0^2 - q^1^2 + q^2^2 - q^3^2) - 2 \times (q^1 \times q^2 - q^0 \times q^3) \\ 2 \times (q^2 \times q^3 - q^0 \times q^1) - 2 \times (q^1 \times q^3 + q^0 \times q^2) \\ -2 \times (q^1 \times q^2 + q^0 \times q^3) - (q^0^2 + q^1^2 - q^2^2 - q^3^2) \\ -(q^0^2 - q^1^2 + q^2^2 - q^3^2) - 2 \times (q^1 \times q^2 - q^0 \times q^3) \\ -2 \times (q^2 \times q^3 - q^0 \times q^1) - 2 \times (q^1 \times q^3 + q^0 \times q^2) \end{bmatrix} \quad (5)$$

[0089] The Xo-axis directional component of the first relative position vector P1 in the absolute coordinate system Σ_0 is denoted by $x1_rel$. The Yo-axis directional component of the first relative position vector P1 in the absolute coordinate system Σ_0 is denoted by $y1_rel$. The Zo-axis directional component of the first relative position vector P1 in the absolute coordinate system Σ_0 is denoted by $z1_rel$. The Xo-axis directional component of the second relative position vector P2 in the absolute coordinate system Σ_0 is denoted by $x2_rel$. The Yo-axis directional component of the second relative position vector P2 in the absolute coordinate system Σ_0 is denoted by $y2_rel$. The Zo-axis directional component of the second relative position vector P2 in the absolute coordinate system Σ_0 is denoted by $z2_rel$. As described above, the first relative position vector P1 is a vector representing the relative position of the first GNSS receiver 11 to the position of the reference GNSS receiver 10 in the absolute coordinate system Σ_0 . The second relative position vector P2 is a vector representing the relative position of the second GNSS receiver 12 to the position of the reference GNSS receiver 10 in the absolute coordinate system Σ_0 .

[0090] Therefore, as shown in the following relational expression (6), $x1_rel$ of the first relative position vector P1 corresponds to $f11$. $y1_rel$ of the first relative position vector P1 corresponds to $f12$. $z1_rel$ of the first relative position vector P1 corresponds to $f13$. $x2_rel$ of the second relative position vector P2 corresponds to $f21$. $y2_rel$ of the second relative position vector P2 corresponds to $f22$. $z2_rel$ of the second relative position vector P2 corresponds to $f23$. In the relation (6), s is a six-dimensional number vector having $x1_rel$, $y1_rel$, $z1_rel$, $x2_rel$, $y2_rel$, and $z2_rel$ as components. $f(q)$ is a six-dimensional number vector with $f11$, $f12$, $f13$, $f21$, $f22$, and $f23$ as components.

$$s = \begin{bmatrix} P1 \\ P2 \end{bmatrix} = \begin{bmatrix} x1_rel \\ y1_rel \\ z1_rel \\ x2_rel \\ y2_rel \\ z2_rel \end{bmatrix} = \begin{bmatrix} Ant1_abs - Ant_ref_abs \\ Ant2_abs - Ant_ref_abs \end{bmatrix} = \begin{bmatrix} f11 \\ f12 \\ f13 \\ f21 \\ f22 \\ f23 \end{bmatrix} = f(q) \quad (6)$$

[0091] It is now assumed that these $f11$, $f12$, $f13$, $f21$, $f22$, $f23$ coincide with $x1_rel$, $y1_rel$, $z1_rel$, $x2_rel$, $y2_rel$, $z2_rel$, respectively. As mentioned above, since $f11$, $f12$, $f13$, $f21$, $f22$, and $f23$ are represented by the attitude quantity q of vehicle 1, the attitude quantity q represented by quaternions can be accurately estimated.

[0092] If $f(q)$ is linear, the calibration apparatus 50 can estimate the attitude quantity q using a Kalman filter. However, $f(q)$ is a quadratic function of $q0$, $q1$, $q2$, and $q3$, as shown in the above relational expression (5), that is, $f(q)$ is nonlinear. As long as $f(q)$ is nonlinear, the calibration apparatus 50 can not use the Kalman filter.

[0093] Here, the partial derivative of $f(q)$ with respect to the attitude quantity q allows $f(q)$ to be linearly approximated. Since $f(q)$ is linearly approximated, the calibration apparatus 50 can estimate the attitude quantity using the Kalman filter. Therefore, using this extended Kalman filter, the calibration apparatus 50 estimates the attitude quantity q of the vehicle 1.

[0094] Therefore, the calibration apparatus 50 uses a state equation in which the attitude quantity q is a state vector, as shown in the following relational expression (7-1). The calibration apparatus 50 uses an observation equation in which the above-mentioned s is an observation vector for attitude, as shown in the following relational expression (7-2). It is assumed in the following that there is no noise in the state equation and the observation equation. The above s is the six-dimensional number vector represented by the first and second relative position vectors P1 and P2. t is an integer equal to or greater than 0 and represents the number of updates. $q(t)$ is the attitude quantity q during the t^{th} update, and B is a state transition matrix from $q(t)$ to $q(t+1)$. In addition, it is assumed here that the attitude quantity q of the vehicle 1 does not change in a small amount of time, and this state transition matrix for attitude B is a 4x4 identity matrix, for example, as shown in the following relational expression (7-3). $H(t)$ is an observation matrix that converts $q(t)$ to $s(t)$. The observation matrix for attitude $H(t)$ is calculated by partial differentiation of $f(q)$ with respect to the attitude quantity q , as shown in the following relational expression (7-4). As described above, the components of $f(q)$, that is, $f11$, $f12$, $f13$, $f21$, $f22$, and $f23$, are based on the positions of the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12, which are preset in the vehicle coordinate system Σ . Therefore, the observation matrix for attitude $H(t)$ is a value based on the positions of the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12 that are preset in the vehicle coordinate system Σ .

$$q(t+1) = B \times q(t) \quad (7-1)$$

$$s(t) = H(t) \times q(t) \quad (7-2)$$

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7-3)$$

-continued

$$H(t) = \begin{bmatrix} \frac{\partial f_{11}}{\partial q_0} & \frac{\partial f_{11}}{\partial q_1} & \frac{\partial f_{11}}{\partial q_2} & \frac{\partial f_{11}}{\partial q_3} \\ \frac{\partial f_{12}}{\partial q_0} & \frac{\partial f_{12}}{\partial q_1} & \frac{\partial f_{12}}{\partial q_2} & \frac{\partial f_{12}}{\partial q_3} \\ \frac{\partial f_{13}}{\partial q_0} & \frac{\partial f_{13}}{\partial q_1} & \frac{\partial f_{13}}{\partial q_2} & \frac{\partial f_{13}}{\partial q_3} \\ \frac{\partial f_{21}}{\partial q_0} & \frac{\partial f_{21}}{\partial q_1} & \frac{\partial f_{21}}{\partial q_2} & \frac{\partial f_{21}}{\partial q_3} \\ \frac{\partial f_{22}}{\partial q_0} & \frac{\partial f_{22}}{\partial q_1} & \frac{\partial f_{22}}{\partial q_2} & \frac{\partial f_{22}}{\partial q_3} \\ \frac{\partial f_{23}}{\partial q_0} & \frac{\partial f_{23}}{\partial q_1} & \frac{\partial f_{23}}{\partial q_2} & \frac{\partial f_{23}}{\partial q_3} \end{bmatrix} = \begin{bmatrix} 2 \times q_3 - 2 \times q_0 & 2 \times q_2 - 2 \times q_1 & 2 \times q_1 + 2 \times q_2 & 2 \times q_0 + 2 \times q_3 \\ 2 \times q_0 + 2 \times q_3 & -2 \times q_1 - 2 \times q_2 & 2 \times q_2 - 2 \times q_1 & -2 \times q_3 + 2 \times q_0 \\ -2 \times q_1 - 2 \times q_2 & -2 \times q_0 - 2 \times q_3 & 2 \times q_3 - 2 \times q_0 & 2 \times q_2 - 2 \times q_1 \\ -2 \times q_3 - 2 \times q_0 & -2 \times q_2 - 2 \times q_1 & -2 \times q_1 + 2 \times q_2 & -2 \times q_0 + 2 \times q_3 \\ -2 \times q_0 + 2 \times q_3 & 2 \times q_1 - 2 \times q_2 & -2 \times q_2 - 2 \times q_1 & 2 \times q_3 + 2 \times q_0 \\ 2 \times q_1 - 2 \times q_2 & 2 \times q_0 - 2 \times q_3 & -2 \times q_3 - 2 \times q_0 & -2 \times q_2 - 2 \times q_1 \end{bmatrix} \quad (7-4)$$

[0095] The calibration apparatus **50** estimates the attitude amount q , for example, using the following relational expressions (8-1) to (8-5). In the relational expressions, $Gq(t)$ is the Kalman gain at the t^{th} update. Pq is an error covariance matrix of the attitude quantity q . $Pq(t|t-1)$ is a priori error covariance matrix, and is a predicted value of the error covariance matrix for attitude Pq at the t^{th} update based on information of up to the $(t-1)^{\text{th}}$ update. $Pq(t|t)$ is the error covariance matrix for attitude Pq based on information of up to the t^{th} update. $q(t|t-1)$ is a priori estimate that is a predicted value of the attitude quantity q at the t^{th} update based on information of up to the $(t-1)^{\text{th}}$ update. $q(t|t)$ is a posteriori estimate that is the optimal estimate of the attitude quantity q based on information of up to the t^{th} update. I is the identity matrix. The superscript ‘T’ is the matrix transpose operator. The superscript ‘-1’ is the matrix inverse operator.

$$Pq(t|t-1) = B \times Pq(t-1|t-1) \times B^T \quad (8-1)$$

$$q(t|t-1) = B \times q(t-1|t-1) \quad (8-2)$$

$$Gq(t) = Pq(t|t-1) \times H(t)^T \times \{H(t) \times Pq(t|t-1) \times H(t)^T\}^{-1} \quad (8-3)$$

$$q(t|t) = q(t|t-1) + Gq(t) \times \{s(t) - H(t) \times q(t|t-1)\} \quad (8-4)$$

$$Pq(t|t) = \{I - Gq(t) \times H(t)\} Pq(t|t-1) \quad (8-5)$$

[0096] Specifically, in the case of the t^{th} update, at step **S104**, the calibration apparatus **50** substitutes the state transition matrix for attitude B , the error covariance matrix for attitude Pq in the previous control cycle, and the transposed matrix of the state transition matrix for attitude B into the above relational expression (8-1). The calibration apparatus **50** thereby calculates $Pq(t|t-1)$. $Pq(t|t-1)$ is a predicted value of the error covariance matrix for attitude Pq in the current control cycle. As the state transition matrix for attitude B is here the identity matrix, $Pq(t|t-1)$ is the same as the error covariance matrix for attitude Pq in the previous control cycle. The initial value of the error covariance matrix for attitude Pq is set by experiment, simulation, or the like.

[0097] The calibration apparatus **50** substitutes the state transition matrix for attitude B and the attitude quantity q in the previous control cycle into the above-mentioned relational expression (8-2). The calibration apparatus **50** thereby calculates $q(t|t-1)$, where $q(t|t-1)$ is a predicted value of the attitude quantity q in the current control cycle. As the state transition matrix for attitude B is here the identity matrix, $q(t|t-1)$ is the same as the attitude quantity q in the previous control cycle. The initial value of the attitude quantity q is set, for example, by experiment, simulation, or the like.

