



(43) International Publication Date
1 October 2015 (01.10.2015)

- (51) **International Patent Classification:**
G01B 7/06 (2006.01) *G01B 7/00* (2006.01)
G01B 7/02 (2006.01)
- (21) **International Application Number:**
PCT/US2015/012707
- (22) **International Filing Date:**
23 January 2015 (23.01.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
61/969,430 24 March 2014 (24.03.2014) US
- (71) **Applicant:** GENERAL ELECTRIC COMPANY
[US/US]; 1 River Road, Schenectady, NY 12345 (US).
- (72) **Inventors:** KNOBLOCH, Aaron, Jay; 1 River Road, Schenectady, NY 12345 (US). PLOTNIKOF, Yuri, Alexeyevich; 1 River Road, Schenectady, NY 12345 (US). KAPUSTA, Christopher, James; 1 River Road, Schenectady, NY 12345 (US). KARP, Jason, Harris; 1 River Road, Schenectady, NY 12345 (US). LIN, Yizhen; 1 River Road, Schenectady, NY 12345 (US).
- (74) **Agent:** WEISSMAN, Peter, S.; Blank Rome LLP, 600 New Hampshire Ave., NW, Washington, DC 20037 (US).

- (81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) **Title:** BATTERY CELL HEALTH MONITORING USING EDDY CURRENTS

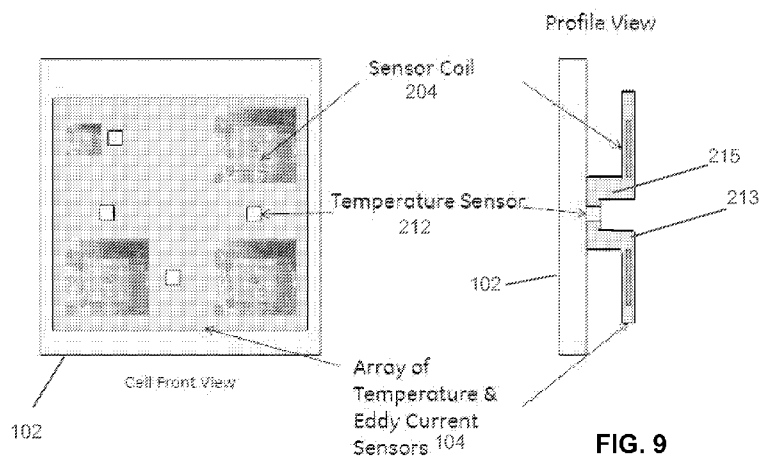


FIG. 9

(57) **Abstract:** The invention provides a battery sensing system comprising a battery module comprising a plurality of battery cells, at least one eddy current sensor coupled to or placed adjacent to one of more of the plurality of battery cells to determine cell expansion during cell operation, and a battery management system comprising one or more processors and/or microcontrollers that control operation of the plurality of battery cells.

BATTERY CELL HEALTH MONITORING USING EDDY CURRENTS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH & DEVELOPMENT

[0001] This invention was made with Government support under contract number DE-AR0000269 awarded by the Department of Energy. The Government has certain rights in the invention.

RELATED APPLICATION

[0002] This application claims priority to U.S. Provisional Application No. 61/969,430 filed March 24, 2014. The content of this application is hereby incorporated by reference.

BACKGROUND

[0003] Embodiments of the present disclosure relate generally to a method and system for monitoring battery cell health. More specifically, the present disclosure relates to a method and system for monitoring battery cell health using eddy current sensing.

[0004] There is an increasing prevalence in electrochemical storage devices such as batteries and capacitors in portable power generation from cell phones and laptops to portable power generation such as those found in automobiles and as part of power stations as grid storage. Electric vehicle (EV) packs (whether Plug-in Hybrid electric vehicle (PHEV), Hybrid Electric Vehicle (HEV) or Battery electric vehicle (BEV)) are composed of cells packaged into modules, which may include one or more cells which may further be arranged in one or more modules within a pack. FIG. 1 shows the arrangement of one such module. FIG. 1 shows a battery module 10 and a plurality of battery cells (1-5). The cells can be formed with many different chemistries and have different outer packages including soft pouch cells with a thin metallic outer case (usually in rectangular form) and hard pouch cells with a thicker metallic outer case (either in cylindrical or prismatic (rectangular cross-section)). As an example, FIG. 1 shows prismatic cells (1-5) with a thick metallic outer case (11) on cell 1.

Typically, the hard pouch cells are wrapped with a thin plastic (12) to prevent shorting between adjacent cells.

[0005] Many of the EV packs that exist today are designed around their cooling systems. Packs from certain automobile manufacturers use cabin air that flows between the cells to maintain a constant uniform temperature across the cells and cool the cells while others use water routed around the outer portion of the pack to cool the cell. In some implementations, the cells are spaced apart thru the use of spacers (13) to keep the cells at fixed gap from one another which allows flow of cabin air on the surface of the cells. In other implementations, the cylindrical cells are held from above and below to maintain spacing between the cells which allows for the flow of air around the cells.

[0006] As cells are charged and discharged, the outer cases of the cells expand and contract due to, for example, the lithiation of the electrodes or as a result of temperature changes that arise within the cell or outside of the cell due to the environment. This expansion is a unique parameter based on the electrode composition and battery chemistry, but is applicable to many battery chemistries including Li-ion batteries. The amount of expansion at any particular State of Charge (SOC) is also a function of the battery temperature and health or remaining life of the battery. In prior work, researchers have examined the deflection of the battery through use of strain gages, neutron scattering measurements of the electrodes themselves or laser based measurements of the deflections of the outside of the cell. However, there has lacked an accurate method to make in-situ measurements of the deflection of the battery when the cell is packaged as part of a pack that would be suitable for field installation either in grid storage or on-road, vehicle applications. Measurements with strain related approaches (such as strain gages or fiber Bragg gratings) could potentially be integrated into a cell or pack to make strain measurements. However, they suffer from several drawbacks. First, they provide an indirect measurement of the deflection of the cell and require the battery system to utilize additional computing power to solve a mechanical model of the cell to determine the electrode displacement from the strain measured on the surface of the cell. This calculation will also incur error on the overall measurement reducing the value of the approach. For optical techniques like fiber Bragg gratings, the cost of the interrogation system would be too high for deployment in cost sensitive applications such as automotive.

