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(54) EMBEDDED ARM STRAIN SENSORS

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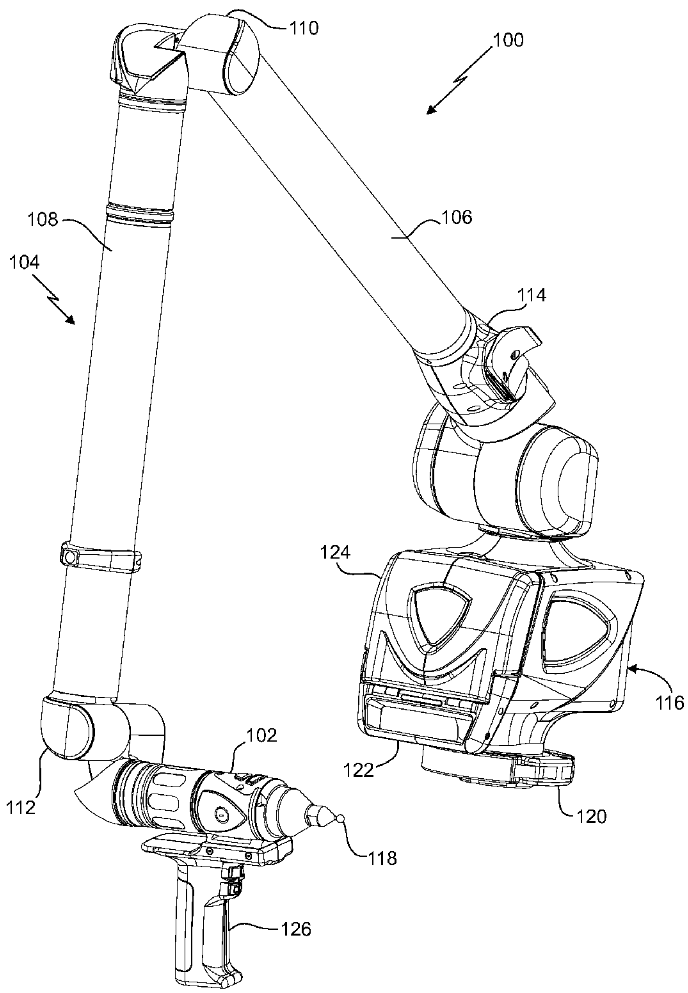
(52) **U.S. Cl.** **340/665**; 33/503

(57) **ABSTRACT**

A portable articulated arm coordinate measurement machine (AACMM) can include a manually positionable articulated arm portion, a measurement device attached to the first end, a structural component of the AACMM, wherein the structural component has an axial direction, at least three strain gage sensors, each having a sensitive axis, coupled to the structural component, wherein the sensitive axis of each strain gage sensor is oriented approximately parallel to the axial direction, each strain gage sensor is approximately intersected by a transverse plane perpendicular to the axial direction, each strain gage sensor produces an analog strain gage signal, and the strain gage sensors are disposed to provide data sufficient to determine a bending strain at any point residing on both the structural component and the transverse plane and an electronic circuit that receives the position signal and provides data corresponding to a position of the measurement device.