[0098] The calibration apparatus **50** substitutes each component of $q(t|t-1)$ calculated above into the above relational expression (7-4). The calibration apparatus **50** thereby calculates the observation matrix for attitude $H(t)$ in the current control cycle.

[0099] Further, the calibration apparatus **50** substitutes the above-calculated $Pq(t|t-1)$, the above-calculated observation matrix for attitude $H(t)$, and the transposed matrix of this observation matrix for attitude $H(t)$ into the above-mentioned relational expression (8-3). The calibration apparatus **50** thereby calculates the Kalman gain for attitude $Gq(t)$ in the current control cycle.

[0100] The calibration apparatus **50** generates an observation vector for attitude in the current control cycle from the components of the first relative position vector **P1** and the components of the second relative position vector **P2** calculated at step **S102** using the above relational expression (6).

[0101] The calibration apparatus **50** substitutes the above calculated $q(t|t-1)$, the above calculated Kalman gain for attitude $Gq(t)$, the above generated observation vector for attitude, and the above calculated observation matrix for attitude $H(t)$ into the above relational expression (8-4). Thus, the calibration apparatus **50** calculates the attitude quantity $q(t|t)$ in the current control cycle.

[0102] The calibration apparatus **50** substitutes the identity matrix I , the Kalman gain for attitude $Gq(t)$ calculated above, the observation matrix for attitude $H(t)$ calculated above, and $Pq(t|t-1)$ calculated above into the above-men-

tioned relational expression (8-5). The calibration apparatus 50 thus calculates the error covariance matrix for attitude $Pq(t|t)$ in the current control cycle. The calibration apparatus 50 can calculate $Pq(t+1|t)$ in the next control cycle using the calculated error covariance matrix for attitude $Pq(t|t)$ in the current control cycle, where $Pq(t+1|t)$ is a predicted value of the error covariance matrix for attitude Pq in the next control cycle.

[0103] In this way, the calibration apparatus 50 estimates the attitude quantity q .

[0104] How the calibration apparatus 50 estimates the change in attitude quantity Δq at step S104 will now be described.

[0105] In the case of the t^{th} update, the calibration apparatus 50 subtracts the attitude quantity q estimated in the previous control cycle from the attitude quantity q estimated in the current control cycle as shown in the following relation (9). In this way, the calibration apparatus 50 estimates the change in attitude quantity Δq . In the following relation (9), $q(t)$ is the attitude quantity q updated for the t^{th} time. $q0(t)$ is $q0$ of the components of the attitude quantity q updated for the t^{th} time. $q1(t)$ is $q1$ of the components of the attitude quantity q updated for the t^{th} time. $q2(t)$ is $q2$ of the components of the attitude quantity q updated for the t^{th} time. $q3(t)$ is $q3$ of the components of the attitude quantity q updated for the t^{th} time.

$$\Delta q = q(t) - q(t-1) \quad (9)$$

$$= \begin{bmatrix} q0(t) - q0(t-1) \\ q1(t) - q1(t-1) \\ q2(t) - q2(t-1) \\ q3(t) - q3(t-1) \end{bmatrix}$$

[0106] As described above, the calibration apparatus 50 estimates the attitude quantity q and the change in attitude quantity Δq .

[0107] Next, how the calibration apparatus 50 calculates the roll angle φ , the pitch angle ψ , and the yaw angle θ of the vehicle 1 at step S106 will be described.

[0108] The calibration apparatus 50 substitutes the attitude quantity q estimated at step S104 into the following relational expression (10). The calibration apparatus 50 thereby calculates the roll angle φ , the pitch angle ψ , and the yaw angle θ of the vehicle 1. The formula (10) is a relational expression for converting the quaternion into the Euler angles.

$$\begin{bmatrix} \varphi \\ \psi \\ \theta \end{bmatrix} = \begin{bmatrix} \arctan \left[\frac{2 \times (q0 \times q1 + q2 \times q3)}{q0^2 - q1^2 - q2^2 + q3^2} \right] \\ \arcsin \left[2 \times (q0 \times q2 - q1 \times q3) \right] \\ \arctan \left[\frac{2 \times (q0 \times q3 + q1 \times q2)}{q0^2 + q1^2 - q2^2 - q3^2} \right] \end{bmatrix} \quad (10)$$

[0109] As described above, the calibration apparatus 50 calculates the roll angle φ , the pitch angle ψ , and the yaw angle θ of the vehicle 1.

[0110] Next, how the calibration apparatus 50 calibrates the gyro sensor 20 and the acceleration sensor 40 by executing a calibration program will be described with

reference to the flowchart of FIG. 4. For example, this calibration program is executed when the ignition of the vehicle 1 is turned on. In the following, a period of a series of operations from the start of step S200 to the return to step S200 is defined as a control cycle of the calibration process performed by the calibration apparatus 50.

[0111] At step S200, the calibration apparatus 50 acquires various information.

[0112] Specifically, the calibration apparatus 50 reads, from the RAM, the determination as to whether there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12 made by executing the above-described positional misalignment detection program. In addition, the calibration apparatus 50 acquires the reference data D_{ref} from the reference GNSS receiver 10. The calibration apparatus 50 acquires the first data $D1$ from the first GNSS receiver 11. The calibration apparatus 50 acquires the second data $D2$ from the second GNSS receiver 12. The calibration apparatus 50 further acquires the detected angular velocity Ω_c of the vehicle 1 from the gyro sensor 20. The calibration apparatus 50 acquires the detected acceleration Ac of the vehicle 1 from the acceleration sensor 40.

[0113] Then, at step S202, the calibration apparatus 50 uses the determination acquired at step S200 to determine whether there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12. The calibration apparatus 50 thereby determines whether to calibrate the gyro sensor 20 and the acceleration sensor 40.

[0114] If there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12, the process flow proceeds to step S204. If there is no positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12, the process flow proceeds to step S206.

[0115] At step S204 subsequent to step S202, there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12. In such cases where there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12, as will be described below, the accuracy of values for the gyro sensor 20 and the acceleration sensor 40 calibrated by the calibration apparatus 50 is reduced as compared to cases where there is no positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12.

[0116] Therefore, for example, the calibration apparatus 50 does not calibrate the gyro sensor 20 and the acceleration sensor 40 and transmits a signal indicating that the gyro sensor 20 and the acceleration sensor 40 are not to be calibrated to a notification device (not shown). This notification device notifies the driver of the vehicle 1 of the gyro sensor 20 and the acceleration sensor 40 being not to be calibrated, for example by means of sound and light. The process flow then returns to step S200.

[0117] At step S206 subsequent to step S202, there is no positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12. In such cases where there is no positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12,

the accuracy of values for the gyro sensor **20** and the acceleration sensor **40** calibrated by the calibration apparatus **50** is higher than in cases where there is a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**.

[0118] Therefore, the calibration apparatus **50** calibrates the gyro sensor **20** and the acceleration sensor **40**. To this end, the calibration apparatus **50** calculates the first relative position vector **P1** and the second relative position vector **P2** in the same manner as at step **S102** above.

[0119] Then, at step **S208**, the calibration apparatus **50** estimates, in the same manner as at step **S104** above, the attitude quantity **q** and the change in attitude quantity Δq of the vehicle **1** based on the first relative position vector **P1** and the second relative position vector **P2** calculated at step **S206**. Step **S206** is performed by the relative position calculator **51** that corresponds to a position calculator. Step **S208** is performed by the attitude estimator **52**.

[0120] Then, at step **S210**, the calibration apparatus **50** calculates the estimated angular velocity Ω_e of the vehicle **1** based on the attitude quantity **q** and the change in attitude quantity Δq estimated at step **S208**. Step **S210** is performed by the angular velocity estimator **55**.

[0121] For example, the calibration apparatus **50** substitutes the attitude quantity **q** and the change in attitude quantity Δq estimated at step **S208** into the following relational expression (11). The calibration apparatus **50** thereby calculates the estimated angular velocity Ω_e of the vehicle **1**. In the relational expression (11), $\omega_e\varphi$ is an angular velocity about the X-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . $\omega_e\psi$ is an angular velocity about the Y-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . $\omega_e\theta$ is an angular velocity about the Z-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . The superscript ‘T’ is the matrix transpose operator. The superscript ‘-1’ is the matrix inverse operator. **t** is an integer equal to or greater than 0 and represents the number of updates. $q_0(t)$ is q_0 of the components of the attitude quantity **q** updated for the t^{th} time. $q_1(t)$ is q_1 of the components of the attitude quantity **q** updated for the t^{th} time. $q_2(t)$ is q_2 of the components of the attitude quantity **q** updated for the t^{th} time. $q_3(t)$ is q_3 of the components of the attitude quantity **q** updated for the t^{th} time.

$$\Omega_e = (G^T \times G)^{-1} \times G^T \times \Delta q \quad (11)$$

$$\Omega_e = \begin{bmatrix} \omega_e\varphi \\ \omega_e\psi \\ \omega_e\theta \end{bmatrix} q = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \Delta q = \begin{bmatrix} \Delta q_0 \\ \Delta q_1 \\ \Delta q_2 \\ \Delta q_3 \end{bmatrix} = \begin{bmatrix} q_0(t) - q_0(t-1) \\ q_1(t) - q_1(t-1) \\ q_2(t) - q_2(t-1) \\ q_3(t) - q_3(t-1) \end{bmatrix}$$

$$G = 0.5 \times \begin{bmatrix} -q_1 & -q_2 & -q_3 \\ q_0 & q_3 & q_2 \\ q_3 & q_0 & q_1 \\ q_2 & q_1 & q_0 \end{bmatrix}$$

[0122] At step **S212**, the calibration apparatus **50** estimates the angular velocity error $\varepsilon\Omega$ based on the estimated angular velocity Ω_e calculated at step **S210** and the detected angular velocity Ω_c acquired from the gyro sensor **20** at step **S200**. Details of estimation of the angular velocity error $\varepsilon\Omega$ will be described later. Step **S212** is performed by the angular velocity error estimator **56** that corresponds to an error estimator.

[0123] At step **S214**, based on the angular velocity error $\varepsilon\Omega$ estimated at step **S212**, the calibration apparatus **50** calibrates the detected angular velocity Ω_c acquired from the gyro sensor **20** at step **S200**. Details of calibration of the detected angular velocity Ω_c will be described later. Step **S214** is performed by the gyro calibrator **57** that corresponds to a calibrator.

[0124] At step **S216**, the calibration apparatus **50** calculates an estimated acceleration A_e of the vehicle **1** based on the attitude quantity **q** estimated at step **S208**. Step **S216** is performed by the acceleration estimator **58**.

[0125] Specifically, since the acceleration sensor **40** is subjected to gravity, the calibration apparatus **50** substitutes q_0 , q_1 , q_2 , and q_3 of the attitude quantity **q** estimated at step **S208** into the following relational expression (12). The calibration apparatus **50** thereby estimates the estimated acceleration A_e of the vehicle **1**. In the relational expression (12), a_{ex} is an X-directional component of the estimated acceleration A_e of the vehicle **1** in the vehicle coordinate system Σ . a_{ey} is a Y-directional component of the estimated acceleration A_e of the vehicle **1** in the vehicle coordinate system Σ . a_{ez} is a Z-directional component of the estimated acceleration A_e of the vehicle **1** in the vehicle coordinate system Σ . **g** represents the gravitational acceleration. The superscript ‘-1’ means the conjugate quaternion.

$$A_e = \begin{bmatrix} a_{ex} \\ a_{ey} \\ a_{ez} \end{bmatrix} = q^{-1} \times \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \times q = Q \times \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \quad (12)$$

$$q^{-1} = q_0 - q_1 \times i - q_2 \times j - q_3 \times k$$

$$Q = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2 \times (q_1 \times q_2 + q_0 \times q_3) & 2 \times (q_1 \times q_3 - q_0 \times q_2) \\ 2 \times (q_1 \times q_2 - q_0 \times q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2 \times (q_2 \times q_3 + q_0 \times q_1) \\ 2 \times (q_1 \times q_3 + q_0 \times q_2) & 2 \times (q_2 \times q_3 - q_0 \times q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$

[0126] At step S218, the calibration apparatus 50 estimates the acceleration error ϵA based on the estimated acceleration A_e calculated at step S216 and the detected acceleration A_c acquired from the acceleration sensor 40 at step S200, estimated. Details of estimation of the acceleration error ϵA will be described later. Step S218 is performed by the acceleration error estimator 59 that corresponds to an error estimator.

