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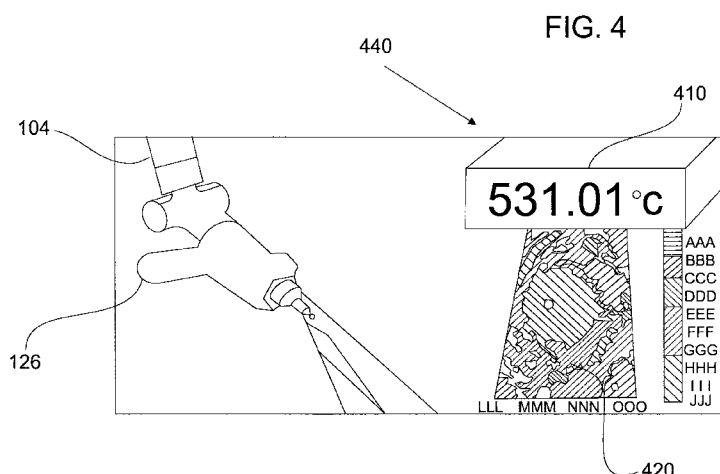
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(54) **Title:** INTEGRATED PART TEMPERATURE MEASUREMENT SYSTEM

(57) **Abstract:** Exemplary embodiments include a portable articulated arm coordinate measurement machine, including a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each of the arm segments including at least one position transducer for producing a position signal, a measurement device attached to a first end of the articulated arm coordinate measurement machine, an electronic circuit for receiving the position signals from the transducers and for providing data corresponding to a position of the measurement device, at least one sensor element, which is disposed on the articulated arm coordinate measurement machine, that is responsive to electromagnetic radiation and produces an electrical signal in response to a temperature of an object and an electronic system that converts the electrical signal into a temperature value.



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INTEGRATED PART TEMPERATURE MEASUREMENT SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of provisional application number 61/296,555 filed January 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 an integrated part temperature measurement system configured to measure the temperature of objects.

[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. Patent 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. Patent 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 a method that can measure the temperatures of an object and the coordinates corresponding to those temperatures.

SUMMARY OF THE INVENTION

[0006] Exemplary embodiments include a portable articulated arm coordinate measurement machine, including a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each of the arm segments including at least one position transducer for producing a position signal, a measurement device attached to a first end of the articulated arm coordinate measurement machine, an electronic circuit for receiving the position signals from the transducers and for providing data corresponding to a position of the measurement device, at least one sensor element, which is disposed on the articulated arm coordinate measurement machine, that is responsive to electromagnetic radiation and produces an electrical signal in response to a temperature of an object and an electronic system that converts the electrical signal into a temperature value.

[0007] Additional exemplary embodiments include a method of implementing a portable articulated arm coordinate measuring machine, the method including measuring a temperature value of an object with an integrated temperature measurement system disposed on the portable articulated arm coordinate measuring machine, wherein the integrated temperature measurement system is responsive to electromagnetic radiation that varies with the temperature of the object, the portable articulated arm coordinate measuring machine comprised of a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal, a measurement device attached to a first end of the articulated arm coordinate measuring machine, and an electronic circuit which receives the position signals from the transducers and provides data corresponding to a position of the measurement device, receiving the temperature value in the electronic circuit and displaying the temperature value on a user

interface.

[0008] Further exemplary embodiments include a computer program product for implementing a portable articulated arm coordinate measuring machine, the computer program product comprising a storage medium having computer-readable program code embodied thereon, which when executed by a computer causes the computer to implement a method, the method including measuring a temperature value of an object with an integrated temperature measurement system disposed on the portable articulated arm coordinate measuring machine, wherein the integrated temperature measurement system is responsive to electromagnetic radiation that varies with the temperature of the object, the portable articulated arm coordinate measuring machine comprised of a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal, a measurement device attached to a first end of the articulated arm coordinate measuring machine, and an electronic circuit which receives the position signals from the transducers and provides data corresponding to a position of the measurement device, receiving the temperature value in the electronic circuit and displaying the temperature value on a user interface.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] 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:

[0010] FIG. 1, including FIGs. 1A and 1B, are perspective views of a portable articulated arm coordinate measuring machine (AACMM) having embodiments of various aspects of the present invention therewithin;

[0011] FIG. 2, including FIGs. 2A- 2D taken together, is a block diagram of electronics utilized as part of the AACMM of FIG. 1 in accordance with an embodiment;

[0012] FIG. 3, including FIGs. 3A and 3B taken together, is a block diagram describing detailed features of the electronic data processing system of FIG. 2 in accordance with an embodiment;

[0013] FIG. 4 illustrates a screenshot of an exemplary graphical user interface in which an operator can detect temperature and changes in temperature in an object measured by the AACMM; and

[0014] FIG. 5 is a flowchart of a method for measuring temperature in accordance with exemplary embodiments.

DETAILED DESCRIPTION

[0015] Exemplary embodiments include systems and methods for measuring with an articulated arm coordinate measurement machine (AACMM) the temperature of an object as a function of position on the object and providing the temperature data to an operator. In some embodiments, the AACMM or software associated with the AACMM provides the operator with visual information about the temperature. It may also provide an audio or visual alarm or alert. In other embodiments, the temperature information is used to correct dimensional measurements taken by the AACMM. To make such corrections, the user of the AACMM provides information about the coefficient of thermal expansion (CTE) of the material being measured. Frequently, specifications recite dimensions at a standard temperature, usually 20 °C, while the object being measured is at another temperature. By knowing the object temperature and the CTE, the measured dimensions can be normalized to the standard temperature. The systems and methods described herein may also be used to check whether the object is in thermal equilibrium (e.g., a part may have been recently machined, welded, or moved from outside and may not be at a uniform temperature). As such, the systems and methods described herein determine whether dimensional measurements are valid.

[0016] In addition, temperature measurement may be used as an end in itself. In exemplary embodiments, the systems and methods described herein can map the temperature of an object in 3-D. For example, a user may want to map the temperature of the surface of a diesel engine under normal and 110% of full load conditions. As another example, a user may want to

map the temperature of electrical components loaded on a printed circuit board, as well as the temperature of the mechanical structure to which the printed circuit board is attached. Such measurements can be used to determine whether additional heat sinking is needed for particular electrical components, for example. It might also be used as part of a finite element model to assist engineers in verifying or improving their designs.

[0017] FIGs. 1A and 1B 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. 1A and 1B, 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.

[0018] 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).

[0019] 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.

[0020] As shown in FIGs. 1A and 1B, 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.

[0021] 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. Patent No. 5,402,582 ('582).

[0022] 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.

[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] The electronic data processing system in the base 116 may communicate with the encoder systems, sensors, and other peripheral hardware located away from the base 116 (e.g., a LLP that can be mounted to the removable handle 126 on the AACMM 100). The electronics

that support these peripheral hardware devices or features may be located in each of the bearing cartridge groupings 110, 112, 114 located within the portable AACMM 100.

[0025] 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.

[0026] 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.

[0027] 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 encoder systems 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.

[0028] 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.

[0029] 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.

[0030] 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.

[0031] 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.

[0032] 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.

[0033] 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 a DC/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 device service provider 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.

[0034] 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.

[0035] Referring to FIG. 4, another aspect of the improvements to the portable AACMM 100 of embodiments of the present invention includes the incorporation of a part temperature measurement and/or profiling system within the AACMM 100. In this aspect of the present invention, the temperature of the part being measured may be captured, integrated with the arm

data stream, and provided to the metrology application software. This temperature may be used in correcting for dimensional changes due to the coefficient of thermal expansion of the part material. Alternatively, it may be used to provide accurate temperature data as a function of position on the object, thereby enabling the temperature profile to be accurately mapped onto a computer-aided design (CAD) model. The temperature profile 440 may be displayed, as illustrated in FIG. 4. The temperature profile 440 can include a numeric readout 410 or other graphical interface, displaying the numeric temperature of the object(s) under test. The temperature profile 440 can further include a color or gray scale plot 420 of temperature distribution in the object(s) under test. The plot 420 can therefore visually display temperature gradients and critical temperatures of objects under test.

