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Chencinski et al.

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(45) **Date of Patent: Aug. 12, 2025**

(54) **MOTION TRACKING CALIBRATION FOR WEARABLE DEVICE**

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(73) Assignee: **Microsoft Technology Licensing, LLC**, Redmond, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 181 days.

(21) Appl. No.: **18/161,687**

(22) Filed: **Jan. 30, 2023**

(65) **Prior Publication Data**

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(51) **Int. Cl.**
H04S 7/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H04S 7/304*** (2013.01)

(58) **Field of Classification Search**
CPC H04S 7/034; H04S 7/304; H04S 3/008; H04S 3/004; H04R 5/033
See application file for complete search history.

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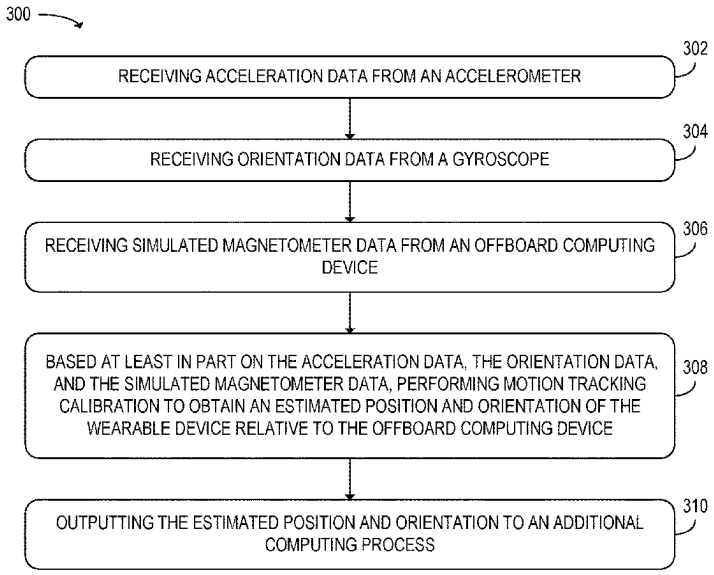
Primary Examiner — Rasha S Al Aubaidi
(74) *Attorney, Agent, or Firm* — Alleman Hall & Tuttle LLP

(57) **ABSTRACT**

A wearable device is provided, including an accelerometer, a gyroscope, and a processing device. The processing device is configured to receive acceleration data from the accelerometer, receive orientation data from the gyroscope, and receive simulated magnetometer data from an offboard computing device. Based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, the processing device is further configured to perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The processing device is further configured to output the estimated position and orientation to an additional computing process.

25 Claims, 20 Drawing Sheets



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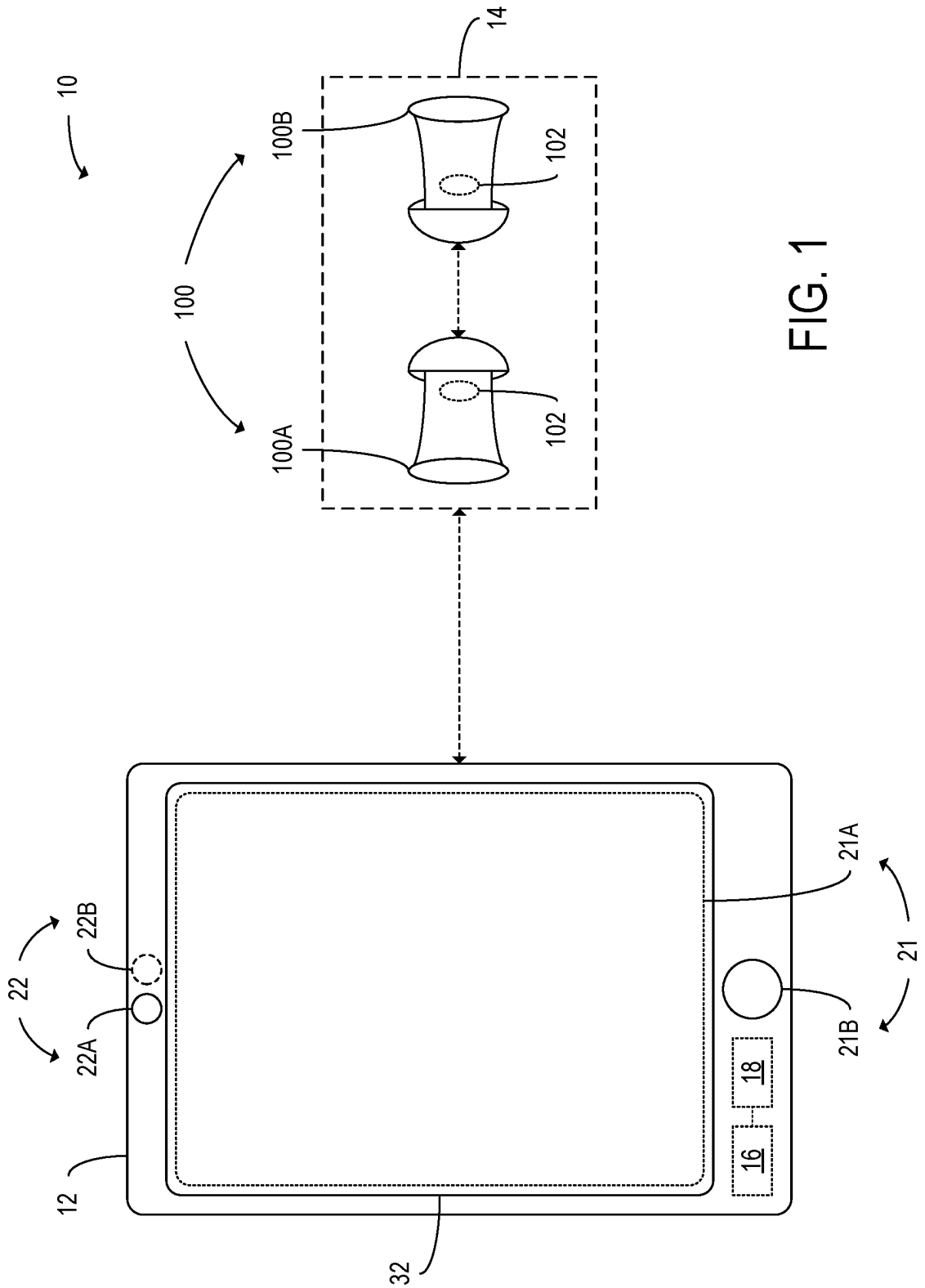


FIG. 1

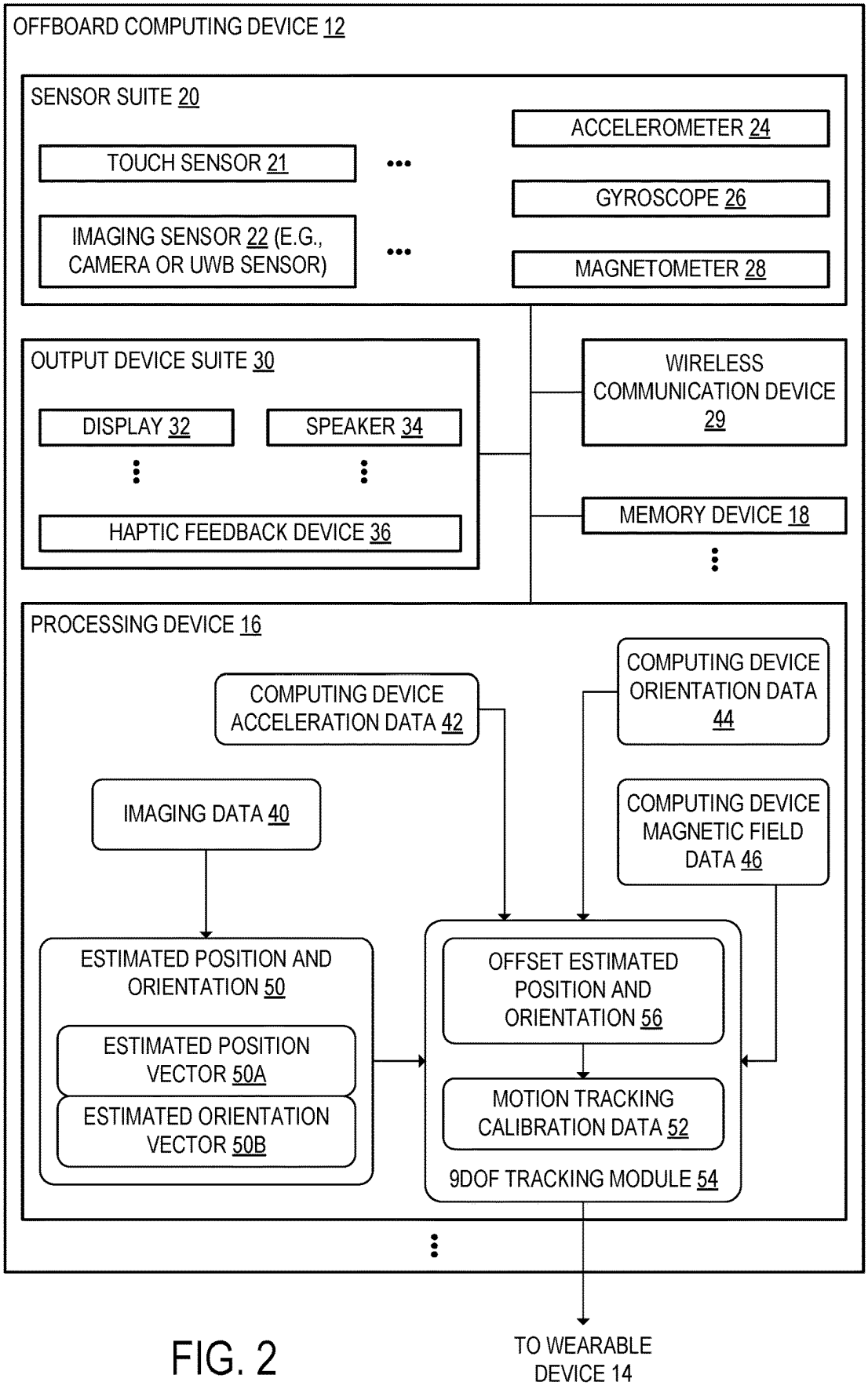

OFFBOARD COMPUTING DEVICE 12
SENSOR SUITE 20
TOUCH SENSOR 21
IMAGING SENSOR 22 (E.G., CAMERA OR UWB SENSOR)
ACCELEROMETER 24
GYROSCOPE 26
MAGNETOMETER 28
OUTPUT DEVICE SUITE 30
DISPLAY 32
SPEAKER 34
HAPTIC FEEDBACK DEVICE 36
WIRELESS COMMUNICATION DEVICE 29
MEMORY DEVICE 18
PROCESSING DEVICE 16
COMPUTING DEVICE ACCELERATION DATA 42
COMPUTING DEVICE ORIENTATION DATA 44
IMAGING DATA 40
COMPUTING DEVICE MAGNETIC FIELD DATA 46
ESTIMATED POSITION AND ORIENTATION 50
ESTIMATED POSITION VECTOR 50A
ESTIMATED ORIENTATION VECTOR 50B
OFFSET ESTIMATED POSITION AND ORIENTATION 56
MOTION TRACKING CALIBRATION DATA 52
9DOF TRACKING MODULE 54
TO WEARABLE DEVICE 14

FIG. 2

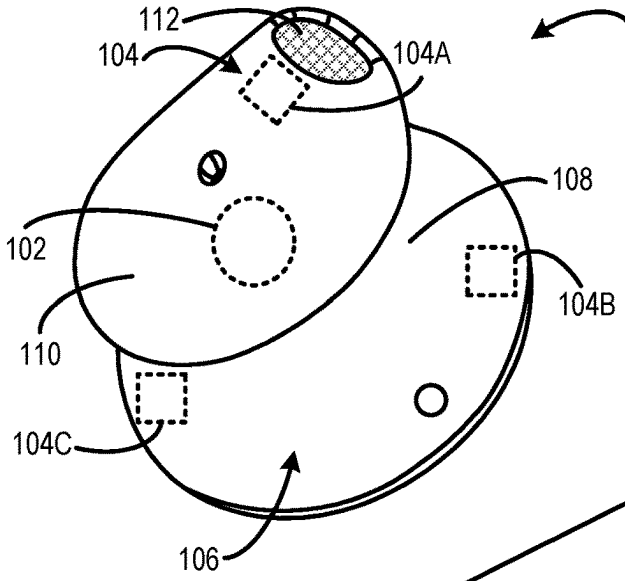


FIG. 3A

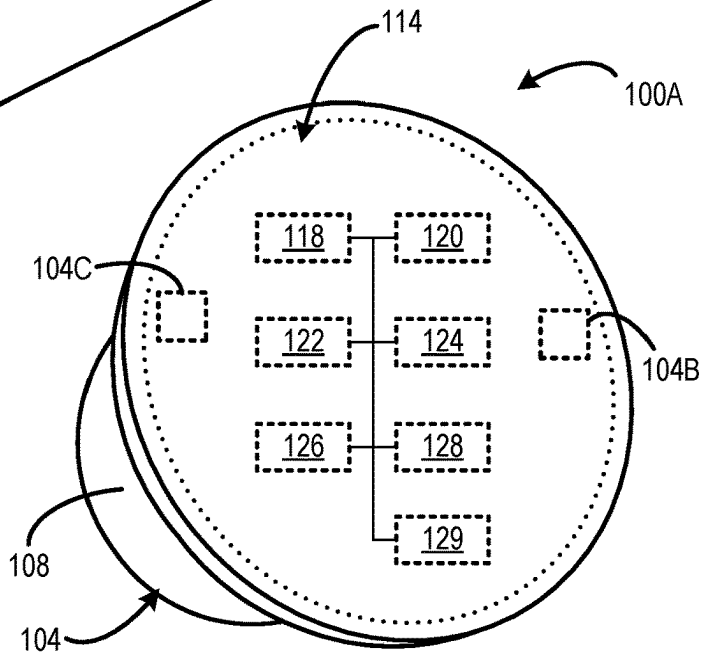


FIG. 3B

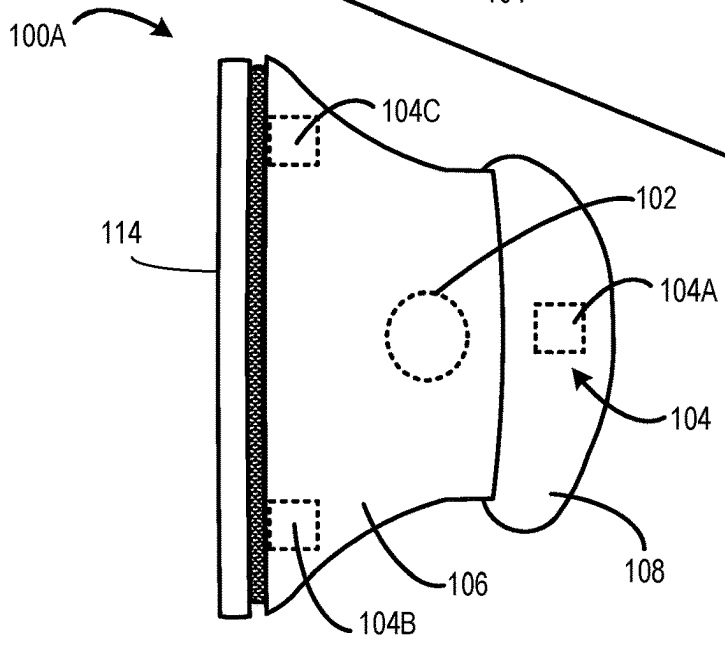
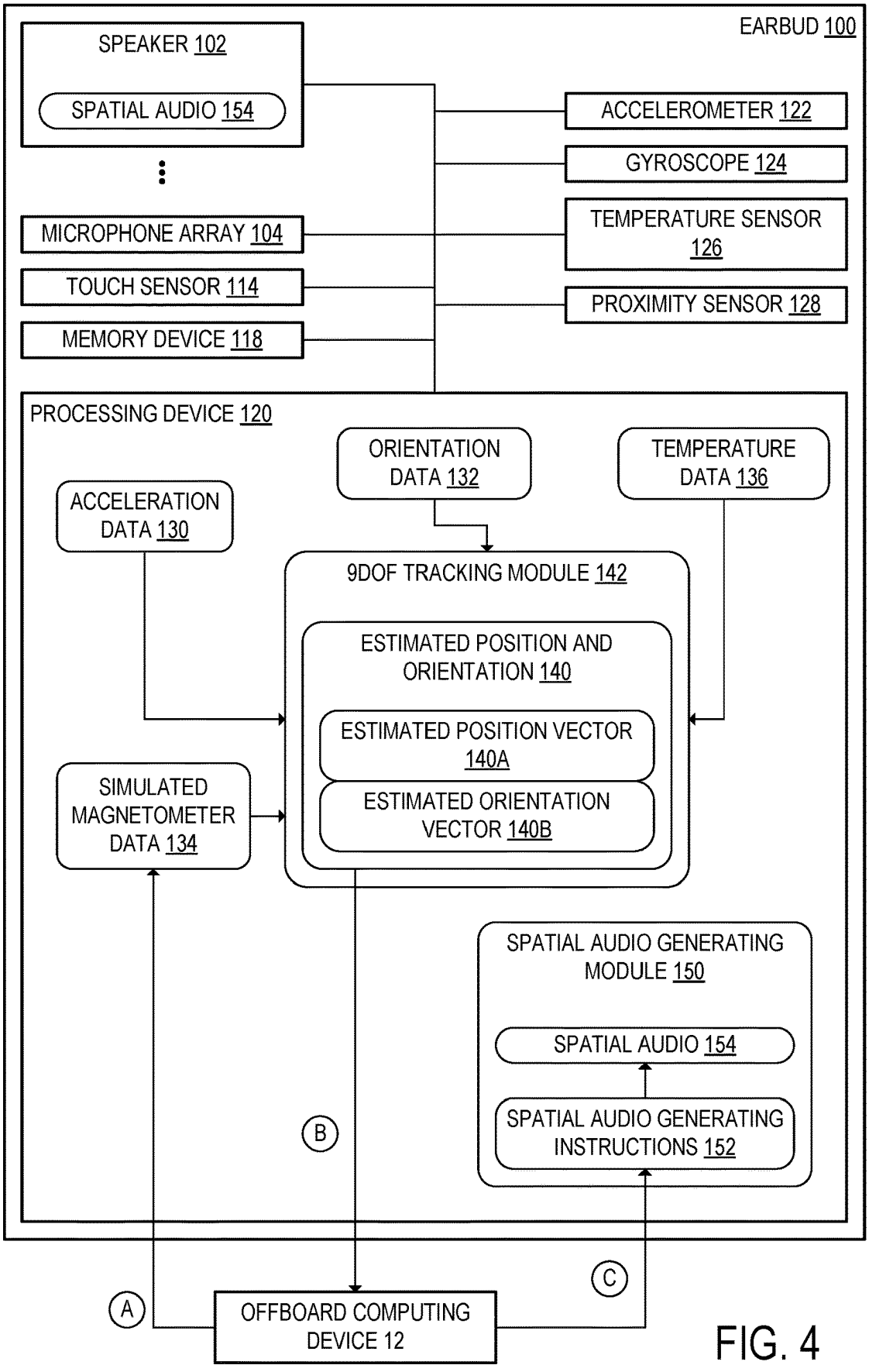