[0007] Thus, there is need for an improved method and system to monitor the health and life of the battery through direct measurements of expansion of the cell that can be placed in-situ within the pack or group of cells or a single cell.

BRIEF DESCRIPTION

[0008] In accordance with one embodiment described herein, a sensing system is presented.

[0009] In one embodiment, the sensing system comprises: a battery module comprising a plurality of battery cells; an eddy current sensor placed adjacent to one or more of the plurality of cells to determine cell expansion during cell operation; and a battery management system to control operation of the battery based on the cell expansion.

[0010] In one embodiment, the battery management system further comprises one or more controllers to control operation of the battery based on one or more control algorithms.

[0011] In one embodiment, the battery cells of the battery sensing system are structured into one or more battery modules, strings or packs.

[0012] In one embodiment, the eddy current sensor of the battery sensing system is placed between two battery cells to measure expansion in one or both of the battery cells.

[0013] In one embodiment, the eddy current sensor of the battery sensing system further comprises a temperature sensor.

[0014] In one embodiment, the eddy current sensor of the battery sensing system further comprises a sensor coil and a reference coil.

[0015] In one embodiment, the eddy current sensor of the battery sensing system further comprises a reference coil located adjacent to or near at least one of the battery cells.

[0016] In one embodiment, the battery management system further comprises sensor electronics and a reference coil located apart from the battery module and adjacent to or within the eddy current sensor.

[0017] In one embodiment, the eddy current sensor of the battery sensing system is thin and flexible.

DRAWINGS

[0018] These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0019] FIG. 1 illustrates a battery module including multiple battery cells;

[0020] FIG. 2 illustrates an overall system block diagram of a battery including a group of cells and one or more eddy current sensors in accordance with one embodiment of the invention;

[0021] FIG. 3 illustrates a block diagram of sensor electronics in accordance with one embodiment of the invention;

[0022] FIG. 4 illustrates two configurations for placement of a reference coil in accordance with one embodiment of the invention;

[0023] FIG. 5 illustrates characteristic sensor output as a function of the gap between the sensor and the cell based on the configurations the reference coil shown in FIG. 4;

[0024] FIG. 6A illustrates an example sensor coil and reference coil manufactured using flexible substrate processing in accordance with one embodiment of the invention;

[0025] FIG. 6B illustrates a sensor coil attached to a fixed body adjacent to the battery cell to measure the expansion of the cell in accordance with one embodiment of the invention;

[0026] FIG. 7 illustrates an eddy current sensor integrated within a battery module in accordance with one embodiment of the invention;

[0027] FIG. 8 illustrates an eddy current sensor integrated within a battery module in accordance with another embodiment of the invention;

[0028] FIG. 9 illustrates arrays of eddy current and temperature sensors integrated within a battery module in accordance with one embodiment of the invention;

[0029] FIG. 10 is a plot illustrating the conversion of sensor voltage to expansion for use in calibrating the eddy current sensor in accordance with one embodiment of the invention; and

[0030] Fig. 11 illustrates an eddy current sensor response when monitoring a prismatic, rectangular hard metallic case cell during a 0.4 C charge and discharge cycle, in accordance with one embodiment.

DETAILED DESCRIPTION

[0031] Reference will be made below in detail to exemplary embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numerals used throughout the drawings refer to the same or like parts.

[0032] As will be described in detail hereinafter, various embodiments of exemplary structures and methods for monitoring the health and life of the battery through in-situ, direct measurements of expansion of the cell are presented. FIG. 2 illustrates an overall system block diagram of a battery sensing system 100 including a pack or group of battery cells or modules 102, and one or more eddy current sensors 104 mounted on or substantially near one or more of the cells to detect expansion within the cells, typically upon operation of the battery. In one embodiment, each cell within the group includes a corresponding sensor, whereas in other embodiments the number of cells and sensors may differ. In one embodiment, two or more eddy current sensors 104 may be utilized to detect expansion within a single cell. In one embodiment, the battery cells 102 are formed of lithium-ion batteries.

[0033] The battery sensing system 100 of FIG. 2 includes a Battery Management System (BMS) 110, which may include sensor electronics 106 and battery model and control algorithms module 108. The sensor electronics 106 controls the powering and reading of the eddy current sensor 104 as well as the processing and interpretation of the information or

signals provided from these sensors. This interpretation may include statistical analysis of the data, comparisons to historical values, comparisons to other sensors in the battery pack and application of calibrations. The sensor electronics 106 may represent one or more processors, or microcontrollers to perform the functions listed. The information from the eddy current sensor 104 is passed from the sensor electronics 106 to the battery model and control algorithms module 108. The battery model and control algorithms module 108 may represent one or more processors or microcontrollers configured to execute programming instructions or control algorithms to control operation of one or more cells within the group of cells 102. In at least one embodiment, the processors or microcontrollers used to form the sensor electronics 106 can be the same as the processors or microcontrollers for the battery model and control algorithms module 108. In addition, temperature sensors can be provided as inputs to the sensor electronics 106 to determine expansion based on lithiation and expansion based on temperature changes of the cell 102.

[0034] In one embodiment, continuous signals are transmitted from the eddy current sensor 104 to the BMS 110 where they are analyzed by the sensor electronics 106 and used as input to a battery control model 108 for the associated battery pack. Such battery control models 108 may include physics based models of the cell or pack operation, equivalent circuit models of the cell or pack operation, or statistical based analysis of the measurements examining changes in values over time. Based on the input signals from the sensors, the BMS 110 can send control commands 109 to effect changes in the operation of the battery cells/modules 102. While FIG. 2 shows the sensor electronics 106 as being part of the BMS 110, in other embodiments the sensor electronics 106 could be integrated as part of the sensors 104 proximal to the sensed location rather than located remotely in the BMS 110. Moreover, other embodiments may involve the use of additional volatile or non-volatile memory as part of the BMS 110 or sensor electronics 106 such that expansion measurements could be kept and downloaded to analyze the cell and pack abuse levels.