[0036] In this context, a critical temperature is a temperature of an object that exceeds some allowable deviation from a reference temperature value. For example, if the dimensions of a particular object are specified at 20 °C, then the allowable range of temperatures for measurement by the AACMM in a particular instance might be 17 – 23 °C. Outside of this value, the operator might be instructed to attach a contact temperature sensor, such as a thermistor, directly to the object so that temperature can be measured and corrections made numerically to account for thermal expansion or contraction. Similarly, it would be possible to specify a critical expansion, for example in parts per million or micrometers. The critical expansion of the object would then be an expansion or contraction of the material considered excessive by the user. Outside of the acceptable range, the user might be instructed to attach a contact temperature sensor to the object.

[0037] The temperature may be displayed directly on a three-dimensional representation of the object being measured. Modern application software provides the ability to rotate a three-dimensional representation of an object on a display. Such a display might be a CAD model of the object, or it might be a representation of the object as measured by the AACMM 100. Measurements by the AACMM might be carried out with probe 118 that makes direct contact with an object or with non-contact devices such as a laser line probe or with a combination of contact and non-contact measurement devices. The temperature can be displayed on such three-dimensional representation in a variety of ways. For example, temperature can be represented by

gray scale, by color, by a contour map, or by “whiskers.” Whiskers are small projections having a length proportional to the deviation from a reference temperature.

[0038] Similarly, thermal expansion or contraction relative to dimensions at a reference temperature can be directly mapped onto a three-dimensional representation of the object. For example, such a contraction might be given in terms of a relative change $\Delta L / L$, where ΔL is the change in some small length at a local position and L is value of the small length. Such a measure is dimensionless and may also be given in parts per million (ppm). The quantity $\Delta L / L$ can be found by multiplying the CTE of the object times the deviation of temperature from a reference value. Alternatively, thermal expansion might be represented in absolute terms using the actual change in length in micrometers or millimeters relative to some datum features such as datum planes or datum points. Graphical representations of thermal expansion or contraction, whether given in relative or absolute terms, may be shown using color, contour maps, or whiskers, for example.

[0039] Measurement of the temperatures or thermal expansions of objects over their three-dimensional coordinates is useful in a variety of ways. As discussed already, such measurements can alert the user that temperatures or thermal expansions or contractions are outside an acceptable range so that corrective action may be taken. In other cases, the temperature profile of an object may be of interest in its own right.

[0040] The software may also use temperature values provided by an exemplary temperature measurement system to directly correct or normalize the measured dimensional values to a reference temperature. The user might enter information on the CTE of the material(s) being measured into the user interface to enable this correction to take place automatically.

[0041] Exemplary embodiments of the temperature measurement system may include an integrated infrared or other non-contact temperature sensor in the handle 126 or in an accessory (e.g., laser line probe) attached to the arm portion 104 of the AACMM 100, and/or a means to connect a contact, or non-contact, remote temperature sensor (via a connector, Bluetooth, Wi-Fi or other protocols) to the AACMM electronics. Also included may be interface electronics to power, read and/or control the temperature measurement hardware, and firmware and/or

software to format the temperature data and pass it via the arm data communication stream to the application software running internal to the AACMM 100 or on an external computer. Further included may be switches, or software controls to initiate and control parameters of the temperature measurement, and a user interface, integrated with the AACMM 100 or on an external computer to display temperature data and control options.

[0042] The non-contact temperature measurement system may be made using sensors that respond to electromagnetic energy. Such sensors are often called infrared sensors although visible wavelengths as well as infrared wavelengths may be important, especially for hot materials. Such sensors that respond to electromagnetic energy come in a variety of types. For example, an infrared sensor may be a single detector (usually sensitive over some range of infrared wavelengths) or it may include an array of optical detectors. FIG. 4 shows an example of data taken with an array of optical detectors, with the temperature at each particular point indicated by a gray scale value.

[0043] Some infrared sensors measure the amount of electromagnetic energy detected over a relatively narrow range of optical wavelengths. The temperature at any particular point can be found from the detected energy if the emissivity of the material is known. Other types of infrared sensors measure the amount of electromagnetic energy over two relatively narrow ranges of optical wavelengths. The two energies can be used to estimate the temperature of the material when the emissivity of the material is not known. Another method for measuring the temperature of a material when emissivity of the material is not known is to put a reference object having a known emissivity (e.g., a black disk) into close thermal contact with the object under test. By measuring the energy returned by the reference object, the temperature of the object under test can be obtained. A method for finding the emissivity of a material is to measure the temperature of the object under test in the vicinity of the reference object. From the collected data, the emissivity of the object under test can be estimated.

[0044] A non-contact temperature sensor that responds to electromagnetic energy converts the electromagnetic energy or power into an electrical signal. This signal may be amplified, filtered, or conditioned in other ways. Such conditioning may take place close to the sensor or it may be performed at some distance from the sensor. The signal may be converted

from analog into digital form for transmission over an electrical wire or an electrical bus, or it may be transmitted wirelessly. Alternatively, the electrical signal may be transmitted some distance in analog form. The digitally converted signal may be analyzed with a processor or other device through the use of equations, for example, equations based on the Planck's law, to find the temperature of the object based on a given emissivity. Alternatively, other methods such as the two color method described above may be evaluated using a processor with appropriate equations based on Planck's law, for example. Because the conversion of the electromagnetic signal received by the sensor element may be electrically processed in a variety of ways and because such processing may be carried out at different locations, either inside or outside the AACMM 100, we may say that an electrical system is used to convert the electrical signal from the sensor element into a temperature value. If a plurality of sensor elements is used, the electrical system is used to convert the plurality of electrical signals obtained from these into a plurality of temperatures. Additional processing elements contained within an electrical circuit are used to provide the temperature information to a display. Such a display may be integrated within the AACMM 100 or outside of the AACMM 100 (for example, an external computer).

[0045] FIG. 5 is a flowchart of a method 500 for measuring temperature in accordance with exemplary embodiments illustrating that the AACMM 100 can continuously measure temperature at block 510 and display the measurements at block 520 continuously for so long as the operator elects to measure and display at block 530.

[0046] Using AACMM 100 with a temperature measurement system is advantageous because it enables the temperatures to be directly related to coordinates of the object under test. Furthermore, the AACMM 100 may be moved to different locations to view the object from all directions. Yet, because the dimensional information collected by the AACMM 100, all of the temperature data can be directly related to the coordinates of the object as seen from all sides.

[0047] A method for associating the temperatures measured by the temperature measurement system with the coordinates of the object as measured by the AACMM 100 will now be described. A sensor that measures electromagnetic energy as a way of finding the temperature of an object may include a single sensor element or multiple sensor elements. A common type of sensor has an array of sensor elements. At any particular time, each sensor

element has a particular position in the local frame of reference of the AACMM 100. In addition, each sensor element has a unique line in the local frame of reference of the AACMM 100. The line extends from the sensor element through the effective center of a lens system that sits in front of the sensor element. The point at which the line intersects the object is the point about which electromagnetic energy resulting from the local temperature of the object is projected toward the sensor element. For a plurality of sensor elements, each line from a particular sensor element intersects the object at a different position.

[0048] The coordinates of the point in three-dimensional space that corresponds to a particular temperature on the object can be found by locating the object in three dimensional space and then finding the point at which the line extending from a particular sensor element intersects the object. One way to establish the position of the object in three-dimensional space is to measure at least three non-collinear points on the object with one or more of the measurement devices of the AACMM 100. These points might be particular features that are clearly identifiable. For example, a point might be the center of a sphere or a corner at which three edges intersect.

[0049] In many cases, a CAD model is available for the thing being measured. In this case, the CAD model may be made to overlay the three measured features (points) to obtain a match. In other cases, the object may have a simple shape – for example, a plane or a sphere. A simple shape of this sort can be fit to the at least three measured points. In still other cases, the shape of the object may not be known. In this instance, the measurement devices of the AACMM may be used to measure enough points on the object to establish the shape of the object. In all of these cases, the measurements by the AACMM enable a mapping of the temperature data onto a dimensional representation of the object.

[0050] Software provided for use with the non-contact temperature sensor may reside within the articulated arm itself or within application software residing in an external computer. Besides displaying measured temperatures on a display, the software may also provide a way for the user to compensate the non-contact temperature sensor or to enter information about emissivity of the materials being measured.