FIG. 3C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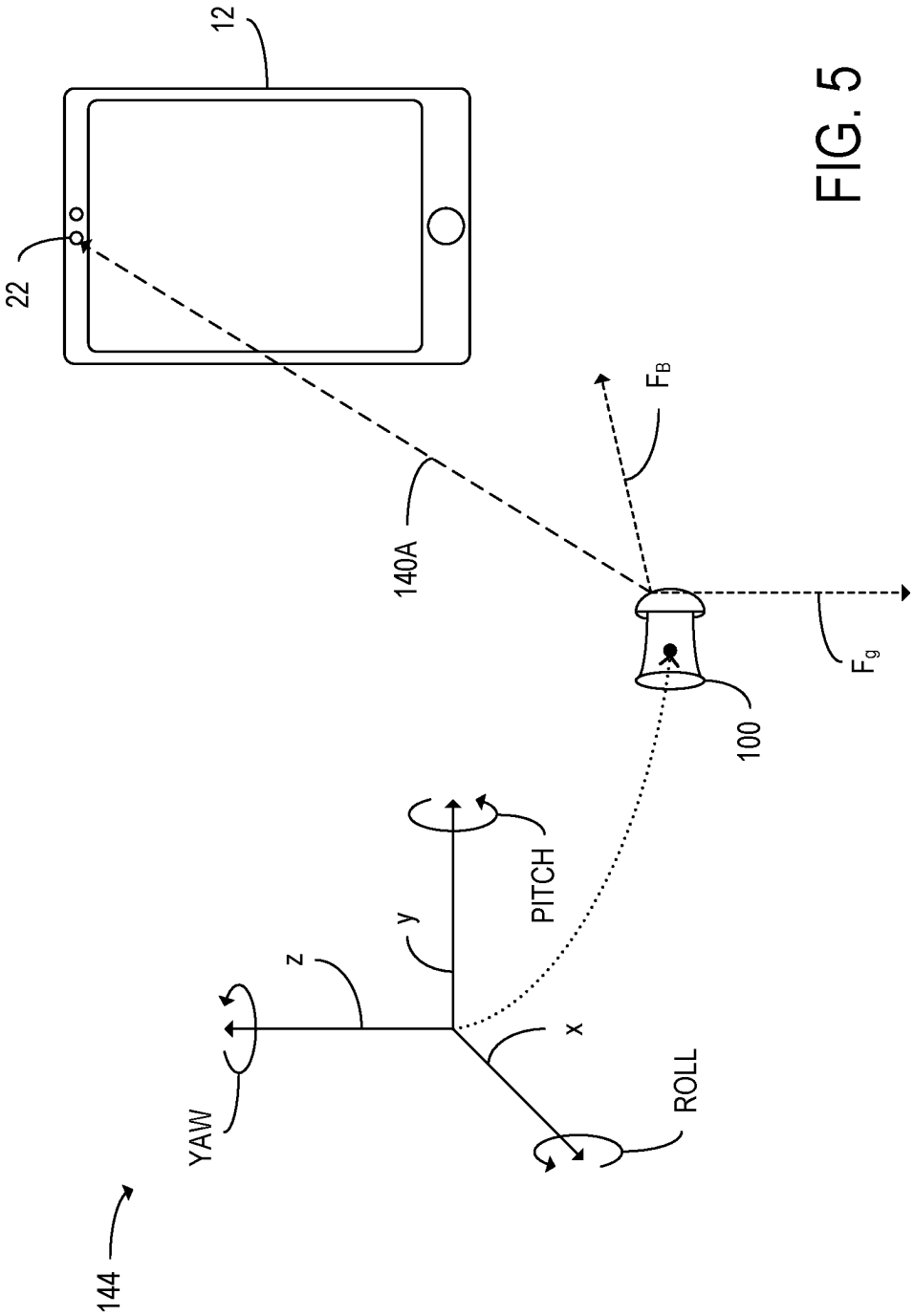
SPEAKER 102
SPATIAL AUDIO 154
MICROPHONE ARRAY 104
TOUCH SENSOR 114
MEMORY DEVICE 118
ACCELEROMETER 122
GYROSCOPE 124
TEMPERATURE SENSOR 126
PROXIMITY SENSOR 128
PROCESSING DEVICE 120
ORIENTATION DATA 132
TEMPERATURE DATA 136
ACCELERATION DATA 130
9DOF TRACKING MODULE 142
ESTIMATED POSITION AND ORIENTATION 140
ESTIMATED POSITION VECTOR 140A
ESTIMATED ORIENTATION VECTOR 140B
SIMULATED MAGNETOMETER DATA 134
SPATIAL AUDIO GENERATING MODULE 150
SPATIAL AUDIO 154
SPATIAL AUDIO GENERATING INSTRUCTIONS 152
A
B
C
OFFBOARD COMPUTING DEVICE 12

FIG. 4



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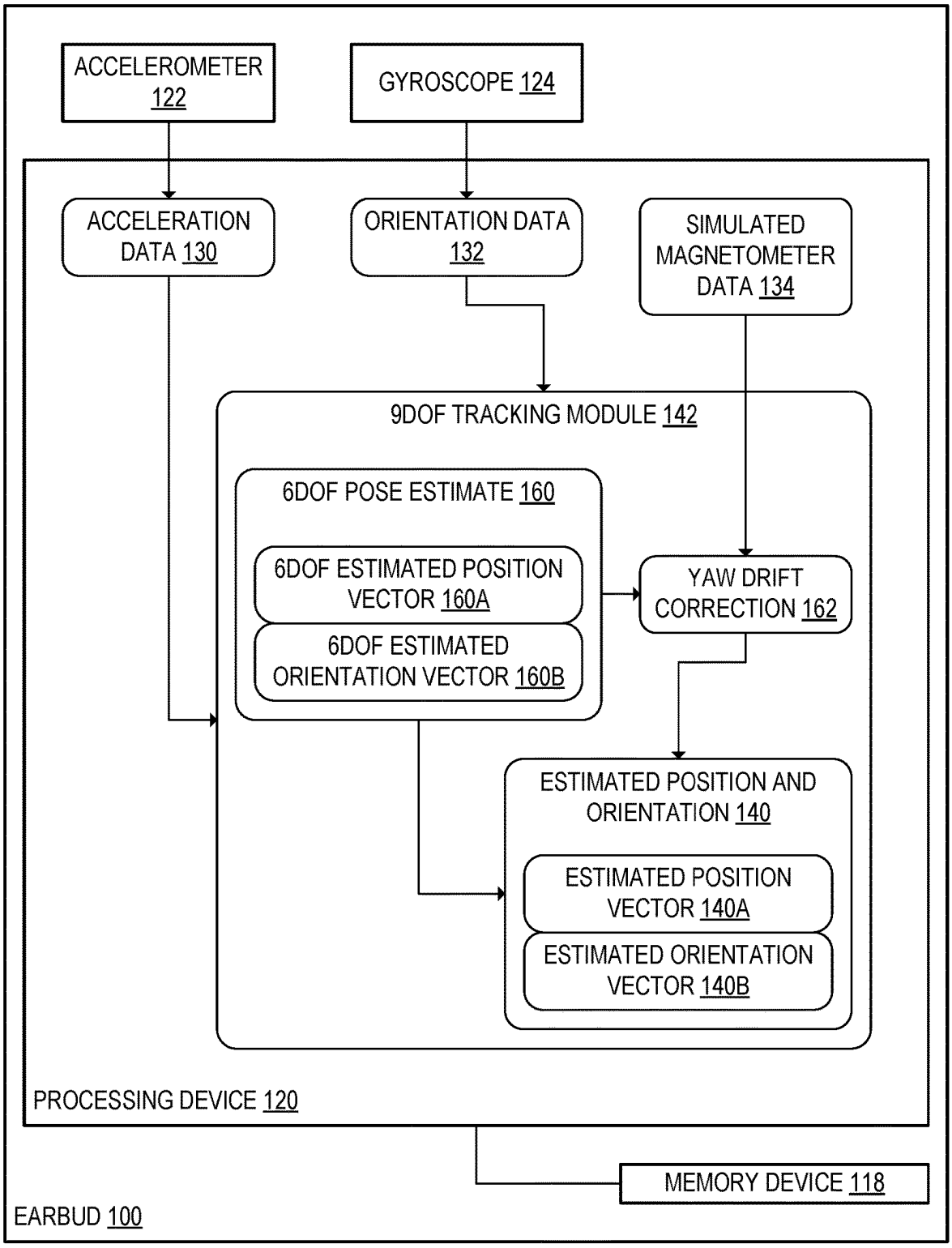
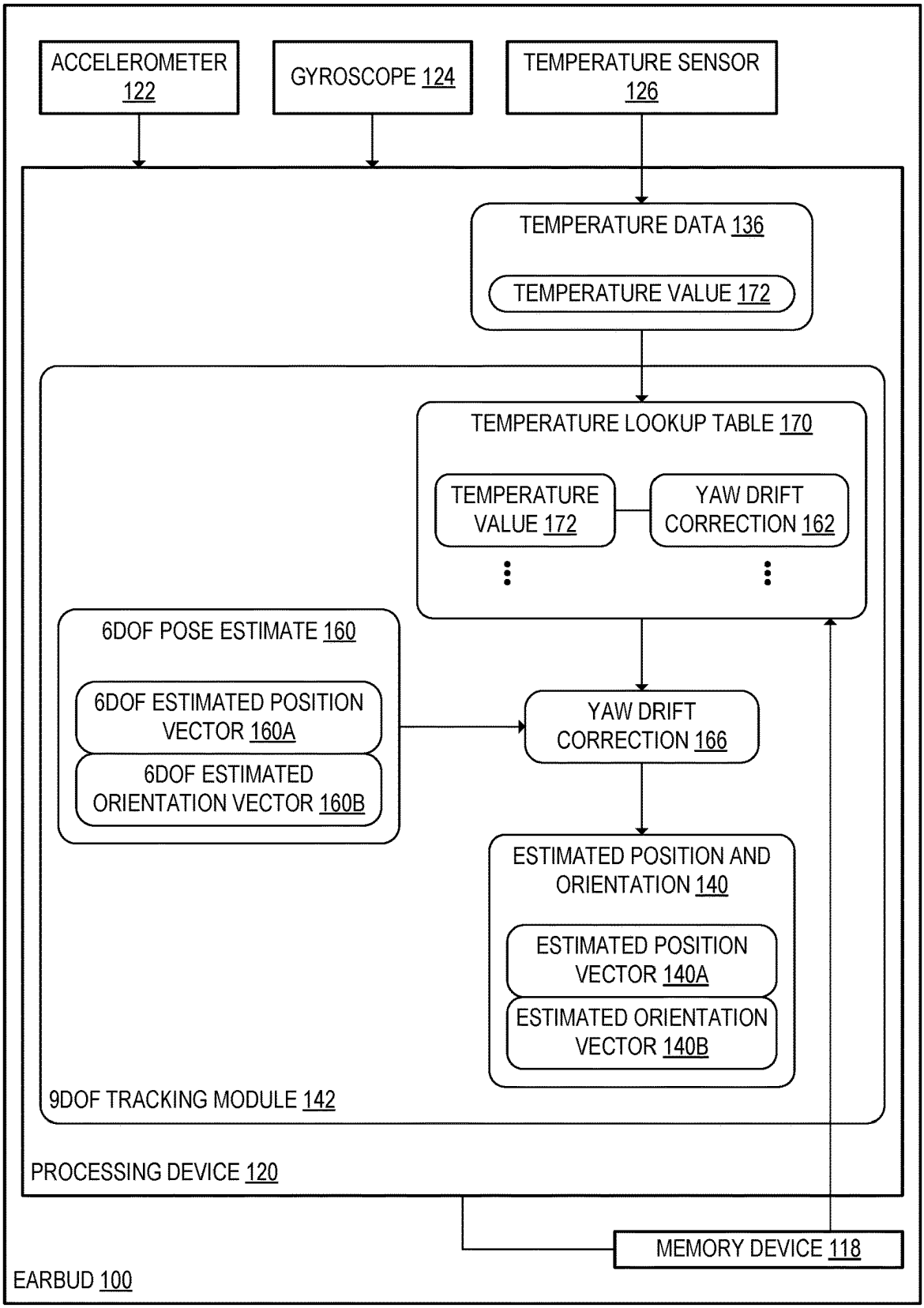

ACCELEROMETER 122
GYROSCOPE 124
ACCELERATION DATA 130
ORIENTATION DATA 132
SIMULATED MAGNETOMETER DATA 134
9DOF TRACKING MODULE 142
6DOF POSE ESTIMATE 160
6DOF ESTIMATED POSITION VECTOR 160A
6DOF ESTIMATED ORIENTATION VECTOR 160B
YAW DRIFT CORRECTION 162
ESTIMATED POSITION AND ORIENTATION 140
ESTIMATED POSITION VECTOR 140A
ESTIMATED ORIENTATION VECTOR 140B
PROCESSING DEVICE 120
MEMORY DEVICE 118
EARBUD 100

FIG. 6A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GYROSCOPE 124
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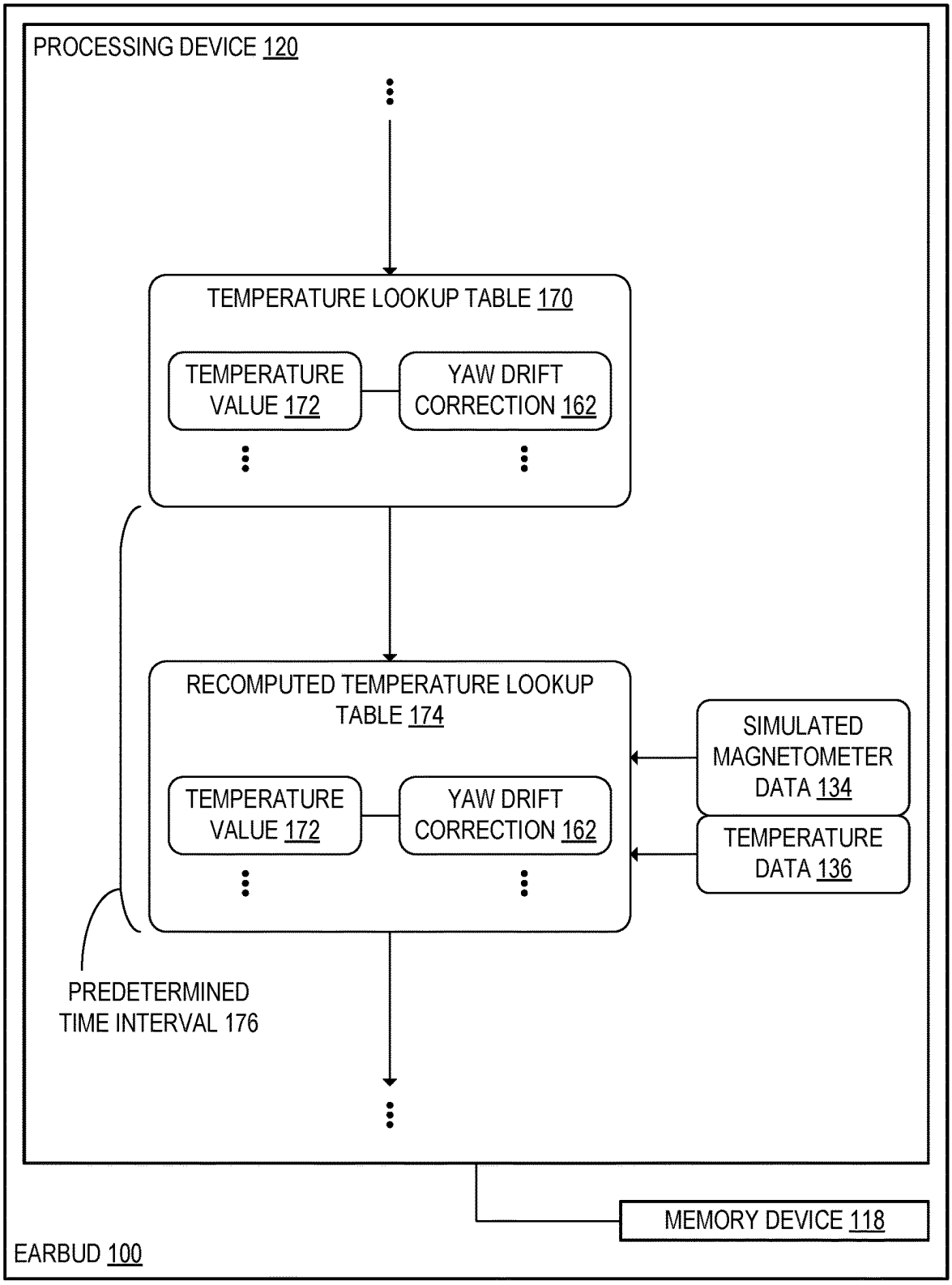
TEMPERATURE DATA 136
TEMPERATURE VALUE 172
TEMPERATURE LOOKUP TABLE 170
TEMPERATURE VALUE 172
YAW DRIFT CORRECTION 162
6DOF POSE ESTIMATE 160
6DOF ESTIMATED POSITION VECTOR 160A
6DOF ESTIMATED ORIENTATION VECTOR 160B
YAW DRIFT CORRECTION 166
ESTIMATED POSITION AND ORIENTATION 140
ESTIMATED POSITION VECTOR 140A
ESTIMATED ORIENTATION VECTOR 140B
9DOF TRACKING MODULE 142
PROCESSING DEVICE 120
MEMORY DEVICE 118
EARBUD 100