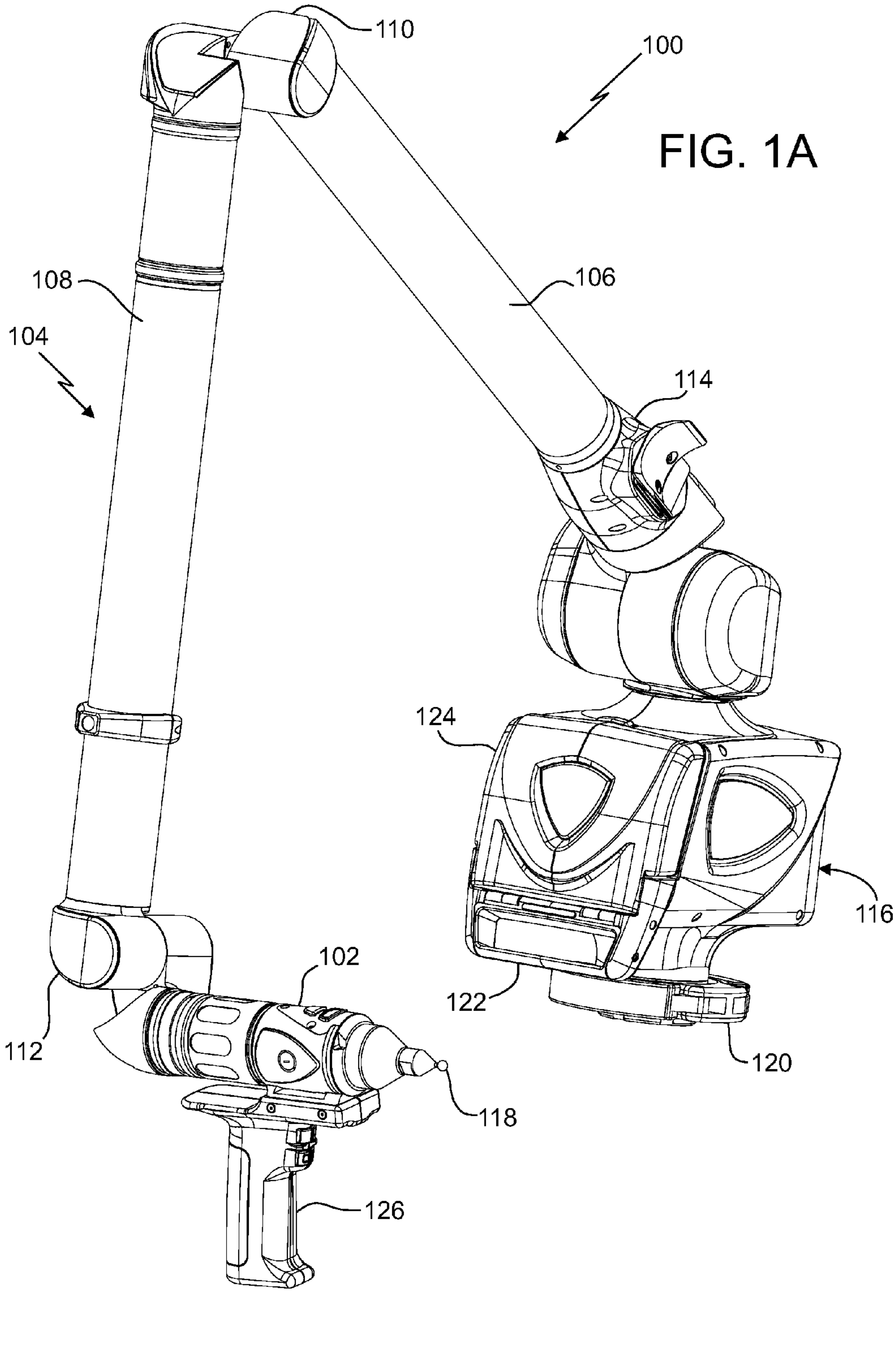


FIG. 1A

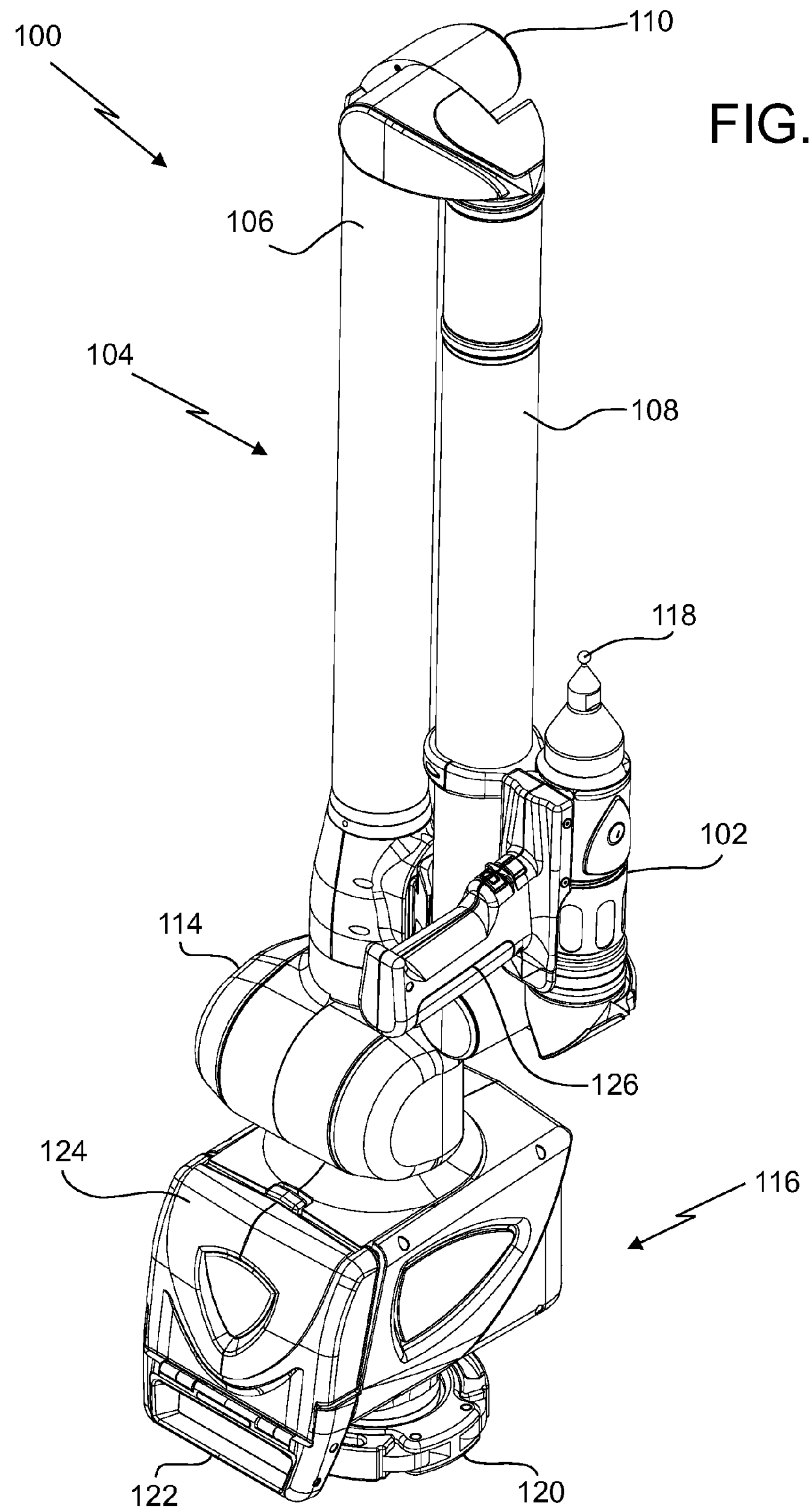
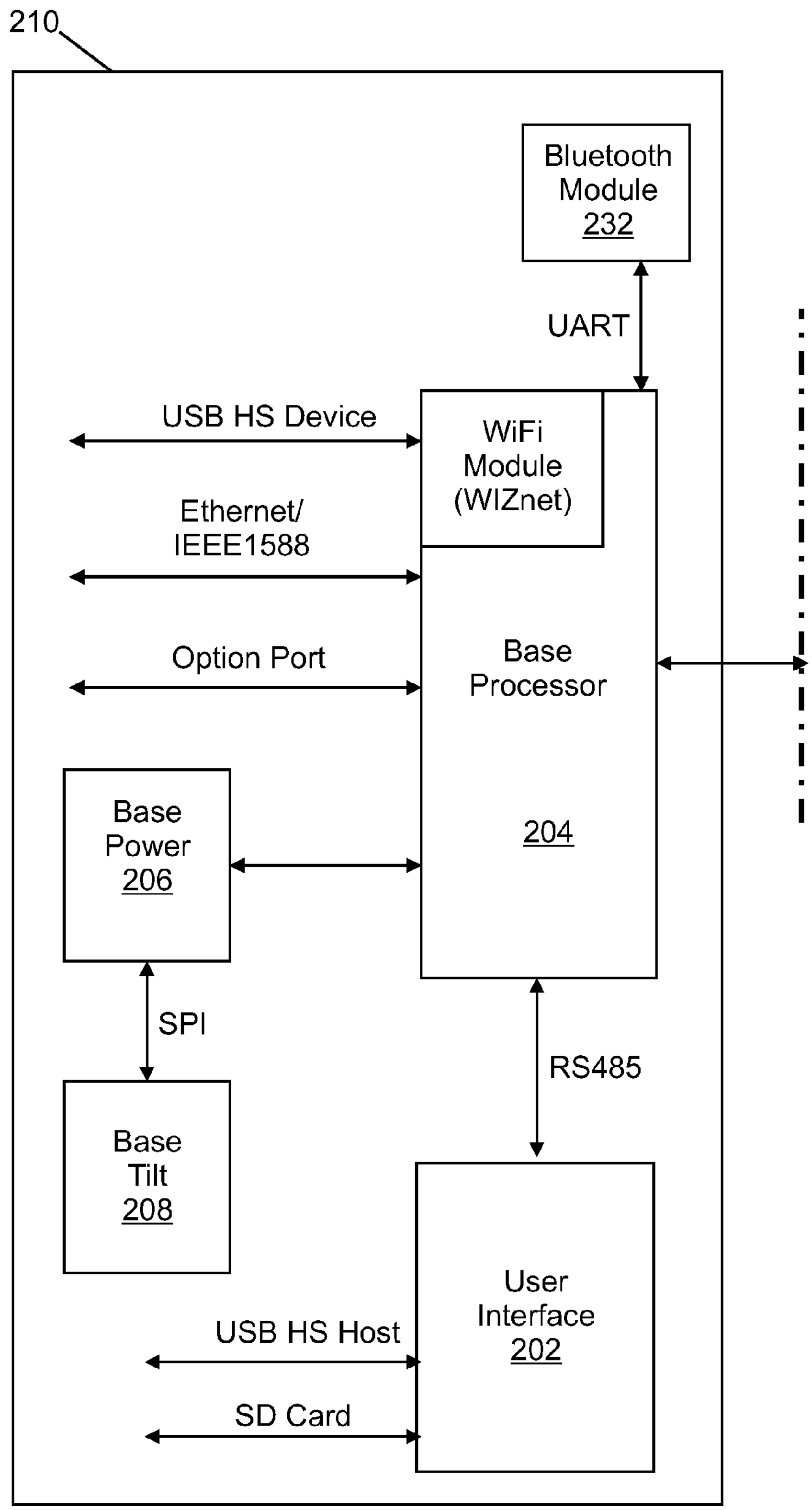


FIG. 1B

FIG. 2A


210
Bluetooth Module 232
UART
USB HS Device
WiFi Module (WIZnet)
Ethernet/ IEEE1588
Option Port
Base Processor
204
Base Power 206
SPI
Base Tilt 208
RS485
User Interface 202
USB HS Host
SD Card