[0051] As explained hereinabove, a contact temperature sensor may be used in addition to, or instead of, a non-contact sensor. One type of contact sensor is attached to a workpiece. Contact sensors can be obtained with relatively high accuracies – in some cases, ± 0.1 °C or better. Contact sensors may measure the temperature of a given point on a workpiece surface continuously regardless of the position of the AACMM 100. Sensing elements within a contact temperature sensor may include thermistors, RTDs, thermocouples, or other devices. The complete temperature sensing device will typically contain electronics and an electrical cable in addition to the sensing element. If the object being measured (the workpiece) is made of a ferromagnetic material such as steel, the temperature sensor may be coupled to the workpiece using a magnet. The temperature sensor may be attached to a workpiece using a fluid or adhesive, for example, a thermal grease or a thermal epoxy. Alternatively, the temperature sensor may be attached to the material using an adhesive tape.

[0052] An important use for contact temperature sensors is to correct for thermal expansion of a workpiece in relation to a reference temperature. To make this correction, it is necessary to know the CTE of the material as well as the change in temperature of the workpiece from the reference temperature. In many cases, the temperature of the object under test is nearly uniform over a volume of the object. In this instance, it may be enough to attach a single temperature sensor to the workpiece. In other cases, it may be desirable to attach a number of temperature sensors to one or more workpieces.

[0053] A temperature sensor may be plugged into a wire-line port such as the USB port 312, for example, or it may be attached to a wireless port by means of Bluetooth module 232, for example. Alternatively, the electrical signal from the sensing element may be delivered in analog form to the articulated arm, where electrical circuitry, for example on base processor board 204, converts the signal into a digital temperature value. The measured temperature value may be delivered to user interface board 202, or it may be delivered to an external computer.

[0054] The user of the AACMM 100 may enter the CTE of the workpiece being tested into the user interface board 202, or the user may enter a range of CTE values for different portions of the workpiece under test. The user may also enter a reference temperature, which is often 20 °C, into the user interface. The user interface board 202 may process the data for

viewing on the display 338 within the AACMM 100. Alternatively, it may export data to an external computer.

[0055] There are many ways in which the temperature data can be used by the user interface board 202 or external computer. For example, an *expansion factor* = $1 + (\text{measured temperature} - \text{reference temperature}) * \text{CTE}$ may be calculated. The expansion factor is also equal to $(L + \text{delta } L) / L$, where L is a length and $\text{delta } L$ is a corresponding change in length. The expansion factor, or any other factor that combines the effects of measured temperature, reference temperature, and CTE, may be used by the user interface board 202 or an external computer. One simple and important way that an expansion factor can be used is to calculate the dimensions the workpiece, normalized to the reference temperature. The calculated dimensions may be referenced by the user interface board 202 to a global frame of reference or to datums on the workpiece. In this way, expansion of the workpiece between any two points is made available and can be graphically visualized. Corrections to account for thermal expansion can be made to points obtained from any measurement device – for example, a contact probe 118 or an LLP 242.

[0056] Suppose that an operator wants to measure points on a workpiece with an AACMM 100 and then display the results normalized to a reference temperature in a global coordinate system. If the global coordinate system has not been established, the operator may measure three or more non-collinear points as a way of establishing the x, y, and z axes of the global coordinate system in terms of the local coordinate system of the AACMM 100. From this same data, a mathematical transformation can be established to convert any coordinates measured by the probe 118 or LLP 242 in the local coordinate system of the AACMM 100 into the global coordinate system. For example, the transformation may be carried out by a 4 x 4 transformation matrix that performs a rotation and a translation. Such transformations are well known to those of ordinary skill in the art and will not be discussed further. To normalize the coordinate values displayed in the global coordinate system to a reference temperature, each of the three measured values x, y, and z of a point is multiplied by an expansion factor obtained using the method described hereinabove. The normalized coordinate values can be shown on the display 338 or sent to an external computer for display or further processing. One advantage of sending normalized data to an external computer is that the operator can have confidence that the

temperature corrections have been performed correctly by the user interface board 202. This can save time by eliminating the need to verify the accuracy of the normalization calculation for each type of application software used with AACMM 100.

[0057] If CAD data is available, the dimensions of the workpiece, as measured by the AACMM 100, may be normalized to the reference temperature and then compared to the CAD model having dimensions specified at the same temperature. Deviations in dimensions from the specified values may be shown on display 338 or on an external computer using color, gray scale, contour map, or whiskers, for example.

[0058] In some cases, it may be desirable to attach several contact temperature sensors to one or more workpieces. One method of doing this is to multiplex the several temperature sensors into one port (wire-line or wireless) of the AACMM 100 and then collect the temperature readings sequentially. An alternative method is to attach each temperature sensor to a different port on the AACMM 100.

[0059] Technical effects and benefits include the ability to continuously measure temperature and changes in temperature of an object being measured by the AACMM 100. As such, the operator may be alerted to changes and take corrective action. Such action may include moving the object under test to a more suitable measurement environment or giving the object time to come to thermal equilibrium. Alternatively, software may be used to normalize test results to account for the temperature and the CTE of the object under test. In addition, the non-contact temperature sensor may be used to measure as an end in itself by measuring the temperature of an object as a function of position on the object. The dimensional information provided by the AACMM 100 can be used to accurately map the measured temperature onto a CAD model of the object under test. This is useful to engineers in determining whether designs need to be changed and in providing accurate information for finite element models.

[0060] 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.

[0061] 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.

[0062] 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.

[0063] 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.

[0064] 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).

[0065] 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.

[0066] 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.

[0067] 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.

[0068] 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.

[0069] 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.

CLAIMS

What is claimed is:

1. A portable articulated arm coordinate measurement machine (AACMM), comprising:
 - a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each of the arm segments including at least one position transducer for producing a position signal;
 - a measurement device attached to a first end of the AACMM;
 - an electronic circuit for receiving the position signals from the transducers and for providing data corresponding to a position of the measurement device;
 - at least one sensor element, which is disposed on the AACMM, that is responsive to electromagnetic radiation and produces an electrical signal in response to a temperature of an object; and
 - an electronic system that converts the electrical signal into a temperature value.
2. The AACMM as claimed in Claim 1 wherein the electronic circuit is configured to display the temperature value.
3. The AACMM as claimed in Claim 2 further comprising a user interface configured to display a plurality of temperature values in a plot.
4. The AACMM as claimed in Claim 1 further comprising a processor configured to associate the temperature value with a coordinate of the object.
5. The AACMM as claimed in Claim 4 wherein the processor is further configured to use coordinates of at least three points measured by the measurement device.

6. The AACMM as claimed in Claim 5 wherein the processor is further configured to overlay a CAD model onto the at least three points.
7. The AACMM as claimed in Claim 5 wherein the processor is further configured to overlay a given geometrical shape onto the at least three points.
8. The AACMM as claimed in Claim 3 wherein the processor is further configured to plot the plurality of temperature values as a function of position on the object.
9. The AACMM as claimed in Claim 8, wherein the processor is further configured to plot the plurality of temperature values onto a three-dimensional representation of the object.
10. The AACMM as claimed in Claim 9, wherein the processor is further configured to represent the temperature values with gray scale, colors, contours, or whiskers.
11. A method of implementing a portable articulated arm coordinate measuring machine (AACMM), the method comprising:

measuring a temperature value of an object with an integrated temperature measurement system disposed on the portable AACMM, wherein the integrated temperature measurement system is responsive to electromagnetic radiation that varies with the temperature of the object, the portable AACMM comprised of a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal, a measurement device attached to a first end of the AACMM, and an electronic circuit which receives the position signals from the transducers and provides data corresponding to a position of the measurement device;