[0127] At step S220, the calibration apparatus 50 calibrates the detected acceleration A_c acquired from the acceleration sensor 40 at step S200 based on the acceleration error ϵA estimated at step S218. Details of calibration of the detected acceleration A_c will be described later. Step S220 is performed by the acceleration calibrator 60 that corresponds to the calibrator.

[0128] At step S222, the calibration apparatus 50 outputs the calibrated angular velocity Ω_{c_cal} calculated at step S214 and the calibrated acceleration A_{c_cal} calculated at step S220 to the outside. Thereafter, the process flow returns to step S200.

[0129] Next, how the calibration apparatus 50 estimates the angular velocity error $\epsilon\Omega$ at step S212 will be described.

[0130] The following terms are defined herein to describe estimation of the angular velocity error $\epsilon\Omega$.

[0131] The angular velocity about the X-axis in the vehicle coordinate system Σ , of the angular velocity Ω_c detected by the gyro sensor 20, is referred to as a detected roll rate $\omega_c\phi$. The angular velocity about the Y axis in the vehicle coordinate system Σ , of the angular velocity Ω_c detected by the gyro sensor 20, is referred to as a detected pitch rate $\omega_c\psi$. The angular velocity about the Z-axis in the vehicle coordinate system Σ , of the detected angular velocity Ω_c by the gyro sensor 20, is referred to as a detected yaw rate $\omega_c\theta$. Each of the detected roll rate $\omega_c\phi$, the detected pitch rate $\omega_c\psi$, and the detected yaw rate $\omega_c\theta$ is detected in, for example, rad/s, where rad means radians.

[0132] The amount by which the detected roll rate $\omega_c\phi$ changes when the angular velocity about the X-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the roll rate of the vehicle 1, changes by a unit amount, is the roll rate sensitivity $\epsilon\phi\phi$. The amount by which the detected pitch rate $\omega_c\psi$ changes when the angular velocity about the Y-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the pitch rate of vehicle 1, changes by a unit amount, is the pitch rate sensitivity $\epsilon\psi\psi$. The amount by which the detected yaw rate $\omega_c\theta$ changes when the angular velocity about the Z-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the yaw rate of the vehicle 1, changes by a unit amount, is the yaw rate sensitivity $\epsilon\theta\theta$. The unit for each of the roll rate sensitivity $\epsilon\phi\phi$, the pitch rate sensitivity $\epsilon\psi\psi$, and the yaw rate sensitivity $\epsilon\theta\theta$ is dimensionless.

[0133] The amount by which the detected roll rate $\omega_c\phi$ changes when the angular velocity about the Y-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the pitch rate of the vehicle 1, changes by a unit amount, is the pitch-roll cross-axis sensitivity $\epsilon\psi\phi$. The amount by which the detected roll rate $\omega_c\phi$ changes when the angular velocity about the Z-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the yaw rate of the vehicle 1, changes by a unit amount, is the yaw-roll cross-axis sensitivity $\epsilon\phi\theta$. The amount by which the detected pitch rate $\omega_c\psi$ changes when the angular velocity about the X-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the roll rate of the vehicle 1, changes by a unit amount, is the roll-pitch

cross-axis sensitivity $\epsilon\phi\psi$. The amount by which the detected pitch rate $\omega_c\psi$ changes when the angular velocity about the Z-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the yaw rate of the vehicle 1, changes by a unit amount, is the yaw-pitch cross-axis sensitivity $\epsilon\theta\psi$. The amount by which the detected yaw rate $\omega_c\theta$ changes when the angular velocity about the X-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the roll rate of the vehicle 1, changes by a unit amount, is the roll-yaw cross-axis sensitivity $\epsilon\phi\theta$. The amount by which the detected yaw rate $\omega_c\theta$ changes when the angular velocity about the Y-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the pitch rate of the vehicle 1, changes by a unit amount, is the pitch-yaw cross-axis sensitivity $\epsilon\psi\theta$. The unit for each of the pitch-roll cross-axis sensitivity $\epsilon\psi\phi$, the yaw-roll cross-axis sensitivity $\epsilon\phi\theta$, the roll-pitch cross-axis sensitivity $\epsilon\phi\psi$, the yaw-pitch cross-axis sensitivity $\epsilon\theta\psi$, the roll-yaw cross-axis sensitivity $\epsilon\phi\theta$, the pitch-yaw cross-axis sensitivity $\epsilon\psi\theta$ is dimensionless

[0134] The detected roll rate $\omega_c\phi$ when the angular velocity about the X-axis in the vehicle coordinate system Σ of the vehicle 1, that is, the roll rate of the vehicle 1 is zero, is referred to as a roll rate zero error $\epsilon\phi 0$. the detected pitch rate $\omega_c\psi$ when the angular velocity about the Y axis in the vehicle coordinate system Σ of vehicle 1, that is, the pitch rate of vehicle 1, is zero is referred to as a pitch rate zero error $\epsilon\psi 0$. The detected yaw rate $\omega_c\theta$ when the angular velocity about the Z axis in the vehicle coordinate system Σ of the vehicle 1, that is, the yaw rate of the vehicle 1 is zero, is referred to as a yaw rate zero error $\epsilon\theta 0$. The unit for each of the roll rate zero error $\epsilon\phi 0$, the pitch rate zero error $\epsilon\psi 0$, and the yaw rate zero error $\epsilon\theta 0$ is, for example, rad/sec, where rad means radians.

[0135] The angular velocity error $\epsilon\Omega$ is represented by a 12-dimensional number vector, as shown in the following relation (13). Components of this angular velocity error $\epsilon\Omega$ include the roll rate sensitivity $\epsilon\phi\phi$, the pitch rate sensitivity $\epsilon\psi\psi$, and the yaw rate sensitivity $\epsilon\theta\theta$. The components of the angular velocity error $\epsilon\Omega$ further include the roll-pitch cross-axis sensitivity $\epsilon\phi\psi$, the roll-yaw cross-axis sensitivity $\epsilon\phi\theta$, the pitch-roll cross-axis sensitivity $\epsilon\psi\phi$, the pitch-yaw cross-axis sensitivity $\epsilon\psi\theta$, the yaw-roll cross-axis sensitivity $\epsilon\theta\phi$, and the yaw-pitch cross-axis sensitivity $\epsilon\theta\psi$. The components of the angular velocity error $\epsilon\Omega$ further include the roll rate zero error $\epsilon\phi 0$, the pitch rate zero error $\epsilon\psi 0$, and the yaw rate zero error $\epsilon\theta 0$. In the relational expression (13), the superscript ‘T’ is the matrix transpose operator.

$$\epsilon\Omega = [\epsilon\phi\phi\ \epsilon\psi\psi\ \epsilon\theta\theta\ \epsilon\psi\phi\ \epsilon\phi\psi\ \epsilon\phi\theta\ \epsilon\psi\theta\ \epsilon\theta\phi\ \epsilon\theta\psi\ \epsilon\phi 0\ \epsilon\psi 0\ \epsilon\theta 0]^T \quad (13)$$

[0136] Then, the calibration apparatus 50 estimates the angular velocity error $\epsilon\Omega$ using, for example, a Kalman filter.

[0137] Specifically, the calibration apparatus 50 uses a state equation in which the angular velocity error $\epsilon\Omega$ is a state vector, as shown in the following relation (14-1) below. The calibration apparatus 50 uses an observation equation in which the detected angular velocity Ω_c detected by the gyro sensor 20 is an observation vector, as shown in relational expression (14-2) below. It is assumed that there is no noise in the following state equation and observation equation. t is an integer equal to or greater than 0 and represents the number of updates. $\epsilon\Omega(t)$ is the angular velocity error $\epsilon\Omega$ during the t^{th} update. C is a state transition matrix from $\epsilon\Omega(t)$ to $\epsilon\Omega(t+1)$. This state transition matrix for angular velocity

C is a 12×12 identity matrix, for example, as shown in relational expression (14-3) below. M(t) is an observation matrix that converts $\varepsilon\Omega(t)$ to $\Omega_c(t)$. Furthermore, this observation matrix for angular velocity M is the matrix represented by $\omega e\varphi$, $\omega e\psi$, and $\omega e\theta$ estimated at step S210, as shown in the following relation (14-4) below. As described above, $\omega e\varphi$ is the angular velocity about the X-axis in the vehicle coordinate system Σ , of the estimated angular velocity Ω_e . $\omega e\psi$ is the angular velocity about the Y-axis in the vehicle coordinate system Σ , of the estimated angular velocity Ω_e . $\omega e\theta$ is the angular velocity about the Z-axis in the vehicle coordinate system Σ , of the estimated angular velocity Ω_e .

$$\varepsilon\Omega(t+1) = C \times \varepsilon\Omega(t) \quad (14-1)$$

$$\Omega_c(t) = M(t) \times \varepsilon\Omega(t) \quad (14-2)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (14-3)$$

$$M(t) = \begin{bmatrix} \omega e\varphi & 0 & 0 & \omega e\psi & \omega e\theta & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \omega e\psi & 0 & 0 & 0 & \omega e\varphi & \omega e\theta & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & \omega e\theta & 0 & 0 & 0 & 0 & \omega e\varphi & \omega e\psi & 0 & 0 & 1 \end{bmatrix} \quad (14-4)$$

[0138] The calibration apparatus 50 estimates the angular velocity error $\varepsilon\Omega$ using, for example, the relational expressions (15-1) to (15-5). In the following relational expressions, $G\omega(t)$ is the Kalman gain during the t^{th} update. $P\omega$ is the error covariance matrix of the angular velocity error $\varepsilon\Omega$, and $P\omega(t|t-1)$ is the priori error covariance matrix that is a predicted value of the error covariance matrix for angular velocity $P\omega$ during the t^{th} update based on the information of up to the $(t-1)^{\text{th}}$ update. $P\omega(t|t)$ is the error covariance matrix for angular velocity $P\omega$ based on the information of up to the t^{th} update. $\varepsilon\Omega(t|t-1)$ is the priori estimate that is a predicted value of the angular velocity error $\varepsilon\Omega$ based on the information of up to the $(t-1)^{\text{th}}$ update. $\varepsilon\Omega(t|t)$ is the posteriori estimate that is the optimal estimate of the angular velocity error $\varepsilon\Omega$ based on the information of up to the t^{th} update. I is the identity matrix. The superscript ‘T’ is the matrix transpose operator. The superscript ‘-1’ is the matrix inverse operator.

$$P\omega(t|t-1) = C \times P\omega(t-1|t-1) \times C^T \quad (15-1)$$

$$\varepsilon\Omega(t|t-1) = C \times \varepsilon\Omega(t-1|t-1) \quad (15-2)$$

$$G\omega(t) = P\omega(t|t-1) \times M(t)^T \times \{M(t) \times P\omega(t|t-1) \times M(t)^T\}^{-1} \quad (15-3)$$

$$\varepsilon\Omega(t|t) = \varepsilon\Omega(t|t-1) + G\omega(t) \times \{\Omega_c(t) - M(t) \times \varepsilon\Omega(t|t-1)\} \quad (15-4)$$

$$P\omega(t|t) = \{I - G\omega(t) \times M(t)\} \times P\omega(t|t-1) \quad (15-5)$$

[0139] Specifically, in the case of the t^{th} update, at step S212, the calibration apparatus 50 substitutes the state transition matrix for angular velocity C, the error covariance matrix for angular velocity $P\omega$ in the previous control cycle, and the transposed matrix of the state transition matrix for angular velocity C into the above relational expression (15-1). The calibration apparatus 50 thereby calculates $P\omega(t|t-1)$. $P\omega(t|t-1)$ is the predicted value of the error covariance matrix for the angular velocity $P\omega$ in the current control cycle. Since the state transition matrix for angular velocity C is the identity matrix, $P\omega(t|t-1)$ is the same as the error covariance matrix for angular velocity $P\omega$ in the previous control cycle. Furthermore, the initial value of the error covariance matrix for angular velocity $P\omega$ is set, for example, by experiment, simulation, or the like.