FIG. 6B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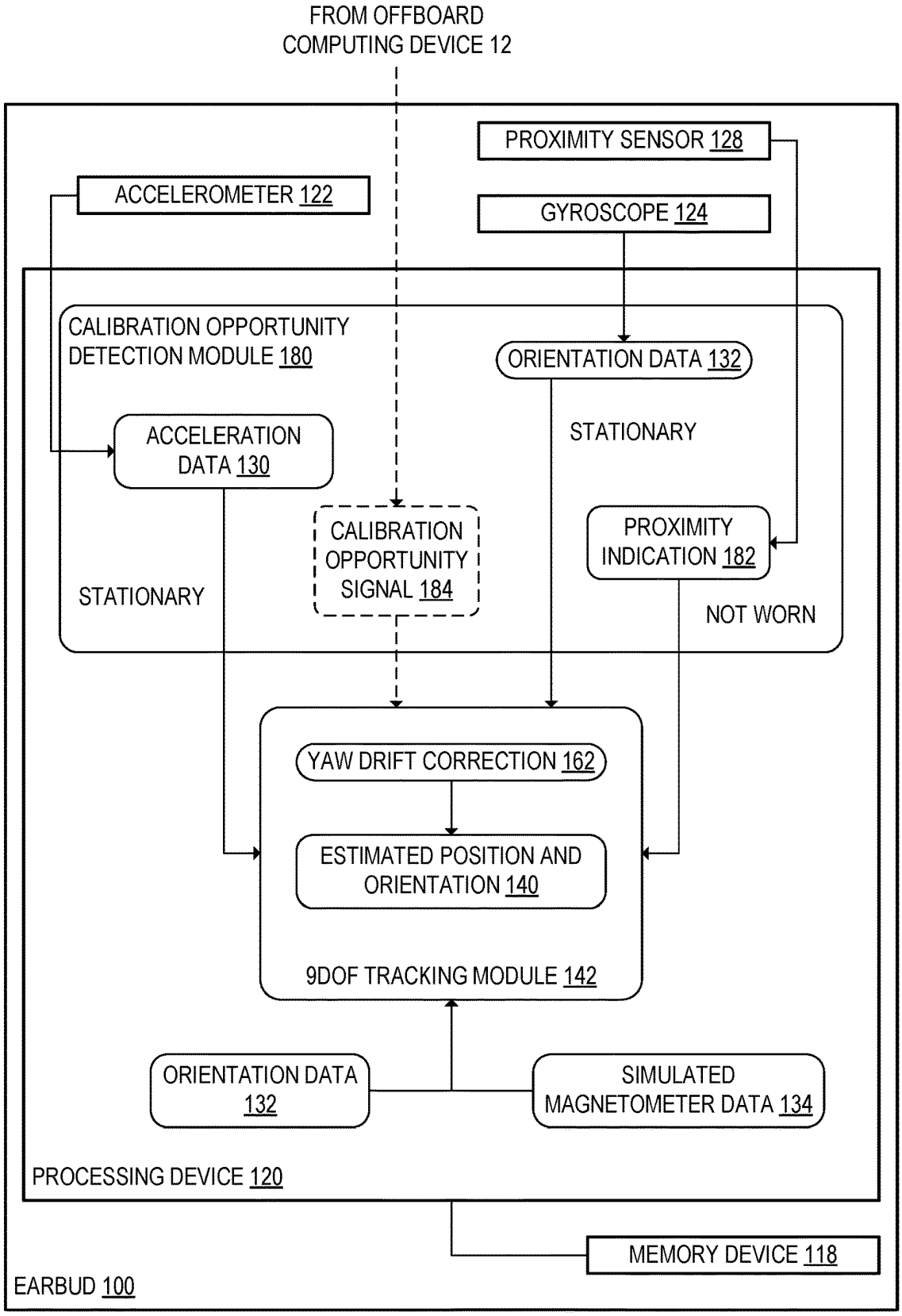
TEMPERATURE LOOKUP TABLE 170
TEMPERATURE VALUE 172
YAW DRIFT CORRECTION 162
RECOMPUTED TEMPERATURE LOOKUP TABLE 174
TEMPERATURE VALUE 172
YAW DRIFT CORRECTION 162
SIMULATED MAGNETOMETER DATA 134
TEMPERATURE DATA 136
PREDETERMINED TIME INTERVAL 176
MEMORY DEVICE 118
EARBUD 100

FIG. 6C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GYROSCOPE 124
CALIBRATION OPPORTUNITY DETECTION MODULE 180
ORIENTATION DATA 132
ACCELERATION DATA 130
STATIONARY
CALIBRATION OPPORTUNITY SIGNAL 184
PROXIMITY INDICATION 182
STATIONARY
NOT WORN
YAW DRIFT CORRECTION 162
ESTIMATED POSITION AND ORIENTATION 140
9DOF TRACKING MODULE 142
ORIENTATION DATA 132
SIMULATED MAGNETOMETER DATA 134
PROCESSING DEVICE 120
MEMORY DEVICE 118
EARBUD 100

FIG. 7A

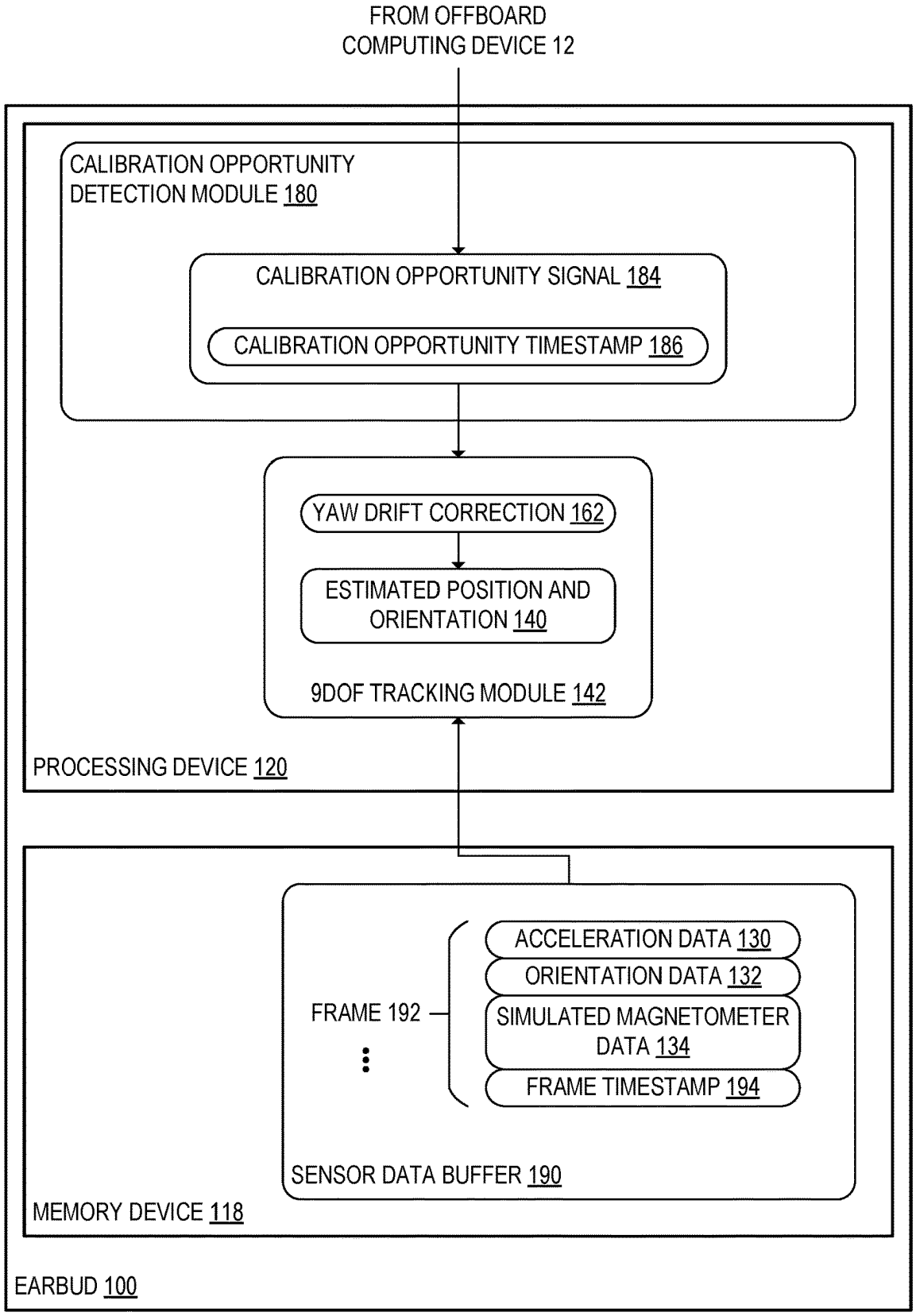

FROM OFFBOARD COMPUTING DEVICE 12
CALIBRATION OPPORTUNITY DETECTION MODULE 180
CALIBRATION OPPORTUNITY SIGNAL 184
CALIBRATION OPPORTUNITY TIMESTAMP 186
YAW DRIFT CORRECTION 162
ESTIMATED POSITION AND ORIENTATION 140
9DOF TRACKING MODULE 142
PROCESSING DEVICE 120
FRAME 192
ACCELERATION DATA 130
ORIENTATION DATA 132
SIMULATED MAGNETOMETER DATA 134
FRAME TIMESTAMP 194
SENSOR DATA BUFFER 190
MEMORY DEVICE 118
EARBUD 100

FIG. 7B

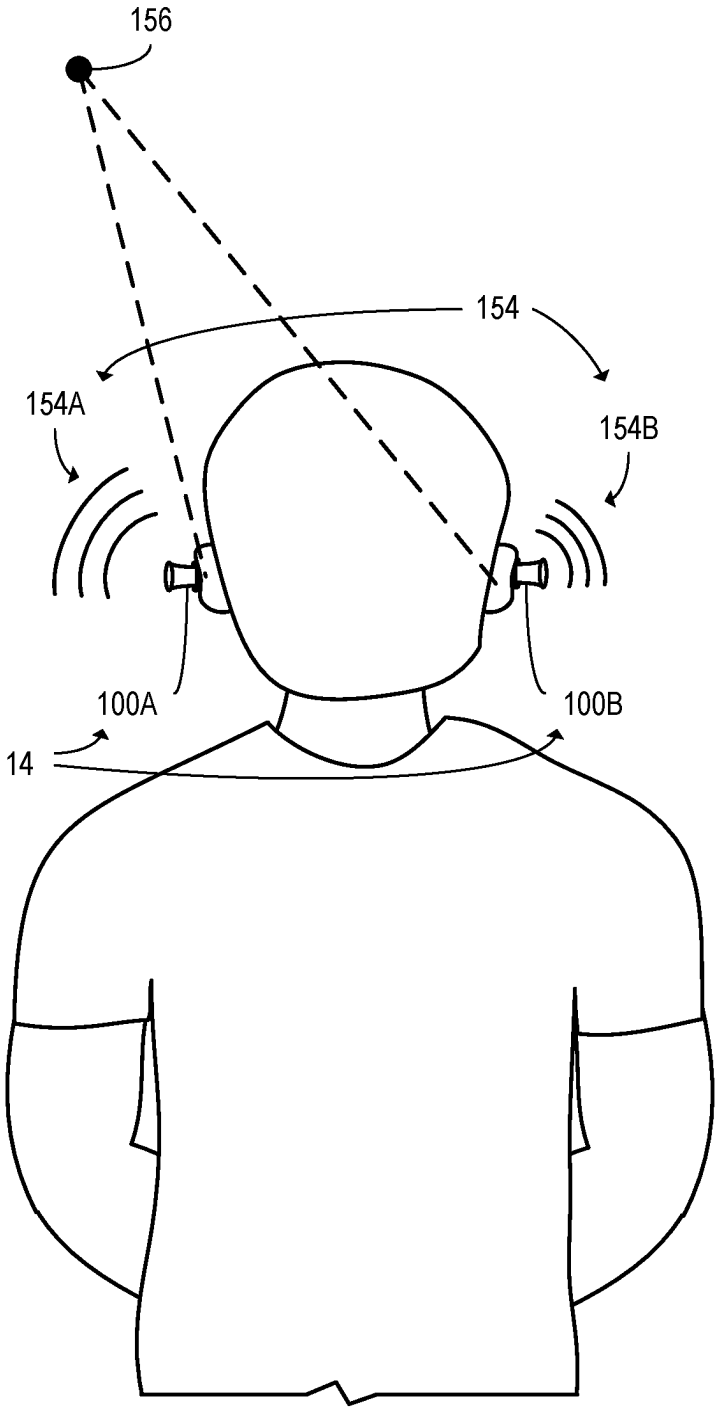
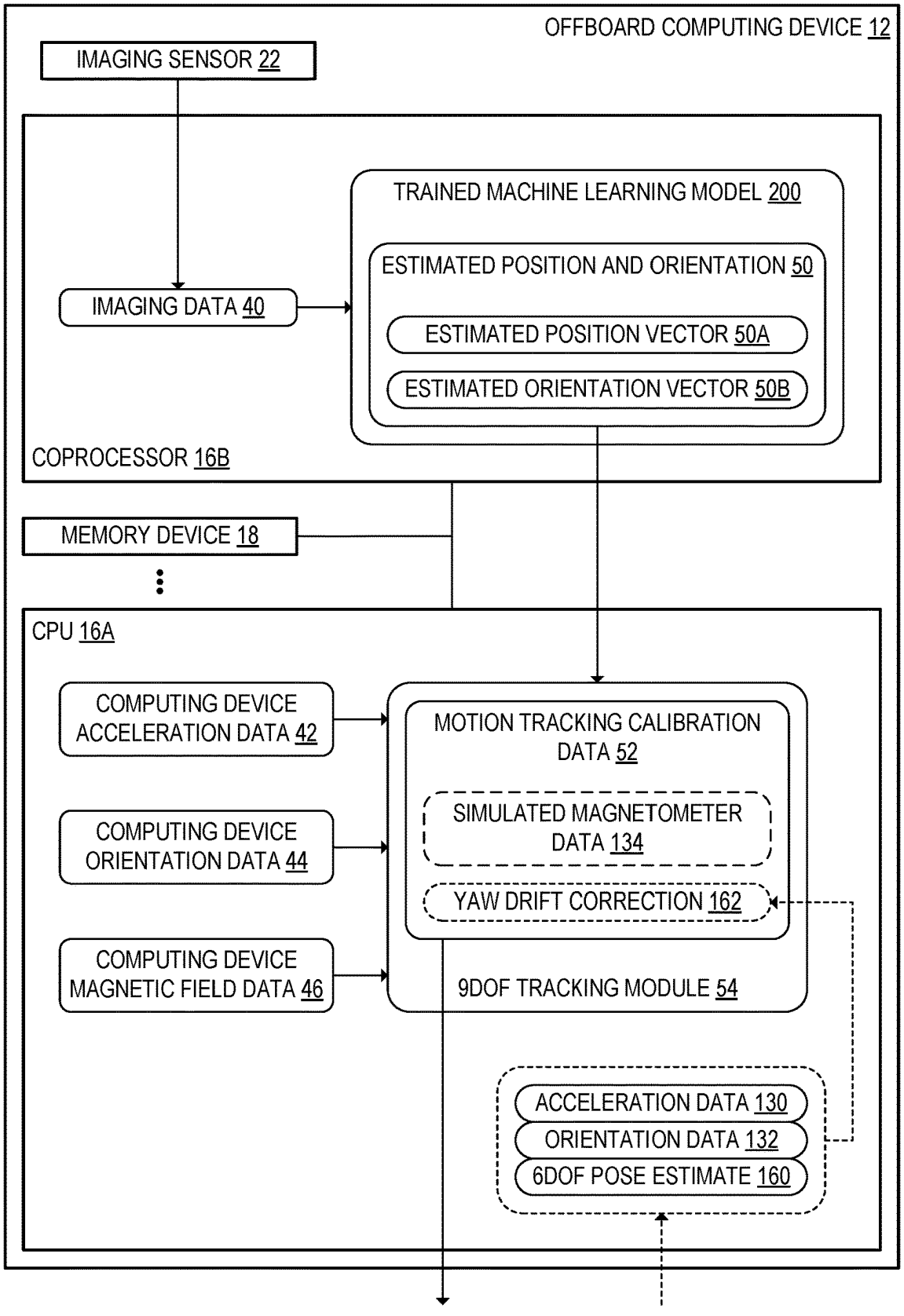


FIG. 8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IMAGING SENSOR 22
TRAINED MACHINE LEARNING MODEL 200
ESTIMATED POSITION AND ORIENTATION 50
IMAGING DATA 40
ESTIMATED POSITION VECTOR 50A
ESTIMATED ORIENTATION VECTOR 50B
COPROCESSOR 16B
MEMORY DEVICE 18
CPU 16A
COMPUTING DEVICE ACCELERATION DATA 42
MOTION TRACKING CALIBRATION DATA 52
SIMULATED MAGNETOMETER DATA 134
COMPUTING DEVICE ORIENTATION DATA 44
YAW DRIFT CORRECTION 162
COMPUTING DEVICE MAGNETIC FIELD DATA 46
9DOF TRACKING MODULE 54
ACCELERATION DATA 130
ORIENTATION DATA 132
6DOF POSE ESTIMATE 160
TO WEARABLE DEVICE 14
FROM WEARABLE DEVICE 14