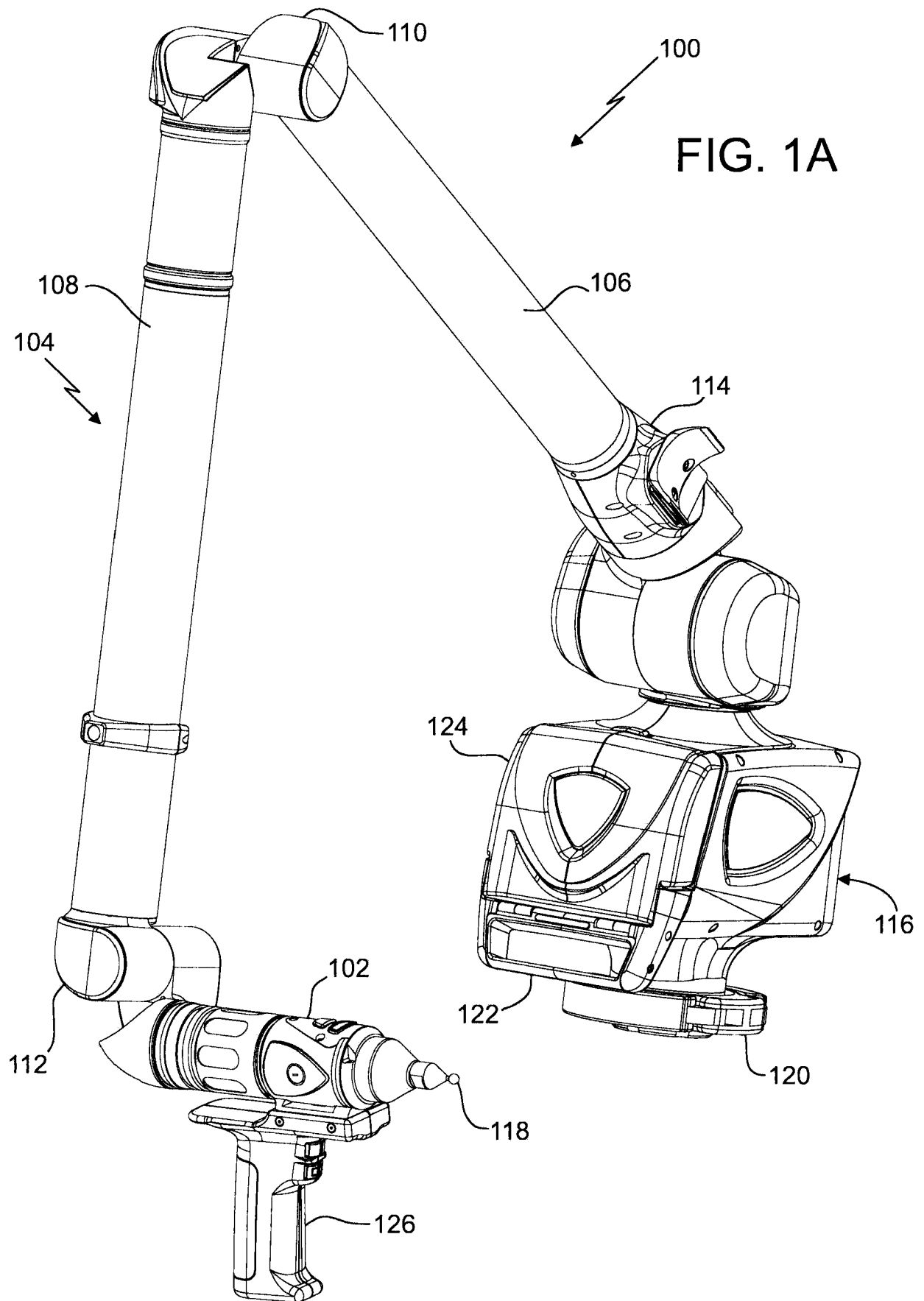
receiving the temperature value in the electronic circuit; and

displaying the temperature value on a user interface.

12. The method as claimed in Claim 11 wherein the user interface is disposed on the AACMM.

13. The method as claimed in Claim 11 wherein the user interface displays a plurality of temperature values in a plot.
14. The method as claimed in Claim 13 wherein the plot displays at least one of a temperature gradient and a critical temperature of the object.
15. The method as claimed in Claim 13 wherein the temperature values are processed to determine if there is at least one of a critical temperature and a critical expansion of the object.
16. The method as claimed in Claim 13 wherein the plot indicates the magnitude of dimensional changes resulting from changes in the temperatures of the object relative to a reference temperature.
17. A computer program product for implementing a portable articulated arm coordinate measuring machine (AACMM), the computer program product comprising a storage medium having computer-readable program code embodied thereon, which when executed by a computer causes the computer to implement a method, the method including:
 - measuring a temperature value of an object with an integrated temperature measurement system disposed on the portable AACMM, wherein the integrated temperature measurement system is responsive to electromagnetic radiation that varies with the temperature of the object, the portable AACMM comprised of a manually positionable articulated arm having opposed first and second ends, the arm including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal, a measurement device attached to a first end of the AACMM, and an electronic circuit which receives the position signals from the transducers and provides data corresponding to a position of the measurement device;
 - receiving the temperature value in the electronic circuit; and
 - displaying the temperature value on a user interface.
18. A computer program product as claimed in Claim 17 wherein the user interface is disposed on the AACMM.

19. The computer program product as claimed in Claim 17 wherein the user interface displays a plurality of temperature values in a plot.
20. The computer program product as claimed in Claim 19 wherein the plot displays at least one of a temperature gradient and a critical temperature of the object.
21. The computer program product as claimed in Claim 19 wherein the temperature values are processed to determine if there is at least one of a critical temperature and a critical expansion of the object.
22. The computer program product as claimed in Claim 19 wherein the plot indicates the magnitude of dimensional changes resulting from changes in the temperatures of the object relative to a reference temperature.