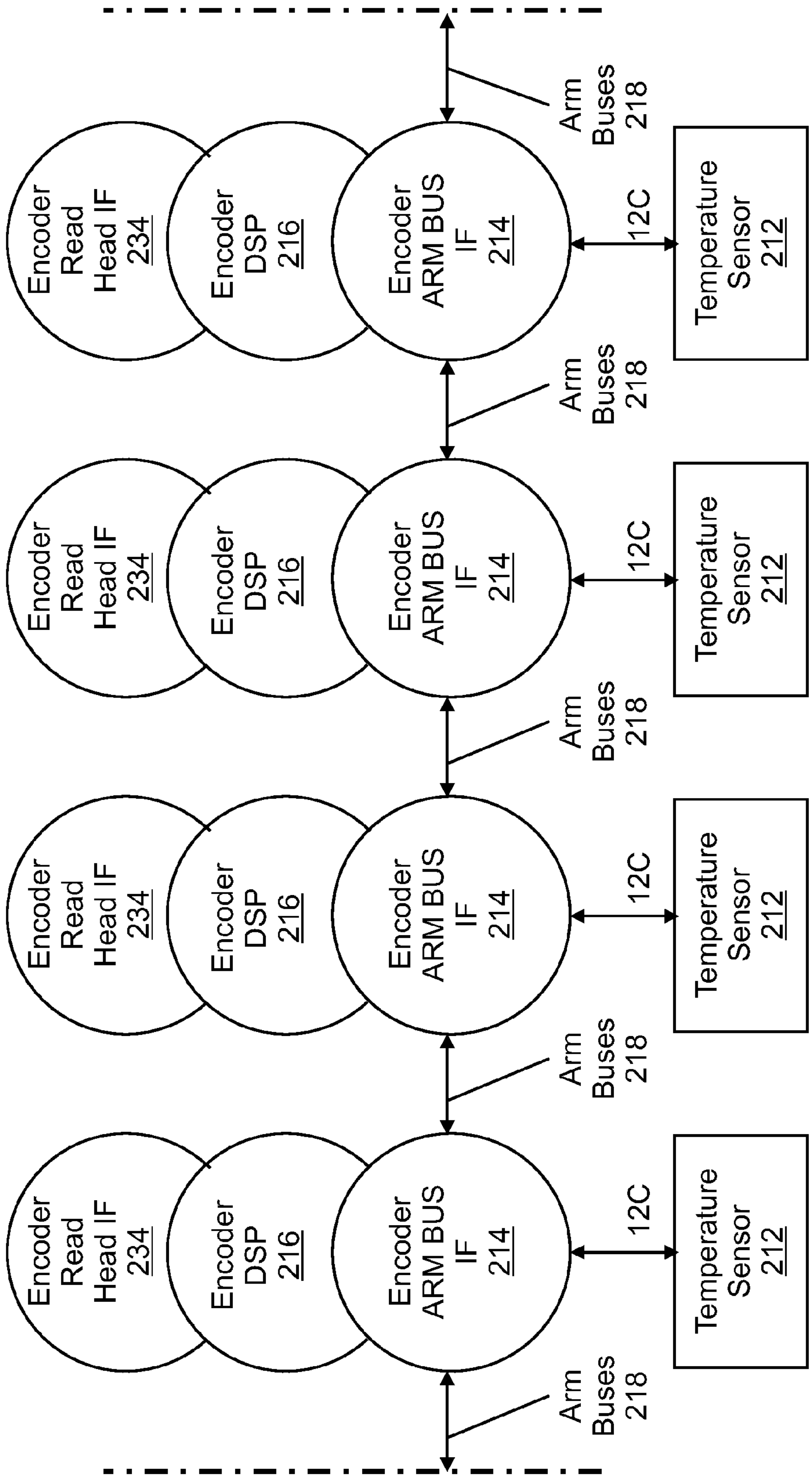

Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218

FIG. 2B

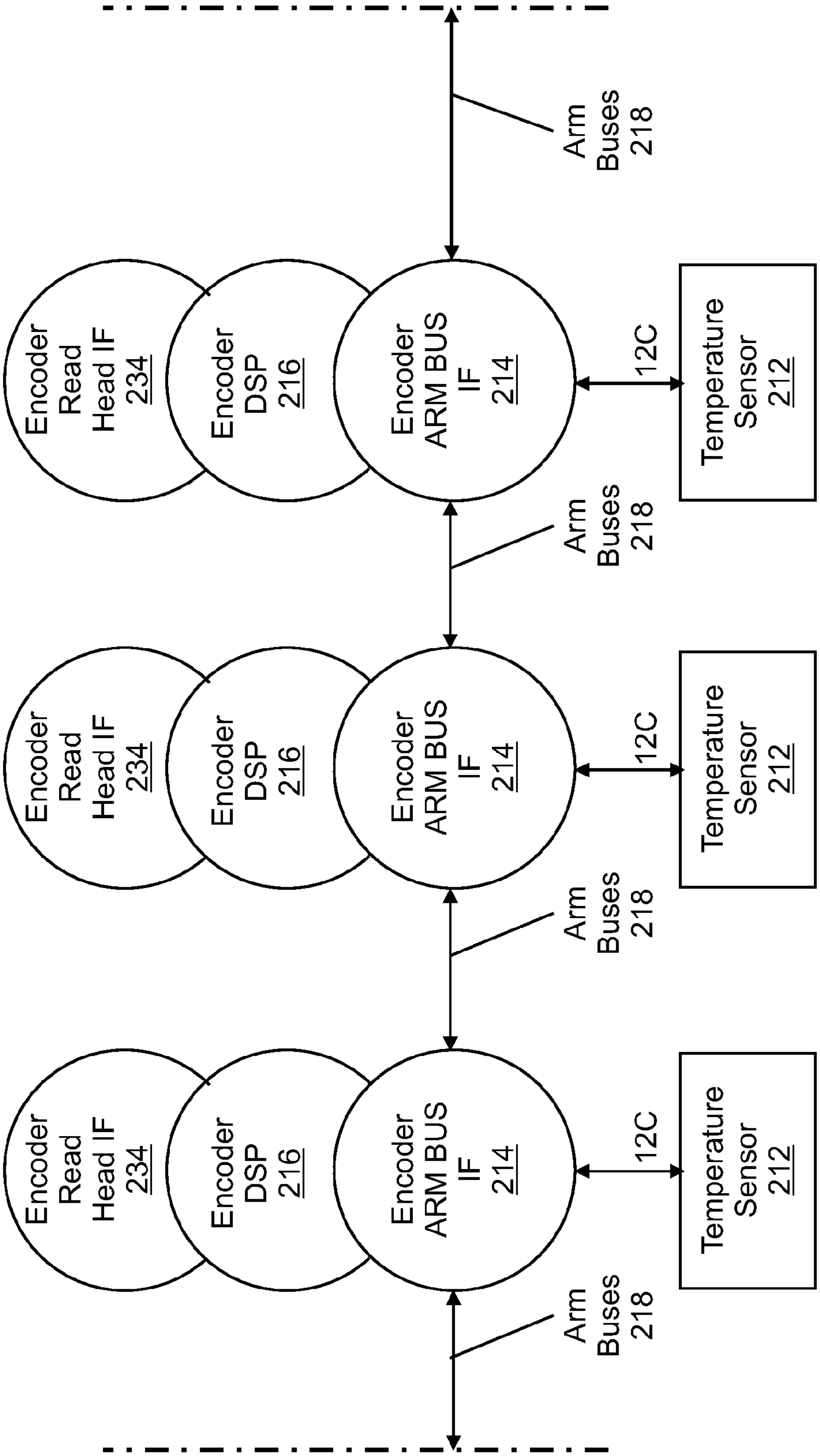

Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Encoder Read Head IF 234
Encoder DSP 216
Encoder ARM BUS IF 214
12C
Temperature Sensor 212
Arm Buses 218
Arm Buses 218

FIG. 2C

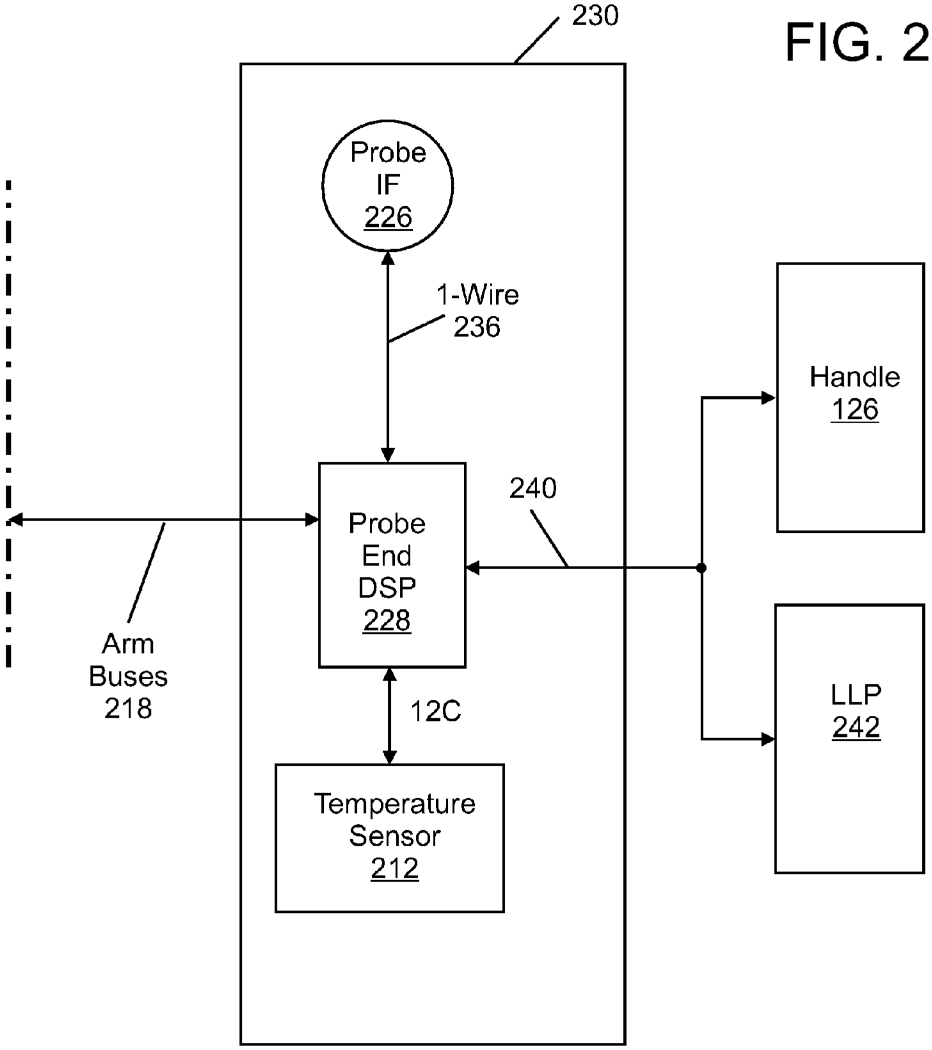

230
Probe
IF
226
1-Wire
236
Probe
End
DSP
228
240
Handle
126
LLP
242
Arm
Buses
218
12C
Temperature
Sensor
212

FIG. 2D

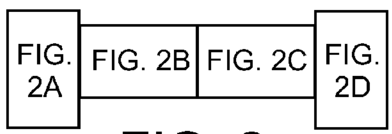
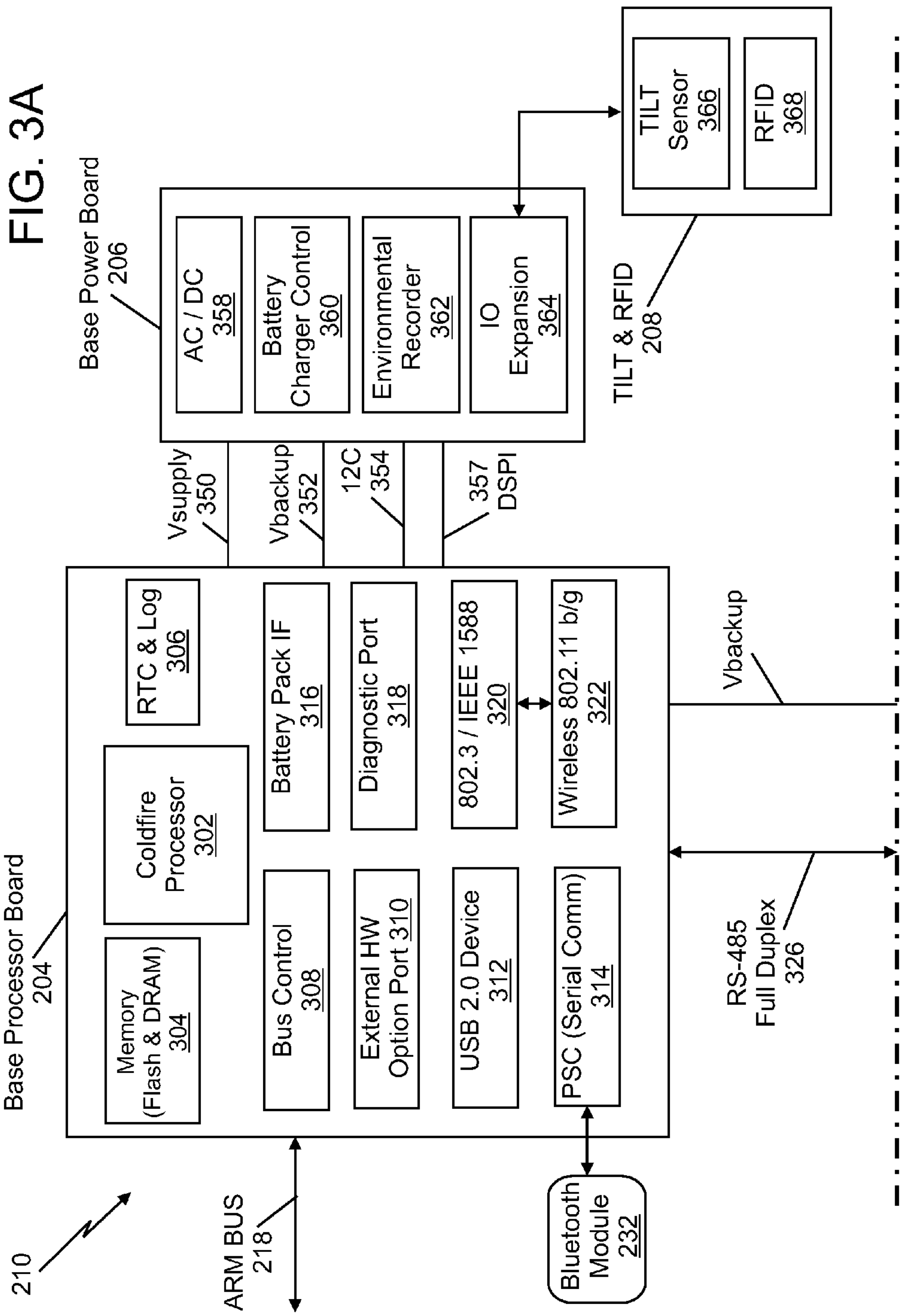