[0140] The calibration apparatus 50 also substitutes the state transition matrix for angular velocity C and the angular velocity error $\varepsilon\Omega$ in the previous control cycle into the above relational expression (15-2). The calibration apparatus 50 thereby calculates $\varepsilon\Omega(t|t-1)$. $\varepsilon\Omega(t|t-1)$ is a predicted value of the angular velocity error $\varepsilon\Omega$ in the current control cycle. Since the state transition matrix for angular velocity C is the identity matrix here, $\varepsilon\Omega(t|t-1)$ is the same as the angular velocity error $\varepsilon\Omega$ in the previous control cycle. Furthermore, the initial value of the angular velocity error $\varepsilon\Omega$ is set, for example, by experiment, simulation, or the like.

[0141] The calibration apparatus 50 substitutes $\omega e\varphi$, $\omega e\psi$, and $\omega e\theta$ estimated at step S210 in the current control cycle into the above relational expression (14-4). The calibration apparatus 50 thereby calculates the observation matrix for angular velocity M(t) in the current control cycle. As described above, $\omega e\varphi$ is the angular velocity about the X-axis in the vehicle coordinate system, of the estimated angular velocity Ω_e . $\omega e\psi$ is the angular velocity about the Y-axis in the vehicle coordinate system Σ , of the estimated angular velocity Ω_e . $\omega e\theta$ is the angular velocity about the Z-axis in the vehicle coordinate system Σ , of the estimated angular velocity Ω_e .

[0142] The calibration apparatus 50 substitutes the above-calculated $P\omega(t|t-1)$, the above-calculated observation matrix for angular velocity M(t), and the transposed matrix of this observation matrix for angular velocity M(t) into the above-mentioned relational expression (15-3). The calibration apparatus 50 thereby calculates the Kalman gain for angular velocity $G\omega(t)$ in the current control cycle.

[0143] The calibration apparatus 50 generates an observation vector for angular velocity in the current control cycle from each component of the detected angular velocity Ω_c acquired from the gyro sensor 20 at step S200. As described above, the components of the detected angular velocity Ω_c acquired from the gyro sensor 20 are the detected roll rate $\omega c\varphi$, the detected pitch rate $\omega c\psi$, and the detected yaw rate $\omega c\theta$. The detected roll rate $\omega c\varphi$ is an angular velocity about the X-axis in the vehicle coordinate system Σ , of the detected angular velocity Ω_c . The detected pitch rate $\omega c\psi$ is an angular velocity about the Y-axis in the vehicle coordinate system Σ , of the detected angular velocity Ω_c . The detected yaw rate $\omega c\theta$ is an angular velocity about the Z-axis in the vehicle coordinate system Σ , of the detected angular velocity Ω_c .

[0144] The calibration apparatus 50 substitutes the above calculated $\varepsilon\Omega(t|t-1)$, the above calculated Kalman gain for angular velocity $G\omega(t)$, the above generated observation

vector for angular velocity, and the above calculated observation matrix for angular velocity $M(t)$ into the relational expression (15-4). The calibration apparatus **50** thereby calculates the angular velocity error $\epsilon\Omega(t|t)$ in the current control cycle.

[0145] The calibration apparatus **50** substitutes the identity matrix I , the above calculated Kalman gain for angular velocity $G\omega(t)$, the above calculated observation matrix for angular velocity $M(t)$, and the above calculated $P\omega(t|t-1)$ into (15-5). The calibration apparatus **50** thereby calculates the error covariance matrix for angular velocity $P\omega(t|t)$ in the current control cycle. Therefore, in the next control cycle, the calibration apparatus **50** can calculate $P\omega(t+1|t)$ using the calculated error covariance matrix for angular velocity $P\omega(t|t)$ in the current control cycle. $P\omega(t+1|t)$ is a predicted value of the error covariance matrix for angular velocity $P\omega$ in the next control cycle.

[0146] In this way, the calibration apparatus **50** estimates the angular velocity error $\epsilon\Omega$.

[0147] Next, how the calibration apparatus **50** calibrates the gyro sensor **20** at step S214 will be described.

[0148] In the case of the t^{th} update, the calibration apparatus **50** substitutes each component of the angular velocity error $\epsilon\Omega$ estimated at step S212 and each component of the detected angular velocity Ω_c acquired from the gyro sensor **20** at step S200 into the following relational expression (16). The calibration apparatus **50** thereby calculates the calibrated angular velocity Ω_{c_cal} . As described above, the calibrated angular velocity Ω_{c_cal} is the detected angular velocity Ω_c calibrated by the calibration apparatus **50**. In the relational expression (16), $\omega c\varphi_cal$ is an angular velocity component about the X-axis in the vehicle coordinate system Σ , of the calibrated angular velocity Ω_{c_cal} . $\omega c\psi_cal$ is an angular velocity component about the Y-axis in the vehicle coordinate system Σ , of the calibrated angular velocity Ω_{c_cal} . $\omega c\theta_cal$ is an angular velocity component about the Z-axis in the vehicle coordinate system Σ , of the calibrated angular velocity Ω_{c_cal} . The superscript ‘T’ is the matrix transpose operator. The superscript ‘-1’ is the matrix inverse operator.

$$\Omega_{c_cal} = \begin{bmatrix} \omega c\varphi_cal \\ \omega c\psi_cal \\ \omega c\theta_cal \end{bmatrix} = \begin{bmatrix} \epsilon\varphi\varphi & \epsilon\psi\varphi & \epsilon\theta\varphi \\ \epsilon\varphi\psi & \epsilon\psi\psi & \epsilon\theta\psi \\ \epsilon\varphi\theta & \epsilon\psi\theta & \epsilon\theta\theta \end{bmatrix}^{-1} \times \begin{bmatrix} \omega c\varphi - \epsilon\varphi 0 \\ \omega c\psi - \epsilon\psi 0 \\ \omega c\theta - \epsilon\theta 0 \end{bmatrix} \quad (16)$$

[0149] In this way, the calibration apparatus **50** calibrates the gyro sensor **20**.

[0150] Next, how the calibration apparatus **50** estimates the acceleration error ϵA at step S218 will be described.

[0151] To describe how to estimate the acceleration error ϵA , some terms are defined as follows.

[0152] The X-axis directional component of the detected acceleration A_c detected by the acceleration sensor **40**, in the vehicle coordinate system Σ , is referred to as an X-directional acceleration acx . The Y-axis directional component of the detected acceleration A_c detected by the acceleration sensor **40**, in the vehicle coordinate system Σ , is referred to as a Y-directional acceleration acy . The Z-axis directional component of the detected acceleration A_c detected by the acceleration sensor **40**, in the vehicle coordinate system Σ , is referred to as a Z-directional acceleration acz .

[0153] The amount by which the X-directional acceleration acx changes when the X-directional acceleration in the vehicle coordinate system Σ of vehicle **1** changes by a unit amount is the X-directional acceleration sensitivity ϵ_{xx} . The amount by which the Y-directional acceleration acy changes when the Y-directional acceleration in the vehicle coordinate system Σ of vehicle **1** changes by a unit amount is the Y-directional acceleration sensitivity ϵ_{yy} . The amount by which the Z-directional acceleration acz changes when the Z-directional acceleration in the vehicle coordinate system Σ of vehicle **1** changes by a unit amount is the Z-directional acceleration sensitivity ϵ_{zz} .

[0154] The amount by which the X-directional acceleration acx changes when the Y-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the YX cross-axis sensitivity ϵ_{yx} . The amount by which the X-directional acceleration acx changes when the Z-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the ZX cross-axis sensitivity ϵ_{zx} . The amount by which the Y-directional acceleration acy changes when the X-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the XY cross-axis sensitivity ϵ_{xy} . The amount by which the Y-directional acceleration acy changes when the Z-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the ZY cross-axis sensitivity ϵ_{zy} . The amount by which the Z-directional acceleration acz changes when the X-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the XZ cross-axis sensitivity ϵ_{xz} . The amount by which the Z-directional acceleration acz changes when the Y-axis directional acceleration in the vehicle coordinate system Σ of the vehicle **1** changes by a unit amount is referred to as the YZ cross-axis sensitivity ϵ_{yz} . The X-directional acceleration sensitivity ϵ_{xx} , the Y-directional acceleration sensitivity ϵ_{yy} , and the Z-directional acceleration sensitivity ϵ_{zz} are dimensionless. The YX cross-axis sensitivity ϵ_{yx} , the ZX cross-axis sensitivity ϵ_{zx} , the XY cross-axis sensitivity ϵ_{xy} , the ZY cross-axis sensitivity ϵ_{zy} , the XZ cross-axis sensitivity ϵ_{xz} , the YZ cross-axis sensitivity ϵ_{yz} are dimensionless.

[0155] The X-directional acceleration acx when the X-axis directional component of the acceleration of the vehicle **1** in the vehicle coordinate system Σ is zero is referred to as an X-directional zero error $\epsilon x0$. The Y-directional acceleration acy when the Y-axis directional component of the acceleration of the vehicle **1** in the vehicle coordinate system Σ is zero is referred to as a Y-directional zero error $\epsilon y0$. The Z-directional acceleration acz when the Z-axis directional component of the acceleration of the vehicle **1** in the vehicle coordinate system Σ is zero is referred to as a Z-directional zero error $\epsilon z0$.

[0156] The acceleration error ϵA is represented by a 12-dimensional number vector, as shown in the following relational expression (17). In the relational expression (17), The superscript ‘T’ is the matrix transpose operator.

$$\epsilon A = [\epsilon_{xx}\epsilon_{yy}\epsilon_{zz}\epsilon_{yx}\epsilon_{zx}\epsilon_{xy}\epsilon_{zy}\epsilon_{xz}\epsilon_{yz}\epsilon x0 \ \epsilon y0 \ \epsilon z0]^T \quad (17)$$

[0157] The calibration apparatus **50** estimates the acceleration error ϵA using, for example, a Kalman filter.