[0035] FIG. 3 illustrates a schematic block diagram of the sensor electronics 106 in accordance with one embodiment. As shown in FIG. 3, the eddy current sensor may contain a pair of inductive coils 204 and 205 placed in an inductive bridge circuit configuration 201. In the illustrated embodiment, the signals from the eddy current sensor 104 (of FIG. 2) may be read through the inductive bridge circuit 201, where the eddy current sensor is denoted by the sensor coil 204 and varies according to the gap between the sensor coil and one or more

of the cells 102. Alternatively, measurements could be made without the use of a bridge circuit or through other readout configurations known in the art including quadrature measurement of amplitude and phase or frequency detection. A reference coil 205 is the fixed portion of the bridge circuit 201 and is typically identical to the sensor coil 204 in either manufacturing or nominal value of inductance and resistance. This reference coil does not see the change in sensed gap thereby providing a differential measurement which is used to reduce noise. Accordingly, one side of the bridge 201 remains fixed in space as a reference while the sensor coil 204 can be loaded by the battery. The output voltage signal is representative of the bridge imbalance and therefore the physical spacing between the sensor coil and metallic surface. The bridge 201 is driven by an oscillator, typically coupled to a current amplifier, to generate an AC current and subsequent magnetic field at each coil. The voltages at the center of each bridge arm are passed to a differential amplifier which is only sensitive to bridge imbalance. The amplifier output may be filtered by the low pass filter (LPF) 207, amplified by the amplifier 209 and rectified by the diode 211 and the low pass filter (LPF) 213 in order to achieve a steady DC output for data acquisition. Changes in the oscillator frequency, current amplification, filter and coil geometry can be tuned to change performance characteristics of the complete sensing system. These characteristics can include the sensor range, voltage output, measurement sensitivity (Volts per microns of expansion), resolution, amongst others.

[0036] Additionally, as shown in FIG. 3, a temperature sensor 215 can be located adjacent to the sensor coil 204 such that any temperature compensation can be performed as part of the sensor electronics 106. The temperature sensor 215 may have a thickness of 125 microns or less. In another embodiment, the temperature sensor 215 can be located directly on at least one of the battery cells 102. In one embodiment, the temperature sensor can be constructed on the same substrate as the sensor coil 204 so that the temperature sensor information can be used to compensate the sensor output for changes in the temperature of cell which could cause expansion of the battery that would not be indicative of the battery health. It is important to note that in contrast to other work on eddy current measurements of a battery in the literature, this sensor does not measure the actual current flow within the battery, but instead measures the expansion of the outer wall of the cell. The temperature sensor 215 may also be integrated within the eddy current sensor 104.

[0037] The reference coil 205 can be implemented either in the sensor electronics 106 or be proximal to the location of the eddy current sensor 104 so that it experiences the same environmental changes as the sensor 104. FIG. 4 illustrates two configurations for placement of the reference coil 205. In a first configuration 410, the reference coil 205 is disposed on or near a cell 102 in an area where the wall of the cell is not moving relative to the reference coil during charge or discharge and thereby, not modulating the reference coil. For instance, the coil 205 can be built on the same flexible substrate. The coil 205 can be placed adjacent to the sensor coil 204 (~3 mm coil diameter) though the distance to the battery cell 102 must be held constant so as to not be affected by displacement changes. One method of doing so is to mount the reference coil 205 directly against the battery surface. Another is to place the reference coil 205 outside its sensitivity range (> 1 mm). In addition, this location could also be an area where the wall of the cell 102 is outside the range of sensitivity (typically > 1 mm) of the reference coil 205. In this configuration, the reference coil 205 is shown as being fabricated as part of the sensor coil 204, but may also be built as a separate component. In a second configuration 420, the reference coil 205 is located as part of the sensor electronics 106 rather than disposed on the battery cell directly. In this configuration, the reference coil does not detect directly the cell expansion during charge and discharge, but is located remotely in the sensor electronics 106 either proximal to the sensor coil 204 or as part of the BMS 110.

[0038] Each sensor coil would have a characteristic response curve that is a function of the drive frequency, coil geometry (size and shape of coil) and the material of the cell case. FIG. 5 shows an example of such response curves for each respective configuration of the reference coil shown in FIG. 4. The voltage response to a changing gap is generally non-linear with changing gap and, in one embodiment, the sensor coil 204 is designed such that it is sensitive in a region between approximately 200 microns and 1000 microns. This regime can be modified thru changes in the dimensions of the sensor coil as well as the drive voltage of the sensor coil. Referring to FIG. 5, response plot 411 corresponds to configuration 410 and response plot 421 corresponds to configuration 420. From response plot 411, it can be seen that the response as a function of gap is substantially linear and a linear response curve can be fitted accordingly. The raw output of the sensor is largely nonlinear (red curve) but a simple calibration transfer function (typically logarithmic) creates a linear calculation with traversed gap. The advantages of the approach of configuration 410 are that the reference

coil will reside in an environment that will closely resemble the environment of the sensor coil and will more effectively remove potential noise sources. As seen by response plot 421, in configuration 420 the sensor may be less effective in removing common mode sources of error and the output is more sensitive to expansion of the cell. Moreover, this configuration also is likely easier to implement in the final application.

[0039] The sensor coil 204 and reference coil 205 may be manufactured using flexible substrate processing. Examples of such coils are shown in FIG. 6A. In one embodiment, further described with respect to FIG. 6A, the eddy current sensor 104 may be fabricated using thin film fabrication techniques. Eddy current sensing coils may be fabricated through several different means, but thin-film fabrication provides flexible sensors which can be integrated into the confined spaces between battery cells. Coils made through thin-film fabrication can be made to be 100 microns or less in total thickness which allows for placement in the tight packaging constraints of modern energy storage systems, such as vehicles.

[0040] The substrate of the sensor, the coils and conductors can be made with a variety of metal or electrically conductive materials. The example coils shown in FIG. 6A were built using copper. The coils can be of a variety of diameters with the example coils being 3mm or 4mm in diameter and can be circular or square or other geometric shape. In one embodiment, the inductors are driven at frequencies of approximately 2MHz which balances a tradeoff between eddy current generation of the coil and losses within interconnect lines. The coils have self resonant frequencies of ~ 50 MHz and so the AC drive signal is operated at frequencies far away from this resonance. The drive frequency can be varied based on the sensing application and its requirements. The coils illustrated in FIG. 6A are co-fabricated with temperature sensors to allow for multiple measurement modalities to exist on a common substrate and provide localized temperature compensation signals as well as accurate temperature monitoring of the battery cell. In the example coils, the total thickness of the sensor is minimized to be as small as 50-100 microns thick. The ability to build sensors in a package this thin and flexible allows for the integration of these sensors into the highly compact packages of capacitors or battery packs including those used in automotive, portable power generation, utility, large ships or aircraft applications. The compact size and high operating frequency enables fast output responses for in-situ monitoring.