FIG.
2A
FIG. 2B
FIG. 2C
FIG.
2D

FIG. 2

FIG. 3A



Base Power Board
206
AC / DC
358
Battery
Charger Control
360
Environmental
Recorder
362
IO
Expansion
364
TILT
Sensor
366
RFID
368
TILT & RFID
208
Vsupply
350
Vbackup
352
12C
354
357
DSPI
Base Processor Board
204
Memory
(Flash & DRAM)
304
Coldfire
Processor
302
RTC & Log
306
Bus Control
308
Battery Pack IF
316
External HW
Option Port 310
Diagnostic Port
318
USB 2.0 Device
312
802.3 / IEEE 1588
320
PSC (Serial Comm)
314
Wireless 802.11 b/g
322
Vbackup
RS-485
Full Duplex
326
210
ARM BUS
218
Bluetooth
Module
232

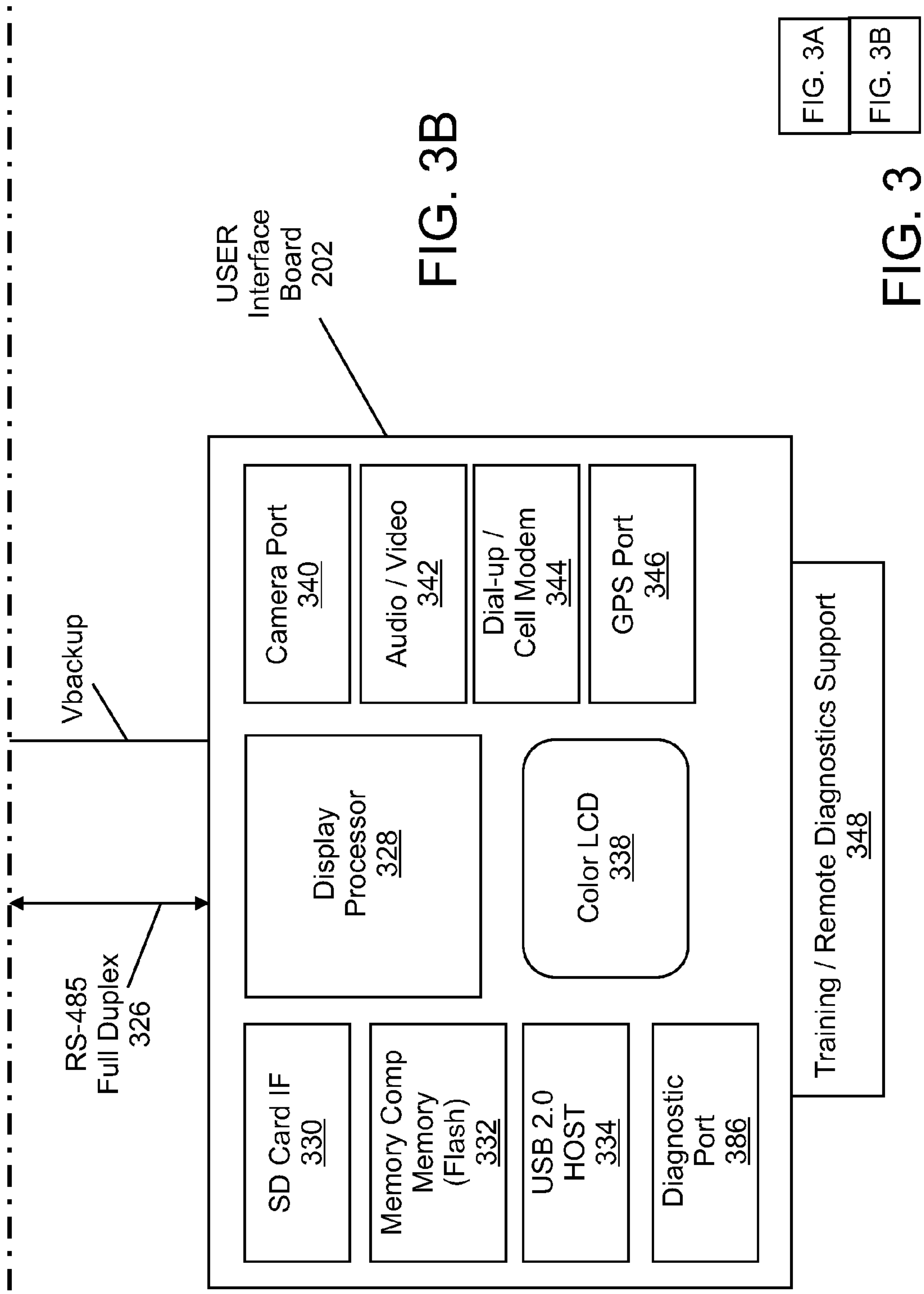

USER Interface Board 202
Vbackup
RS-485 Full Duplex 326
Camera Port 340
Audio / Video 342
Dial-up / Cell Modem 344
GPS Port 346
Display Processor 328
Color LCD 338
SD Card IF 330
Memory Comp Memory (Flash) 332
USB 2.0 HOST 334
Diagnostic Port 386
Training / Remote Diagnostics Support 348
FIG. 3A
FIG. 3B