[0158] Specifically, the calibration apparatus **50** uses a state equation in which the acceleration error ϵA is a state

vector, as shown in the following relational expression (18-1). The calibration apparatus **50** uses an observation equation in which the detected acceleration A_c detected by the acceleration sensor **40** is an observation vector, as shown in the following relational expression (18-2). In the state equation and the observation equation below, it is assumed that there is no noise. t is an integer equal to or greater than 0 and represents the number of updates. $\varepsilon A(t)$ is the acceleration error εA during the t^{th} update. D is a state transition matrix from $\varepsilon A(t)$ to $\varepsilon A(t+1)$. This state transition matrix for acceleration D is a 12×12 identity matrix, for example, as shown in the following relational expression (18-3). Furthermore, this observation matrix for acceleration N is a matrix represented by a_{ex} , a_{ey} , a_{ez} of the estimated acceleration A_e calculated at step **S216**, as shown in the following relational expression (18-4). As described above, a_{ex} is the X-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ . a_{ey} is the Y-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ . a_{ez} is the Z-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ .

$$\varepsilon A(t+1) = D \times \varepsilon A(t) \quad (18-1)$$

$$A_c(t) = N(t) \times \varepsilon A(t) \quad (18-2)$$

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (18-3)$$

$$N(t) = \begin{bmatrix} a_{ex} & 0 & 0 & a_{ey} & a_{ez} & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & a_{ey} & 0 & 0 & 0 & a_{ex} & a_{ez} & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & a_{ez} & 0 & 0 & 0 & 0 & a_{ex} & a_{ey} & 0 & 0 & 1 \end{bmatrix} \quad (18-4)$$

[0159] In addition, the calibration apparatus **50** estimates the acceleration error εA using, for example, the following relational expressions (19-1) to (19-5). In the following relational expressions, $G_a(t)$ is the Kalman gain during the t^{th} update. P_a is an error covariance matrix of the acceleration error εA . $P_a(t|t-1)$ is a priori error covariance matrix that is a predicted value of the error covariance matrix for acceleration P_a during the t^{th} update based on information of up to the $(t-1)^{\text{th}}$ update. $P_a(t|t)$ is the error covariance matrix for acceleration P_a based on the information of up to the t^{th} update. $\varepsilon A(t|t-1)$ is a priori estimate that is a predicted value of the acceleration error εA during the t^{th} update based on information of up to the $(t-1)^{\text{th}}$ update. $\varepsilon A(t|t)$ is a posteriori estimate that is the optimal estimate of the acceleration error εA based on information of up to the t^{th} update. I is the identity matrix. The superscript 'T' is the matrix transpose operator. The superscript '-1' is the matrix inverse operator.

$$P_a(t|t-1) = D \times P_a(t-1|t-1) \times D^T \quad (19-1)$$

$$\varepsilon A(t|t-1) = D \times \varepsilon A(t-1|t-1) \quad (19-2)$$

$$G_a(t) = P_a(t|t-1) \times N(t)^T \times \{N(t) \times P_a(t|t-1) \times N(t)^T\}^{-1} \quad (19-3)$$

$$\varepsilon A(t|t) = \varepsilon A(t|t-1) + G_a(t) \times \{A_c(t) - N(t) \times \varepsilon A(t|t-1)\} \quad (19-4)$$

$$P_a(t|t) = \{I - G_a(t) \times N(t)\} \times P_a(t|t-1) \quad (19-5)$$

[0160] Specifically, in the case of the t^{th} update, at step **S220**, the calibration apparatus **50** substitutes the state transition matrix for acceleration D , the error covariance matrix for acceleration P_a in the previous control cycle, and the transposed matrix of the state transition matrix for acceleration D into the above relational expression (19-1). The calibration apparatus **50** thereby calculates $P_a(t|t-1)$. $P_a(t|t-1)$ is the predicted value of the error covariance matrix for acceleration P_a in the current control cycle. Since the state transition matrix for acceleration D is the identity matrix, $P_a(t|t-1)$ is the same as the error covariance matrix for acceleration $P_a(t-1|t-1)$ in the previous control cycle. In addition, the initial value of the error covariance matrix for acceleration P_a is set, for example, by experiment, simulation, or the like.

[0161] In addition, the calibration apparatus **50** substitutes the state transition matrix for acceleration D and the acceleration error εA in the previous control cycle into the above-mentioned relational expression (19-2). The calibration apparatus **50** thereby calculates $\varepsilon A(t|t-1)$. $\varepsilon A(t|t-1)$ is a predicted value of the acceleration error εA in the current control cycle. Since the state transition matrix for acceleration D is the identity matrix here, $\varepsilon A(t|t-1)$ is the same as the acceleration error $\varepsilon A(t-1|t-1)$ in the previous control cycle. The initial value of the acceleration error εA is set, for example, by experiment, simulation, or the like.

[0162] The calibration apparatus **50** substitutes a_{ex} , a_{ey} , and a_{ez} estimated at step **S216** in the current control cycle into the above-mentioned relational expression (18-4). The calibration apparatus **50** thereby calculates the observation matrix for acceleration $N(t)$ in the current control cycle. As described above, a_{ex} is the X-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ . a_{ey} is the Y-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ . a_{ez} is the Z-directional component of the estimated acceleration A_e in the vehicle coordinate system Σ .

[0163] The calibration apparatus **50** substitutes the above-calculated $P_a(t|t-1)$, the above-calculated observation matrix for acceleration $N(t)$, and the transposed matrix of this observation matrix for acceleration $N(t)$ into the above-mentioned relational expression (19-3). The calibration apparatus **50** thereby calculates the Kalman gain for acceleration $G_a(t)$ in the current control cycle.

[0164] The calibration apparatus **50** generates the observation vector for acceleration in the current control cycle from components of the detected acceleration A_c acquired from the acceleration sensor **40** at step **S200**. The components of the detected acceleration A_c acquired from the acceleration sensor **40** are the X-directional acceleration a_{cx} , the Y-directional acceleration a_{cy} , and the Z-directional acceleration a_{cz} . As described above, the X-directional acceleration a_{cx} is the X-axis directional component of the detected acceleration A_c in the vehicle coordinate system Σ . The Y-directional acceleration a_{cy} is the Y-axis directional component of the detected acceleration A_c in the vehicle coordinate system Σ . The Z-directional acceleration a_{cz} is the Z-axis directional component of the detected acceleration A_c in the vehicle coordinate system Σ .

[0165] In addition, the calibration apparatus 50 substitutes the $\epsilon A(t|t-1)$ calculated above, the Kalman gain for acceleration $G_a(t)$ calculated above, the observation vector for acceleration generated above, and the observation matrix for acceleration $N(t)$ calculated above into the relational expression (19-4). The calibration apparatus 50 thereby calculates the acceleration error $\epsilon A(t|t)$ in the current control cycle.

[0166] The calibration apparatus 50 substitutes the identity matrix I , the Kalman gain for acceleration $G_a(t)$ calculated above, the observation matrix for acceleration $N(t)$ calculated above, and $P_a(t|t-1)$ calculated above into (19-5). The calibration apparatus 50 thereby calculates the error covariance matrix for acceleration $P_a(t|t)$ in the current control cycle. Therefore, in the next control cycle, the calibration apparatus 50 can calculate $P_a(t+1|t)$ using the calculated error covariance matrix for acceleration $P_a(t|t)$ in the current control cycle. $P_a(t+1|t)$ is a predicted value of the error covariance matrix for acceleration P_a in the next control cycle.

[0167] In this way, the calibration apparatus 50 estimates the acceleration error ϵA .

[0168] Next, how the calibration apparatus 50 calibrates the acceleration sensor 40 at step S220 will be described.

[0169] In the case of the t^{th} update, the calibration apparatus 50 substitutes each component of the acceleration error ϵA estimated at step S218 and each component of the detected acceleration A_c acquired from the acceleration sensor 40 at step S200 into the following relational expression (20). The calibration apparatus 50 thereby calculates the calibrated acceleration A_{c_cal} . The calibrated acceleration A_{c_cal} is the detected acceleration A_c calibrated by the calibration apparatus 50. In the relational expression (20), acx_cal is an X-axis directional component of the calibrated acceleration A_{c_cal} in the vehicle coordinate system Σ . acy_cal is a Y-axis directional component of the calibrated acceleration A_{c_cal} in the vehicle coordinate system Σ . acz_cal is a Z-axis directional component of the calibrated acceleration A_{c_cal} in the vehicle coordinate system Σ . The superscript '-1' is the matrix inverse operator.

$$A_{c_cal} = \begin{bmatrix} acx_cal \\ acy_cal \\ acz_cal \end{bmatrix} = \begin{bmatrix} \epsilon xx & \epsilon yx & \epsilon zx \\ \epsilon xy & \epsilon yy & \epsilon zy \\ \epsilon xz & \epsilon yz & \epsilon zz \end{bmatrix}^{-1} \times \begin{bmatrix} acx - \epsilon x0 \\ acy - \epsilon y0 \\ acz - \epsilon z0 \end{bmatrix} \quad (20)$$

[0170] In this way, the calibration apparatus 50 calibrates the acceleration sensor 40.

[0171] As described above, the calibration apparatus 50 calibrates the gyro sensor 20 and the acceleration sensor 40.

[0172] It will now be described that it is possible for the calibration apparatus 50 to calibrate the gyro sensor 20 and the acceleration sensor 40, whether the vehicle 1 is stopped or traveling.

[0173] The calibration apparatus 50, at step S206, estimates the attitude quantity q and the change in attitude quantity Δq of the vehicle 1 based on the first relative position vector $P1$ and the second relative position vector $P2$.

[0174] As described above, the first relative position vector $P1$ is a vector representing a relative position of the first GNSS receiver 11 to a position of the reference GNSS receiver 10 in the absolute coordinate system Σ_0 . The second relative position vector $P2$ is a vector representing a relative

position of the second GNSS receiver 12 to the position of the reference GNSS receiver 10 in the absolute coordinate system Σ_0 . The reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12 are disposed in the vehicle 1. Therefore, the first relative position vector $P1$ and the second relative position vector $P2$ do not vary, whether the vehicle 1 is stopped or traveling. Therefore, whether the vehicle 1 is stopped or traveling, the calibration apparatus 50 can estimate the attitude quantity q and the change in attitude quantity Δq of the vehicle 1.

[0175] In addition, the calibration apparatus 50 estimates, at step S210, the estimated angular velocity Ω_e based on the attitude quantity q and the change in attitude quantity Δq . The calibration apparatus 50 further estimates, at step S212, the angular velocity error $\epsilon \Omega$ of the vehicle 1 based on this estimated angular velocity Ω_e and the detected angular velocity Ω_c detected by the gyro sensor 20. The calibration apparatus 50 calibrates the detected angular velocity Ω_c detected by the gyro sensor 20 based on this angular velocity error $\epsilon \Omega$ at step S214. Therefore, the calibration apparatus 50 can calibrate the gyro sensor 20 whether the vehicle 1 is stopped or traveling.

[0176] Further, the calibration apparatus 50 estimates, at step S216, the estimated acceleration A_e based on this attitude quantity q . The calibration apparatus 50, at step S218, estimates the acceleration error ϵA of the vehicle 1 based on the estimated acceleration A_e and the detected acceleration A_c detected by the acceleration sensor 40. The calibration apparatus 50 calibrates, at step S220, the detected acceleration A_c detected by the acceleration sensor 40 based on this acceleration error ϵA . Therefore, the calibration apparatus 50 can calibrate the acceleration sensor 40 whether the vehicle 1 is stopped or traveling.

[0177] The calibration apparatus 50 can also provide the following advantages.

[0178] As described above, the calibration apparatus 50 estimates the attitude quantity q and the change in attitude quantity Δq of the vehicle 1 based on the first relative position vector $P1$ and the second relative position vector $P2$.