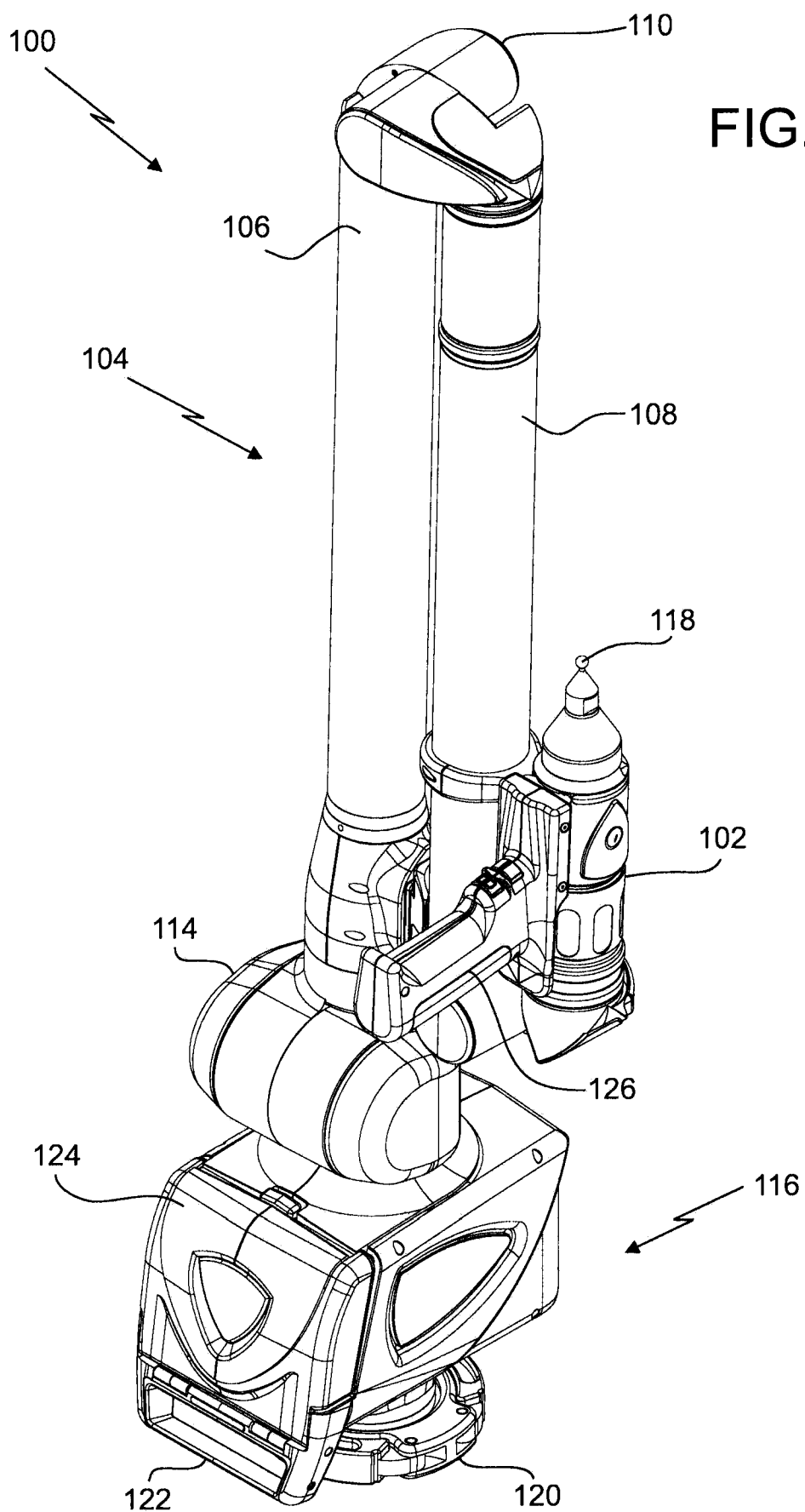
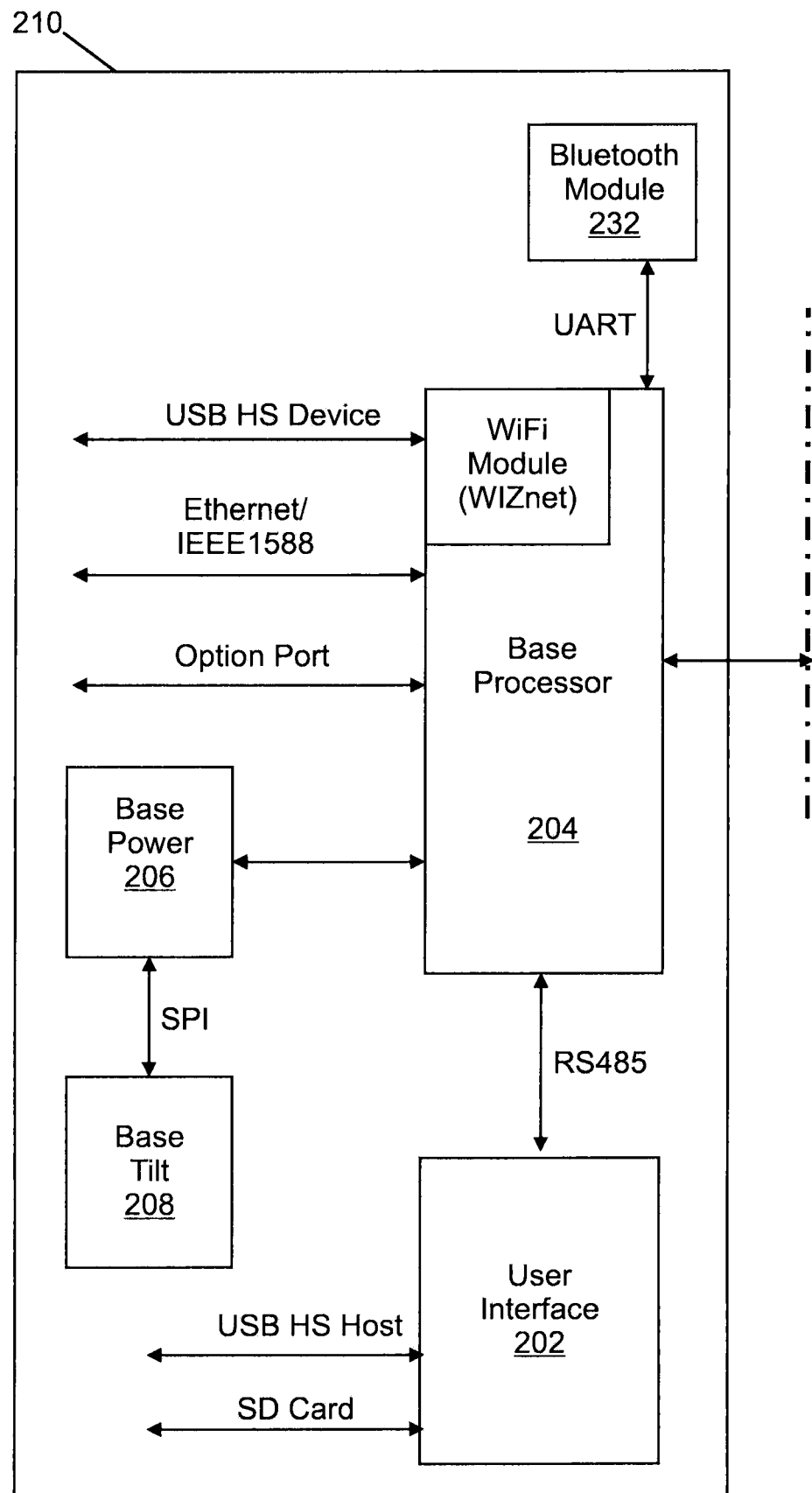