FIG. 3B

FIG. 3

FIG. 4

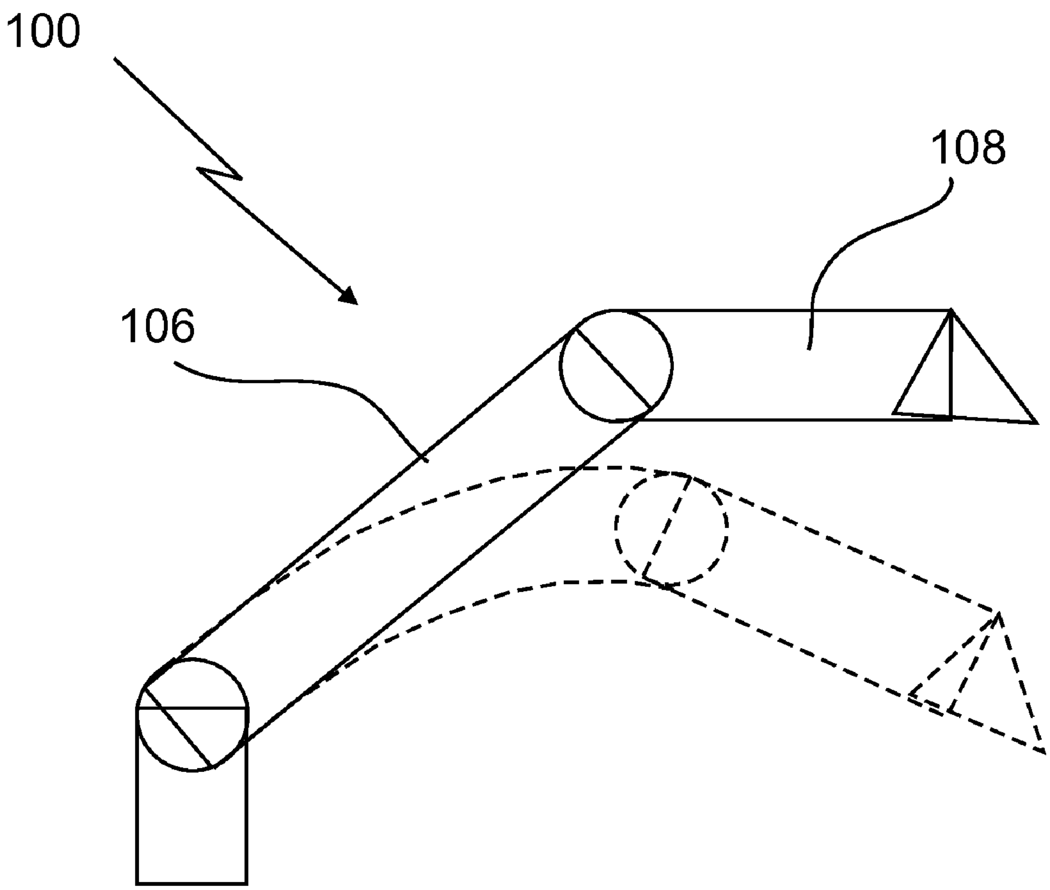


FIG. 5

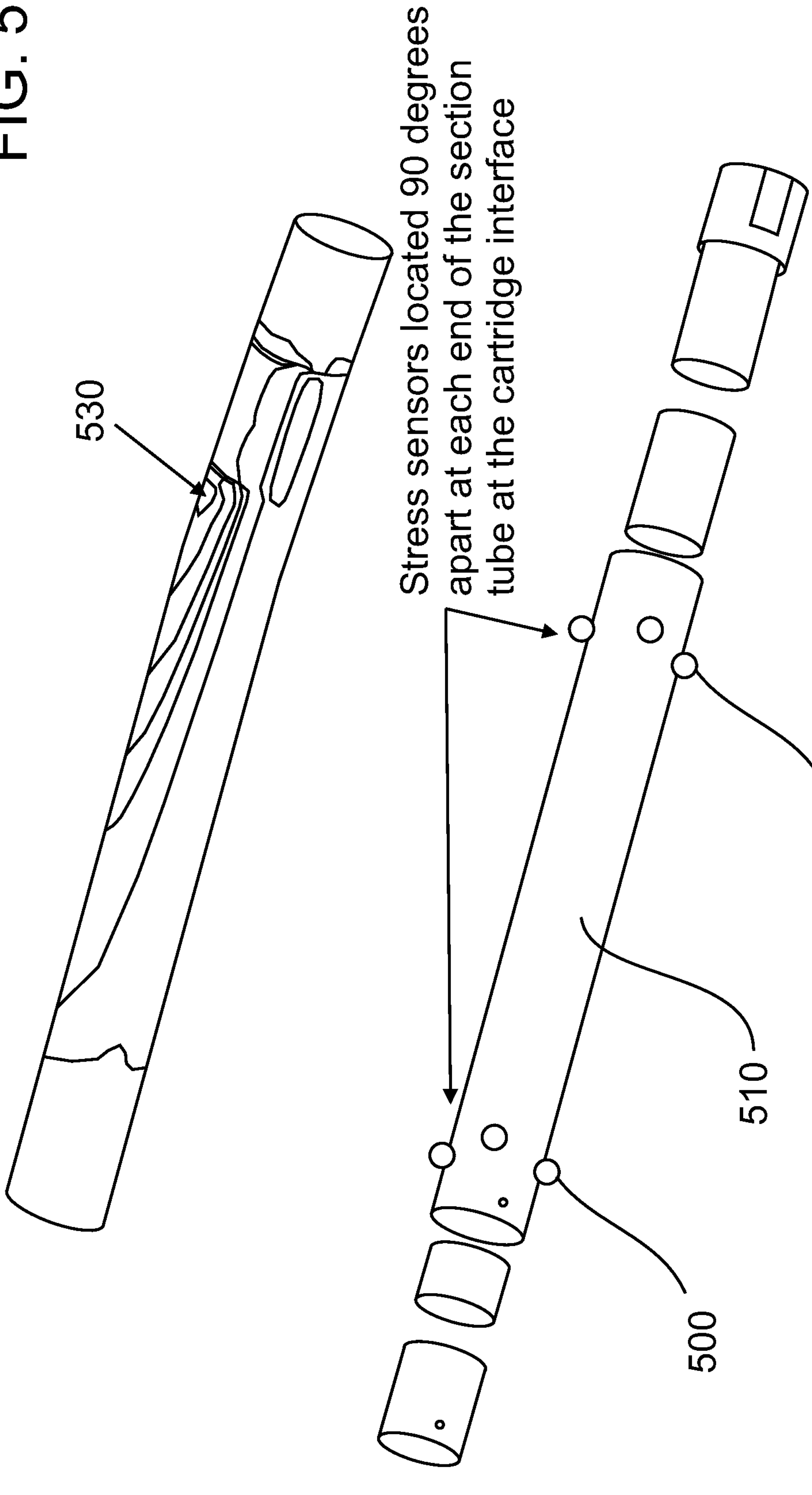
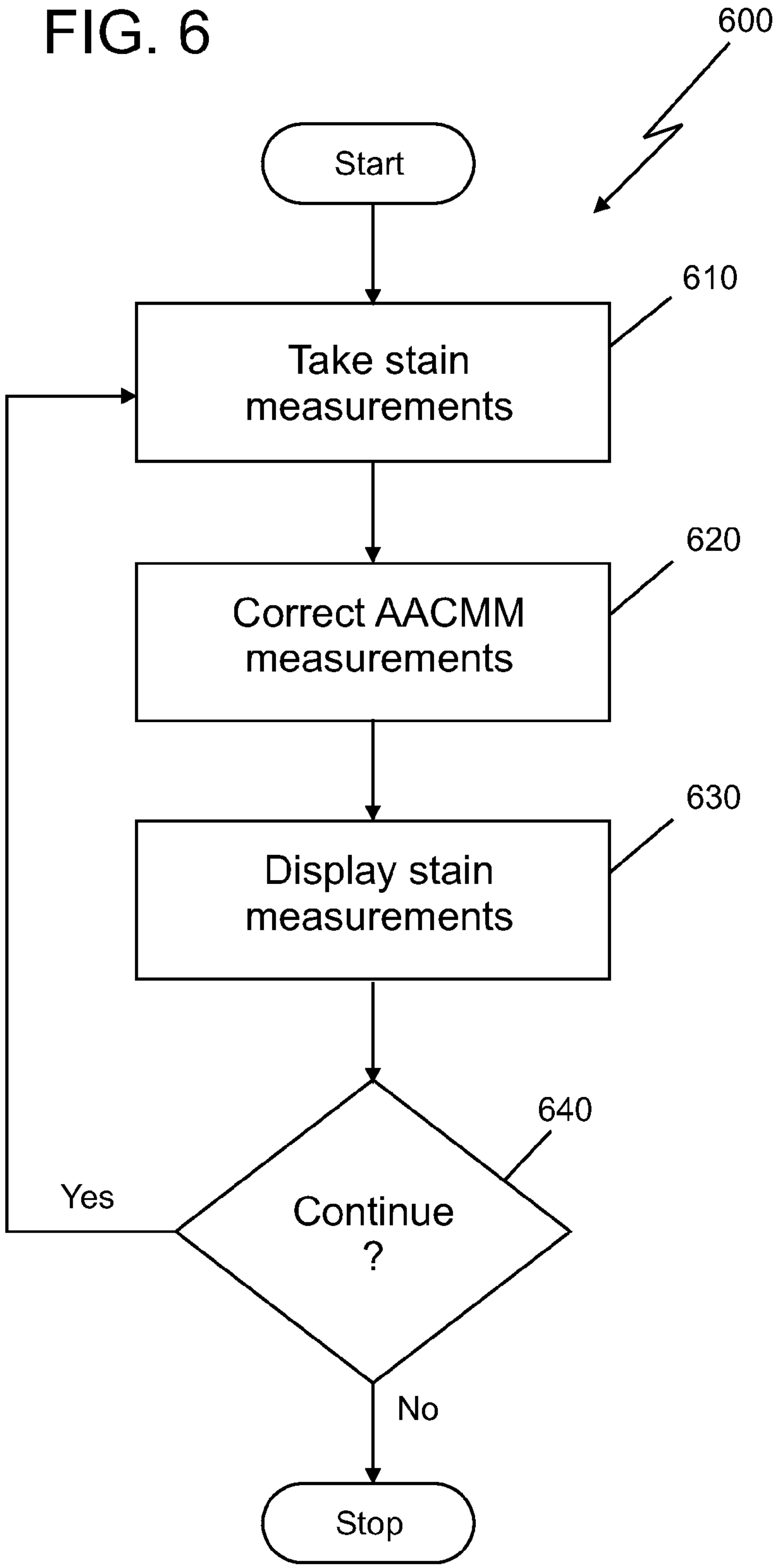

Stress sensors located 90 degrees
apart at each end of the section
tube at the cartridge interface
530
500
510
500

FIG. 6


600
Start
610
Take stain measurements
620
Correct AACMM measurements
630
Display stain measurements
640
Continue ?
Yes
No
Stop

EMBEDDED ARM STRAIN SENSORS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of provisional application No. 61/296,555 filed Jan. 20, 2010, the content of which is hereby incorporated by reference in its entirety.

BACKGROUND

[0002] The present disclosure relates to a coordinate measuring machine, and more particularly to a portable articulated arm coordinate measuring machine having strain gage sensors configured to measure strain in structural components of the portable articulated arm coordinate measuring machine.

[0003] Portable articulated arm coordinate measuring machines (AACMMs) have found widespread use in the manufacturing or production of parts where there is a need to rapidly and accurately verify the dimensions of the part during various stages of the manufacturing or production (e.g., machining) of the part. Portable AACMMs represent a vast improvement over known stationary or fixed, cost-intensive and relatively difficult to use measurement installations, particularly in the amount of time it takes to perform dimensional measurements of relatively complex parts. Typically, a user of a portable AACMM simply guides a probe along the surface of the part or object to be measured. The measurement data are then recorded and provided to the user. In some cases, the data are provided to the user in visual form, for example, three-dimensional (3-D) form on a computer screen. In other cases, the data are provided to the user in numeric form, for example when measuring the diameter of a hole, the text “Diameter=1.0034” is displayed on a computer screen.

[0004] An example of a prior art portable articulated arm CMM is disclosed in commonly assigned U.S. Pat. No. 5,402,582 (’582), which is incorporated herein by reference in its entirety. The ’582 patent discloses a 3-D measuring system comprised of a manually-operated articulated arm CMM having a support base on one end and a measurement probe at the other end. Commonly assigned U.S. Pat. No. 5,611,147 (’147), which is incorporated herein by reference in its entirety, discloses a similar articulated arm CMM. In the ’147 patent, the articulated arm CMM includes a number of features including an additional rotational axis at the probe end, thereby providing for an arm with either a two-two-two or a two-two-three axis configuration (the latter case being a seven axis arm).

[0005] What is needed is an apparatus and method that can measure strain associated with AACMMs.

SUMMARY OF THE INVENTION

[0006] Exemplary embodiments include a portable articulated arm coordinate measurement machine (AACMM) for measuring coordinates of an object in space, including a manually positionable articulated arm portion having opposed first and second ends, the arm portion including a plurality of connected arm segments, the plurality of connected arm segments including an arm segment adjacent the first end, each arm segment including at least one position transducer that produces a position signal, a measurement device attached to the first end, a structural component of the AACMM, wherein the structural component has an axial direction, at least three strain gage sensors, each having a sensitive axis, coupled to the structural component, wherein the sensitive axis of each strain gage sensor is oriented approximately parallel to the axial direction, each strain gage sensor is approximately intersected by a transverse plane perpendicular to the axial direction, each strain gage sensor produces an analog strain gage signal, and the strain gage sensors are disposed to provide data sufficient to determine a bending strain at any point residing on both the structural component and the transverse plane and an electronic circuit that receives the position signal and provides data corresponding to a position of the measurement device.

[0007] Further exemplary embodiments include a method for measuring strain in an articulated arm coordinate measurement machine (AACMM) including providing a manually positionable articulated arm portion having opposed first and second ends, the arm portion including a plurality of connected arm segments, each attached to at least one bearing cartridge, the plurality of connected arm segments including an arm segment adjacent to the first end, each arm segment including at least one position transducer that produces a position signal; a measurement device attached to the first end; a structural component of the articulated arm coordinate measurement machine, wherein the structural component has an axial direction; at least a first strain gage sensor disposed on the structural component, each strain gage sensor producing an analog strain gage signal, converting a combination of the analog strain gage signals into at least one digital strain gage signal, sending the at least one digital strain gage signal through at least one of the at least one bearing cartridges to an electronic circuit that receives the position signal and the at least one digital strain gage signal, providing and storing data corresponding to a position of the measurement device and storing the at least one digital strain gage signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Referring now to the drawings, exemplary embodiments are shown which should not be construed to be limiting regarding the entire scope of the disclosure, and wherein the elements are numbered alike in several FIGURES:

[0009] FIG. **1**, including FIGS. **1**A and **1**B, are perspective views of a portable articulated arm coordinate measuring machine (AACMM) having embodiments of various aspects of the present invention therewithin;

[0010] FIG. **2**, including FIGS. **2**A-**2**D taken together, is a block diagram of electronics utilized as part of the AACMM of FIG. **1** in accordance with an embodiment;

[0011] FIG. **3**, including FIGS. **3**A and **3**B taken together, is a block diagram describing detailed features of the electronic data processing system of FIG. **2** in accordance with an embodiment;

[0012] FIG. **4** illustrates a schematic view of the AACMM of FIG. **1** showing bending of a component of the AACMM;

[0013] FIG. **5** illustrates view of exemplary strain gage sensors disposed on structural components of the AACMM; and

[0014] FIG. **6** is a flowchart of a method for detecting strain in accordance with exemplary embodiments.