[0041] Integration method 410 (of FIG. 4) is further illustrated in FIG. 6B, whose response appears as plot 411 (FIG. 5, top). The reference coil 205 touches the battery 102 and therefore does not experience any expansion change while the sensing coil 204 is situated with a 600 micron offset from the battery. This gap will change as the cell expands. Note this is only one integration scheme that leverages a plastic spacer within the battery module, and other approaches may be more/less suitable depending on battery geometry, cooling methods (air versus water) and sensing location.

[0042] One embodiment of the integration of the eddy current sensor 104 (of FIG. 2) is shown in FIG. 7. A pack or group of cells 102 can be packaged such that there is a gap between each cell 102. The cells 102 can be either prismatic or cylindrical cell geometries. In some embodiments, the cells can be separated physically with a fixed structural member such as a plastic spacer or frame (not shown) which allows air flow but also allows for the cells to be compressed as part of the pack or group of cells. In this embodiment, the sensor 104 can be mounted on this plastic frame such that the gap between the sensor coil and the cell is within the sensitive regime of the sensor. In this embodiment the plastic frame is approximately 3mm in thickness and the position of the sensor coil 204 is such that the adjacent cell is outside the sensitive regime of the sensor. In this embodiment, it is desirable for the mechanism holding the sensor to be stable and not move with respect to the cell during operation of the cell. Other structures known in the art may be used to hold the sensor 104 between the cells 102 as shown in FIG. 7 or adjacent to a battery cell 102. The thinness of the sensor allows for mounting the sensor without interfering with the cooling flow (into or out of the page as shown in Fig. 7). During the operation of the cell, the outer portion of the cell case can deform (as indicated by the dashed lines) changing the gap between the sensor 104 and the cell 102. The cell 102 in this embodiment can have a metallic case or have a polymeric case with a thin metal coating 215 (as shown in FIG. 8) to allow for the eddy current measurement.

[0043] The sensing coil 104 in FIG. 7 functions the same as the coils 204 shown in FIG. 6. The coil turns are situated into the page so as the 3mm diameter is parallel to the cell surface and the 100um cross-sectional thickness is highlighted. Eddy current sensing requires a conductive surface to generate mutual inductance, hence the ability to measure deflection of the outer metallic case of the battery cell 102. If the outside casing is not conductive, a metal

reflector or foil can be added to the cell surface. FIG. 7 shows the coil 204 situated away from the cell case (~600um) and detects small expansions during cell operation. If the coil 204 comes in direct contact with the battery casing, the output may become saturated.

[0044] Another embodiment of the integration of the eddy current sensor 104 within a battery module 102 (as shown in FIG. 2) is shown in FIG. 8. Here the sensor 104 is shown mounted on the wall of the adjacent cell 102 and the measured change in gap would be a combination of the expansion of the cell 102 on which the sensor 104 is mounted on and deflection of the adjacent cell 102. In this embodiment, the sensor coil 204 is designed such that it is sensitive in the range of the gap between the cells 102 through modification of the driving frequency, coil geometry or material choices. In the illustrated embodiment, the gap may be 1-3 mm, however, other gap distances are contemplated. If that is not possible, another embodiment (not shown) would have the sensor 104 mounted on the adjacent cell 102 on top of a pillar of an non-electrically conductive material such that the gap across which the measurement is made is in the sensitive regime of the sensor coil 204. The pillar includes a standoff (ceramic or non-conductive) from the cell so that the mounted sensor coil 204 is not driven into saturation by being mounted directly to a conductive surface. Thin-film ferrite absorbers may also be used to suppress the magnetic field generated by the side of the coil 204 mounted to the conductive wall.

[0045] In the prior disclosed embodiments, individual measurements of cell deflection have been on each cell 102. FIG. 9 shows arrays of eddy current 104 and temperature sensors 212 that can take multiple measurements of deflection and temperature across the surface of a cell 102 to look at differences in the expansion across the cell surface. Individual outputs can share the same sensing electronics through the use of a multiplexer. The arrangement of the temperature sensors 212 is not limited, and they can be placed at a number of positions as shown. The temperature sensors 212 may be connected via traces that connect to the battery cell 102. Although in the illustrated embodiment a prismatic cell is shown, the eddy current sensor 104 could instead be curved and used to measure the deflection of a cylindrical cell. Also shown as part of this embodiment are temperature sensors 212 to take temperature measurements that could be made across the surface in tandem with the measurements of cell expansion. Due to the flexibility of the substrate material 213, the surface of the substrate can conform to allow for the gap necessary for the eddy current sensor 104 and contact with

the cell 102 required for the temperature sensor 212. As shown in the profile view of FIG. 9, the flexible substrate 213 may be formed with a standoff 215 that extends outward from the surface of the cell 102 adjacent the temperature sensor 212. Thus, the flexible substrate 213 has a top portion, a bottom portion, and the standoffs 215, all of which are integrally formed. The top portion can be flat, contains the coils 204, and is spaced apart from the cell 102. The bottom portion can also be flat, and contains the temperature sensors 212 adjacent the cell 102. The standoffs 215 integrally couple the top portion with the bottom portion. In this way, the temperature sensor 212 can directly contact the cell 102, while the standoff 215 forms a gap between the eddy current sensor array 104 and the cell 102. The sensing coils 204 could then be used to measure cell expansions of an adjacent cell. A common reference coil (not shown in FIG. 9) such as those discussed herein can also be used when having multiple sensors on a particular cell or multiple sensors across a pack and the sensor electronics 106 could be multiplexed to reduce cost.

[0046] FIG. 10 is a plot illustrating the conversion of the sensor voltage to expansion that is performed as part of the calibration for the eddy current sensor in accordance with one embodiment of the invention. The output signal of the eddy current sensor electronics 106 can be approximated by the function: $S'(G)=a/(\exp(b \cdot G))+c$ where S' is a signal approximation, G is the gap (in mm or microns), a , b and c are constants. Using an inverse function: $G^*=\ln(a/(S-c))/b$ the values of the gap or expansion can be computed using a processing unit such as a processor or a microcontroller. In this embodiment, the sensor is operated at 2 MHz. For example, the inverse function provides a linear relationship between eddy current sensor electronics signals and a gap in the range of interest for battery cell monitoring (for example, 1 -- 3 mm). This allows the sensitivity not to depend on the initial gap between the cell housing, but rather the change in gap. The linear range and sensitivity are a function of the sensor coil design (geometry of the coil, coil material, target material) and operation conditions such as frequency. Alternate processing schemes may use a lookup table instead of an inverse function to convert output voltage to a physical distance.