[0179] In cases where there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12, values of the first relative position vector $P1$ and the second relative position vector $P2$ may change. This reduces the accuracy of the attitude quantity q and the change in attitude quantity Δq of the vehicle 1 and thus reduces the accuracy of the values for the gyro sensor 20 and the acceleration sensor 40 calibrated by the calibration apparatus 50.

[0180] Thus, the calibration apparatus 50 determines whether there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12.

[0181] More specifically, the calibration apparatus 50 calculates, at step S106, the yaw angle θ of the vehicle 1 based on the attitude quantity q . Further, the calibration apparatus 50 calculates, at step S110, the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ based on the reference data D_{ref} , the first data $D1$, and the second data $D2$. The calibration apparatus 50 also calculates the estimated yaw angle θ_e of the vehicle 1 based on the reference receiver velocity V_{ref} , the first receiver velocity $V1$, and the second receiver velocity $V2$ at step S112. As described above, the reference data D_{ref} is

data transmitted from the reference GNSS receiver 10 to the calibration apparatus 50, and includes the wavenumber and the phase of the carrier wave and the ephemeris from each positioning satellite with respect to time. The first data D1 is data transmitted from the first GNSS receiver 11 to the calibration apparatus 50, and includes the wavenumber and the phase of the carrier wave and the ephemeris from each positioning satellite with respect to time. The second data D2 is data transmitted from the second GNSS receiver 12 to the calibration apparatus 50, and includes the wavenumber and the phase of the carrier wave and the ephemeris from each positioning satellite with respect to time. The ephemeris is orbital information of the positioning satellite. The reference receiver velocity V_{ref} is a velocity vector of the reference GNSS receiver 10 in the absolute coordinate system Σ_o . The first receiver velocity V_1 is a velocity vector of the first GNSS receiver 11 in the absolute coordinate system Σ_o . The second receiver velocity V_2 is a velocity vector of the second GNSS receiver 12 in the absolute coordinate system Σ_o .

[0182] The calibration apparatus 50, at step S114, determines, based on the above-calculated yaw angle θ and the estimated yaw angle θ_e , whether there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12. This determination is stored, for example, in RAM of the calibration apparatus 50. The calibration apparatus 50, at step S202, also reads from the RAM the determination as to whether there is a positional misalignment between the reference GNSS receiver 10 and the first GNSS receiver 11 or the second GNSS receiver 12.

[0183] In cases where there is no positional misalignment between the reference GNSS receiver 10, the first GNSS receiver 11, and the second GNSS receiver 12, the accuracy of the attitude quantity q and the change in attitude quantity Δq of the vehicle 1 is improved. Therefore, in such cases, the calibration apparatus 50 calibrates the gyro sensor 20 and the acceleration sensor 40. This improves the accuracy of calibration of the gyro sensor 20 and the acceleration sensor 40 by the calibration apparatus 50.

[0184] The calibration apparatus 50, at step S108, determines whether the vehicle speed V_c is equal to or higher than the vehicle speed threshold V_{c_th} . In cases where the vehicle speed V_c is equal to or higher than the vehicle speed threshold V_{c_th} , the calibration apparatus 50 calculates the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 at step S110. Where, the reference receiver velocity V_{ref} , the first receiver velocity V_1 and the second receiver velocity V_2 are higher as compared to cases where the vehicle speed V_c is lower than the vehicle speed threshold V_{c_th} . This stabilizes values of the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 , which improves the accuracy of calculation of the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 . Therefore, the accuracy of calculation of the estimated yaw angle θ_e at step S112 is improved.

[0185] Modification

[0186] In one modification, the calibration apparatus 50 differs in process steps from in the above-described embodiment. More specifically, the calibration apparatus 50 further includes a vehicle stop determiner 65 as a functional block, as illustrated in FIG. 5.

[0187] The vehicle stop determiner 65 determines whether the vehicle 1 is stopped, based on the estimated angular velocity Ω_e calculated by the angular velocity estimator 55 described above. The vehicle stop determiner 65 is responsible for execution of step S300 described later.

[0188] When the vehicle 1 is stopped, the acceleration error estimator 59 estimates the acceleration error ϵ_A of the vehicle 1 based on the estimated acceleration A_e calculated by the acceleration estimator 58 and the detected acceleration A_c detected by the acceleration sensor 40. The acceleration error estimator 59 does not estimate the acceleration error ϵ_A of the vehicle 1 when the vehicle 1 is not stopped.

[0189] Calibration of the gyro sensor 20 and the acceleration sensor 40 performed by the calibration apparatus 50 executing the program according to the modification will now be described with reference to the flowchart of FIG. 6.

[0190] The process steps from step S200 to step S216 are the same as above.

[0191] At step S300 subsequent to step S216, the calibration apparatus 50 determines whether the vehicle 1 is stopped, based on the estimated angular velocity Ω_e calculated at step S210. Step S300 is performed by the vehicle stop determiner 65.

[0192] More specifically, the calibration apparatus 50 determines whether $\omega_{e\phi}$ of the estimated angular velocity Ω_e is less than a first threshold ω_{e_th1} , $\omega_{e\psi}$ of the estimated angular velocity Ω_e is less than a second threshold ω_{e_th2} , and $\omega_{e\theta}$ of the estimated angular velocity Ω_e is less than a third threshold ω_{e_th3} . As described above, $\omega_{e\phi}$ is the angular velocity about the X-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . $\omega_{e\psi}$ is the angular velocity about the Y-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . $\omega_{e\theta}$ is the angular velocity about the Z-axis, of the estimated angular velocity Ω_e , in the vehicle coordinate system Σ . The first threshold ω_{e_th1} , the second threshold ω_{e_th2} , and the third threshold ω_{e_th3} are set by experiment, simulation, or the like.

[0193] If $\omega_{e\phi}$ is less than the first threshold ω_{e_th1} , $\omega_{e\psi}$ is less than the second threshold ω_{e_th2} , and $\omega_{e\theta}$ is less than the third threshold ω_{e_th3} , then the calibration apparatus 50 determines that the vehicle 1 is stopped as the angular velocity of the vehicle 1 is relatively small. Thereafter, the process flow proceeds to step S218. If $\omega_{e\phi}$ is equal to or greater than the first threshold ω_{e_th1} , or $\omega_{e\psi}$ is equal to or greater than the second threshold ω_{e_th2} , or $\omega_{e\theta}$ is equal to or greater than the third threshold ω_{e_th3} , then the calibration apparatus 50 determines that the vehicle 1 is not stopped as the vehicle 1 is moving. Thereafter, the process flow proceeds to step S222.

[0194] At step S218 subsequent to step S300, the calibration apparatus 50 estimates the acceleration error ϵ_A based on the estimated acceleration A_e calculated at step S216 and the detected acceleration A_c acquired from the acceleration sensor 40 at step S200. Since the vehicle 1 is stopped, only gravity is likely to be applied to the vehicle 1. This reduces noise detected by the acceleration sensor 40, thus improving the accuracy of calculation of the acceleration error ϵ_A by the calibration apparatus 50.

[0195] Then, at step S220, the calibration apparatus 50 calibrates, in the same manner as described above, the detected acceleration A_c acquired from the acceleration sensor 40 at step S200 based on the acceleration error ϵ_A estimated at step S218.

[0196] At step S222, if at step S300 the calibration apparatus 50 determines that the vehicle 1 is stopped, the calibration apparatus 50 outputs the calibrated angular velocity Ω_{c_cal} calculated at step S214 and the calibrated acceleration A_{c_cal} calculated at step S220 to the outside. If at step S300 the calibration apparatus 50 determines that the vehicle 1 is not stopped, the calibration apparatus 50 outputs only the calibrated angular velocity Ω_{c_cal} calculated at step S214 to the outside as the detected acceleration A_c is uncalibrated. Thereafter, the process flow returns to step S200.

[0197] As described above, the calibration apparatus 50 according to the modification calibrates the gyro sensor 20 and the acceleration sensor 40.

[0198] The modification described above can also provide the same advantages as the above embodiment. In the modification, the calibration apparatus 50 estimates the acceleration error ϵA when the vehicle 1 is stopped. Therefore, as described above, noise detected by the acceleration sensor 40 is reduced, which can improve the accuracy of calculation of the acceleration error ϵA by the calibration apparatus 50.

[0199] The calibration apparatus 50 determines whether the vehicle 1 is stopped, based on the estimated angular velocity Ω_e calculated at step S210. This allows the calibration apparatus 50 to determine whether the vehicle 1 is stopped without depending on the vehicle speed V_c detected by the vehicle speed sensor 30.

Other Embodiments

[0200] The present disclosure should not be limited to the embodiments described above and can be modified as deemed appropriate. The above-described embodiments are not independent from one another, and some of them can be combined as deemed appropriate unless such a combination is unreasonable. Needless to say, in the above-described embodiments, the components of the embodiments should not be necessarily deemed to be essential unless explicitly described or they are fundamentally and obviously essential, for example.

[0201] In the above-described embodiments and modifications, the calculator, the estimator, the calibrator, and the determiner and their methods described in the present disclosure may be implemented by a dedicated computer including a processor and a memory programmed to execute one or more functions embodied by computer programs. Alternatively, the calculator, the estimator, the calibrator, and the determiner and their methods described in the present disclosure may be implemented by a dedicated computer including a processor formed of one or more dedicated hardware logic circuits, or may be implemented by one or more dedicated computers including a combination of a processor and a memory programmed to execute one or more functions and a processor formed of one or more dedicated hardware logic circuits. The computer programs may be stored, as instructions to be executed by a computer, in a non-transitory, tangible computer-readable storage medium.

[0202] In the above-described embodiments, the vehicle 1 is provided with one reference GNSS receiver 10, one first GNSS receiver 11, and one second GNSS receiver 12. In an alternative embodiment, the number of reference GNSS receivers 10 is not limited to one, but may be two or more. For example, when the number of reference GNSS receivers

10 is two, the first relative position vector P1 is calculated based on the reference data Dref from one of the two reference GNSS receivers 10 and the first data D1 from the first GNSS receiver 11. The second relative position vector P2 may be calculated based on the reference data Dref from the other of the two reference GNSS receivers 10 and the second data D2 from the second GNSS receiver 12.

[0203] The number of the first GNSS receivers 11 may be two or more, not limited to one. Further, the number of the second GNSS receivers 12 may be two or more, not limited to one.

[0204] The vehicle 1 may be provided with a third GNSS receiver (not shown) different from any one of the first GNSS receiver 11 and the second GNSS receiver 12. In such an alternative embodiment, the first relative position vector P1 may be calculated based on the reference data Dref from the reference GNSS receiver 10 and data from the third GNSS receiver. The second relative position vector P2 may be calculated based on the reference data Dref from the reference GNSS receiver 10 and data from the third GNSS receiver.

[0205] In the above-described embodiments, the calibration apparatus 50 uses a wavenumber and a phase of the contemporaneous carrier wave in each of the reference data Dref and the first data D1 to calculate the first relative position vector P1 using the Moving Baseline RTK method. The calibration apparatus 50 uses a wavenumber and a phase of the contemporaneous carrier wave in each of the data for reference Dref and the second data D2 to calculate the second relative position vector P2 using the Moving Baseline RTK method.