DETAILED DESCRIPTION

[0015] Exemplary embodiments include systems and methods for measuring strain on arm segments of a portable articulated arm coordinate measuring machine either to compensate measurement results to improve accuracy or to alert the operator of the need for corrective action.

[0016] FIGS. **1**A and **1**B illustrate, in perspective, a portable articulated arm coordinate measuring machine (AACMM) **100** according to various embodiments of the present invention, an articulated arm being one type of coordinate measuring machine. As shown in FIGS. **1**A and **1**B, the exemplary AACMM **100** may comprise a six or seven axis articulated measurement device having a measurement probe housing **102** coupled to an arm portion **104** of the AACMM **100** at one end. The arm portion **104** comprises a first arm segment **106** coupled to a second arm segment **108** by a first grouping of bearing cartridges **110** (e.g., two bearing cartridges). A second grouping of bearing cartridges **112** (e.g., two bearing cartridges) couples the second arm segment **108** to the measurement probe housing **102**. A third grouping of bearing cartridges **114** (e.g., three bearing cartridges) couples the first arm segment **106** to a base **116** located at the other end of the arm portion **104** of the AACMM **100**. Each grouping of bearing cartridges **110**, **112**, **114** provides for multiple axes of articulated movement. Also, the measurement probe housing **102** may comprise the shaft of the seventh axis portion of the AACMM **100** (e.g., a cartridge containing an encoder system that determines movement of the measurement device, for example a probe **118**, in the seventh axis of the AACMM **100**). In use of the AACMM **100**, the base **116** is typically affixed to a work surface.

[0017] Each bearing cartridge within each bearing cartridge grouping **110**, **112**, **114** typically contains an encoder system (e.g., an optical angular encoder system). The encoder system (i.e., transducer) provides an indication of the position of the respective arm segments **106**, **108** and corresponding bearing cartridge groupings **110**, **112**, **114** that all together provide an indication of the position of the probe **118** with respect to the base **116** (and, thus, the position of the object being measured by the AACMM **100** in a certain frame of reference—for example a local or global frame of reference). The arm segments **106**, **108** may be made from a suitably rigid material such as but not limited to a carbon composite material for example. A portable AACMM **100** with six or seven axes of articulated movement (i.e., degrees of freedom) provides advantages in allowing the operator to position the probe **118** in a desired location within a 360° area about the base **116** while providing an arm portion **104** that may be easily handled by the operator. However, it should be appreciated that the illustration of an arm portion **104** having two arm segments **106**, **108** is for exemplary purposes, and the claimed invention should not be so limited. An AACMM **100** may have any number of arm segments coupled together by bearing cartridges (and, thus, more or less than six or seven axes of articulated movement or degrees of freedom).

[0018] The probe **118** is detachably mounted to the measurement probe housing **102**, which is connected to bearing cartridge grouping **112**. A handle **126** is removable with respect to the measurement probe housing **102** by way of, for example, a quick-connect interface. The handle **126** may be replaced with another device (e.g., a laser line probe, a bar code reader), thereby providing advantages in allowing the operator to use different measurement devices with the same AACMM **100**. In exemplary embodiments, the probe housing **102** houses a removable probe **118**, which is a contacting measurement device and may have different tips **118** that physically contact the object to be measured, including, but not limited to: ball, touch-sensitive, curved and extension type probes. In other embodiments, the measurement is performed, for example, by a non-contacting device such as a laser line probe (LLP). In an embodiment, the handle **126** is replaced with the LLP using the quick-connect interface. Other types of measurement devices may replace the removable handle **126** to provide additional functionality. Examples of such measurement devices include, but are not limited to, one or more illumination lights, a temperature sensor, a thermal scanner, a bar code scanner, a projector, a paint sprayer, a camera, or the like, for example.

[0019] As shown in FIGS. **1**A and **1**B, the AACMM **100** includes the removable handle **126** that provides advantages in allowing accessories or functionality to be changed without removing the measurement probe housing **102** from the bearing cartridge grouping **112**. As discussed in more detail below with respect to FIG. **2**, the removable handle **126** may also include an electrical connector that allows electrical power and data to be exchanged with the handle **126** and the corresponding electronics located in the probe end.

[0020] In various embodiments, each grouping of bearing cartridges **110**, **112**, **114** allows the arm portion **104** of the AACMM **100** to move about multiple axes of rotation. As mentioned, each bearing cartridge grouping **110**, **112**, **114** includes corresponding encoder systems, such as optical angular encoders for example, that are each arranged coaxially with the corresponding axis of rotation of, e.g., the arm segments **106**, **108**. The optical encoder system detects rotational (swivel) or transverse (hinge) movement of, e.g., each one of the arm segments **106**, **108** about the corresponding axis and transmits a signal to an electronic data processing system within the AACMM **100** as described in more detail herein below. Each individual raw encoder count is sent separately to the electronic data processing system as a signal where it is further processed into measurement data. No position calculator separate from the AACMM **100** itself (e.g., a serial box) is required, as disclosed in commonly assigned U.S. Pat. No. 5,402,582 ('582).

[0021] The base **116** may include an attachment device or mounting device **120**. The mounting device **120** allows the AACMM **100** to be removably mounted to a desired location, such as an inspection table, a machining center, a wall or the floor for example. In one embodiment, the base **116** includes a handle portion **122** that provides a convenient location for the operator to hold the base **116** as the AACMM **100** is being moved. In one embodiment, the base **116** further includes a movable cover portion **124** that folds down to reveal a user interface, such as a display screen.

[0022] In accordance with an embodiment, the base **116** of the portable AACMM **100** contains or houses an electronic data processing system that includes two primary components: a base processing system that processes the data from the various encoder systems within the AACMM **100** as well as data representing other arm parameters to support three-dimensional (3-D) positional calculations; and a user interface processing system that includes an on-board operating system, a touch screen display, and resident application software that allows for relatively complete metrology functions to be implemented within the AACMM **100** without the need for connection to an external computer.

[0023] In accordance with an embodiment, the base **116** of the portable AACMM **100** contains or houses an electronic data processing system that includes two primary components: a base processing system that processes the data from the various encoder systems within the AACMM **100** as well as data representing other arm parameters to support three-dimensional (3-D) positional calculations; and a user interface processing system that includes an on-board operating system, a touch screen display, and resident application software that allows for relatively complete metrology functions to be implemented within the AACMM **100** without the need for connection to an external computer.

[0024] FIG. **2** is a block diagram of electronics utilized in an AACMM **100** in accordance with an embodiment. The embodiment shown in FIG. **2** includes an electronic data processing system **210** including a base processor board **204** for implementing the base processing system, a user interface board **202**, a base power board **206** for providing power, a Bluetooth module **232**, and a base tilt board **208**. The user interface board **202** includes a computer processor for executing application software to perform user interface, display, and other functions described herein.

[0025] As shown in FIG. **2**, the electronic data processing system **210** is in communication with the aforementioned plurality of encoder systems via one or more arm buses **218**. In the embodiment depicted in FIG. **2**, each encoder system generates encoder data and includes: an encoder arm bus interface **214**, an encoder digital signal processor (DSP) **216**, an encoder read head interface **234**, and a temperature sensor **212**. Other devices, such as strain sensors, may be attached to the arm bus **218**.

[0026] Also shown in FIG. **2** are probe end electronics **230** that are in communication with the arm bus **218**. The probe end electronics **230** include a probe end DSP **228**, a temperature sensor **212**, a handle/LLP interface bus **240** that connects with the handle **126** or the LLP **242** via the quick-connect interface in an embodiment, and a probe interface **226**. The quick-connect interface allows access by the handle **126** to the data bus, control lines, and power bus used by the LLP **242** and other accessories. In an embodiment, the probe end electronics **230** are located in the measurement probe housing **102** on the AACMM **100**. In an embodiment, the handle **126** may be removed from the quick-connect interface and measurement may be performed by the laser line probe (LLP) **242** communicating with the probe end electronics **230** of the AACMM **100** via the handle/LLP interface bus **240**. In an embodiment, the electronic data processing system **210** is located in the base **116** of the AACMM **100**, the probe end electronics **230** are located in the measurement probe housing **102** of the AACMM **100**, and the encoders are located in the bearing cartridge groupings **110**, **112**, **114**. The probe interface **226** may connect with the probe end DSP **228** by any suitable communications protocol, including commercially-available products from Maxim Integrated Products, Inc. that embody the 1-Wire® communications protocol **236**.

[0027] FIG. **3** is a block diagram describing detailed features of the electronic data processing system **210** of the AACMM **100** in accordance with an embodiment. In an embodiment, the electronic data processing system **210** is located in the base **116** of the AACMM **100** and includes the base processor board **204**, the user interface board **202**, a base power board **206**, a Bluetooth module **232**, and a base tilt module **208**.

[0028] In an embodiment shown in FIG. **3**, the base processor board **204** includes the various functional blocks illustrated therein. For example, a base processor function **302** is utilized to support the collection of measurement data from the AACMM **100** and receives raw arm data (e.g., encoder system data) via the arm bus **218** and a bus control module function **308**. The memory function **304** stores programs and static arm configuration data. The base processor board **204** also includes an external hardware option port function **310** for communicating with any external hardware devices or accessories such as an LLP **242**. A real time clock (RTC) and log **306**, a battery pack interface (IF) **316**, and a diagnostic port **318** are also included in the functionality in an embodiment of the base processor board **204** depicted in FIG. **3**.