FIG. 2A



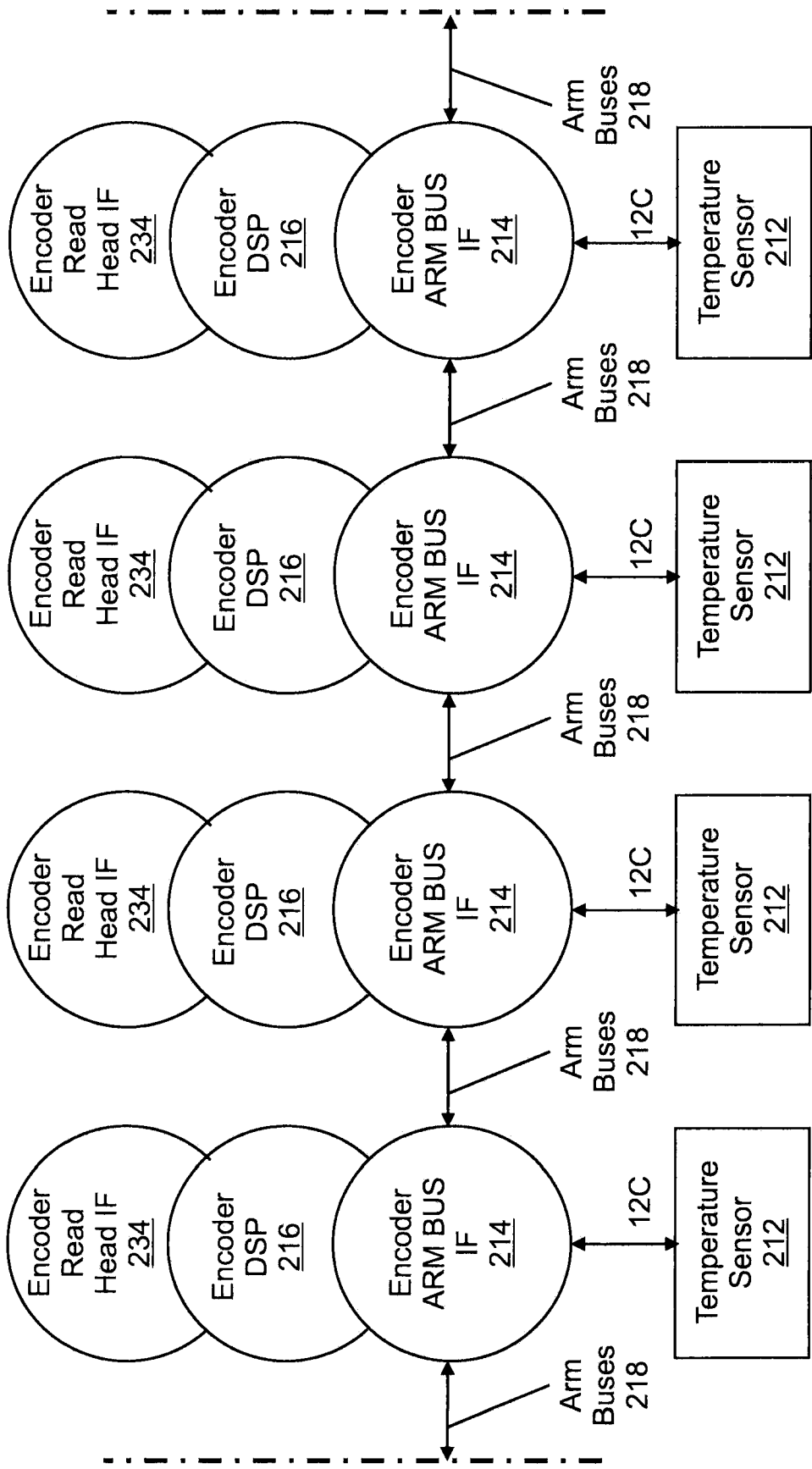


FIG. 2B

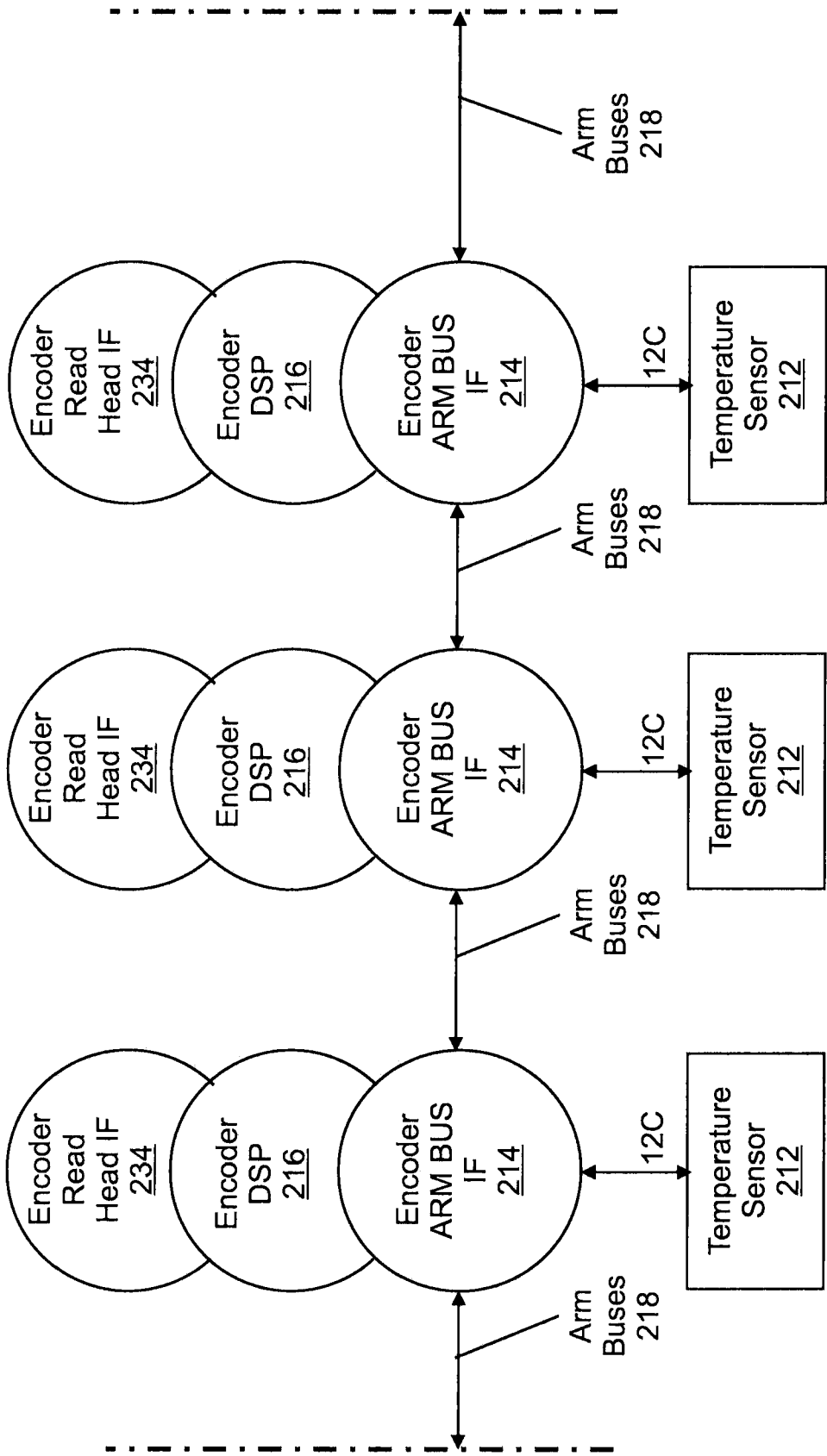


FIG. 2C