FIG. 9

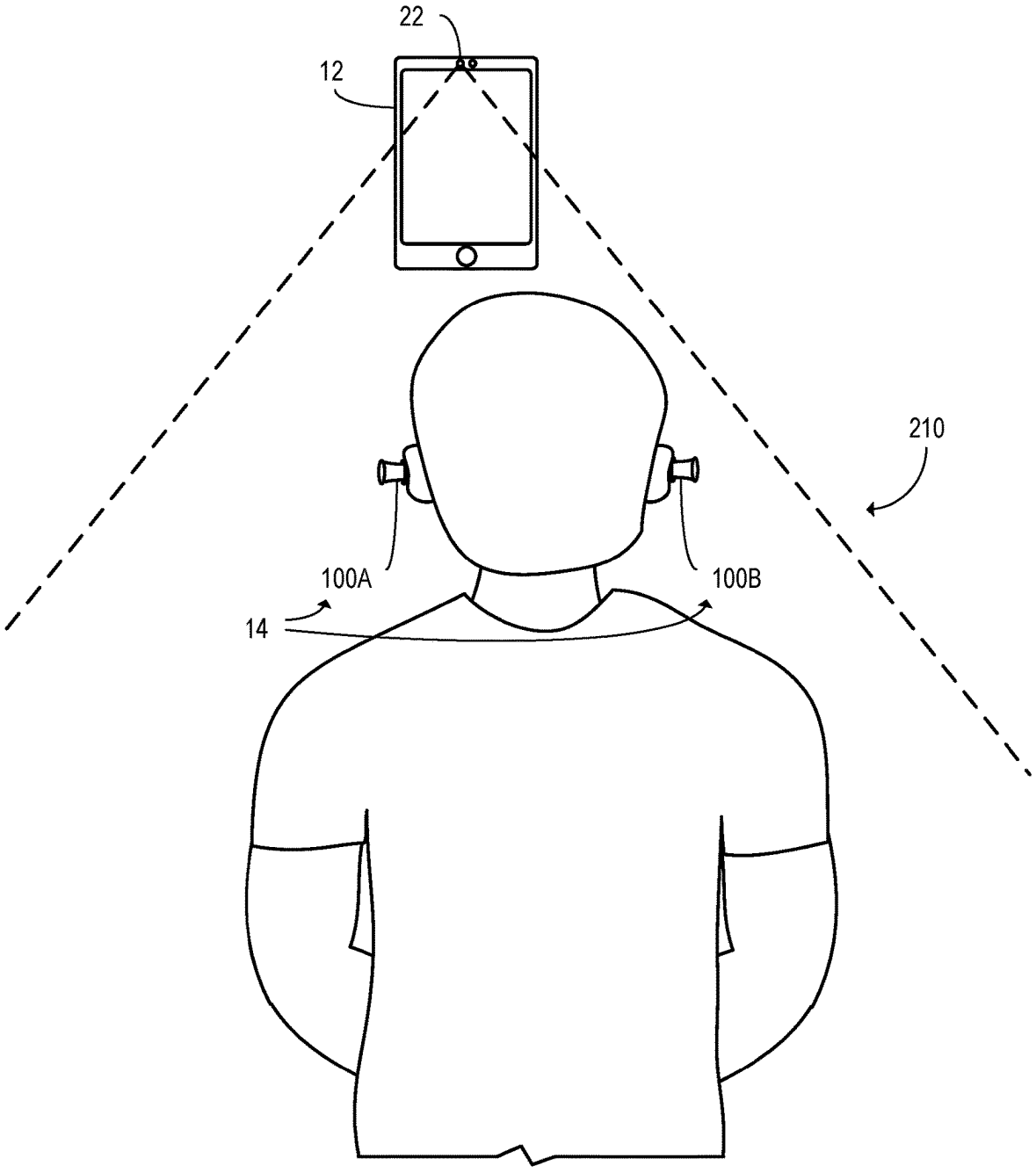


FIG. 10

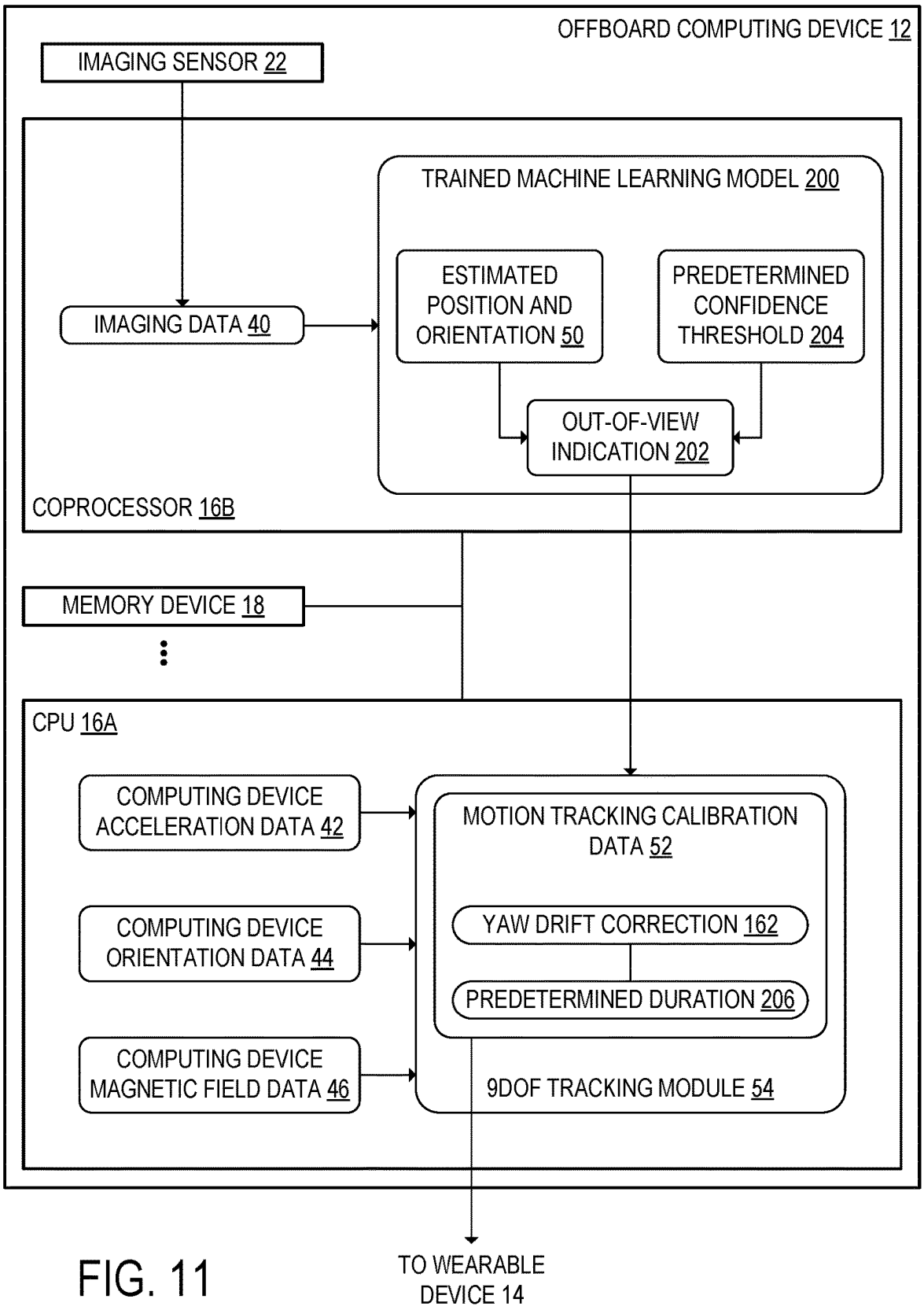

OFFBOARD COMPUTING DEVICE 12
IMAGING SENSOR 22
TRAINED MACHINE LEARNING MODEL 200
ESTIMATED POSITION AND ORIENTATION 50
PREDETERMINED CONFIDENCE THRESHOLD 204
IMAGING DATA 40
OUT-OF-VIEW INDICATION 202
COPROCESSOR 16B
MEMORY DEVICE 18
CPU 16A
COMPUTING DEVICE ACCELERATION DATA 42
MOTION TRACKING CALIBRATION DATA 52
COMPUTING DEVICE ORIENTATION DATA 44
YAW DRIFT CORRECTION 162
PREDETERMINED DURATION 206
COMPUTING DEVICE MAGNETIC FIELD DATA 46
9DOF TRACKING MODULE 54
TO WEARABLE DEVICE 14

FIG. 11

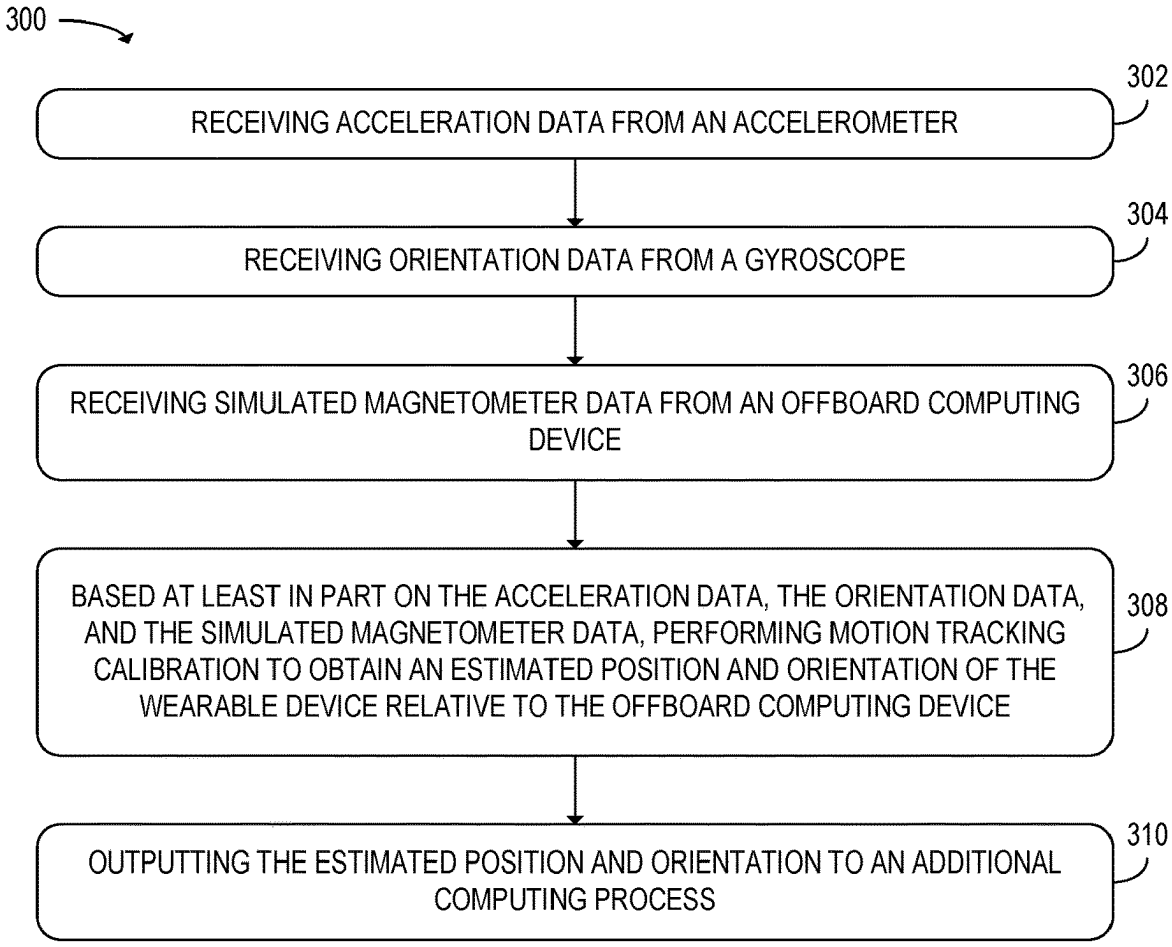


FIG. 12A

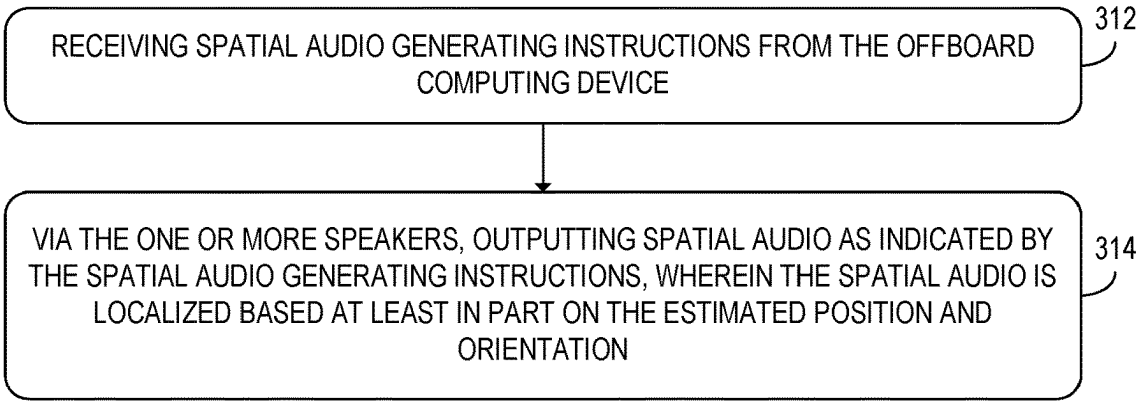


FIG. 12B

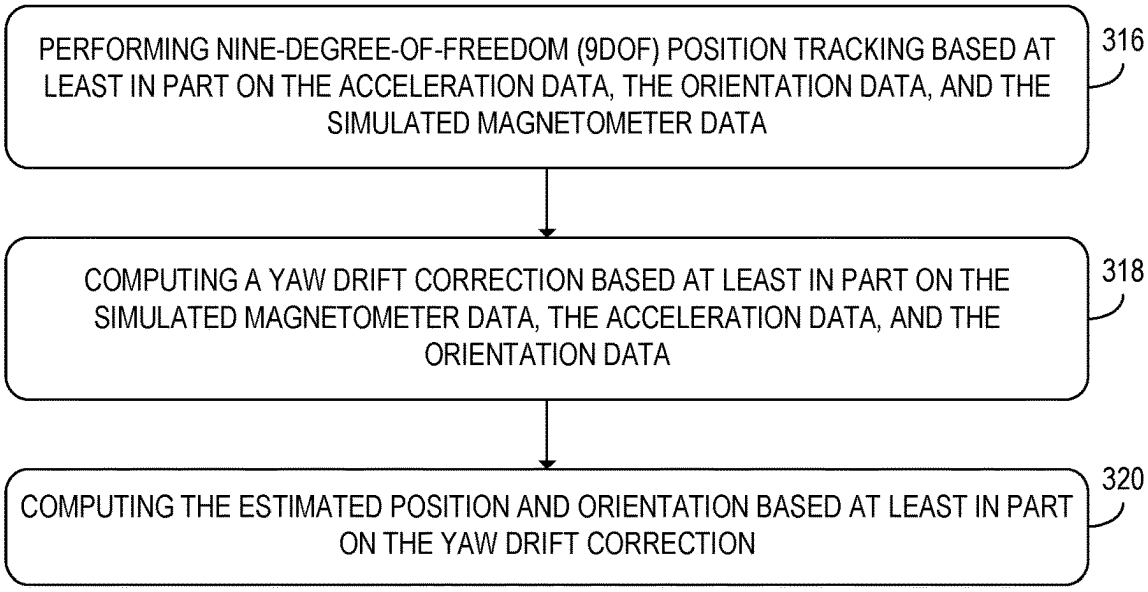
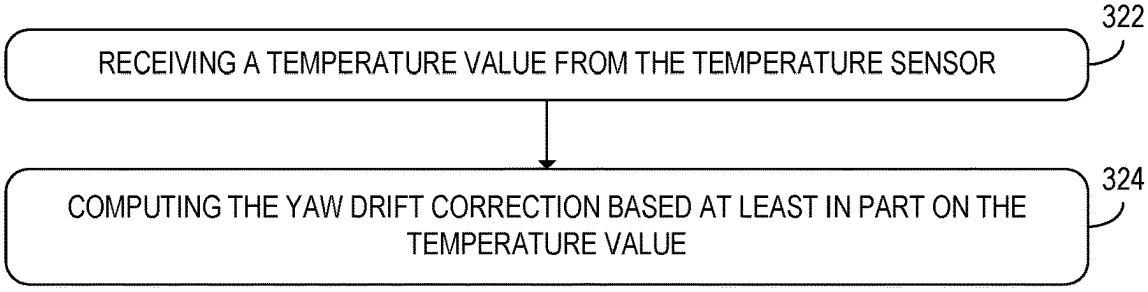


FIG. 12C



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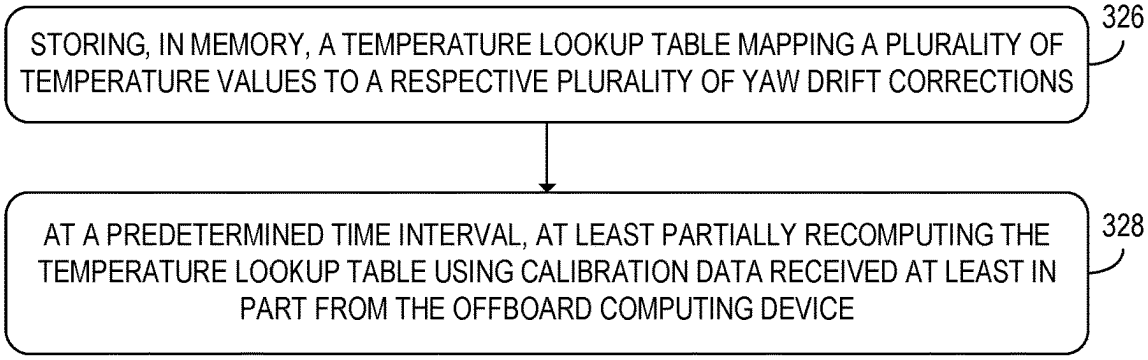