[0206] In an alternative embodiment, the reference GNSS receiver 10 may calculate an absolute position of the reference GNSS receiver 10 based on signals from a plurality of positioning satellites (not shown). The reference GNSS receiver 10 may also transmit data of this calculated absolute position of the reference GNSS receiver 10 to the calibration apparatus 50. Further, the first GNSS receiver 11 may calculate an absolute position of the first GNSS receiver 11 based on signals from the plurality of positioning satellites (not shown). The first GNSS receiver 11 may also transmit data of this calculated absolute position of the first GNSS receiver 11 to the calibration apparatus 50. Further, the second GNSS receiver 12 may calculate an absolute position of the second GNSS receiver 12 based on signals from the plurality of positioning satellites (not shown). The second GNSS receiver 12 may also transmit data of this calculated absolute position of the second GNSS receiver 12 to the calibration apparatus 50.

[0207] In such an alternative embodiment, the X_o-axis directional component of the absolute position of the reference GNSS receiver 10 in the absolute coordinate system Σ_o is denoted by x_{ref} . The Y_o-axis directional component of the absolute position of the reference GNSS receiver 10 in the absolute coordinate system Σ_o is denoted by y_{ref} . The Z_o-axis directional component of the absolute position of the reference GNSS receiver 10 in the absolute coordinate system Σ_o is denoted by z_{ref} . The X_o-axis directional component of the absolute position of the first GNSS receiver 11 in the absolute coordinate system Σ_o is denoted by x_1 . The Y_o-axis directional component of the absolute position of the first GNSS receiver 11 in the absolute coordinate system Σ_o is denoted by y_1 . The Z_o-axis directional component of the absolute position of the first GNSS

receiver **11** in the absolute coordinate system Σ_o is denoted by z_1 . The Xo-axis directional component of the absolute position of the second GNSS receiver **12** in the absolute coordinate system Σ_o is denoted by x_2 . The Yo-axis directional component of the absolute position of the second GNSS receiver **12** in the absolute coordinate system Σ_o is denoted by y_2 . The Zo-axis directional component of the absolute position of the second GNSS receiver **12** in the absolute coordinate system Σ_o is denoted by z_2 .

[0208] Then, the calibration apparatus **50** may calculate the first relative position vector **P1** based on the absolute position of the reference GNSS receiver **10** and the absolute position of the first GNSS receiver **11**. The calibration apparatus **50** may also calculate the second relative position vector **P2** based on the absolute position of the reference GNSS receiver **10** and the absolute position of the second GNSS receiver **12**.

[0209] More specifically, as shown in the following relational expression (21), the calibration apparatus **50** calculates x_{1_rel} by subtracting x_{ref} from x_1 . The calibration apparatus **50** calculates the y_{1_rel} by subtracting the y_{ref} from the y_1 . The calibration apparatus **50** calculates z_{1_rel} by subtracting z_{ref} from z_1 . The calibration apparatus **50** calculates x_{2_rel} by subtracting x_{ref} from x_2 . The calibration apparatus **50** calculates y_{2_rel} by subtracting y_{ref} from y_2 . The calibration apparatus **50** calculates z_{2_rel} by subtracting z_{ref} from z_2 . As described above, x_{1_rel} is the Xo-axis directional component of the first relative position vector **P1** in the absolute coordinate system Σ_o . y_{1_rel} is the Yo-axis directional component of the first relative position vector **P1** in the absolute coordinate system Σ_o . z_{1_rel} is the Zo-axis directional component of the first relative position vector **P1** in the absolute coordinate system Σ_o . x_{2_rel} is the Xo-axis directional component of the second relative position vector **P2** in the absolute coordinate system Σ_o . y_{2_rel} is the Yo-axis directional component of the second relative position vector **P2** in the absolute coordinate system Σ_o . z_{2_rel} is the Zo-axis directional component of the second relative position vector **P2** in the absolute coordinate system Σ_o .

$$\begin{bmatrix} x_{1_rel} \\ y_{1_rel} \\ z_{1_rel} \\ x_{2_rel} \\ y_{2_rel} \\ z_{2_rel} \end{bmatrix} = \begin{bmatrix} x_1 - x_{ref} \\ y_1 - y_{ref} \\ z_1 - z_{ref} \\ x_2 - x_{ref} \\ y_2 - y_{ref} \\ z_2 - z_{ref} \end{bmatrix} \quad (21)$$

[0210] In this manner, the calibration apparatus **50** may calculate the first relative position vector **P1** and the second relative position vector **P2**.

[0211] In the above-described embodiments, the calibration apparatus **50**, at step **S112**, calculates the estimated yaw angle θ_e based on the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 calculated at step **S110**. In an alternative embodiment, the calibration apparatus **50** may calculate the estimated yaw angle θ_e based on one or more of the reference receiver velocity V_{ref} , the first receiver velocity V_1 , and the second receiver velocity V_2 calculated at step **S110**.

[0212] In the above-described embodiments, the calibration apparatus **50**, at step **S114**, calculates the absolute value

of a difference between the yaw angle θ calculated at step **S106** and the estimated yaw angle θ_e calculated at step **S112**, $|\theta - \theta_e|$. The calibration apparatus **50** determines whether the calculated absolute value $|\theta - \theta_e|$ is greater than the displacement threshold $\Delta\theta_{th}$. The calibration apparatus **50** thereby detects the positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12**. In an alternative embodiment, the calibration apparatus **50** is not limited in configuration to calculating the above absolute value $|\theta - \theta_e|$.

[0213] For example, the calibration apparatus **50** may divide the yaw angle θ calculated at step **S106** by the estimated yaw angle θ_e calculated at step **S112**. The calibration apparatus **50** may detect a positional misalignment between the reference GNSS receiver **10** and the first GNSS receiver **11** or the second GNSS receiver **12** by comparing this divided value with a threshold value. The threshold value for the divided value is set by experiment, simulation, or the like.

[0214] In the above-described embodiments, it is assumed that there is no noise in the state equation and the observation equation. In an alternative embodiment, noise may be taken into account in the state equation and the observation equation. For example, noise in the state equation and the observation equation for the attitude quantity q is an error in data received by each of the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12**. Noise in the state equation and the observation equation for the angular velocity error $\epsilon\Omega$ is an error in each component caused by a temperature change of the gyro sensor **20**. Further, noise in the state equation and the observation equation for the acceleration error ϵA is an error in each component caused by a temperature change of the acceleration sensor **40**.

[0215] In the above-described embodiments, the calibration apparatus **50** estimates the angular velocity error $\epsilon\Omega$ of the vehicle **1** at step **S212**. In the above-described embodiments, this angular velocity error $\epsilon\Omega$ is any one of a value for a change in detected angular velocity Ω_c detected by the gyro sensor **20** when the angular velocity of the vehicle **1** changes and a value for the detected angular velocity Ω_c detected by the gyro sensor **20** when the vehicle **1** is stopped. In an alternative embodiment, the calibration apparatus **50** may estimate only the value for the change in detected angular velocity Ω_c detected by the gyro sensor **20** when the angular velocity of the vehicle **1** changes. In another alternative embodiment, the calibration apparatus **50** may estimate only the value for the detected angular velocity Ω_c detected by the gyro sensor **20** when the vehicle **1** is stopped.

[0216] In the above-described embodiments, the calibration apparatus **50** estimates the acceleration error ϵA of the vehicle **1** at step **S218**. In the above-described embodiments, this acceleration error ϵA is any one of a value for a change in detected acceleration A_c detected by the acceleration sensor **40** when the acceleration of the vehicle **1** changes and a value for the detected acceleration A_c detected by the acceleration sensor **40** when the vehicle **1** is stopped. In an alternative embodiment, the calibration apparatus **50** may estimate only the value for the change in detected acceleration A_c detected by the acceleration sensor **40** when the acceleration of the vehicle **1** changes. In another alternative embodiment, the calibration apparatus **50** may estimate only the value for the detected acceleration A_c detected by the acceleration sensor **40** when the vehicle **1** is stopped.

[0217] In the above-described embodiments, the position coordinates of the reference GNSS receiver **10** in the vehicle coordinate system Σ are represented by Ant_ref. The position coordinates of the first GNSS receiver **11** in the vehicle coordinate system Σ are represented by Ant1. The position coordinates of the second GNSS receiver **12** in the vehicle coordinate system Σ are represented by Ant2. Here, the X coordinate of Ant_ref in the vehicle coordinate system Σ is set to 1. The Y coordinate of Ant_ref in the vehicle coordinate system Σ is set to 0. The Z coordinate of Ant_ref in the vehicle coordinate system Σ is set to 0. The X coordinate of Ant1 in the vehicle coordinate system Σ is set to 0. The Y-coordinate of Ant1 in the vehicle coordinate system Σ is set to 1. The Z-coordinate of Ant1 in the vehicle coordinate system Σ is set to 0. The X-coordinate of Ant2 in the vehicle coordinate system Σ is set to 0. The Y-coordinate of Ant2 in the vehicle coordinate system Σ is set to -1. The Z-coordinate of Ant2 in the vehicle coordinate system Σ is set to 0.

[0218] The position coordinates of each of Ant_ref, Ant1, and Ant2 are not limited to the above values. In an alternative embodiment, the position coordinates of each of Ant_ref, Ant1, and Ant2 may be set according to the reference GNSS receiver **10**, the first GNSS receiver **11**, and the second GNSS receiver **12** arranged in the vehicle **1**.

[0219] In the above-described embodiments, the calibration apparatus **50** estimates the attitude quantity q of the vehicle **1** using the extended Kalman filter. In an alternative embodiment, the calibration apparatus **50** is not limited in configuration to estimating the attitude quantity q of the vehicle **1** using the extended Kalman filter. For example, the calibration apparatus **50** may estimate the attitude quantity q of the vehicle **1** based on a direction of the first relative position vector $P1$ or a direction of the second relative position vector $P2$.

[0220] In the above-described embodiments, the calibration apparatus **50** estimates the angular velocity error $\epsilon\Omega$ using the Kalman filter. The calibration apparatus **50** is not limited in configuration to using the Kalman filter to estimate the angular velocity error $\epsilon\Omega$. For example, the calibration apparatus **50** may estimate the angular velocity error $\epsilon\Omega$ based on a difference between the estimated angular velocity Ω_e and the detected angular velocity Ω_c detected by the gyro sensor **20**.

[0221] In the above-described embodiments, the calibration apparatus **50** estimates the acceleration error ϵA using the Kalman filter. The calibration apparatus **50** is not limited in configuration to using the Kalman filter to estimate the acceleration error ϵA . For example, the calibration apparatus **50** may estimate the acceleration error ϵA based on a difference between the estimated acceleration A_e and the detected acceleration A_c detected by the acceleration sensor **40**.

[0222] In the above-described embodiments, the state transition matrix for attitude B , the state transition matrix for angular velocity C , and the state transition matrix for acceleration D are unit matrices. The state transition matrix for attitude B , the state transition matrix for angular velocity C , and the state transition matrix for acceleration D are not limited to unit matrices, and may be set to predetermined values by experiment, simulation, or the like.

[0223] In the above modification, at step **S300**, the calibration apparatus **50** determines, based on the estimated angular velocity Ω_e calculated at step **S210**, whether the vehicle **1** is stopped. The calibration apparatus **50** is not

limited in configuration to determining whether the vehicle **1** is stopped based on the estimated angular velocity Ω_e .

[0224] For example, the calibration apparatus **50** may determine whether the vehicle **1** is stopped, based on the vehicle speed V_c detected by the vehicle speed sensor **30**. More specifically, the calibration apparatus **50** may determine that the vehicle **1** is stopped when the vehicle speed V_c is lower than a threshold value. The calibration apparatus **50** may determine that the vehicle **1** is not stopped when the vehicle speed V_c is equal to or higher than the threshold value. This threshold value for the vehicle speed V_c may be set by experiment, simulation, or the like.