[0047] Fig. 11 shows the response of the eddy current sensor when monitoring a prismatic, rectangular hard metallic case cell during a 0.4 C charge and discharge cycle. The upper curve shows the voltage rise during charge and the voltage decrease as the cell is being discharged. Between charge and discharge, there is a 3 hr dwell to let the cell equilibrate. The lower curve shows the eddy current sensor response using the electronics and

linearization detailed previously. The eddy current sensor is sensitive to expansion changes on the order of 1 micron while being situated >500 microns from the cell surface in this embodiment.

[0048] Certain embodiments contemplate methods, systems and programming instructions or data encoded on machine-readable media to implement functionality described above. Certain embodiments may be implemented using an existing computer processor, or by a special purpose computer processor incorporated for this or another purpose or by a hardwired and/or firmware system, for example. Certain embodiments include computer-readable media for carrying or having computer-executable instructions or data structures stored thereon. Such computer-readable media may be any available media that may be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such computer-readable media may comprise RAM, ROM, PROM, EPROM, EEPROM, Flash, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of computer-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of computer-readable media. Computer-executable instructions comprise, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0049] Generally, computer-executable instructions include routines, programs, objects, components, data structures, etc., that perform particular tasks or implement particular abstract data types. Computer-executable instructions, associated data structures, and program modules represent examples of program code for executing steps of certain methods and systems disclosed herein. The particular sequence of such executable instructions or associated data structures represent examples of corresponding acts for implementing the functions described in such steps.

[0050] Embodiments of the present disclosure may be practiced in a networked environment using logical connections to one or more remote computers having processors. Logical connections may include a local area network (LAN) and a wide area network (WAN) that are presented here by way of example and not limitation. Such networking environments are commonplace in office-wide or enterprise-wide computer networks, intranets and the

Internet, and may use a wide variety of different communication protocols. Those skilled in the art will appreciate that such network-computing environments will typically encompass many types of computer system configurations, including personal computers, handheld devices, multi-processor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. Embodiments of the disclosure may also be practiced in distributed computing environments where tasks are performed by local and remote processing devices that are linked (either by hardwired links, wireless links, or by a combination of hardwired or wireless links) through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

[0051] It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments (and/or aspects thereof) may be used in combination with each other. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. While the dimensions and types of materials described herein are intended to define the parameters of the invention, they are by no means limiting and are exemplary embodiments. Many other embodiments will be apparent to those of ordinary skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein.” Moreover, in the following claims, the terms “first,” “second,” etc. are used merely as labels, and are not intended to impose numerical or positional requirements on their objects. Further, the limitations of the following claims are not written in means-plus-function format and are not intended to be interpreted based on 35 U.S.C. § 112, sixth paragraph, unless and until such claim limitations expressly use the phrase “means for” followed by a statement of function void of further structure.

[0052] This written description uses examples to disclose several embodiments of the invention, including the best mode, and also to enable any person of ordinary skill in the art to practice the embodiments of invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those of ordinary skill in the art.

Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

[0053] As used herein, an element or step recited in the singular and proceeded with the word “a” or “an” should be understood as not excluding plural of said elements or steps, unless such exclusion is explicitly stated. Furthermore, references to “one embodiment” of the present invention are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. Moreover, unless explicitly stated to the contrary, embodiments “comprising,” “including,” or “having” an element or a plurality of elements having a particular property may include additional such elements not having that property.

[0054] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

What is claimed is:

1. A battery sensing system comprising:
a battery module comprising a plurality of battery cells;
at least one eddy current sensor coupled to or placed adjacent to one of more of the plurality of battery cells to determine cell expansion during cell operation; and
a battery management system comprising one or more processors and/or microcontrollers that control operation of the plurality of battery cells.
2. The battery sensing system according to claim 1, further comprising a plurality of spacers or a frame placed between each of the plurality of battery cells so as to form a gap therebetween.
3. The battery sensing system according to claim 2, wherein the eddy current sensor is mounted adjacent to one of the plurality of battery cells on a fixed structural member such that the gap between the eddy current sensor and the one battery cell is within a sensitive regime of the eddy current sensor.
4. The battery sensing system according to claim 1, wherein the eddy current sensor is placed between two of the plurality of battery cells to measure expansion in at least one of the plurality of battery cells.
5. The battery sensing system according to claim 1, wherein each of the plurality of battery cells has either prismatic or cylindrical cell geometry.
6. The battery sensing system according to claim 1, wherein the plurality of battery cells are structured into one or more battery modules.
7. The battery sensing system according to claim 1, further comprising memory integrated within or outside of the battery management system in order to store data signals transmitted from the plurality of battery cells.

8. The battery sensing system according to claim 1, wherein a first portion of the one or more processors and/or microcontrollers of the battery management system form sensor electronics and a second portion of the one or more processors and/or microcontrollers perform battery model and control algorithms.

9. The battery sensing system according to claim 8, wherein the sensor electronics control the powering and reading of the eddy current sensor and the processing and interpretation of data signals provided from the eddy current sensor.

10. The battery sensing system according to claim 8, wherein the second portion of the one or more processors and/or microcontrollers execute programming instructions and/or control algorithms to control operation of the plurality of battery cells.

11. The battery sensing system according to claim 9, wherein the data signals are transmitted from the eddy current sensor to the battery management system where they are analyzed by the sensor electronics.

12. The battery sensing system according to claim 8, wherein the sensor electronics may be integrated within or outside of the battery management system or may be physically integrated with the eddy current sensor.

13. The battery sensing system according to claim 9, wherein the eddy current sensor is a sensor coil and the data signals provided from the sensor coil are read through an inductive bridge circuit having a fixed reference coil.

14. The battery sensing system according to claim 13, wherein the sensor coil and reference coil are manufactured of electrically conductive materials.