FIG. 12E

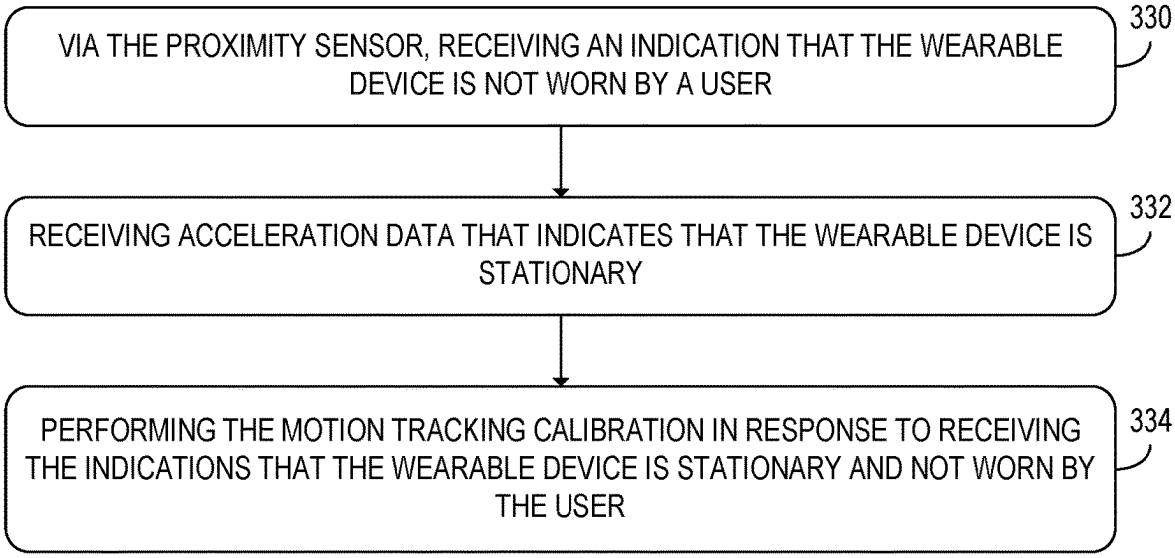

FIG. 12F

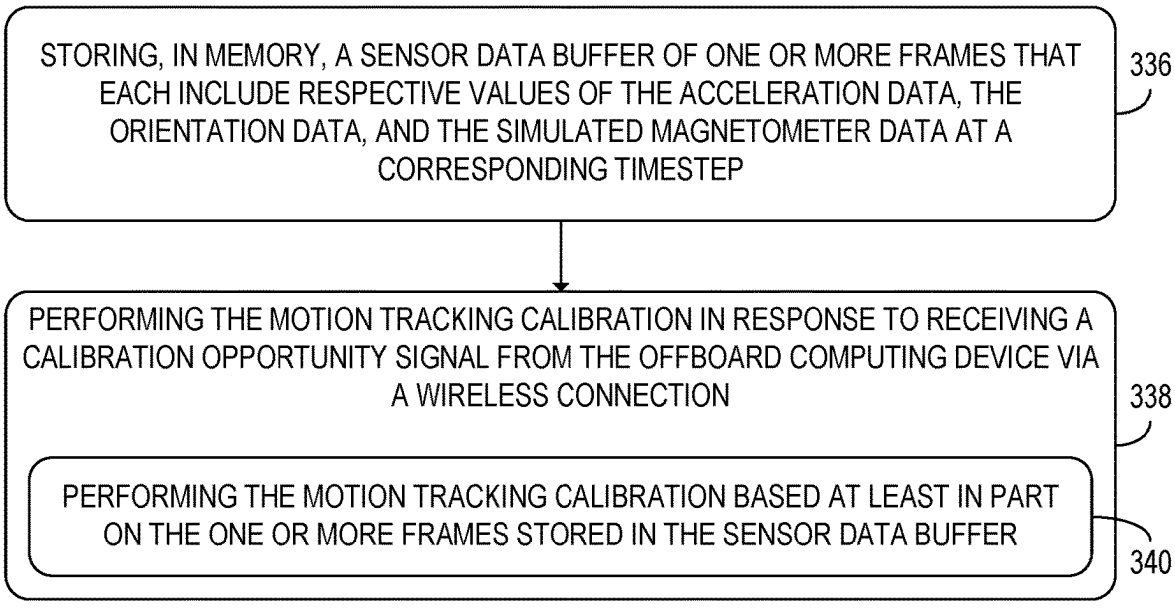

FIG. 12G

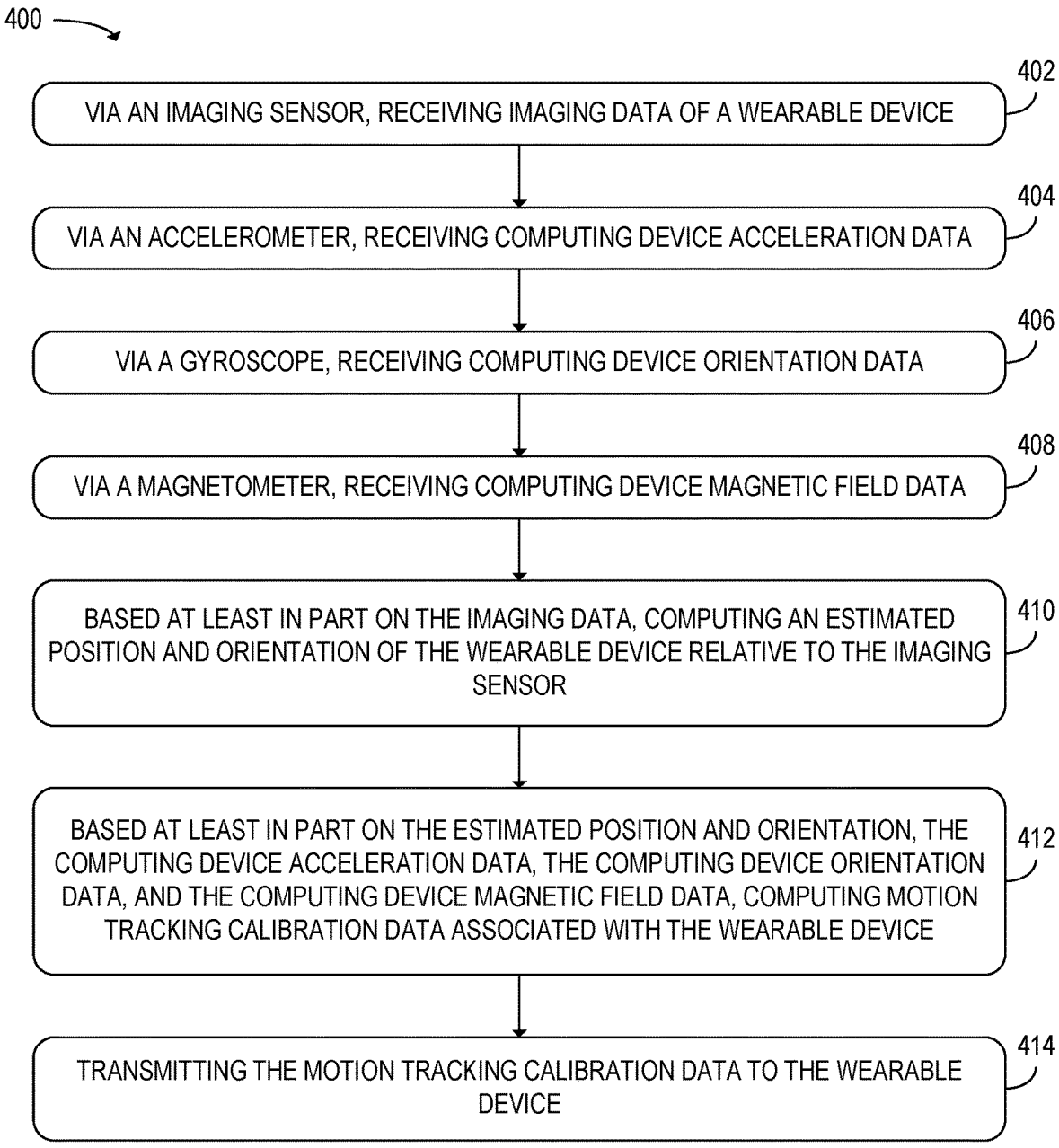
400
VIA AN IMAGING SENSOR, RECEIVING IMAGING DATA OF A WEARABLE DEVICE
402
VIA AN ACCELEROMETER, RECEIVING COMPUTING DEVICE ACCELERATION DATA
404
VIA A GYROSCOPE, RECEIVING COMPUTING DEVICE ORIENTATION DATA
406
VIA A MAGNETOMETER, RECEIVING COMPUTING DEVICE MAGNETIC FIELD DATA
408
BASED AT LEAST IN PART ON THE IMAGING DATA, COMPUTING AN ESTIMATED POSITION AND ORIENTATION OF THE WEARABLE DEVICE RELATIVE TO THE IMAGING SENSOR
410
BASED AT LEAST IN PART ON THE ESTIMATED POSITION AND ORIENTATION, THE COMPUTING DEVICE ACCELERATION DATA, THE COMPUTING DEVICE ORIENTATION DATA, AND THE COMPUTING DEVICE MAGNETIC FIELD DATA, COMPUTING MOTION TRACKING CALIBRATION DATA ASSOCIATED WITH THE WEARABLE DEVICE
412
TRANSMITTING THE MOTION TRACKING CALIBRATION DATA TO THE WEARABLE DEVICE
414

FIG. 13A

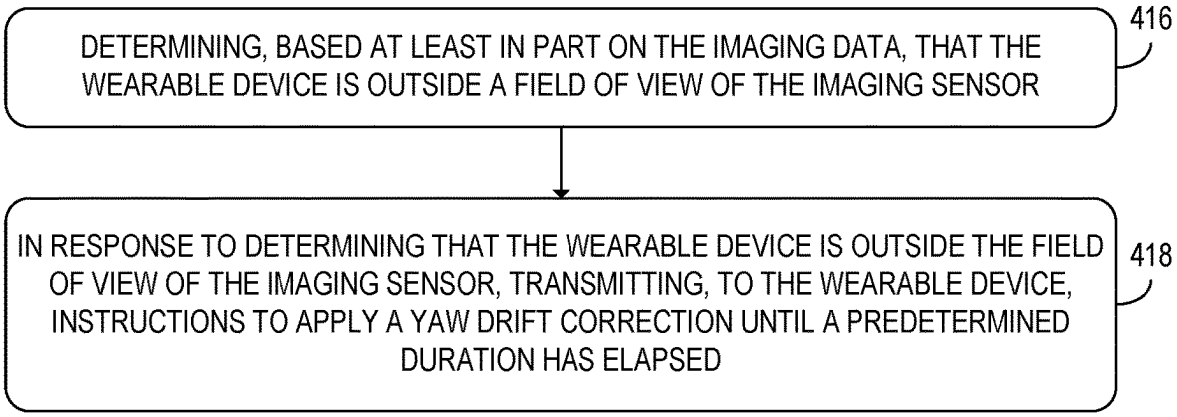

FIG. 13B

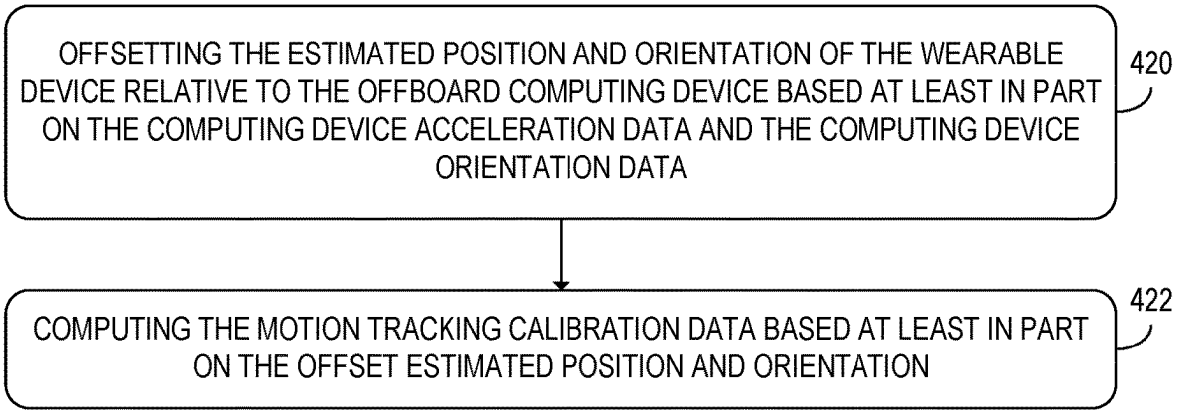

FIG. 13C

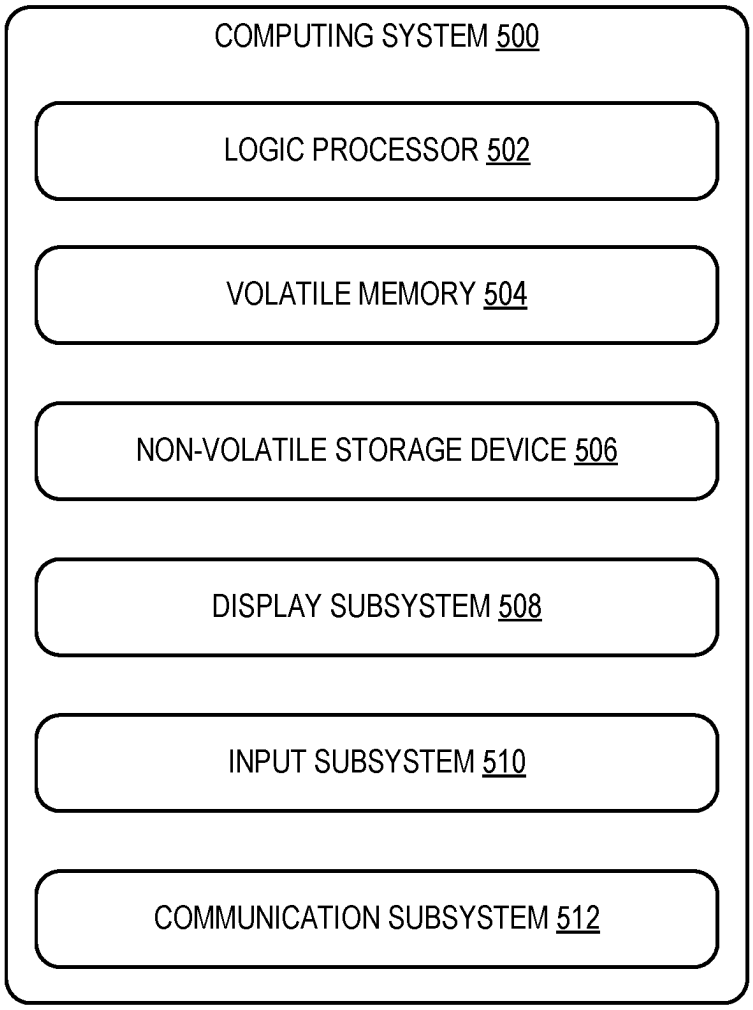
COMPUTING SYSTEM 500
LOGIC PROCESSOR 502
VOLATILE MEMORY 504
NON-VOLATILE STORAGE DEVICE 506
DISPLAY SUBSYSTEM 508
INPUT SUBSYSTEM 510
COMMUNICATION SUBSYSTEM 512

FIG. 14

MOTION TRACKING CALIBRATION FOR WEARABLE DEVICE

BACKGROUND

Spatial audio is a type of audio output in which the spatial location and/or orientation of the user affects how an audio output is generated. Spatial data for a user may be used to produce an audio output that sounds as though it is localized at a particular location in the user's environment other than the location of a speaker producing the audio output. In some examples, the spatial audio output may be generated so as to sound as though its source is moving through the user's surroundings. Spatial audio outputs may be generated at wearable audio devices (e.g., headphones or earbuds) or at other types of audio devices.

SUMMARY

According to one aspect of the present disclosure, a wearable device is provided, including an accelerometer, a gyroscope, and a processing device. The processing device is configured to receive acceleration data from the accelerometer, receive orientation data from the gyroscope, and receive simulated magnetometer data from an offboard computing device. Based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, the processing device is further configured to perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The processing device is further configured to output the estimated position and orientation to an additional computing process.

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Furthermore, the claimed subject matter is not limited to implementations that solve any or all disadvantages noted in any part of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** schematically shows a computing system that includes a wearable device and an offboard computing device, according to one example embodiment.

FIG. **2** schematically shows the offboard computing device when motion tracking calibration data is computed, according to the example of FIG. **1**.

FIGS. **3**A-**3**C respectively show three views of an example left earbud included in the wearable device, according to the example of FIG. **1**.

FIG. **4** schematically shows an earbud included in the wearable device when an estimated position and orientation are computed, according to the example of FIG. **1**.

FIG. **5** schematically shows a coordinate system of the earbud, according to the example of FIG. **4**.

FIG. **6**A schematically shows the earbud of FIG. **4** when a nine-degree-of-freedom (9DOF) tracking module is executed.

FIG. **6**B schematically shows the earbud when the 9DOF tracking module receives temperature data from a temperature sensor, according to the example of FIG. **6**A.

FIG. **6**C schematically shows the earbud of FIG. **6**B when a temperature lookup table is at least partially recomputed.

FIG. **7**A schematically shows the earbud of FIG. **4** when a calibration opportunity detection module is executed.

FIG. **7**B schematically shows the earbud of FIG. **7**A in an example in which a memory device of the earbud stores a sensor data buffer.

FIG. **8** shows an example of a perceived spatial audio location generated at the wearable device, according to the example of FIG. **1**.

FIG. **9** schematically shows the offboard computing device when imaging data is processed, according to the example of FIG. **2**.

FIG. **10** shows the offboard computing device when the imaging sensor collects imaging data of a user wearing the wearable device, according to the example of FIG. **2**.

FIG. **11** schematically shows the offboard computing device when the wearable device is determined to be outside the field of view of the imaging sensor, according to the example of FIG. **9**.

FIG. **12**A shows a flowchart of a method for use with a wearable device to generate an estimated position and orientation, according to the example of FIG. **1**.

FIGS. **12**B-**12**G show additional steps of the method of FIG. **12**A that are performed in some examples.

FIG. **13**A shows a flowchart of a method for use with an offboard computing device to generate motion tracking calibration data for a wearable device, according to the example of FIG. **1**.

FIGS. **13**B-**13**C show additional steps of the method of FIG. **13**A that are performed in some examples.

FIG. **14** shows a schematic view of an example computing environment in which the computing system of FIG. **1** may be enacted.

DETAILED DESCRIPTION

In order to accurately produce spatial audio outputs that are perceived as having sources located at intended locations, devices that are used to generate spatial audio may track the spatial location and orientation of the user. This tracking may be performed using sensors located in a wearable audio device. For example, an accelerometer and a gyroscope included in a wearable audio device may be used to provide position and orientation data for a user wearing the device. The position and orientation data may then be used as inputs to a spatial audio generating module at which the position and orientation of the user are used to set parameters of an audio output such that the audio output sounds as though it originates from an intended location.

In other types of computing devices, magnetometers are frequently used when tracking the position and orientation of the device. A magnetometer may use the direction of the Earth's magnetic field to determine a spatial orientation of the computing device. However, the speakers used in wearable audio devices include magnets that are subjected to induced magnetic fields to produce sound by causing the magnets to vibrate. These magnets, as well as the magnetic fields used to produce vibrations, may produce inaccuracies in magnetometer readouts. Accordingly, wearable audio devices do not typically include magnetometers.

The positions and orientations of wearable audio devices may be more difficult to accurately estimate than the positions and orientations of other types of computing devices due to the typical lack of magnetic field data. In particular, estimates of the device orientation in the yaw direction (the direction of rotation in a horizontal plane) may be difficult to measure accurately without a magnetometer. Horizontal drift, in which the sensors of the wearable audio device

detect an inaccurate angular velocity in the yaw direction, frequently occurs for wearable audio devices. As one previous solution to the problem of horizontal drift, the angular velocity of the wearable audio device may be calibrated in the yaw direction when the wearable audio device is manufactured. However, due to hardware aging, changes in temperatures, and other post-manufacturing changes to the wearable audio device, calibration drift may occur.

Using the devices and methods discussed below, motion tracking calibration is performed for a wearable audio device. Thus, the problems discussed above may be addressed. FIG. **1** schematically shows a computing system **10** that includes a wearable device **14** and an offboard computing device **12**. The wearable device **14** may, as shown in the example of FIG. **1**, be a wearable audio device that includes one or more speakers **102**. In the example of FIG. **1**, the wearable device **14** is an earbud system that includes a plurality of earbuds **100**, including a left earbud **100**A and a right earbud **100**B. In other examples, the wearable device **14** may be a pair of headphones or some other wearable audio device. The earbuds **100** included in the wearable device **14** are configured to wirelessly communicate with each other and with the offboard computing device **12**.

In the example of FIG. **1**, the offboard computing device **12** is shown as a tablet computing device. The offboard computing device **12** includes one or more processing devices **16** and one or more memory devices **18** that are communicatively coupled to execute computing processes. In addition, the offboard computing device **12** shown in the example of FIG. **1** includes a display **32**. The example offboard computing device **12** further includes a plurality of touch sensors **21**, including a first touch sensor **21**A that overlaps the display **32** and a second touch sensor **21**B that is provided apart from the display **32**. The offboard computing device **12** shown in FIG. **1** further includes imaging sensors **22**, including an inward-facing imaging sensor **22**A and an outward-facing imaging sensor **22**B. The imaging sensors **22** may, for example, be cameras or ultra-wideband (UWB) sensors.

FIG. **2** schematically shows the offboard computing device **12** in additional detail. As depicted in the example of FIG. **2**, the offboard computing device **12** includes a sensor suite **20**. The sensor suite includes the one or more touch sensors **21** and the one or more imaging sensors **22**. In addition, the sensor suite **20** shown in the example of FIG. **2** includes an accelerometer **24**, a gyroscope **26**, and a magnetometer **28**. The accelerometer **24** is configured to measure computing device acceleration data **42** that indicates linear acceleration of the offboard computing device **12**. The gyroscope **26** is configured to measure computing device orientation data **44** that indicates an angular orientation of the offboard computing device **12** with respect to the direction of gravity. The orientation data **44** further indicates an angular velocity of the offboard computing device **12**. The magnetometer **28** is configured to measure computing device magnetic field data **46** that indicates the strength and direction of a magnetic field to which the offboard computing device **12** is subjected. Since the main source of magnetic fields at the offboard computing device **12** is typically the Earth's magnetic field, the computing device magnetic field data **46** may indicate an orientation of the offboard computing device **12** relative to the Earth's magnetic field.

As shown in the example of FIG. **2**, the offboard computing device **12** further includes a wireless communication device **29** that is configured to transmit data to and receive data from the one or more processing devices **16**. Via the wireless communication device **29**, the offboard computing device **12** is configured to communicate with one or more other computing devices, including the wearable device **14**.

FIGS. **3**A-**3**C respectively show three views of an example left earbud **100**A that may be included in the wearable device **14**. The right earbud **100**B included in the wearable device **14** as shown in the example of FIG. **1** may have an at least partially mirrored structure compared to the left earbud **100**A of FIGS. **3**A-**3**C, such that the left earbud **100**A is configured to be worn in a user's left ear and the right earbud **100**B is configured to be worn in the user's right ear.

The left earbud **100**A shown in FIGS. **3**A-**3**C includes a speaker **102** configured to emit sound into the user's left ear. The left earbud **100**A further includes a microphone array **104** configured to capture sound emitted from the user's mouth and the surrounding environment. The microphone array **104** includes a plurality of microphones **104**A, **104**B, **104**C. In other examples, the microphone array **104** may include some other number of microphones.

The left earbud **100**A of FIGS. **3**A-**3**C includes a housing **106**. The housing **106** may be formed from any suitable materials including, but not limited to, plastic, metal, ceramic, glass, crystalline materials, composite materials, or other suitable materials. As shown in FIGS. **3**A-**3**C, the housing **106** includes a neck **108** and a bud **110**. The neck **108** is sized and shaped to position the bud **110** against the concha, a hollow depression in the user's ear, when the left earbud **100**A is placed in the user's ear. The bud **110** includes a speaker port **112**. The bud **110** is sized and shaped to align the speaker port **112** to direct sound emitted from the speaker **102** into the user's ear canal when the left earbud **100**A is worn in the user's ear.