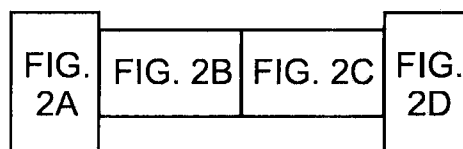
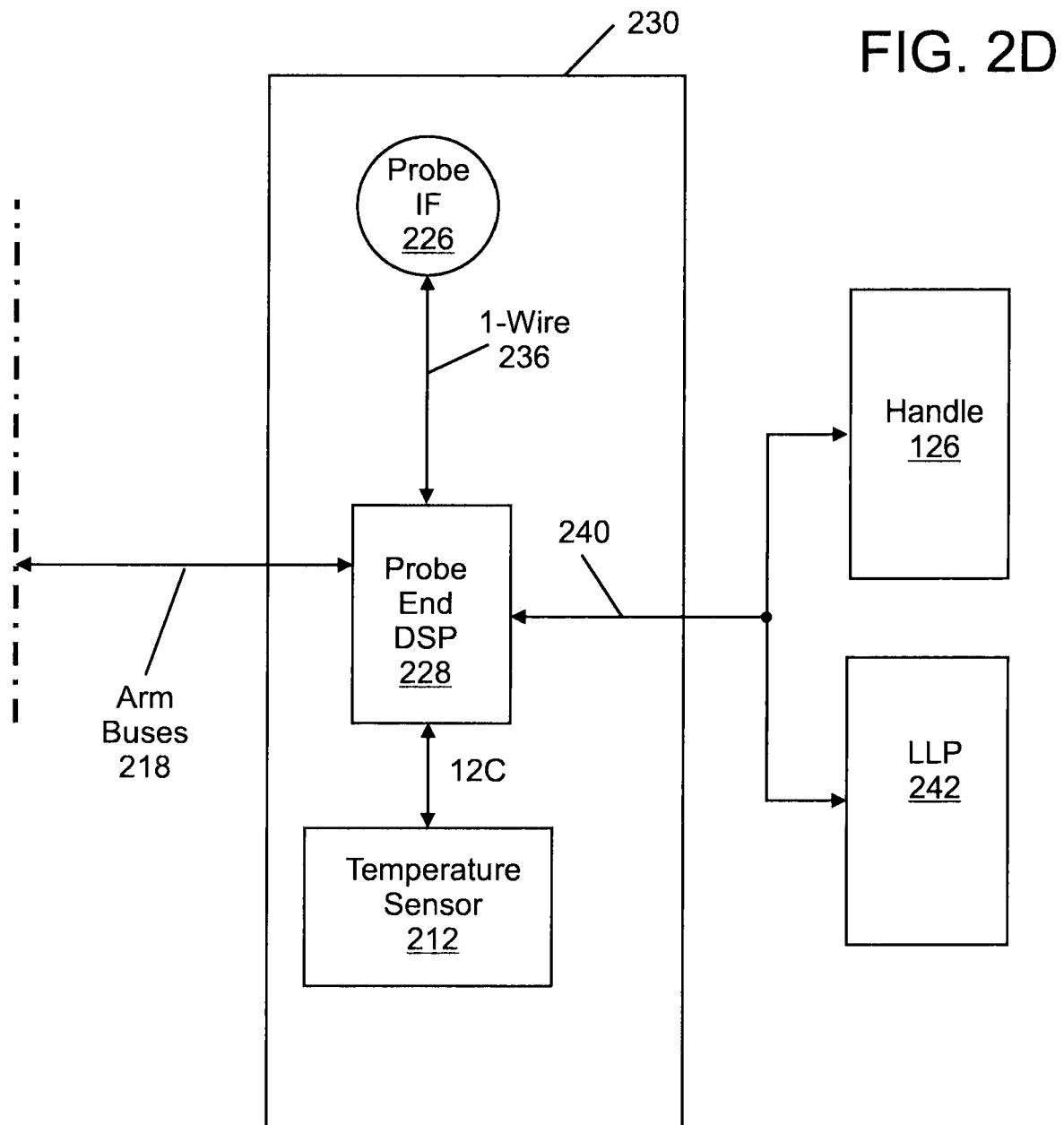
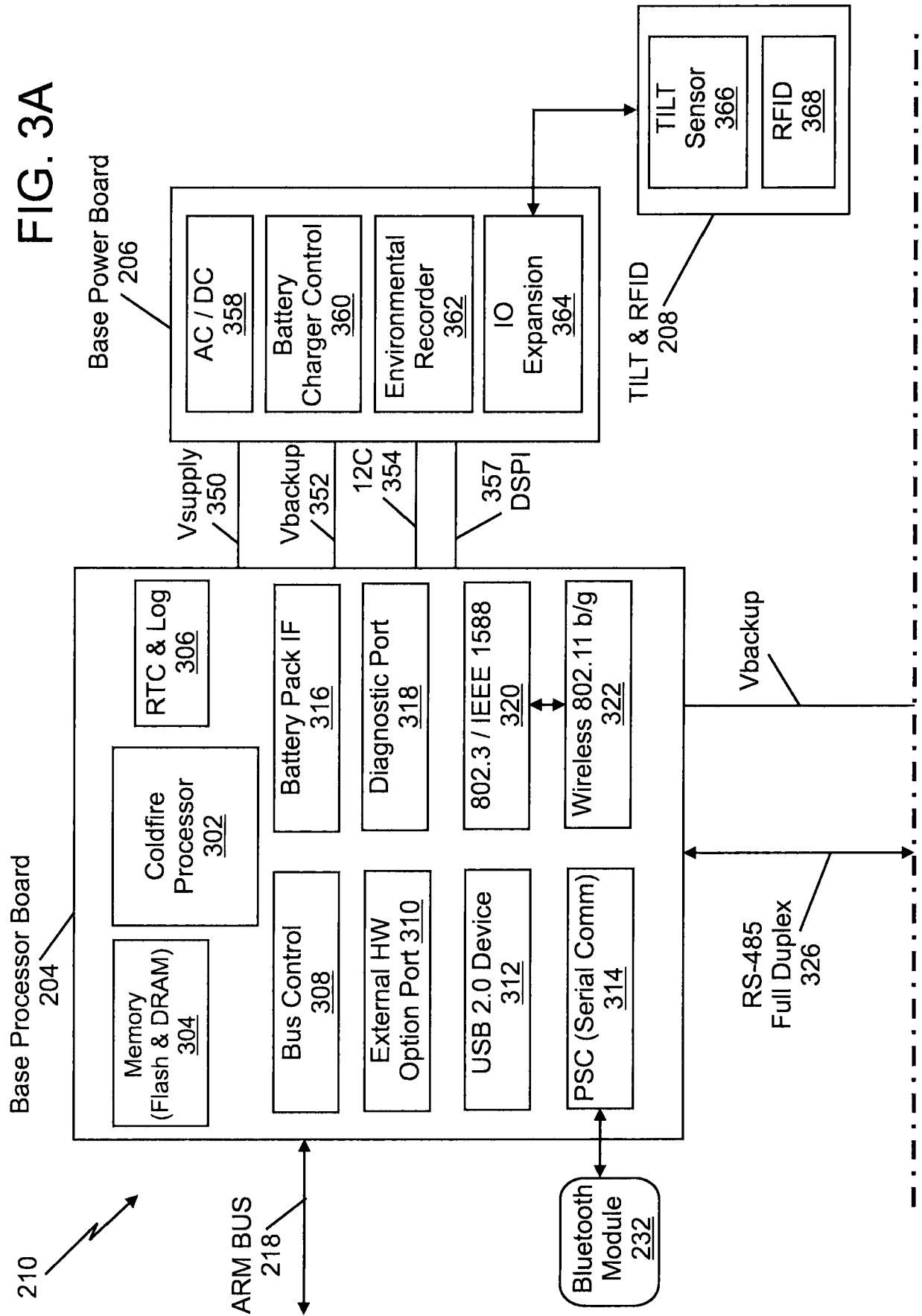