15. The battery sensing system according to claim 13, wherein the sensor coil and fixed reference coil are fabricated on a thin, flexible dielectric material.
16. The battery sensing system according to claim 15, wherein the thin, flexible dielectric material is polyimide film.
17. The battery sensing system according to claim 13, wherein the eddy current sensor includes a pair of inductive coils placed in the inductive bridge circuit.
18. The battery sensing system according to claim 13, wherein the fixed reference coil is disposed on or near at least one of the plurality of battery cells or is configured within the sensor electronics.
19. The battery sensing system according to claim 1, further comprising a temperature sensor.
20. The battery sensing system according to claim 19, wherein the temperature sensor is adjacent to or integrated within the eddy current sensor.
21. The battery sensing system according to claim 19, wherein the temperature sensor is less than 125 microns in thickness.
22. The battery sensing system according to claim 1, wherein each of the plurality of battery cells has a metallic case or a polymeric case with a thin metal coating.
23. The battery sensing system according to claim 1, wherein the battery sensing system comprises a plurality of eddy current sensors and temperature sensors positioned in at least one array.

24. The battery sensing system according to claim 1, wherein each of the plurality of battery cells has at least one cell wall and the eddy current sensor can be used to measure expansions of the at least one cell wall of 1 to 500 microns.
25. The battery sensing system according to claim 1, wherein at least one of the plurality of battery cells is a lithium-ion battery.
26. The battery sensing system according to claim 1, wherein the eddy current sensor determines cell expansion using quadrature measurement of amplitude and phase or frequency detection.
27. A method of measuring battery cell expansion comprising the steps of:
- a) providing a battery sensing system comprising:
 - i. a battery module comprising a plurality of battery cells,
 - ii. at least one eddy current sensor coupled to or placed adjacent to one of more of the plurality of battery cells, and
 - iii. a battery management system comprising one or more processors and/or microcontrollers,
 - b) activating the eddy current sensor so as to detect expansion of each of the plurality of battery cells while the battery module is in operation;
 - c) transferring data signals corresponding to the expansion of each of the plurality of data cells from the eddy current sensor to the battery management system where the data signals are analyzed;
 - d) communicating with a portion of the one or more processors and/or microcontrollers to control operation of the battery module using algorithms based on the analyzed data signals.