In the example of FIGS. **3**A-**3**C, the microphone array **104** includes an in-ear microphone **104**A, a first voice microphone **104**B, and a second voice microphone **104**C. The in-ear microphone **104**A is positioned proximate to the speaker port **112** in the bud **110**. The first voice microphone **104**B and the second voice microphone **104**C are positioned at the base of the neck **108**. In this example, the in-ear microphone **104**A is configured to capture primarily sound in the user's ear, the first voice microphone **104**B is configured to capture primarily sound emitted from the user's mouth, and the second voice microphone **104**C is configured to capture primarily background noise outside of the earbud **100**.

The view of the left earbud **100**A shown in FIG. **3**B schematically shows components of the left earbud **100**A at which computing processes are configured to be performed. The earbuds **100** each include respective memory devices **118** and a respective processing device **120**. The memory device **118** and the processing device **120** are also communicatively coupled to a plurality of sensors that, in the example of FIGS. **3**A-**3**B, include an accelerometer **122**, a gyroscope **124**, a temperature sensor **126**, and a proximity sensor **128**. The earbuds **100** further include respective wireless communication devices **129** that are configured to receive data from and transmit data to their respective processing devices **120**. The wireless communication devices **129** allow the processing devices **120** of the earbuds **100** to communicate with other computing devices, including the offboard computing device **12**.

FIG. **4** schematically shows the components of an earbud **100** in additional detail. In the example of FIG. **4**, the processing device **120** of the earbud **100** is configured to receive acceleration data **130** from the accelerometer **122**

and to receive orientation data **132** from the gyroscope **124**. The orientation data **132** indicates an angular orientation and angular velocity of the earbud **100**. The processing device **120** is configured to input the acceleration data **130** and the orientation data **132** into a nine-degree-of-freedom (9DOF) tracking module **142**. As discussed in further detail below, simulated magnetometer data **134** is also input into the 9DOF tracking module **142**. The processing device **120** is further configured to receive temperature data **136** from the temperature sensor **126** in some examples, as shown in FIG. **4**.

In addition to the data received from onboard sensors included in the earbud **100**, the processing device **120** is further configured to receive simulated magnetometer data **134** from the offboard computing device **12**. The simulated magnetometer data **134** indicates an angle at which the earbud **100** is oriented relative to the Earth's magnetic field or the magnetic force exerted by the Earth's magnetic field. Thus, the simulated magnetometer data **134** acts as a substitute for magnetometer data that would be collected at the earbud **100** if the earbud **100** included a magnetometer.

Based at least in part on the acceleration data **130**, the orientation data **132**, and the simulated magnetometer data **134**, the processing device **120** of the earbud **100** is further configured to perform motion tracking calibration to obtain an estimated position and orientation **140** of the wearable device **14** relative to the offboard computing device **12**. In the example of FIG. **4**, the processing device **120** is configured to perform 9DOF position tracking at the 9DOF tracking module **142** using the acceleration data **130**, the orientation data **132**, and the simulated magnetometer data **134** to compute the estimated position and orientation **140**. Thus, the processing device **120** is configured to perform sensor fusion of the acceleration data **130**, the orientation data **132**, and the simulated magnetometer data **134**. Incorporating the simulated magnetometer data **134** into the estimation of the position and orientation of the wearable device **14** allows the processing device **120** to perform 9DOF tracking instead of 6DOF tracking, thereby resulting in higher accuracy for the estimated position and orientation **140**. The nine degrees of freedom used at the 9DOF tracking module **142** in the example of FIG. **4** are respective components of the acceleration data **130**, the orientation data **132**, and the simulated magnetometer data **134**, which are expressed as vectors in three spatial dimensions. In some examples, the estimated position and orientation **140** may be expressed as an estimated position vector **140**A and an estimated orientation vector **140**B.

FIG. **5** schematically shows a coordinate system **148** of the earbud **100**. The coordinate system **148** includes positional coordinates indicated as x, y, and z, as well as rotational coordinates indicated as roll, pitch, and yaw. In addition, FIG. **5** shows the estimated position vector **140**A of the earbud **100** relative to the imaging sensor **22** of the offboard computing device **12**. Vectors indicating the directions of the gravitational force F_g and the magnetic force FB on the earbud **100** are also depicted in the example of FIG. **5**.

FIGS. **6**A-**6**B schematically show the processing device **120** of the earbud **100** in additional detail when the 9DOF tracking module **142** is executed. In the example of FIG. **6**A, at the 9DOF tracking module **142**, the processing device **120** is configured to perform six-degree-of-freedom (6DOF) tracking using the acceleration data **130** received from the accelerometer **122** and the orientation data **132** received from the gyroscope **124**. Thus, the processing device **120** is configured to compute a 6DOF pose estimate **160**, which may include a 6DOF estimated position vector **160**A and a 6DOF estimated orientation vector **160**B.

As discussed above, since the earbud **100** does not include a magnetometer, the 6DOF pose estimate **160** may be inaccurate due to calibration drift in the yaw direction. Accordingly, at the 9DOF tracking module **142**, the processing device **120** is further configured to compute a yaw drift correction **162** based at least in part on the simulated magnetometer data **134**, the acceleration data **130**, and the orientation data **132**. The yaw drift correction **162** may be expressed as an angular velocity in the yaw direction. When the processing device **120** utilizes the acceleration data **130** and the orientation data **132** during computation of the yaw drift correction **162**, the processing device **120** may be configured to compute the yaw drift correction **162** based at least in part on the 6DOF pose estimate **160**. In such examples, the processing device **120** may be configured to compare a yaw value indicated in the simulated magnetometer data **134** to a yaw value included in the 6DOF pose estimate **160** to determine a yaw drift. Alternatively, the processing device **120** may utilize the acceleration data **130** and the orientation data **132** without pre-processing them into a 6DOF pose estimate **160**. When the yaw drift correction **162** is computed, the simulated magnetometer data **134**, the acceleration data **130**, and the orientation data **132** may be input into a 9DOF tracking algorithm such as a Kalman filtering algorithm or a complementary filtering algorithm. By performing the 9DOF tracking algorithm, the processing device **120** is further configured to compute the estimated position and orientation **140** based at least in part on the yaw drift correction **162**. Thus, the processing device **120** is configured to perform motion tracking calibration for the earbud **100** in a manner that results in more accurate yaw values for the wearable device **14**.

In some examples, as shown in FIG. **6**B, the processing device **120** is further configured to receive a temperature value **172** from the temperature sensor **126** at the 9DOF tracking module **142**. The temperature value **172** is included in the temperature data **136**. In some examples, a sample of a plurality of temperature values **172** included in the temperature data **136** may be received at the 9DOF tracking module **142**. In such examples, the processing device **120** is further configured to compute the yaw drift correction **162** based at least in part on the temperature value **172**. In some examples, the memory device **118** stores a temperature lookup table **170** mapping a plurality of temperature values **172** to a respective plurality of yaw drift corrections **162**. The temperature lookup table **170** may accordingly indicate a dependence between temperature and yaw drift. By retrieving the yaw drift correction **162** associated with a detected temperature value **172** from the temperature lookup table **170**, the processing device **120** is configured to adjust the estimated position and orientation **140** for the effects of temperature on yaw drift, thereby resulting in more accurate 9DOF tracking.

The processing device **120** may be configured to retrieve the yaw drift correction **162** from the temperature lookup table **170** even when simulated magnetometer data **134** is not received from the offboard computing device **12**. Thus, the processing device **120** may continue to correct for yaw drift when the earbud **100** is not receiving the simulated magnetometer data **134**. The values of the yaw drift correction **162** may be used, for example, when the offboard computing device **12** is unable to obtain accurate values of quantities with which the simulated magnetometer data **134** is computed.

In some examples in which the memory device **118** stores a temperature lookup table **170**, as schematically depicted in the example of FIG. **6**C, the processing device **120** is further configured to at least partially recompute the temperature lookup table **170** at a predetermined time interval **176**. The temperature lookup table **170** is recomputed using calibration data received at least in part from the offboard computing device **12**. In the example of FIG. **6**C, the processing device **120** generates a recomputed temperature lookup table **174** using calibration data that includes the simulated magnetometer data **134** and the temperature data **136**. In some examples, values of the yaw drift correction **162** may be maintained from the previous iteration of the temperature lookup table **170** for temperature values **172** not included in the temperature data **136** received during the predetermined time interval **176**. In other examples, such values of the yaw drift correction **162** may be adjusted via interpolation between updated values of the yaw drift correction **162**. By iteratively recomputing the temperature lookup table **170**, the processing device **120** may account for changes in the yaw drift due to device aging.

FIG. **7**A schematically shows the earbud **100** when the processing device **120** is configured to execute a calibration opportunity detection module **180**. At the calibration opportunity detection module **180**, the processing device **120** is configured to identify a time at which accurate motion tracking calibration may be performed. The calibration opportunity detection module **180** may utilize acceleration data **130** received from the accelerometer **122** and a proximity indication **182** received from the proximity sensor **128**. In some examples, the calibration opportunity detection module **180** is further configured to receive orientation data **132** from the gyroscope **124**.

The proximity sensor **128** is configured to detect objects adjacent to the earbud **100**, and may, for example, be an infrared sensor. Using the proximity indication **182** received from the proximity sensor **128**, the processing device **120** is configured to detect whether the earbud **100** is worn by a user.

The calibration opportunity detection module **180**, according to the example of FIG. **7**A, is configured to use the acceleration data **130** and the proximity indication **182** to identify a time at which the position and orientation of the earbud **100** are likely to remain constant during motion tracking calibration. Via the proximity sensor **128**, the processing device **120** is configured to receive a proximity indication **182** indicating that the wearable device **14** is not worn by a user. In addition, via the accelerometer **122**, the processing device **120** is configured to receive acceleration data **130** indicating that the wearable device **14** is stationary. In some examples, the processing device **120** is further configured to receive orientation data **132** from the gyroscope **124** indicating that the wearable device **14** is stationary in its angular orientation.

The processing device **120** is further configured to perform the motion tracking calibration in response to receiving the indications that the wearable device **14** is stationary and not worn by the user. Accordingly, the calibration opportunity detection module **180** is configured to instruct the 9DOF tracking module **142** to perform the motion tracking calibration (e.g., by computing the yaw drift correction **162**). The processing device **120** may therefore perform the motion tracking calibration under conditions in which the angular velocity of the wearable device **14** in the yaw direction is expected to be zero. By performing the motion tracking calibration when the angular velocity in the yaw direction is expected to be zero, the processing device **120** may determine a baseline value of the yaw drift and use that baseline value to compute the yaw drift correction **162**, thereby resulting in more accurate calibration.

In some examples, additionally or alternatively to detecting a calibration opportunity based on acceleration data **130** and a proximity indication **182**, the processing device **120** may be further configured to receive a calibration opportunity signal **184** from the offboard computing device via a wireless connection. In such examples, the calibration opportunity signal **184** instructs the processing device **120** to perform the motion tracking calibration at the 9DOF tracking module **142**. Calibration opportunity detection may therefore be at least partially offloaded to the offboard computing device **12**, such that the greater processing capabilities of the offboard computing device **12** are used to identify conditions that are likely to result in accurate calibration. Additionally or alternatively, sensor data collected at both the offboard computing device **12** and the wearable device **14** may be used to identify the calibration opportunity. For example, the offboard computing device **12** may be configured to transmit the calibration opportunity signal **184** to the wearable device **14** in response to the one or more processing devices **16** of the offboard computing device **12** determining, based at least in part on computing device acceleration data **42** and computing device orientation data **44** detected by the accelerometer **24** and the gyroscope **26** of the offboard computing device **12**, that the offboard computing device **12** is stationary. The calibration opportunity detection module **180** may be configured to perform the motion tracking calibration in such examples in response to determining that both the offboard computing device **12** and the wearable device **14** are stationary. Thus, the processing device **120** may avoid calibration errors associated with correcting for movement of the offboard computing device **12**.

FIG. **7**B schematically shows the earbud **100** of FIG. **7**A in an example in which the memory device **118** is configured to store a sensor data buffer **190** of one or more frames **192**. The frames **192** each include respective values of the acceleration data **130**, the orientation data **132**, and the simulated magnetometer data **134** at a corresponding timestep. For example, the sensor data buffer **190** may store sensor data collected at the earbud **100** in a predetermined number of timesteps prior to a current timestep. Each frame **192** may further include a respective frame timestamp **194**.

In examples in which the memory device **118** stores the sensor data buffer **190**, the processing device **120** may, in response to receiving the calibration opportunity signal **184**, be further configured to perform the motion tracking calibration based at least in part on the one or more frames **192** stored in the sensor data buffer **190**. For example, the calibration opportunity signal **184** may include a calibration opportunity timestamp **186**, and the processing device **120** may be configured to select sensor data stored in a frame **192** with a corresponding frame timestamp **194**. By performing the motion tracking calibration based at least in part on the one or more frames **192**, the processing device **120** may be configured to account for a delay between the generation of the calibration opportunity signal **184** at the offboard computing device **12** and computation of the yaw drift correction **162** at the processing device **120** of the earbud **100**. The conditions that facilitate accurate calibration, as indicated in the calibration opportunity signal **184**, may end before the calibration opportunity signal **184** is received at the processing device **120**. Therefore, by utilizing sensor data stored in the sensor data buffer **190** at a timestep during which the calibration opportunity is detected, as indicated by

the calibration opportunity timestamp **186**, the processing device **120** may increase the accuracy of the motion tracking calibration.

Returning to the example of FIG. **4**, the processing device **120** is further configured to output the estimated position and orientation **140** to an additional computing process. The estimated position and orientation **140** are transmitted to the offboard computing device **12** for further processing in the example of FIG. **4**. In the example of FIG. **4**, the processing device **120** is further configured to receive spatial audio generating instructions **152** from the offboard computing device **12** at a spatial audio generating module **150**. The processing device **120** is further configured to output spatial audio **154** generated at the spatial audio generating module **150** via the one or more speakers **102**. When the processing device **120** generates the spatial audio **154**, the processing device **120** is configured to localize the spatial audio **154** based at least in part on the estimated position and orientation **140**.

FIG. **8** shows an example of a perceived spatial audio location **156** generated at the wearable device **14**. The spatial audio **154** is localized at the perceived spatial audio location **156** by outputting a first spatial audio signal **154**A from the left earbud **100**A and a second spatial audio signal **154**B from the right earbud **100**B. Differences between the respective waveforms of the first spatial audio signal **154**A and the second spatial audio signal **154**B mimic the differences between sounds that would be heard at the user's left and right ears, respectively, if the a sound were emitted at the perceived spatial audio location **156**. The processing device **120** may introduce these differences between the first spatial audio signal **154**A and the second spatial audio signal **154**B by offsetting the respective waveforms of the first spatial audio signal **154**A and the second spatial audio signal **154**B from each other in time. The first spatial audio signal **154**A and the second spatial audio signal **154**B may also differ in amplitude. In order to accurately localize the perceived spatial audio location **156**, the processing device **120** is configured to account for the spatial position and orientation of the wearable device **14** when the spatial audio **154** is generated. Accordingly, increasing the accuracy of the estimated position and orientation **140** of the wearable device **14** may allow the processing device **120** to generate spatial audio **154** that is perceived as closer to an intended location. The spatial audio **154** will thus be reproduced with greater fidelity, user may therefore have a more authentic and immersive experience of the spatial audio **154** as the designer of the audio experience intended.

As depicted in the example of FIG. **4**, communication between the earbud **100** and the offboard computing device **12** is performed in a sequence of steps A, B, and C. In step A, the earbud **100** receives the simulated magnetometer data **134** from the offboard computing device **12**. In step B, the earbud **100** transmits the estimated position and orientation **140** to the offboard computing device **12**. In step C, the earbud **100** receives the spatial audio generating instructions **152** from the offboard computing device **12**. The computing system **10** may accordingly utilize the higher computing power of the offboard computing device **12**, as well as one or more of the sensors included in the sensor suite **20** of the offboard computing device **12**, when computing the simulated magnetometer data **134** and the spatial audio generating instructions **152**.

Returning to the example of FIG. **2**, additional details related to computing processes performed at the offboard computing device **12** are now provided. The sensors included in the sensor suite **20** of the offboard computing device **12** are configured to transmit data to the one or more processing devices **16** included in the offboard computing device **12**. The one or more processing devices **16** are configured to receive imaging data **40** of the wearable device **14** via the imaging sensor **22**. In addition, the one or more processing devices **16** are further configured to receive computing device acceleration data **42** via the accelerometer **24**, receive computing device orientation data **44** via the gyroscope **26**, and receive computing device magnetic field data **46** via the magnetometer **28**. In some examples, as discussed in further detail below, the imaging data **40** may be received at a separate processing device **16** from the computing device acceleration data **42**, the computing device orientation data **44**, and the computing device magnetic field data **46**.

Based at least in part on the imaging data **40**, the one or more processing devices **16** are further configured to compute an estimated position and orientation **50** of the wearable device **14** relative to the imaging sensor **22**. The estimated position and orientation **50** may, for example, be expressed as an estimated position vector **50**A and an estimated orientation vector **50**B. The one or more processing devices **16** are further configured to compute motion tracking calibration data **52** associated with the wearable device **14** based at least in part on the estimated position and orientation **50**, the computing device acceleration data **42**, the computing device orientation data **44**, and the computing device magnetic field data **46**. The motion tracking calibration data **52** is computed at a 9DOF tracking module **54** executed at the one or more processing devices **16** in the example of FIG. **2**. In addition, the one or more processing devices **16** are further configured to transmit the motion tracking calibration data **52** to the wearable device **14**.

When computing the motion tracking calibration data **52**, the one or more processing devices **16** are configured to account for movement of the offboard computing device **12**. The one or more processing devices **16** are further configured to offset the estimated position and orientation **50** of the wearable device **14** relative to the offboard computing device **12** based at least in part on the computing device acceleration data **42** and the computing device orientation data **44**. Thus, the one or more processing devices **16** are configured to compute an offset estimated position and orientation **56** of the wearable device **14**. The computing device magnetic field data **46** may additionally be utilized when computing the offset estimated position and orientation **56**. The one or more processing devices **16** are therefore configured to estimate the position and orientation of the wearable device **14** in a reference frame defined by a fixed location in the user's physical environment rather than a reference frame defined relative to the offboard computing device **12**. The one or more processing devices **16** are further configured to compute the motion tracking calibration data **52** based at least in part on the offset estimated position and orientation **56**. The motion tracking calibration data **52** may therefore be expressed in the same reference frame as the estimated position and orientation **140** computed at the wearable device **14**.

FIG. **9** shows the offboard computing device **12** in additional detail when the imaging data **40** is processed at the one or more processing devices **16**. In the example of FIG. **9**, the computing device acceleration data **42**, the computing device orientation data **44**, and the computing device magnetic field data **46** are received at a central processing unit (CPU) **16**A included among the one or more processing devices **16**, whereas the imaging data **40** is received at a coprocessor **16**B. At the coprocessor **16**B, the offboard

computing device **12** is configured to compute the estimated position and orientation **50** of the wearable device **14** at least in part at a trained machine learning model **200**. The trained machine learning model **200** in the example of FIG. **9** is configured to perform object recognition on the imaging data **40** to identify the wearable device **14** within the field of view of the imaging sensor **22**. The trained machine learning model **200** may, for example, be a multi-layer perceptron (MLP) model, a convolutional neural network (CNN), a transformer network, or some other type of machine learning model. In the example of FIG. **9**, the coprocessor **16**B is further configured to output the estimated position and orientation **50** to the CPU **16**A.