What is claimed is:

1. An apparatus for calibrating an inertial sensor configured to detect an angular velocity of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the apparatus comprising:

a position calculator configured to calculate a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculate a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites;

an attitude estimator configured to estimate a value for an attitude of the vehicle and a value for a change in attitude of the vehicle based on the first relative position and the second relative position;

an angular velocity estimator configured to estimate a value for an angular velocity of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator and the value for the change in attitude of the vehicle estimated by the attitude estimator;

an error estimator configured to, based on the value for the angular velocity of the vehicle estimated by the angular velocity estimator and a value for the angular velocity of the vehicle detected by the inertial sensor, estimate a value for an angular velocity error that is an error between the value for the angular velocity of the vehicle estimated by the angular velocity estimator and the value for the angular velocity of the vehicle detected by the inertial sensor; and

a calibrator configured to calibrate the value for the angular velocity of the vehicle detected by the inertial sensor based on the value for the angular velocity error estimated by the error estimator.

2. The apparatus according to claim 1, wherein

the attitude estimator is configured to calculate a predicted value for the attitude of the vehicle at a current time based on the values for the attitude of the vehicle before the current time, and estimate the value for the attitude of the vehicle at the current time based on the predicted value for the attitude of the vehicle calculated, the first relative position, and the second relative position, and

- estimate a value for a change in attitude of the vehicle at the current time based on the values for the attitude of the vehicle before the current time and the estimated value for the attitude of the vehicle at the current time.
3. The apparatus according to claim 1, wherein the value for the angular velocity error includes values for a change in angular velocity of the vehicle detected by the inertial sensor when the angular velocity of the vehicle changes or values for the angular velocity of the vehicle detected by the inertial sensor when the vehicle is stopped, and the error estimator is configured to calculate the predicted value for the angular velocity error at the current time based on the values for the angular velocity error before the current time, and estimate the value for the angular velocity error at the current time based on the predicted value for the angular velocity error calculated, the value for the angular velocity of the vehicle estimated by the angular velocity estimator, and the value for the angular velocity of the vehicle detected by the inertial sensor.
 4. The apparatus according to claim 1, wherein the attitude estimator is configured to estimate the value for the attitude of the vehicle based on the positions of the reference receiver, the first receiver, and the second receiver that are preset in the vehicle.
 5. The apparatus according to claim 1, further comprising a positional misalignment determiner configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, wherein the calibrator is configured to, in response to the positional misalignment determiner determining that there is no positional misalignment between the reference receiver, the first receiver, and the second receiver, calibrate the inertial sensor.
 6. The apparatus according to claim 5, further comprising: a converter configured to estimate a value for a yaw angle of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator; a speed calculator configured to calculate a speed of the reference receiver using the data based on the signals received by the reference receiver from the positioning satellites, a speed of the first receiver using the data based on the signals received by the first receiver from the positioning satellites, and a velocity of the second receiver using the data based on the signals received by the second receiver from the positioning satellites; and a yaw angle estimator configured to estimate the value for the yaw angle of the vehicle based on the speed of the reference receiver, the speed of the first receiver, and the speed of the second receiver, wherein the positional misalignment determiner is configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, based on the value for the yaw angle of the vehicle estimated by the converter and the value for the yaw angle of the vehicle estimated by the yaw angle estimator.
 7. The apparatus according to claim 5, further comprising: a converter configured to estimate a value for a yaw angle of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator; a speed calculator configured to calculate at least one of a speed of the reference receiver using the data based on the signals received by the reference receiver from the positioning satellites, a speed of the first receiver using the data based on the signals received by the first receiver from the positioning satellites, and a velocity of the second receiver using the data based on the signals received by the second receiver from the positioning satellites; and a yaw angle estimator configured to estimate the value for the yaw angle of the vehicle based on the calculated at least one of the speed of the reference receiver, the speed of the first receiver, and the speed of the second receiver, wherein the positional misalignment determiner is configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, based on the value for the yaw angle of the vehicle estimated by the converter and the value for the yaw angle of the vehicle estimated by the yaw angle estimator.
 8. The apparatus according to claim 5, further comprising a speed determiner configured to determine whether a speed of the vehicle is equal to or higher than a threshold value for the speed of the vehicle, wherein the positional misalignment determiner is configured to, in response to the speed determiner determining that the speed of the vehicle being equal to or higher than the threshold value for the speed of the vehicle, determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver.
 9. An apparatus for calibrating an inertial sensor configured to detect an acceleration of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the apparatus comprising:
 - a position calculator configured to calculate a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculate a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites;
 - an attitude estimator configured to estimate a value for an attitude of the vehicle based on the first relative position and the second relative position;
 - an acceleration estimator configured to estimate a value for an acceleration of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator;
 - an error estimator configured to, based on the value for the acceleration of the vehicle estimated by the acceleration estimator and a value for the acceleration of the vehicle detected by the inertial sensor, estimate a value for an acceleration error that is an error between the value for the acceleration of the vehicle estimated by

- the acceleration estimator and the value for the acceleration of the vehicle detected by the inertial sensor; and
- a calibrator configured to calibrate the value for the acceleration of the vehicle detected by the inertial sensor based on the value for the acceleration error estimated by the error estimator.
- 10.** The apparatus according to claim **9**, wherein the attitude estimator is configured to calculate a predicted value for the attitude of the vehicle at a current time based on the values for the attitude of the vehicle before the current time, and estimate the value for the attitude of the vehicle based on the predicted value for the attitude of the vehicle calculated, the first relative position, and the second relative position.
- 11.** The apparatus according to claim **9**, wherein the value for the acceleration error includes values for a change in acceleration of the vehicle detected by the inertial sensor when the acceleration of the vehicle changes or values for the acceleration of the vehicle detected by the inertial sensor when the vehicle is stopped, and the error estimator is configured to calculate the predicted value for the acceleration error at a current time based on the values for the acceleration error before the current time, and estimate the value for the acceleration error at the current time based on the predicted value for the acceleration error calculated, the value for the acceleration of the vehicle estimated by the acceleration estimator, and the value for the acceleration of the vehicle detected by the inertial sensor.
- 12.** The apparatus according to claim **9**, further comprising a vehicle stop determiner configured to determine whether the vehicle is stopped, wherein the calibrator is configured to calibrate the value for the acceleration of the vehicle detected by the inertial sensor when the vehicle is stopped.
- 13.** The apparatus according to claim **12**, wherein the attitude estimator is configured to estimate a value for a change in attitude of the vehicle at the current time based on the values for the attitude of the vehicle before the current time and the value for the attitude of the vehicle at the current time, the apparatus further comprises an angular velocity estimator configured to estimate values for the angular velocity of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator and the value for the change in attitude of the vehicle estimated by the attitude estimator, and the vehicle stop determiner is configured to, in response to each of the values for the angular velocity of the vehicle estimated by the angular velocity estimator being less than a threshold value, determine that the vehicle is stopped, and in response to at least one of the values for the angular velocity of the vehicle estimated by the angular velocity estimator being equal to or greater than the threshold value, determine that the vehicle is not stopped.
- 14.** The apparatus according to claim **9**, wherein the attitude estimator is configured to estimate the value for the attitude of the vehicle based on the positions of the reference receiver, the first receiver, and the second receiver that are preset in the vehicle.
- 15.** The apparatus according to claim **9**, further comprising a positional misalignment determiner configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, wherein the calibrator is configured to, in response to the positional misalignment determiner determining that there is no positional misalignment between the reference receiver, the first receiver, and the second receiver, calibrate the inertial sensor.
- 16.** The apparatus according to claim **15**, further comprising: a converter configured to estimate a value for a yaw angle of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator; a speed calculator configured to calculate a speed of the reference receiver using the data based on the signals received by the reference receiver from the positioning satellites, a speed of the first receiver using the data based on the signals received by the first receiver from the positioning satellites, and a velocity of the second receiver using the data based on the signals received by the second receiver from the positioning satellites; and a yaw angle estimator configured to estimate the value for the yaw angle of the vehicle based on the speed of the reference receiver, the speed of the first receiver, and the speed of the second receiver, wherein the positional misalignment determiner is configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, based on the value for the yaw angle of the vehicle estimated by the converter and the value for the yaw angle of the vehicle estimated by the yaw angle estimator.
- 17.** The apparatus according to claim **15**, further comprising: a converter configured to estimate a value for a yaw angle of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator; a speed calculator configured to calculate at least one of a speed of the reference receiver using the data based on the signals received by the reference receiver from the positioning satellites, a speed of the first receiver using the data based on the signals received by the first receiver from the positioning satellites, and a velocity of the second receiver using the data based on the signals received by the second receiver from the positioning satellites; and a yaw angle estimator configured to estimate the value for the yaw angle of the vehicle based on the calculated at least one of the speed of the reference receiver, the speed of the first receiver, and the speed of the second receiver, wherein the positional misalignment determiner is configured to determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver, based on the value for the yaw angle of the vehicle estimated by the converter and the value for the yaw angle of the vehicle estimated by the yaw angle estimator.
- 18.** The apparatus according to claim **15**, further comprising

a speed determiner configured to determine whether a speed of the vehicle is equal to or higher than a threshold value for the speed of the vehicle,

wherein the positional misalignment determiner is configured to, in response to the speed determiner determining that the speed of the vehicle being equal to or higher than the threshold value for the speed of the vehicle, determine whether there is a positional misalignment between the reference receiver and the first receiver or the second receiver.

19. A method for calibrating an inertial sensor configured to detect an angular velocity of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the method comprising:

calculating a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculating a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites;

estimating a value for an attitude of the vehicle and a value for a change in attitude of the vehicle based on the first relative position and the second relative position;

estimating a value for an angular velocity of the vehicle based on the value for the attitude of the vehicle estimated by the attitude estimator and the value for the change in attitude of the vehicle estimated by the attitude estimator;

based on the value for the angular velocity of the vehicle estimated and a value for the angular velocity of the vehicle detected by the inertial sensor, estimating a value for an angular velocity error that is an error

between the value for the angular velocity of the vehicle estimated and the value for the angular velocity of the vehicle detected by the inertial sensor; and calibrating the value for the angular velocity of the vehicle detected by the inertial sensor based on the value for the angular velocity error estimated by the error estimator.

20. A method for calibrating an inertial sensor configured to detect an acceleration of a vehicle, the vehicle being equipped with at least one reference receiver which receives signals from a plurality of positioning satellites, at least one first receiver which receives signals from the plurality of positioning satellites, and at least one second receiver which receives signals from the plurality of positioning satellites, the method comprising:

calculating a first relative position of the first receiver to a position of the reference receiver based on data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the first receiver from the positioning satellites, and calculating a second relative position of the second receiver to the position of the reference receiver based on the data based on the signals received by the reference receiver from the positioning satellites and data based on the signals received by the second receiver from the positioning satellites;

estimating a value for an attitude of the vehicle based on the first relative position and the second relative position;

estimating a value for an acceleration of the vehicle based on the value for the attitude of the vehicle estimated; based on the value for the acceleration of the vehicle estimated and a value for the acceleration of the vehicle detected by the inertial sensor, estimating a value for an acceleration error that is an error between the value for the acceleration of the vehicle estimated and the value for the acceleration of the vehicle detected by the inertial sensor; and

calibrating the value for the acceleration of the vehicle detected by the inertial sensor based on the value for the acceleration error estimated.

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