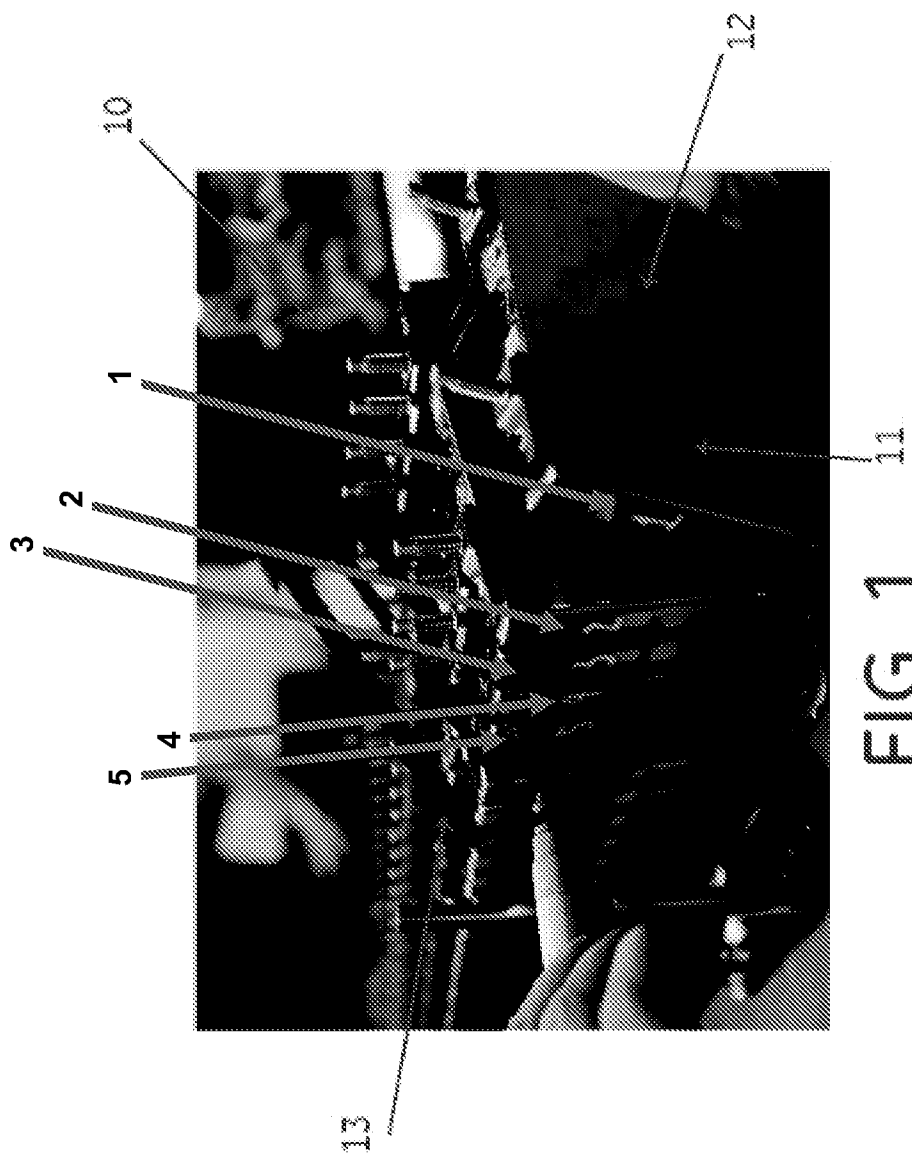


FIG. 1

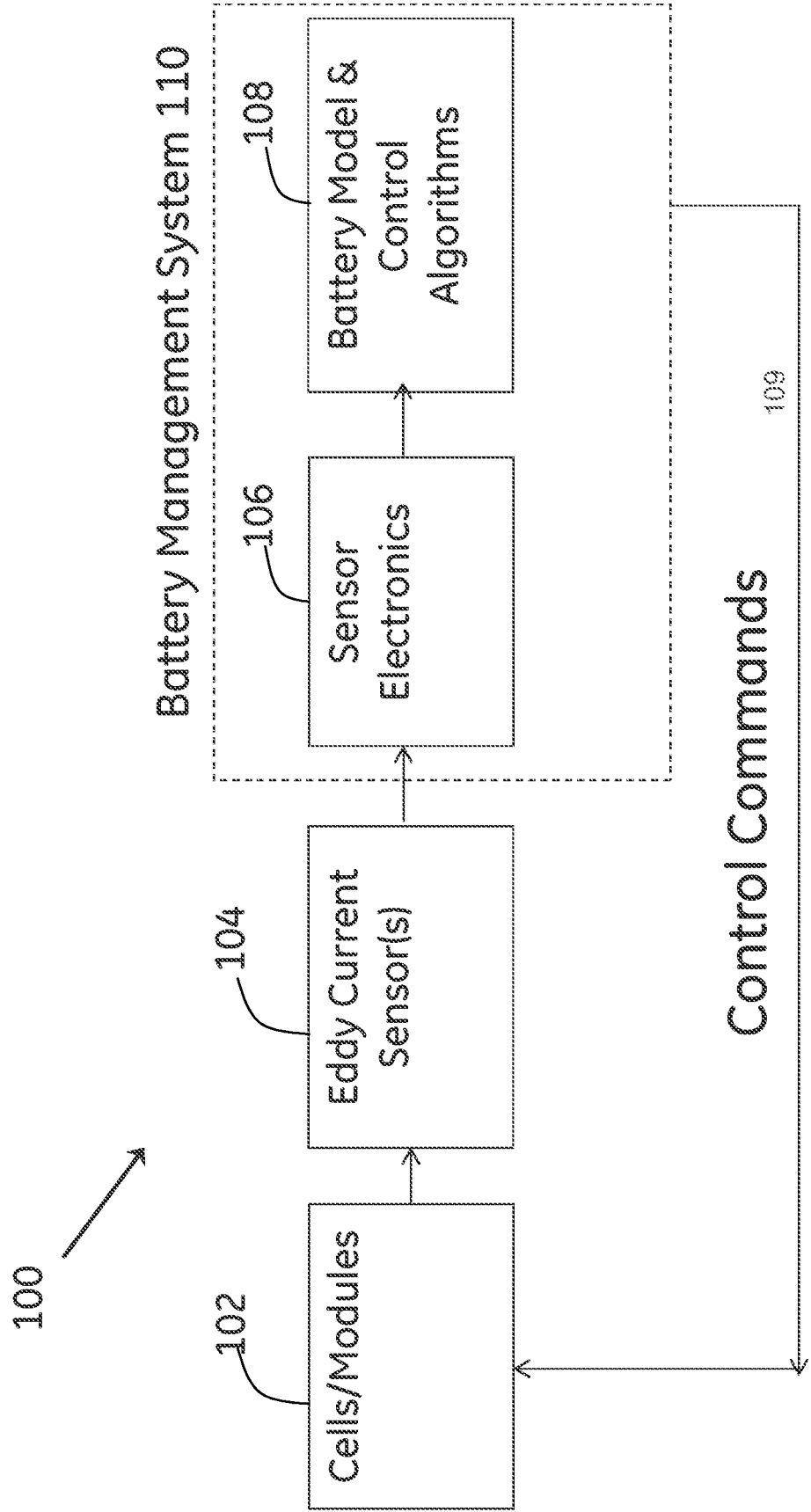
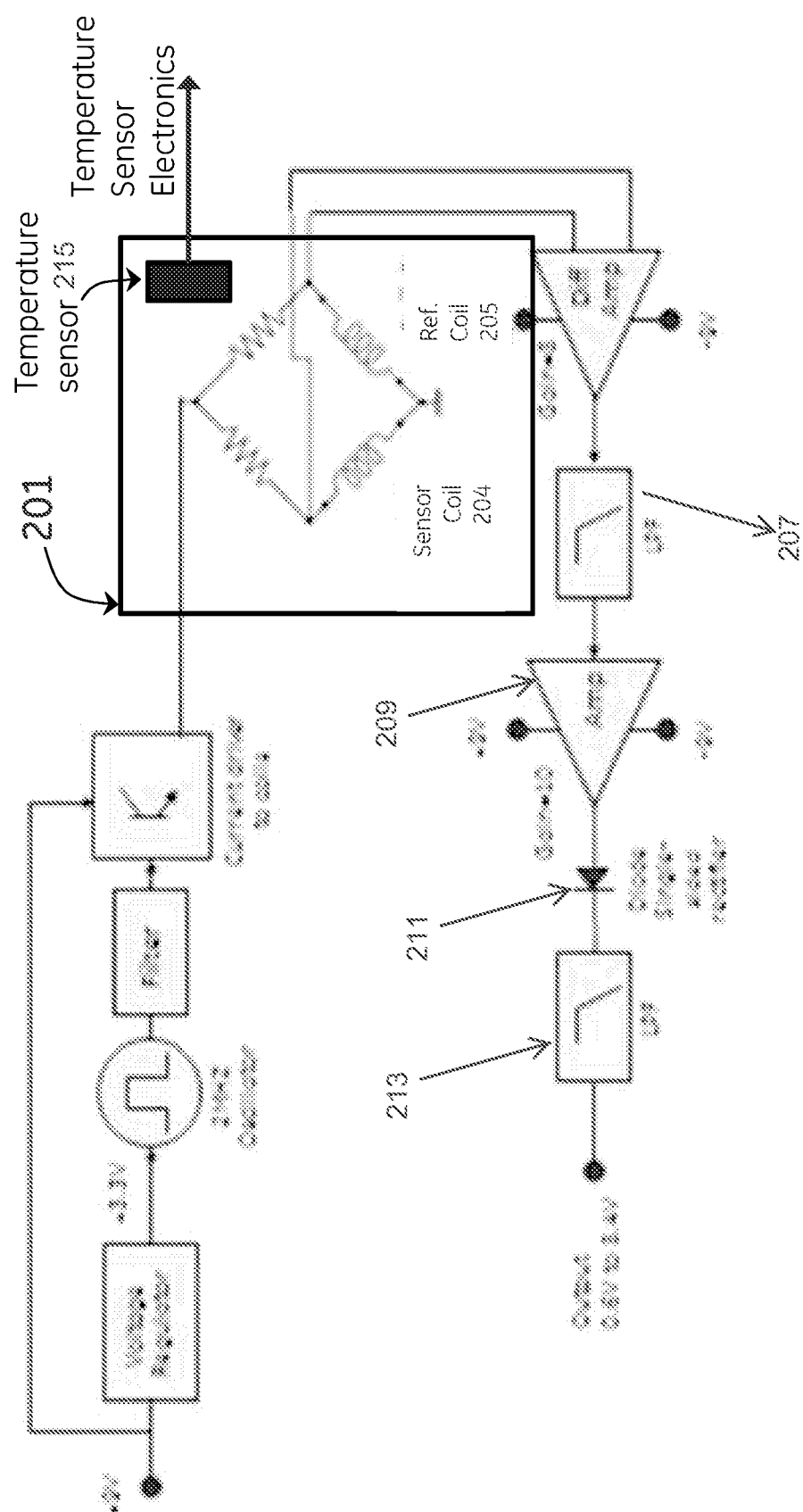