By computing the estimated position and orientation **50** from the imaging data **40** at the coprocessor **16**B rather than at the CPU **16**A, the offboard computing device **12** may utilize a processing device architecture that performs machine learning model inferencing more quickly and efficiently than the CPU **16**A. For example, the coprocessor **16**B may be a graphics processing unit (GPU). In addition, the offboard computing device **12** may avoid transmitting the raw imaging data **40** to the CPU **16**A by processing the imaging data **40** at the coprocessor **16**B and transmitting the estimated position and orientation **50** of the wearable device **14** to the CPU **16**A instead. Thus, processing the imaging data **40** at the coprocessor **16**B may function as a security feature that makes unauthorized access to the raw imaging data **40** more difficult for malicious programs executed at the CPU **16**A.

In some examples in which the imaging data **40** is processed at a coprocessor **16**B, the imaging data **40** received at the coprocessor **16**B may have a lower resolution than other imaging data received from the imaging sensor **22** at the CPU **16**A when performing other computing processes. For example, a photography application program may collect imaging data with a higher image resolution than the imaging data **40** used to compute the estimated position and orientation **50**. Using low-resolution imaging data **40** may reduce power consumption by the offboard computing device **12** while still allowing the position and orientation of the wearable device **14** to be estimated accurately.

As depicted in FIG. **9**, the motion tracking calibration data **52** generated at the CPU **16**A may include the simulated magnetometer data **134** in some examples. The offboard computing device **12** is configured to transmit the simulated magnetometer data **134** to the wearable device **14** in such examples. Thus, in such examples, motion tracking calibration data **52** that provides information about the yaw of the wearable device **14** is obtained via imaging at the offboard computing device **12** and is converted into a form in which it is usable as an input to a 9DOF motion tracking algorithm executed at the wearable device **14**.

In some examples, as an alternative to generating simulated magnetometer data **134** that is transmitted to the wearable device **14**, the motion tracking calibration data **52** may include the yaw drift correction **162**. In examples in which the motion tracking calibration data **52** includes the yaw drift correction **162**, the wearable device **14** may be configured to offload the computation of the yaw drift correction **162** to the offboard computing device **12**. The CPU **16**A may, in such examples, be configured to receive the acceleration data **130** and the orientation data **132** from the wearable device **14**. Alternatively, the CPU **16**A may be configured to receive the 6DOF pose estimate **160** from the wearable device **14**. By offloading computation of the motion tracking calibration data **52** to the offboard computing device **12**, motion tracking calibration for the wearable device **14** may be performed using larger amounts of computing resources that would be available at the processing device **120** and memory device **118** of the wearable device **14**.

FIG. **10** shows the offboard computing device **12** when the imaging sensor **22** collects imaging data of a user wearing the wearable device **14**, according to one example. In the example of FIG. **10**, the left earbud **100**A and the right earbud **100**B included in the wearable device **14** are within a field of view **210** of the imaging sensor **22**.

FIG. **11** schematically shows the offboard computing device **12** when the wearable device **14** is determined to be outside the field of view **210** of the imaging sensor **22**. As depicted in the example of FIG. **11**, when the one or more processing devices **16** of the offboard computing device **12** process the imaging data **40**, the one or more processing devices **16** are further configured to determine, based at least in part on the imaging data **40**, that the wearable device **14** is outside a field of view **210** of the imaging sensor **22**. For example, the out-of-view indication **202** may be an output of the trained machine learning model **200** that is generated when the trained machine learning model **200** does not detect the wearable device **14** with a confidence above a predetermined confidence threshold **204** at any location in the field of view **210**. The coprocessor **16**B may be configured to output an out-of-view indication **202** to the CPU **16**A in response to determining that the wearable device **14** is outside the field of view **210**.

The CPU **16**A is configured to receive the out-of-view indication **202** from the coprocessor **16**B. In response to determining that the wearable device **14** is outside the field of view **210** of the imaging sensor **22**, as indicated by the out-of-view indication **202**, the CPU **16**A is further configured to transmit, to the wearable device **14**, instructions to apply the yaw drift correction **162** until a predetermined duration **206** has elapsed. Accordingly, the wearable device **14** may continue to correct for yaw drift even when the wearable device **14** is outside the field of view of the imaging sensor **22**. The estimated position and orientation **140** computed at the wearable device **14** may therefore remain accurate for a longer period of time.

Although, in the above examples, motion tracking of the wearable device **14** is performed in order to provide spatial audio **154** via the wearable device **14**, motion tracking may additionally or alternatively be performed for the wearable device **14** in other contexts. For example, 9DOF tracking of the position and orientation of the wearable device **14** may be performed when the position and orientation of the wearable device **14** are used to provide user input to the offboard computing device **12**, such as by controlling the location of a cursor. As another example, the position and orientation of the wearable device **14** may be tracked in order to identify whether the user is looking at the imaging sensor **22** of the offboard computing device **12**. In such examples, image tracking may allow the offboard computing device **12** to determine whether the user is looking at the imaging sensor **22** in scenarios in which the user's eyes are at least partially obscured.

FIG. **12**A shows a flowchart of a method **300** for use with a wearable device. The wearable device may be a wearable audio device that includes one or more speakers, such as a headphone device or earbud device. In the example of FIG. **12**A, the wearable device further includes an accelerometer and a gyroscope but does not include a magnetometer. At step **302**, the method **300** includes receiving acceleration data from the accelerometer. In addition, at step **304**, the

method **300** further includes receiving orientation data from the gyroscope. The orientation data includes an angular orientation and an angular velocity of the wearable device.

At step **306**, the method **300** further includes receiving simulated magnetometer data from an offboard computing device. The simulated magnetometer data may be a simulation of magnetic field data that would be collected at the wearable device if the wearable device included a magnetometer, and the magnetometer did not experience electromagnetic interference from the one or more speakers or other electronic components of the wearable device. The simulated magnetometer data is computed at the offboard computing device using data collected from sensors included in the offboard computing device and is transmitted to the wearable device via a wireless connection.

At step **308**, the method **300** further includes performing motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The motion tracking calibration is performed based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data. For example, sensor fusion of the simulated magnetometer data with the acceleration data and the orientation data may be used to increase the accuracy of 6DOF position and orientation estimates computed from the acceleration data and the orientation data.

At step **310**, the method **300** further includes outputting the estimated position and orientation to an additional computing process. In some examples, the estimated position and orientation are transmitted to the offboard computing device. Additionally or alternatively, the estimated position and orientation of the wearable device may be used as inputs to an additional computing process executed onboard the wearable device. As discussed below, the additional computing process may be a spatial audio generating module in some examples. Alternatively, some other additional computing process such as a gaze tracking module and/or a user input module may receive the estimated position and orientation. This may enable improved accuracy in tracking a user's gaze and/or improved accuracy in detecting a user input, for example.

FIGS. **12**B-**12**G show additional steps of the method **300** that may be performed in some examples. FIG. **12**B shows steps that may be performed in examples in which the wearable device is a wearable audio device. At step **312**, the method **300** further includes receiving spatial audio generating instructions from the offboard computing device. The spatial audio generating instructions may, for example, specify a perceived spatial audio location in the physical environment within which the user of the wearable device is located.

At step **314**, the method **300** further includes outputting spatial audio as indicated by the spatial audio generating instructions via the one or more speakers. The spatial audio is localized based at least in part on the estimated position and orientation. For example, the location of the wearable device relative to the perceived spatial audio location may be computed using the estimated position and orientation. The wearable device may then apply one or more temporal offsets and/or amplitude changes to one or more respective audio outputs generated at the one or more speakers such that the spatial audio has the perceived spatial audio location. For example, the wearable device may transmit differing audio signals to a left earbud and a right earbud. These differing audio signals may be computed based at least in part on the estimated position and orientation of the wearable device relative to the perceived spatial audio location.

FIG. **12**C shows additional steps of the method **300** that may be performed when performing motion tracking calibration at step **308**. At step **316**, the method **300** further includes performing 9DOF position tracking based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data. A 9DOF sensor fusion algorithm such as Kalman filtering or complementary filtering may be used to perform the 9DOF position tracking.

At step **318**, the method **300** further includes computing a yaw drift correction based at least in part on the simulated magnetometer data, the acceleration data, and the orientation data. The yaw drift correction adjusts for calibration drift in the yaw direction. In computing devices that include magnetometers, yaw drift is typically corrected via sensor fusion utilizing magnetometer data. The simulated magnetometer data is instead used to compute the yaw drift correction in the example of FIG. **12**C. At step **320**, the method **300** further includes computing the estimated position and orientation based at least in part on the yaw drift correction. Thus, the estimated position and orientation are corrected for yaw drift.

FIG. **12**D shows additional steps of the method **300** that may be performed in examples in which the steps of FIG. **12**C are performed and in which the wearable device includes a temperature sensor. At step **322**, the method **300** further includes receiving a temperature value from the temperature sensor. At step **324**, the method **300** further includes computing the yaw drift correction based at least in part on the temperature value. Since the amount of yaw drift that occurs at the wearable device may vary as a function of temperature, the wearable device may use the temperature value as an additional input when computing the yaw drift correction.

FIG. **12**E shows additional steps of the method **300** that may be performed in examples in which the steps of FIG. **12**D are performed. Via the steps shown in FIG. **12**E, the relationship between temperature and yaw drift may be determined. At step **326**, the method **300** further includes storing, in memory, a temperature lookup table mapping a plurality of temperature values to a respective plurality of yaw drift corrections. The entries included in the temperature lookup table may be generated over time as motion tracking calibration is performed for the wearable device at a plurality of different temperatures. At step **328**, the method **300** further includes at least partially recomputing the temperature lookup table at a predetermined time interval. The temperature lookup table may be recomputed using calibration data received at least in part from the offboard computing device. For example, the calibration data may include the simulated magnetometer data. Additionally or alternatively, the calibration data may include one or more values of the yaw drift correction received from the offboard computing device. By recomputing the temperature lookup table, the wearable device may account for the effects of device aging on the yaw drift.

FIG. **12**F shows additional steps of the method **300** that may be performed in examples in which the wearable device further includes a proximity sensor. At step **330**, the method **300** further includes, via the proximity sensor, receiving an indication that the wearable device is not worn by a user. In addition, at step **332**, the method **300** further includes receiving acceleration data that indicates that the wearable device is stationary. At step **334**, the method **300** further includes performing the motion tracking calibration in response to receiving the indications that the wearable device is stationary and not worn by the user. In some examples, the motion tracking calibration may be performed

in response to additionally or alternatively receiving orientation data that indicates that the orientation of the wearable device is constant. Thus, the motion tracking of the wearable device may be calibrated under conditions in which the angular velocity of the wearable device in the yaw direction is expected to be zero.

Additional steps of the method **300** are shown in FIG. **12**G. At step **336**, the method **300** further includes storing, in memory, a sensor data buffer of one or more frames that each include respective values of the acceleration data, the orientation data, and the simulated magnetometer data at a corresponding timestep. At step **338**, the method **300** further includes performing the motion tracking calibration in response to receiving a calibration opportunity signal from the offboard computing device via a wireless connection. For example, the calibration opportunity signal may indicate that the offboard computing device is stationary, as indicated by computing device acceleration data and computing device orientation data collected at the accelerometer and gyroscope of the offboard computing device. At step **340**, step **338** includes performing the motion tracking calibration based at least in part on the one or more frames stored in the sensor data buffer. By performing the motion tracking calibration using the sensor data stored in the sensor data buffer, the wearable device may account for lag in the detection of the calibration opportunity.

FIG. **13**A shows a flowchart of a method **400** for use with the offboard computing device communicatively coupled to the wearable device. In the example of FIG. **13**A, the offboard computing device includes an imaging sensor, an accelerometer, a gyroscope, and a magnetometer. At step **402**, the method **400** includes receiving imaging data of the wearable device via the imaging sensor. At step **404**, the method **400** further includes receiving computing device acceleration data via the accelerometer. At step **406**, the method **400** further includes receiving computing device orientation data via the gyroscope. The orientation data includes an angular orientation and an angular velocity of the offboard computing device. At step **408**, the method **400** further includes receiving computing device magnetic field data via the magnetometer.

The method **400** further includes, at step **410**, computing an estimated position and orientation of the wearable device relative to the imaging sensor based at least in part on the imaging data. In some examples, the estimated position and orientation are computed at least in part at a trained machine learning model. When the estimated position and orientation of the wearable device are computed, the offboard computing device may perform image recognition on the imaging data to identify the position and orientation of the wearable device within a field of view of the imaging sensor.

At step **412**, the method **400** further includes computing motion tracking calibration data based at least in part on the estimated position and orientation, the computing device acceleration data, the computing device orientation data, and the computing device magnetic field data. In some examples, the motion tracking calibration data includes simulated magnetometer data associated with the wearable device. Additionally or alternatively, the motion tracking calibration data may include a yaw drift correction for the wearable device. At step **414**, the method **400** further includes transmitting the motion tracking calibration data to the wearable device.

FIGS. **13**B and **13**C show additional steps of the method **400** that may be performed in some examples. The additional steps performed in FIG. **13**B may be performed in examples in which the motion tracking calibration data includes a yaw drift correction. At step **416**, shown in FIG. **13**B, the method **400** further includes determining, based at least in part on the imaging data, that the wearable device is outside a field of view of the imaging sensor. At step **418**, in response to determining that the wearable device is outside the field of view of the imaging sensor, the method **400** further includes transmitting, to the wearable device, instructions to apply the yaw drift correction until a predetermined duration has elapsed. The wearable device may accordingly continue to adjust for yaw drift when outside the field of view of the imaging sensor included in the offboard computing device.

FIG. **13**C shows additional steps that may be performed to adjust for movement of the offboard computing device. At step **420**, the method **400** further includes offsetting the estimated position and orientation of the wearable device relative to the offboard computing device based at least in part on the computing device acceleration data and the computing device orientation data. At step **422**, the method **400** further includes computing the motion tracking calibration data based at least in part on the offset estimated position and orientation. The offboard computing device may accordingly compute the motion tracking calibration data in a reference frame of the user's physical environment rather than a reference frame of the offboard computing device.

Using the devices and methods discussed above, accurate motion tracking may be performed at a wearable device that experiences high levels of electromagnetic interference from an electronic component such as a speaker. Thus, the increase in motion tracking accuracy that would typically be achieved using a magnetometer may be provided even for devices in which a magnetometer would output inaccurate readouts. The increase in position and orientation tracking accuracy achieved using the devices and methods discussed above may allow spatial audio signals to be more accurately produced such that the user perceives the spatial audio as originating from an intended location.

In some embodiments, the methods and processes described herein may be tied to a computing system of one or more computing devices. In particular, such methods and processes may be implemented as a computer-application program or service, an application-programming interface (API), a library, and/or other computer-program product.

FIG. **14** schematically shows a non-limiting embodiment of a computing system **500** that can enact one or more of the methods and processes described above. Computing system **500** is shown in simplified form. Computing system **500** may embody the computing system **10** described above and illustrated in FIG. **1**. Components of computing system **500** may be included in one or more personal computers, server computers, tablet computers, home-entertainment computers, network computing devices, video game devices, mobile computing devices, mobile communication devices (e.g., smart phone), and/or other computing devices, and wearable computing devices such as smart wristwatches and head mounted augmented reality devices.

Computing system **500** includes a logic processor **502** volatile memory **504**, and a non-volatile storage device **506**. Computing system **500** may optionally include a display subsystem **508**, input subsystem **510**, communication subsystem **512**, and/or other components not shown in FIG. **14**.

Logic processor **502** includes one or more physical devices configured to execute instructions. For example, the logic processor may be configured to execute instructions that are part of one or more applications, programs, routines, libraries, objects, components, data structures, or other logi-

cal constructs. Such instructions may be implemented to perform a task, implement a data type, transform the state of one or more components, achieve a technical effect, or otherwise arrive at a desired result.

The logic processor may include one or more physical processors (hardware) configured to execute software instructions. Additionally or alternatively, the logic processor may include one or more hardware logic circuits or firmware devices configured to execute hardware-implemented logic or firmware instructions. Processors of the logic processor **502** may be single-core or multi-core, and the instructions executed thereon may be configured for sequential, parallel, and/or distributed processing. Individual components of the logic processor optionally may be distributed among two or more separate devices, which may be remotely located and/or configured for coordinated processing. Aspects of the logic processor may be virtualized and executed by remotely accessible, networked computing devices configured in a cloud-computing configuration. In such a case, these virtualized aspects are run on different physical logic processors of various different machines, it will be understood.

Non-volatile storage device **506** includes one or more physical devices configured to hold instructions executable by the logic processors to implement the methods and processes described herein. When such methods and processes are implemented, the state of non-volatile storage device **506** may be transformed—e.g., to hold different data.

Non-volatile storage device **506** may include physical devices that are removable and/or built-in. Non-volatile storage device **506** may include optical memory, semiconductor memory, and/or magnetic memory, or other mass storage device technology. Non-volatile storage device **506** may include nonvolatile, dynamic, static, read/write, read-only, sequential-access, location-addressable, file-addressable, and/or content-addressable devices. It will be appreciated that non-volatile storage device **506** is configured to hold instructions even when power is cut to the non-volatile storage device **506**.

Volatile memory **504** may include physical devices that include random access memory. Volatile memory **504** is typically utilized by logic processor **502** to temporarily store information during processing of software instructions. It will be appreciated that volatile memory **504** typically does not continue to store instructions when power is cut to the volatile memory **504**.

Aspects of logic processor **502**, volatile memory **504**, and non-volatile storage device **506** may be integrated together into one or more hardware-logic components. Such hardware-logic components may include field-programmable gate arrays (FPGAs), program- and application-specific integrated circuits (PASIC/ASICs), program- and application-specific standard products (PSSP/ASSPs), system-on-a-chip (SOC), and complex programmable logic devices (CPLDs), for example.

The terms "module," "program," and "engine" may be used to describe an aspect of computing system **500** typically implemented in software by a processor to perform a particular function using portions of volatile memory, which function involves transformative processing that specially configures the processor to perform the function. Thus, a module, program, or engine may be instantiated via logic processor **502** executing instructions held by non-volatile storage device **506**, using portions of volatile memory **504**. It will be understood that different modules, programs, and/or engines may be instantiated from the same application, service, code block, object, library, routine, API, function, etc. Likewise, the same module, program, and/or engine may be instantiated by different applications, services, code blocks, objects, routines, APIs, functions, etc. The terms "module," "program," and "engine" may encompass individual or groups of executable files, data files, libraries, drivers, scripts, database records, etc.

When included, display subsystem **508** may be used to present a visual representation of data held by non-volatile storage device **506**. The visual representation may take the form of a graphical user interface (GUI). As the herein described methods and processes change the data held by the non-volatile storage device, and thus transform the state of the non-volatile storage device, the state of display subsystem **508** may likewise be transformed to visually represent changes in the underlying data. Display subsystem **508** may include one or more display devices utilizing virtually any type of technology. Such display devices may be combined with logic processor **502**, volatile memory **504**, and/or non-volatile storage device **506** in a shared enclosure, or such display devices may be peripheral display devices.