[0029] The base processor board **204** also manages all the wired and wireless data communication with external (host computer) and internal (display processor **202**) devices. The base processor board **204** has the capability of communicating with an Ethernet network via an Ethernet function **320** (e.g., using a clock synchronization standard such as Institute of Electrical and Electronics Engineers (IEEE) 1588), with a wireless local area network (WLAN) via a LAN function **322**, and with Bluetooth module **232** via a parallel to serial communications (PSC) function **314**. The base processor board **204** also includes a connection to a universal serial bus (USB) device **312**.

[0030] The base processor board **204** transmits and collects raw measurement data (e.g., encoder system counts, temperature readings) for processing into measurement data without the need for any preprocessing, such as disclosed in the serial box of the aforementioned '582 patent. The base processor **204** sends the processed data to the display processor **328** on the user interface board **202** via an RS485 interface (IF) **326**. In an embodiment, the base processor **204** also sends the raw measurement data to an external computer.

[0031] Turning now to the user interface board **202** in FIG. **3**, the angle and positional data received by the base processor is utilized by applications executing on the display processor **328** to provide an autonomous metrology system within the AACMM **100**. Applications may be executed on the display processor **328** to support functions such as, but not limited to: measurement of features, guidance and training graphics, remote diagnostics, temperature corrections, control of various operational features, connection to various networks, and display of measured objects. Along with the display processor **328** and a liquid crystal display (LCD) **338** (e.g., a touch screen LCD) user interface, the user interface board **202** includes several interface options including a secure digital (SD) card interface **330**, a memory **332**, a USB Host interface **334**, a diagnostic port **336**, a camera port **340**, an audio/video interface **342**, a dial-up/cell modem **344** and a global positioning system (GPS) port **346**.

[0032] The electronic data processing system **210** shown in FIG. **3** also includes a base power board **206** with an environmental recorder **362** for recording environmental data. The base power board **206** also provides power to the electronic data processing system **210** using an AC/DC converter **358** and a battery charger control **360**. The base power board **206** communicates with the base processor board **204** using inter-integrated circuit (I2C) serial single ended bus **354** as well as via a DMA serial peripheral interface (DSPI) **356**. The base power board **206** is connected to a tilt sensor and radio frequency identification (RFID) module **208** via an input/output (I/O) expansion function **364** implemented in the base power board **206**.

[0033] Though shown as separate components, in other embodiments all or a subset of the components may be physically located in different locations and/or functions combined in different manners than that shown in FIG. **3**. For example, in one embodiment, the base processor board **204** and the user interface board **202** are combined into one physical board.

[0034] FIG. **4** depicts an exaggerated view of bending in the first arm segment **106**. Bending and twisting of components of the AACMM **100** (e.g., the first and second arm segments **106**, **108**) can result from the forces due to gravity, the counter balance spring, or handling of the AACMM **100** by the operator. If the kinematic model calculations performed by the base processor board **204** do not take these forces into account, it may not account fully account for bending or twisting of the arm segments when calculating the coordinates of a point. By directly measuring the bending strains of the arm, the effects of the forces applied to the AACMM **100** can be included in the kinematic model calculations, thereby improving the measurement accuracy of the AACMM **100**.

[0035] Referring to FIG. **5**, strain gage sensors **500** are attached to a structural part **510**, which may include arm segments **106**, **108**, bearing cartridge groupings **110**, **112**, **114**, or other mechanical components of AACMM **100**. The strain gage sensors **500** may be adhesively bonded, for example with epoxy, or otherwise suitably connected to the structural part **510**. The particular mounting configuration of the strain gage sensors **500** in four quadrants on the structural part **510**, which is cylindrically shaped in this instance, is particularly favorable as it provides a way to distinguish between two types of strain seen in the arm segments of AACMMs—bending strain and axial strain—and in addition determines the direction of bending of the arm segment. For the arm segments of FIG. **5**, the strain gage sensors **500** can be mounted on the outer surface, the inner surface, or embedded within the material of structural part **510**.

[0036] The axial direction of a beam is the long axis of the beam. Transverse directions are perpendicular to the axial direction. Forces may be applied to a beam in axial and transverse directions. Strain ϵ is defined as the ratio of the change in length dL to the corresponding length L: $\epsilon = dL/L$. Axial strain in a beam results from a stretching or contraction of the beam along the axial direction—that is, without bending. Bending strain in a beam results from bending of the beam, as illustrated in FIG. **4**. Bending strain may result from applying a force to the beam along a transverse direction or by applying a force to the beam along the axial direction, but off the neutral axis of the beam. For a straight, cylindrically symmetric beam, the neutral axis runs along the center of the cylinder.

[0037] If a first strain gage sensor is placed on top of a beam and a second strain gage sensor is placed on the bottom of a beam, it is possible to distinguish bending strain from axial strain for any forces that lie in a vertical plane passing through the strain gage sensors and the neutral axis. For example, if the strain measured by both the upper sensor and lower sensor decrease by the same amount, then the strain along the vertical cross section is compressive and entirely axial. On the other hand, if the strain in the upper sensor is positive by a particular amount and the strain in the lower sensor is negative by the same amount, then the upper portion of the beam has stretched and the lower portion of the beam has contracted, and the strain along the vertical cross section is entirely bending strain. By placing two strain gage sensors 180 degrees apart on a beam, it is possible to calculate the amount of bending strain and axial strain from the readings of the two strain gage sensors.

[0038] For the AACMM **100**, each arm segment **106**, **108** has the ability to swivel around its long axis. Consequently, the forces applied to one of the arm segments (e.g., by the counterbalance spring) may be in any direction. To predict the effect of forces or strains on one of the arm segments **106**, **108**, it is not enough to place two strain gage sensors 180 degrees apart on the arm segment. Rather, to find the axial and bending strains at an arbitrary point on the cross section of an arm segment, at least three strain gages sensors **500** must be properly placed on the arm segments. In an embodiment, the arm segments **106**, **108** are cylindrical tubes, with three strain gage sensors **500** placed on the outer surface of one of the arm segments. The three strain gage sensors are separated by 120 degrees and aligned approximately with a plane perpendicular to the axial direction. With this configuration, the three strain gage sensors **500** provide enough information to calculate axial and bending strains at arbitrary positions around the tube at the plane of the cross section. The three strain gage sensors **500** do not have to be placed 120 degrees apart, but not all placements of the three strain gages provide the desired information. For example, two of the three strain gage sensors cannot be placed 180 degrees apart as this provides information on axial and bending strain for only one plane—the plane that contains the neutral axis and the two strain gages sensors that are 180 degrees apart.

[0039] In an embodiment, structural components include arm segments **106**, **108** that have the form of cylindrical tubes. Three or more strain gage sensors **500** on the outer surfaces of the cylindrical tubes are placed so that the strain gage sensors are intersected by a plane perpendicular to the axial direction. With this arrangement, the bending strain can be calculated for each point that resides on both the structural component and the transverse plane. By selecting positions on the outside of the tube (at the position of the transverse plane) for which the bending strains have the extreme positive and extreme negative values, the direction and magnitude of the bending can be calculated. By combining the direction and magnitude of the bending for each of the structural elements with the readings of the transducers (e.g., angular encoders), the overall displacement of the measurement device can be calculated in the local frame of reference of the AACMM **100**. The displacement might be, for example, the displacement of the probe tip of the probe **118** as a result of the forces applied to the arm segments.

[0040] The strain gage sensors **500** may be resistive, acoustic, capacitive, inductive, mechanical, optical, piezo-resistive, or semi-conductive. In an embodiment, the strain gage sensor **500** is resistive, with a metal foil form that is bonded to an elastic backing (e.g., thin polyimide). The metal in the foil may be self-temperature-compensated (STC) constantan alloy. The self-temperature-compensation is achieved through proper processing of the constantan alloy, especially through cold working, so that the constantan gage wire has very low thermally induced strain over a wide range of temperatures. In an embodiment, structural parts **510** include the arm segments **106**, **108**, which are hollow tubes made of carbon-fiber composite having low CTE. The metal in the foil of the strain gage sensor is constantan alloy (or other alloy) selected to have a similar low CTE. The foil pattern may be a zig-zag pattern of parallel lines such that a small amount of stress in the direction of the parallel lines multiplies the strain over the effective length of the foil pattern. The direction of the parallel lines is said to be the sensitive direction of the strain gage sensor. The parallel lines in the foil pattern of strain gage sensors **500** are placed parallel to the axial direction of the structural part **510**. In an embodiment, the accuracy of a strain reading of an STC strain gage is further improved by applying a correction factor based on a curve or a polynomial equation provided by the manufacturer of the STC strain gage.

[0041] The strain gages **500** may be placed in a Wheatstone bridge circuit, which may, for example, be located on a circuit board near temperature sensor **212**. In one embodiment arrangement, the strain gage sensor **500** provides one resistance in the four resistor network. The other three resistances are provided by fixed resistors having resistances that change very little with temperature. In an alternative embodiment, two strain sensors separated by 180 degrees provide two resistances in the four resistance network of the Wheatstone bridge. The Wheatstone bridge may be configured in a three wire network to remove the effects of parasitic resistances of wires run from the electronics to the strain gage sensors **500**. In an embodiment, the signal from the Wheatstone bridge is sent to an analog-to-digital converter circuit, where the analog signal from the Wheatstone bridge is converted into a digital strain gage signal. All of the digital strain gage signals are put onto the arm buses **218**.

[0042] Although the discussion so far has considered the effect of strains on beams, and particularly on cylindrically shaped beams such as arm segments **106**, **108**, strain gage sensors **500** may be used to find the strains in other structures. If the particular structure being considered is not symmetrical about the axial direction, then it may be necessary to perform a further analysis to properly interpret the meaning of the strain gage readings. For example, in a complicated structural component, finite element analysis (FEA) performed on a computer using a detailed CAD model of the particular structure may be used to find the axial and bending strains based on the readings of four strain gages. In such cases, four or more strain gages, rather than three, may be required.