FIG. 2

FIG. 3A



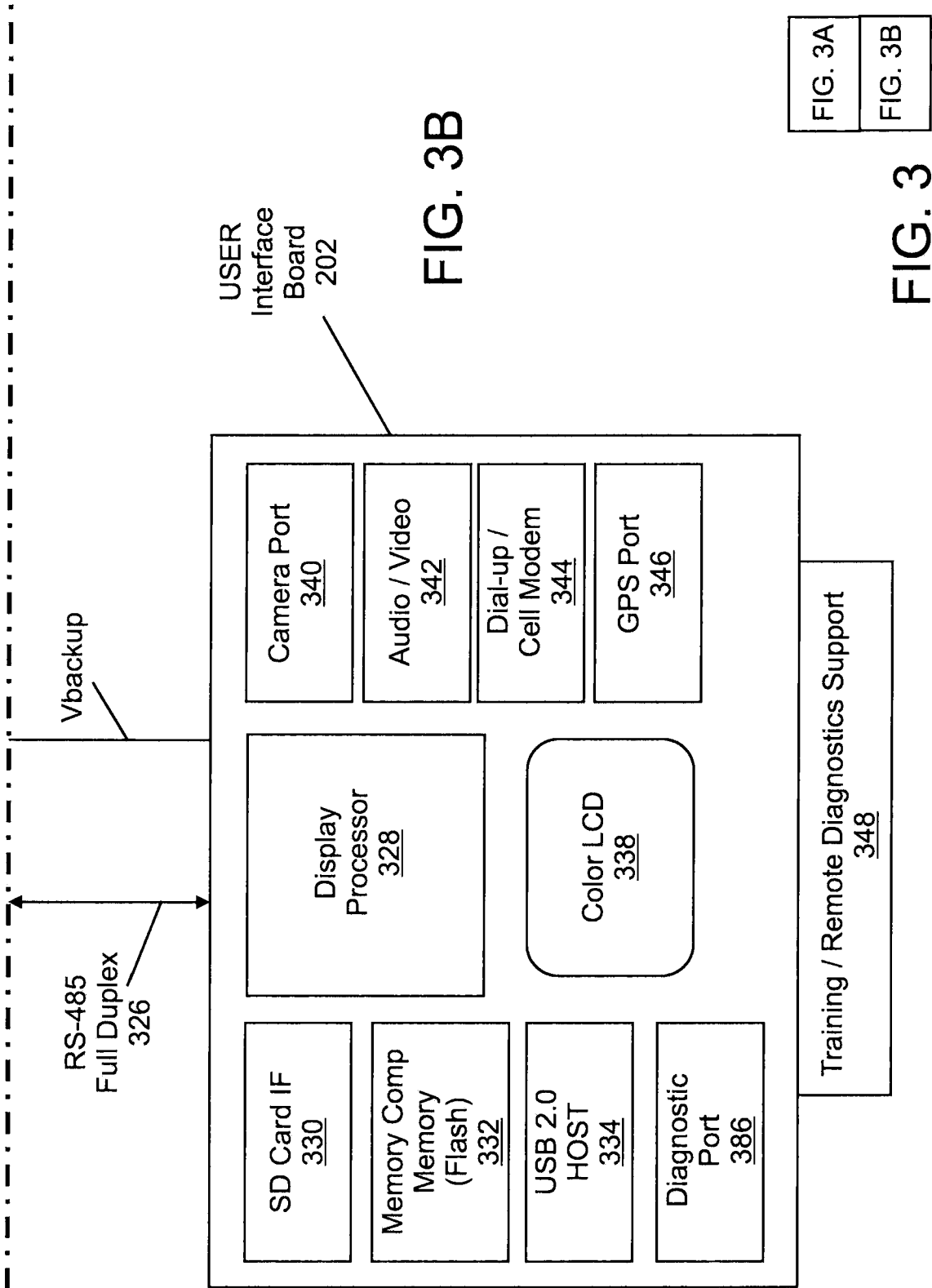


FIG. 4

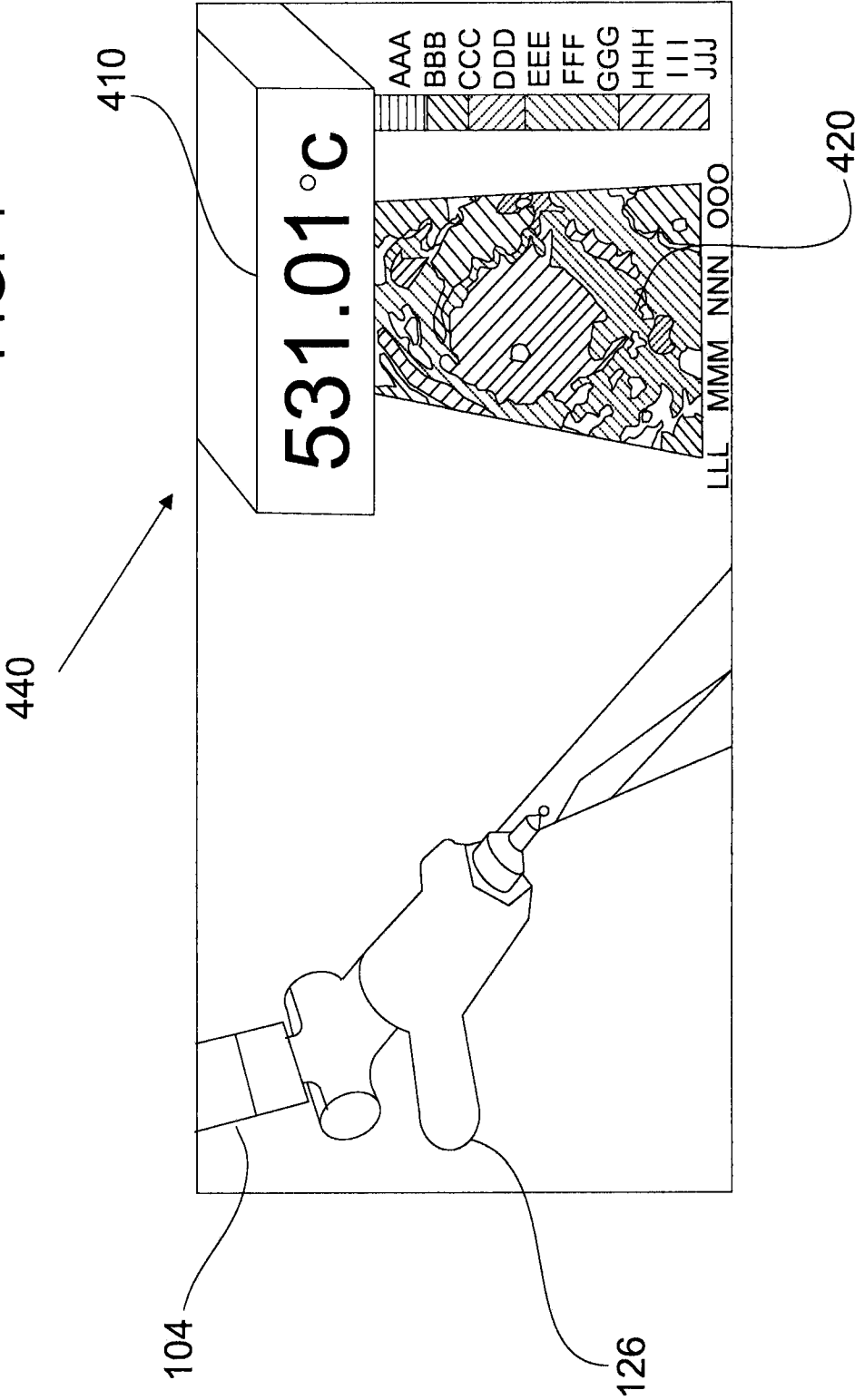
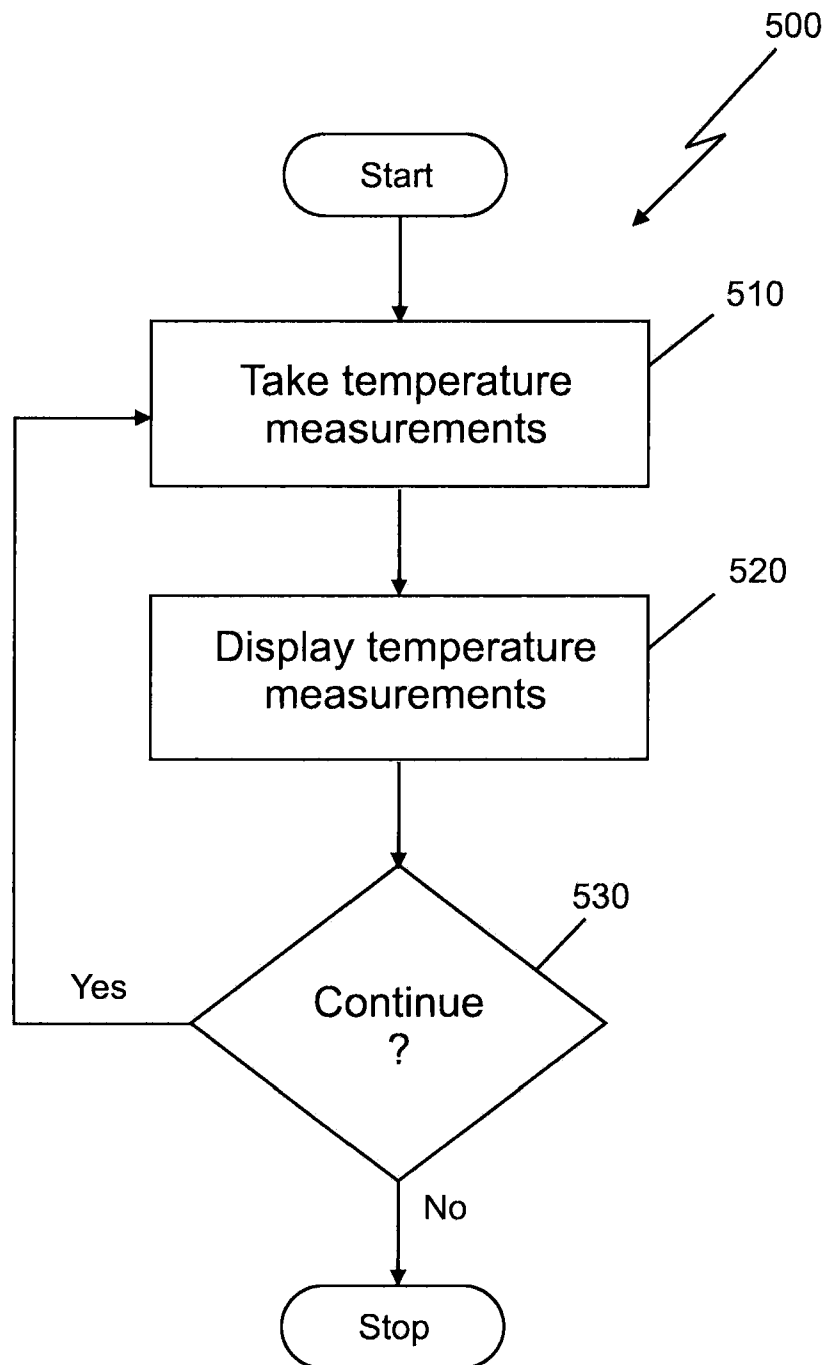


FIG. 5



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/021274

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B5/00 G01B11/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01B B25J G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EP0-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 591 078 B2 (CRAMPTON STEPHEN JAMES [GB]) 22 September 2009 (2009-09-22) column 15, line 15 - column 16, line 67; figures 1-4 column 27, line 36 - column 31, line 12; figures 10-11 column 51, line 15 - column 52, line 28 column 91, line 36 - column 95, line 33; figures 67,68	1-22
X	----- WO 2008/027588 A2 (FARO TECH INC [US]; BRIGGS CLARK H [US]; MACFARLANE KEITH GEORGE [US];) 6 March 2008 (2008-03-06) paragraphs [0023], [0 24], [0 44]; figure 1 paragraph [0048] - paragraph [0050] paragraph [0083] - paragraph [0088] ----- -/--	1-22

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

28 April 2011

Date of mailing of the international search report

06/05/2011

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
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Authorized officer

Rueda Gomez, Adriana

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/021274

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
L	US 6 920 697 B2 (RAAB SIMON [US] ET AL) 26 July 2005 (2005-07-26) Completes the disclosure of WO 2008/027588 with respect to the details of the portable coordinate measuring machine.; column 6, line 17 - line 30; figures 1-3 column 7, line 20 - column 9, line 42 column 13, line 23 - column 14, line 14 -----	1-22
A	DE 198 20 307 A1 (MYCRONA GES FUER INNOVATIVE ME [DE]) 18 November 1999 (1999-11-18) the whole document -----	1-22

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Information on patent family members

International application No

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