When included, input subsystem **510** may comprise or interface with one or more user-input devices such as a keyboard, mouse, touch screen, or game controller. In some embodiments, the input subsystem may comprise or interface with selected natural user input (NUI) componentry. Such componentry may be integrated or peripheral, and the transduction and/or processing of input actions may be handled on- or off-board. Example NUI componentry may include a microphone for speech and/or voice recognition; an infrared, color, stereoscopic, and/or depth camera for machine vision and/or gesture recognition; a head tracker, eye tracker, accelerometer, and/or gyroscope for motion detection and/or intent recognition; as well as electric-field sensing componentry for assessing brain activity; and/or any other suitable sensor.

When included, communication subsystem **512** may be configured to communicatively couple various computing devices described herein with each other, and with other devices. Communication subsystem **512** may include wired and/or wireless communication devices compatible with one or more different communication protocols. As non-limiting examples, the communication subsystem may be configured for communication via a wireless telephone network, or a wired or wireless local- or wide-area network. In some embodiments, the communication subsystem may allow computing system **500** to send and/or receive messages to and/or from other devices via a network such as the Internet.

The following paragraphs discuss several aspects of the present disclosure. According to one aspect of the present disclosure, a wearable device is provided, including an accelerometer, a gyroscope, and a processing device. The processing device is configured to receive acceleration data from the accelerometer, receive orientation data from the gyroscope, and receive simulated magnetometer data from an offboard computing device. Based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, the processing device is further configured to perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The processing device is further configured to output the estimated position and orientation to an additional computing process. The above features may have the technical effect of increasing the accuracy of the motion tracking calibration.

According to this aspect, the wearable device may be a wearable audio device that includes one or more speakers. The processing device may be further configured to receive

spatial audio generating instructions from the offboard computing device. Via the one or more speakers, the processing device may be further configured to output spatial audio as indicated by the spatial audio generating instructions. The processing device may be configured to localize the spatial audio based at least in part on the estimated position and orientation. The above features may have the technical effect of producing spatial audio that is more accurately localized at a perceived location.

According to this aspect, the processing device may be further configured to perform nine-degree-of-freedom (9DOF) position tracking using the acceleration data, the orientation data, and the simulated magnetometer data to compute the estimated position and orientation. The above features may have the technical effect of increasing the accuracy of the motion tracking calibration.

According to this aspect, the processing device may be configured to perform the motion tracking calibration at least in part by computing a yaw drift correction based at least in part on the simulated magnetometer data, the acceleration data, and the orientation data. Performing the motion tracking calibration may further include computing the estimated position and orientation based at least in part on the yaw drift correction. The above features may have the technical effect of correcting for yaw drift when computing the estimated position and orientation.

According to this aspect, the wearable device may further include a temperature sensor. The processing device may be further configured to receive a temperature value from the temperature sensor. The processing device may be further configured to compute the yaw drift correction based at least in part on the temperature value. The above features may have the technical effect of adjusting for temperature dependence of the yaw drift when computing the estimated position and orientation.

According to this aspect, the wearable device may further include a memory device. The memory device may store a temperature lookup table mapping a plurality of temperature values to a respective plurality of yaw drift corrections. At a predetermined time interval, the processing device may be further configured to at least partially recompute the temperature lookup table using calibration data received at least in part from the offboard computing device. The above features may have the technical effect of allowing the temperature correction to be applied to the yaw value of the wearable device without having to receive the yaw drift correction from the offboard computing device. The above features may have the additional technical effect of adjusting the temperature lookup table for device aging.

According to this aspect, the wearable device may further include a proximity sensor. Via the proximity sensor, the processing device may be further configured to receive an indication that the wearable device is not worn by a user. The acceleration data may further indicate that the wearable device is stationary. The processing device may be further configured to perform the motion tracking calibration in response to receiving the indications that the wearable device is stationary and not worn by the user. The above features may have the technical effect of obtaining a baseline value of the yaw drift.

According to this aspect, the processing device may be configured to perform the motion tracking calibration in response to receiving a calibration opportunity signal from the offboard computing device via a wireless connection. The above features may have the technical effect of offloading, to the offboard computing device, determination of the timing at which the motion tracking calibration is performed.

According to this aspect, the wearable computing device may further include a memory device. The memory device may be configured to store a sensor data buffer of one or more frames that each include respective values of the acceleration data, the orientation data, and the simulated magnetometer data at a corresponding timestep. In response to receiving the calibration opportunity signal, the processing device may be further configured to perform the motion tracking calibration based at least in part on the one or more frames stored in the sensor data buffer. The above features may have the technical effect of adjusting for lag in receiving the calibration opportunity signal from the offboard computing device after conditions conducive to performing motion tracking calibration have been detected.

According to another aspect of the present disclosure, a method for use with a wearable device is provided. The method includes receiving acceleration data from an accelerometer, receiving orientation data from a gyroscope, and receiving simulated magnetometer data from an offboard computing device. Based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, the method further includes performing motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The method further includes outputting the estimated position and orientation to an additional computing process. The above features may have the technical effect of increasing the accuracy of the motion tracking calibration.

According to this aspect, the wearable device may be a wearable audio device that includes one or more speakers. The method may further include receiving spatial audio generating instructions from the offboard computing device. Via the one or more speakers, the method may further include outputting spatial audio as indicated by the spatial audio generating instructions. The spatial audio may be localized based at least in part on the estimated position and orientation. The above features may have the technical effect of producing spatial audio that is more accurately localized at a perceived location.

According to this aspect, performing the motion tracking calibration may include performing nine-degree-of-freedom (9DOF) position tracking based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data. The above features may have the technical effect of increasing the accuracy of the motion tracking calibration.

According to this aspect, performing the motion tracking calibration may include computing a yaw drift correction based at least in part on the simulated magnetometer data, the acceleration data, and the orientation data. Performing the motion tracking calibration may further include computing the estimated position and orientation based at least in part on the yaw drift correction. The above features may have the technical effect of correcting for yaw drift when computing the estimated position and orientation.

According to this aspect, the method may further include receiving a temperature value from a temperature sensor. The method may further include computing the yaw drift correction based at least in part on the temperature value. The above features may have the technical effect of adjusting for temperature dependence of the yaw drift when computing the estimated position and orientation.

According to another aspect of the present disclosure, a computing device is provided, including an imaging sensor, an accelerometer, a gyroscope, a magnetometer, and one or more processing devices. Via the imaging sensor, the one or more processing devices are configured to receive imaging data of a wearable device. Via the accelerometer, the one or more processing devices are configured to receive computing device acceleration data. Via the gyroscope, the one or more processing devices are configured to receive computing device orientation data. Via the magnetometer, the one or more processing devices are configured to receive computing device magnetic field data. Based at least in part on the imaging data, the one or more processing devices are configured to compute an estimated position and orientation of the wearable device relative to the imaging sensor. Based at least in part on the estimated position and orientation, the computing device acceleration data, the computing device orientation data, and the computing device magnetic field data, the one or more processing devices are configured to compute motion tracking calibration data associated with the wearable device. The one or more processing devices are configured to transmit the motion tracking calibration data to the wearable device. The above features may have the technical effect of providing the wearable device with motion tracking calibration data that the wearable device may use to perform more accurate motion tracking calibration.

According to this aspect, the motion tracking calibration data may include simulated magnetometer data associated with the wearable device. The above features may have the technical effect of allowing the wearable device to perform 9DOF position tracking as though it included a magnetometer even when the wearable device does not include a magnetometer.

According to this aspect, the motion tracking calibration data may include a yaw drift correction associated with the wearable device. The above features may have the technical effect of allowing the wearable device to correct for drift in yaw values when performing motion tracking calibration.

According to this aspect, the one or more processing devices may be further configured to determine, based at least in part on the imaging data, that the wearable device is outside a field of view of the imaging sensor. In response to determining that the wearable device is outside the field of view of the imaging sensor, the one or more processing devices may be further configured to transmit, to the wearable device, instructions to apply the yaw drift correction until a predetermined duration has elapsed. The above features may have the technical effect of allowing the wearable device to continue correcting for the yaw drift even when outside the field of view of the imaging sensor.

According to this aspect, the one or more processing devices may be further configured to offset the estimated position and orientation of the wearable device relative to the offboard computing device based at least in part on the computing device acceleration data and the computing device orientation data. The one or more processing devices may be further configured to compute the motion tracking calibration data based at least in part on the offset estimated position and orientation. The above features may have the technical effect of adjusting the motion tracking calibration data to account for movement of the offboard computing device.

According to this aspect, the one or more processing devices are configured to compute the estimated position and orientation at least in part at a trained machine learning model. The above features may have the technical effect of performing image recognition to accurately identify the position and orientation of the wearable device from the imaging data.

According to this aspect, the imaging sensor may be a camera or an ultra-wideband (UWB) sensor. The above features may have the technical effect of allowing the computing device to collect the imaging data of the wearable device.

According to another aspect of the present disclosure, a computing system is provided, including a wearable device. The wearable device includes an accelerometer configured to collect acceleration data, a gyroscope configured to collect orientation data, and a first processor. The computing system further includes an offboard computing device. The offboard computing device includes an imaging sensor configured to capture imaging data of a user wearing the wearable device, and further includes a second processor. The offboard computing device is configured to process the imaging data to generate simulated magnetometer data. The first processor and/or the second processor is configured to, based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device. The above features may have the technical effect of increasing the accuracy of the motion tracking calibration.

According to this aspect, the first processor may be configured to receive the simulated magnetometer data from the offboard computing device. The first processor may be further configured to compute the estimated position and orientation at least in part by performing sensor fusion of the acceleration data, the orientation data, and the simulated magnetometer data. The above features may have the technical effect of allowing the wearable device to perform 9DOF position tracking as though it included a magnetometer even when the wearable device does not include a magnetometer.

According to this aspect, the second processor may be further configured to compute a yaw drift correction associated with the wearable device at least in part by computing the estimated position and orientation of the wearable device relative to the offboard computing device. Computing the yaw drift correction may further include receiving the acceleration data and the gyroscope data from the wearable device. The yaw drift correction may be computed based at least in part on the estimated position and orientation, the acceleration data, and the gyroscope data. The second processor may be further configured to transmit the yaw drift correction to the wearable device. The first processor may be further configured to apply the yaw drift correction to the estimated position and orientation. The above features may have the technical effect of allowing the wearable device to correct for drift in yaw values when performing motion tracking calibration.

According to this aspect, the offboard computing device may further include an offboard computing device accelerometer and an offboard computing device gyroscope. The second processor may be further configured to receive offboard computing device acceleration data from the offboard computing device accelerometer. The second processor may be further configured to receive offboard computing device orientation data from the offboard computing device gyroscope. The second processor may be further configured to offset the estimated position and orientation of the wearable device relative to the offboard computing device based at least in part on the offboard computing device acceleration

data and the offboard computing device orientation data. The second processor may be further configured to compute the yaw drift correction based at least in part on the offset estimated position and orientation. The above features may have the technical effect of adjusting the motion tracking calibration data to account for movement of the offboard computing device.

"And/or" as used herein is defined as the inclusive or V, as specified by the following truth table:

A	B	A ∨ B
True	True	True
True	False	True
False	True	True
False	False	False

It will be understood that the configurations and/or approaches described herein are exemplary in nature, and that these specific embodiments or examples are not to be considered in a limiting sense, because numerous variations are possible. The specific routines or methods described herein may represent one or more of any number of processing strategies. As such, various acts illustrated and/or described may be performed in the sequence illustrated and/or described, in other sequences, in parallel, or omitted. Likewise, the order of the above-described processes may be changed.

The subject matter of the present disclosure includes all novel and non-obvious combinations and sub-combinations of the various processes, systems and configurations, and other features, functions, acts, and/or properties disclosed herein, as well as any and all equivalents thereof.

The invention claimed is:

1. A wearable device comprising:
an accelerometer;
a gyroscope; and
a processing device configured to:
receive acceleration data from the accelerometer;
receive orientation data from the gyroscope;
receive simulated magnetometer data from an offboard computing device, wherein the simulated magnetometer data includes an estimated direction of the Earth's magnetic field at the wearable device;
based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device; and
output the estimated position and orientation to an additional computing process.

2. The wearable device of claim **1**, wherein:
the wearable device is a wearable audio device that includes one or more speakers; and
the processing device is further configured to:
receive spatial audio generating instructions from the offboard computing device; and
via the one or more speakers, output spatial audio as indicated by the spatial audio generating instructions, wherein the processing device is configured to localize the spatial audio based at least in part on the estimated position and orientation.

3. The wearable device of claim **1**, wherein the processing device is further configured to perform nine-degree-of-freedom (9DOF) position tracking using the acceleration data, the orientation data, and the simulated magnetometer data to compute the estimated position and orientation.

4. The wearable device of claim **1**, wherein the processing device is configured to perform the motion tracking calibration at least in part by:
computing a yaw drift correction based at least in part on the simulated magnetometer data, the acceleration data, and the orientation data; and
computing the estimated position and orientation based at least in part on the yaw drift correction.

5. The wearable device of claim **4**, further comprising a temperature sensor, wherein the processing device is further configured to:
receive a temperature value from the temperature sensor; and
compute the yaw drift correction based at least in part on the temperature value.

6. The wearable device of claim **5**, further comprising a memory device, wherein:
the memory device stores a temperature lookup table mapping a plurality of temperature values to a respective plurality of yaw drift corrections;
at a predetermined time interval, the processing device is further configured to at least partially recompute the temperature lookup table using calibration data received at least in part from the offboard computing device.

7. The wearable device of claim **1**, further comprising a proximity sensor, wherein:
via the proximity sensor, the processing device is further configured to receive an indication that the wearable device is not worn by a user;
the acceleration data indicates that the wearable device is stationary; and
the processing device is further configured to perform the motion tracking calibration in response to receiving the indications that the wearable device is stationary and not worn by the user.

8. The wearable device of claim **1**, wherein the processing device is configured to perform the motion tracking calibration in response to receiving a calibration opportunity signal from the offboard computing device via a wireless connection.

9. The wearable device of claim **8**, further comprising a memory device, wherein:
the memory device is configured to store a sensor data buffer of one or more frames that each include respective values of the acceleration data, the orientation data, and the simulated magnetometer data at a corresponding timestep; and
in response to receiving the calibration opportunity signal, the processing device is further configured to perform the motion tracking calibration based at least in part on the one or more frames stored in the sensor data buffer.

10. A method for use with a wearable device, the method comprising:
receiving acceleration data from an accelerometer;
receiving orientation data from a gyroscope;
receiving simulated magnetometer data from an offboard computing device, wherein the simulated magnetometer data includes an estimated direction of the Earth's magnetic field at the wearable device;
based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, performing motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device; and

outputting the estimated position and orientation to an additional computing process.

11. The method of claim **10**, wherein:

the wearable device is a wearable audio device that includes one or more speakers; and

the method further comprises:

receiving spatial audio generating instructions from the offboard computing device; and

via the one or more speakers, outputting spatial audio as indicated by the spatial audio generating instructions, wherein the spatial audio is localized based at least in part on the estimated position and orientation.

12. The method of claim **10**, wherein performing the motion tracking calibration includes performing nine-degree-of-freedom (9DOF) position tracking based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data.

13. The method of claim **10**, wherein performing the motion tracking calibration includes:

computing a yaw drift correction based at least in part on the simulated magnetometer data, the acceleration data, and the orientation data; and

computing the estimated position and orientation based at least in part on the yaw drift correction.

14. The method of claim **13**, further comprising:

receiving a temperature value from a temperature sensor; and

computing the yaw drift correction based at least in part on the temperature value.

15. A computing device comprising:

an imaging sensor;

an accelerometer;

a gyroscope;

a magnetometer; and

one or more processing devices configured to:

via the imaging sensor, receive imaging data of a wearable device;

via the accelerometer, receive computing device acceleration data;

via the gyroscope, receive computing device orientation data;

via the magnetometer, receive computing device magnetic field data, wherein the simulated magnetometer data includes an estimated direction of the Earth's magnetic field at the wearable device;

based at least in part on the imaging data, compute an estimated position and orientation of the wearable device relative to the imaging sensor;

based at least in part on the estimated position and orientation, the computing device acceleration data, the computing device orientation data, and the computing device magnetic field data, compute motion tracking calibration data associated with the wearable device; and

transmit the motion tracking calibration data to the wearable device.

16. The computing device of claim **15**, wherein the motion tracking calibration data includes simulated magnetometer data associated with the wearable device.

17. The computing device of claim **15**, wherein the motion tracking calibration data includes a yaw drift correction associated with the wearable device.

18. The computing device of claim **17**, wherein the one or more processing devices are further configured to:

determine, based at least in part on the imaging data, that the wearable device is outside a field of view of the imaging sensor; and

in response to determining that the wearable device is outside the field of view of the imaging sensor, transmit, to the wearable device, instructions to apply the yaw drift correction until a predetermined duration has elapsed.

19. The computing device of claim **15**, wherein the one or more processing devices are further configured to:

offset the estimated position and orientation of the wearable device relative to the offboard computing device based at least in part on the computing device acceleration data and the computing device orientation data; and

compute the motion tracking calibration data based at least in part on the offset estimated position and orientation.

20. The computing device of claim **15**, wherein the one or more processing devices are configured to compute the estimated position and orientation at least in part at a trained machine learning model.

21. The computing device of claim **15**, wherein the imaging sensor is a camera or an ultra-wideband (UWB) sensor.

22. A computing system, comprising:

a wearable device including an accelerometer configured to collect acceleration data, a gyroscope configured to collect orientation data, and a first processor; and

an offboard computing device including an imaging sensor configured to capture imaging data of a user wearing the wearable device, and further including a second processor, wherein:

the offboard computing device is configured to process the imaging data to generate simulated magnetometer data;

the simulated magnetometer data includes an estimated direction of the Earth's magnetic field at the wearable device; and

the first processor and/or the second processor is configured to, based at least in part on the acceleration data, the orientation data, and the simulated magnetometer data, perform motion tracking calibration to obtain an estimated position and orientation of the wearable device relative to the offboard computing device.

23. The computing system of claim **22**, wherein the first processor is configured to:

receive the simulated magnetometer data from the offboard computing device; and

compute the estimated position and orientation at least in part by performing sensor fusion of the acceleration data, the orientation data, and the simulated magnetometer data.

24. The computing system of claim **22**, wherein:

the second processor is further configured to:

compute a yaw drift correction associated with the wearable device at least in part by:

computing the estimated position and orientation of the wearable device relative to the offboard computing device;

receiving the acceleration data and the gyroscope data from the wearable device; and

computing the yaw drift correction based at least in part on the estimated position and orientation, the acceleration data, and the gyroscope data; and

transmit the yaw drift correction to the wearable device; and

the first processor is further configured to apply the yaw drift correction to the estimated position and orientation.

25. The computing system of claim **24**, wherein:

the offboard computing device further includes an offboard computing device accelerometer and an offboard computing device gyroscope; and

the second processor is further configured to:

receive offboard computing device acceleration data from the offboard computing device accelerometer;

receive offboard computing device orientation data from the offboard computing device gyroscope;

offset the estimated position and orientation of the wearable device relative to the offboard computing device based at least in part on the offboard computing device acceleration data and the offboard computing device orientation data; and

compute the yaw drift correction based at least in part on the offset estimated position and orientation.

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