[0043] The readings obtained from the strain gages may be used either to improve the accuracy of AACMM **100** measurements or to give an alarm to the operator to indicate that corrective action needs to be taken. For the best accuracy, strain gage readings are correlated to the encoder readings. This may be done by capturing the strain gage readings at the same instant as the encoder readings. In an embodiment, the readings may be captured by all of the sensors in the AACMM **100**, including the strain gages and encoders, in response to a capture signal sent over a bus within the arm buses **218**. For example, the strain gage sensors **500** may provide strain data to correct the position of AACMM **100** in real time (e.g., ~1000 points per second) without operator intervention.

[0044] Data from the strain gage monitoring system can also be used to provide direct feedback to the operator, either in the form of audible or visual warnings. Such warnings may be issued when the strain gage readings, especially for bending strain, deviate from established (expected) values by more than a pre-determined value. These warnings may be supplemented by application software designed to teach and refine measurement techniques. In exemplary embodiments, visible warnings can include a visual display **520** of the structural parts **510**, showing a color or gray scale **530** to represent the severity of the strain.

[0045] To obtain a simple but effective kinematic model for the AACMM **100** that accounts for the effects of bending strain and axial strain, it may be helpful to use FEA to observe the effects of forces on the AACMM **100**. An example of such an FEA is shown in the upper inset **520** of FIG. **5**. In this inset, differing amounts of strain (or stress) are indicated by the gray-scale values. In the instance shown, the greatest concentration of strain is at the region **530**. As a further refinement, experiments may be conducted to measure the force applied by the counterbalance spring as a function of the orientation of the arm segments in space. These force values may be used to improve the FEA analysis.

[0046] The main purpose of FEA is to assist in establishing a relatively simple, but accurate, form for the kinematic model of AACMM **100**. Once the form of the kinematic model has been established, a large amount of data is collected and fit to the model. An optimization method is used to select the best numerical parameter values for the model. The combined steps of collecting data and solving for the optimum parameter values is called compensation or calibration. The collecting of data may include measuring the coordinates of a probe fixed in a nest while arm segments are moved into a variety of orientations. Since the coordinate value should be constant for a probe tip that does not move, the parameter values may be selected to minimize the difference in probe readings for the different orientations of the arm segments. The collecting of data may also include measuring the distance between points on one or more artifacts of known length.

[0047] As stated hereinabove, the strain gage sensor **500** may be placed on the outer surface, the inner surface, or embedded within the material of structural part **510**. In the latter case, the strain gage sensors **500** may be embedded in the carbon fiber of the tubes **510** that connect the joints. In the fabrication process, the carbon fiber fabric is typically wound on a mandrel and the strain gage sensors **500** may be installed prior to completing the final wrap, thus protecting the strain gage sensors **500** and embedding them into the part. By placing the strain gage sensors **500** at opposite ends of the arm tube **510**, and ninety degrees apart (i.e., orthogonally arranged) on the circumference of the tube **510**, tube deformation can be fully characterized in the area of the strain gages, near the bond joints of mating components where the greatest deformation occurs, as shown in the stress diagram of FIG. **5**.

[0048] FIG. **6** is a flowchart of a method **600** for measuring strain in accordance with exemplary embodiments illustrating that the AACMM **100** can continuously measure strain at block **610**, make appropriate corrections to the AACMM **100** arm model at block **620**, and display the measurements at block **630** continuously for so long as the operator elects to measure and display at block **640**.

[0049] Technical effects and benefits include the ability to continuously measure strains on the structural parts **510** of the AACMM **100**. As such, the operator can know if the AACMM **100** is undergoing any strains during a measurement to take into account the strain during the measurement or to take corrective actions.

[0050] As will be appreciated by one skilled in the art, aspects of the present invention may be embodied as a system, method, or computer program product. Accordingly, aspects of the present invention may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Furthermore, aspects of the present invention may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon.

[0051] Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that may contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

[0052] A computer readable signal medium may include a propagated data signal with computer readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A computer readable signal medium may be any computer readable medium that is not a computer readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

[0053] Program code embodied on a computer readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0054] Computer program code for carrying out operations for aspects of the present invention may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++, C# or the like and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0055] Aspects of the present invention are described with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, may be implemented by computer program instructions.

[0056] These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer program instructions may also be stored in a computer readable medium that may direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0057] The computer program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0058] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function (s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the Figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, may be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

[0059] While the invention has been described with reference to example embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims. Moreover, the use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another. Furthermore, the use of the terms a, an, etc. do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item.

What is claimed is:

1. A portable articulated arm coordinate measurement machine (AACMM) for measuring coordinates of an object in space, comprising:

a manually positionable articulated arm portion having opposed first and second ends, the arm portion including a plurality of connected arm segments, the plurality of connected arm segments including an arm segment adjacent the first end, each arm segment including at least one position transducer that produces a position signal;

a measurement device attached to the first end;

a structural component of the AACMM, wherein the structural component has an axial direction;

at least three strain gage sensors, each having a sensitive axis, coupled to the structural component, wherein the sensitive axis of each strain gage sensor is oriented approximately parallel to the axial direction, each strain gage sensor is approximately intersected by a transverse plane perpendicular to the axial direction, each strain gage sensor produces an analog strain gage signal, and the strain gage sensors are disposed to provide data sufficient to determine a bending strain at any point residing on both the structural component and the transverse plane; and

an electronic circuit that receives the position signal and provides data corresponding to a position of the measurement device.

2. The AACMM of claim **1** further comprising an analog-to-digital converter circuit that converts some combination of the analog strain gage signals into a plurality of digital strain gage signals, wherein the electronic circuit receives the plurality of digital strain gage signals.

3. The AACMM of claim **2** wherein the electronic circuit calculates the magnitude and direction of maximum bending of the structural component.

4. The AACMM of claim **3** wherein the electronic circuit uses the digital strain gage signals from the at least three strain gage sensors to modify the provided data corresponding to the position of the measurement device.

5. The AACMM of claim **4** further comprising a capture signal, wherein the position signal and the digital strain gage signals are collected in response to the capture signal.

6. The AACMM of claim **4** further comprising parameters obtained from a compensation procedure and stored in the electronic circuit, wherein the parameters are obtained in part by a collecting of data by the AACMM in response to movement of the arm segments.

7. The AACMM of claim **6**, wherein the electronic circuit uses the parameters and the calculated magnitude and direction of maximum bending to modify the provided data corresponding to the position of the measurement device.

8. The AACMM of claim **3** wherein the structural component has a coefficient of thermal expansion and the strain gage sensor is selected to match the coefficient of thermal expansion of the structural component.

9. The AACMM of claim **3**, further comprising a fourth strain gage sensor.

10. The AACMM of claim **3** wherein the electronic circuit produces a warning in response to the strain gage signals.

11. The AACMM of claim **10** wherein the warning is one of a visual warning and an audible warning.

12. The AACMM of claim **10** wherein the warning is produced when the bending strain has a value that falls outside pre-determined limits.

13. A method for measuring strain in an articulated arm coordinate measurement machine (AACMM) comprising the steps of:

providing a manually positionable articulated arm portion having opposed first and second ends, the arm portion including a plurality of connected arm segments, each attached to at least one bearing cartridge, the plurality of connected arm segments including an arm segment adjacent to the first end, each arm segment including at least one position transducer that produces a position signal; a measurement device attached to the first end; a structural component of the articulated arm coordinate measurement machine, wherein the structural component has an axial direction; at least a first strain gage sensor disposed on the structural component, each strain gage sensor producing an analog strain gage signal;

converting a combination of the analog strain gage signals into at least one digital strain gage signal;

sending the at least one digital strain gage signal through at least one of the at least one bearing cartridges to an electronic circuit that receives the position signal and the at least one digital strain gage signal;

providing and storing data corresponding to a position of the measurement device; and

storing the at least one digital strain gage signal.

14. The method according to claim **13** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of providing a second strain gage sensor on the structural component and a third strain gage sensor on the structural component, wherein the first, second, and third strain gage sensors produce analog strain gage signals;

converting some combination of the analog strain gage signals into a plurality of digital strain gage signals;

sending the plurality of digital strain gage signals through at least one of the at least one bearing cartridges to the electronic circuit, wherein the electronic circuit stores the digital strain gage signals.

15. The method according to claim **14** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the steps of:

coupling the first, second, and third strain gage sensor, each having a sensitive axis, to the structural component, wherein the sensitive axis of each strain gage sensor is oriented approximately parallel to the axial direction;

disposing each strain gage sensor on the structural component to be approximately intersected by a transverse plane perpendicular to the axial direction of the structural component; and

disposing the first, second, and third strain gage sensor to provide data sufficient to determine a bending strain at any point residing on both the structural component and the transverse plane.

16. The method according to claim **15** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of calculating the magnitude and direction of maximum bending of the structural component.

17. The method according to claim **16** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of using the plurality of digital strain gage signals to modify the provided data corresponding to the position of the measurement device.

18. The method according to claim **17** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the steps of

providing a capture signal; and

collecting the position signal and the digital strain gage signals in response to the capture signal.

19. The method according to claim **18** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of obtaining parameters from a compensation procedure, wherein the parameters are obtained in part by the collecting of data by the articulated arm coordinate measurement machine in response to movement of the arm segments.

20. The method according to claim **19** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of using the parameters and the calculated magnitude and direction of maximum bending of the structural element to modify the provided data corresponding to the position of the measurement device.

21. The method according to claim **15** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of selecting a coefficient of thermal expansion for each strain gage sensor to match a coefficient of thermal expansion of the structural component.

22. The method according to claim **14** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of producing a warning in response to the strain gage signals.

23. The method according to claim **22** for measuring strain in an articulated arm coordinate measurement machine (AACMM), wherein the warning is one of a visual warning and an audible warning.

24. The method according to claim **16** for measuring strain in an articulated arm coordinate measurement machine (AACMM), further comprising the step of producing a warning in response to the strain gage signals when the bending strain has a value that falls outside pre-determined limits.

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