FIG. 2



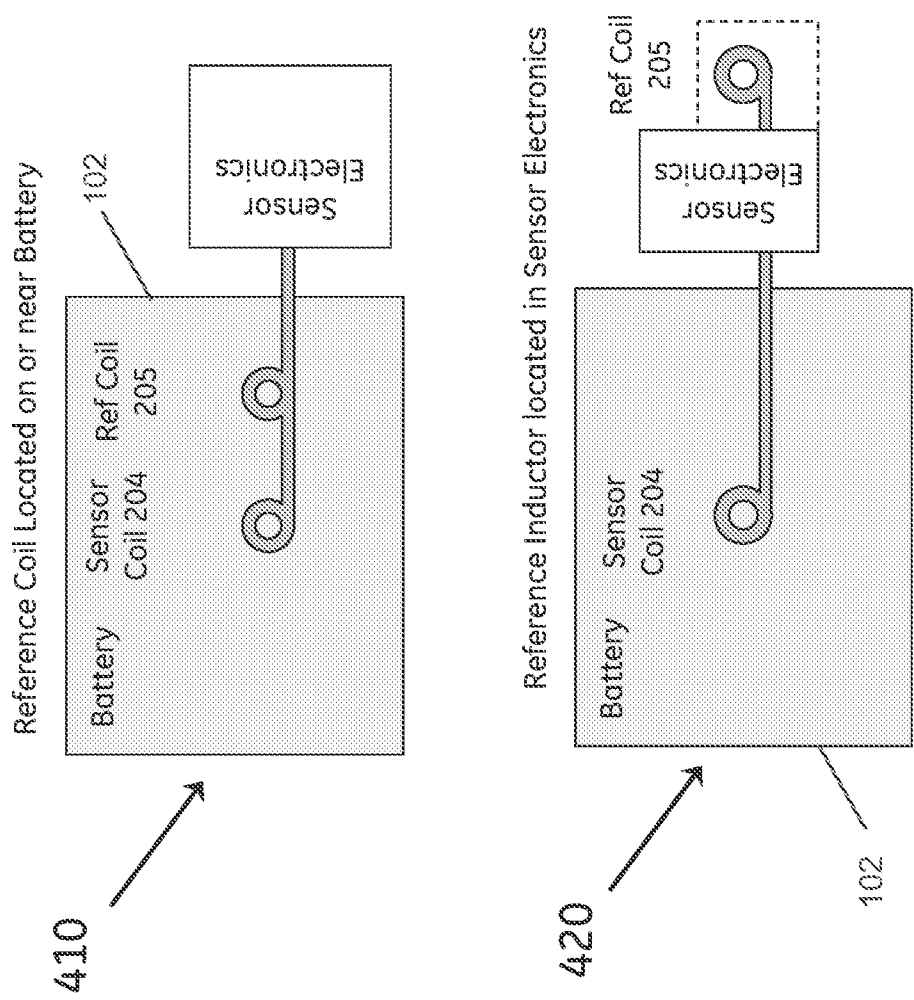
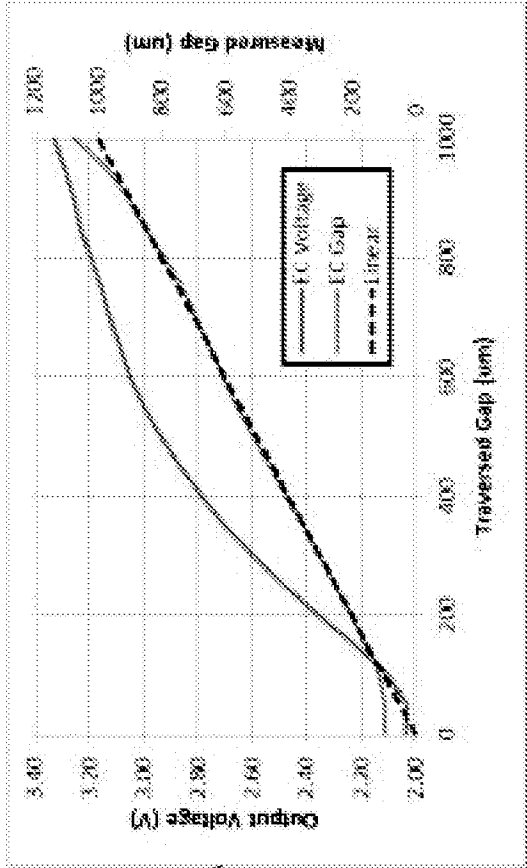
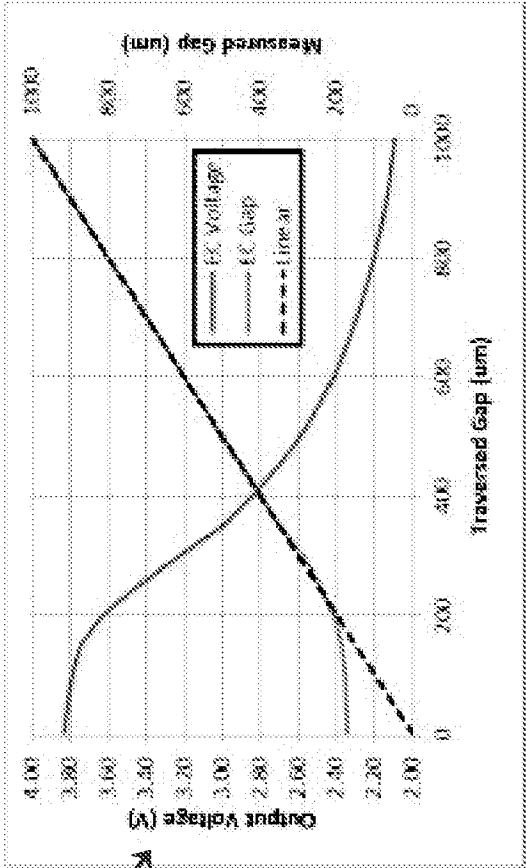


FIG. 4



411



421

FIG. 5

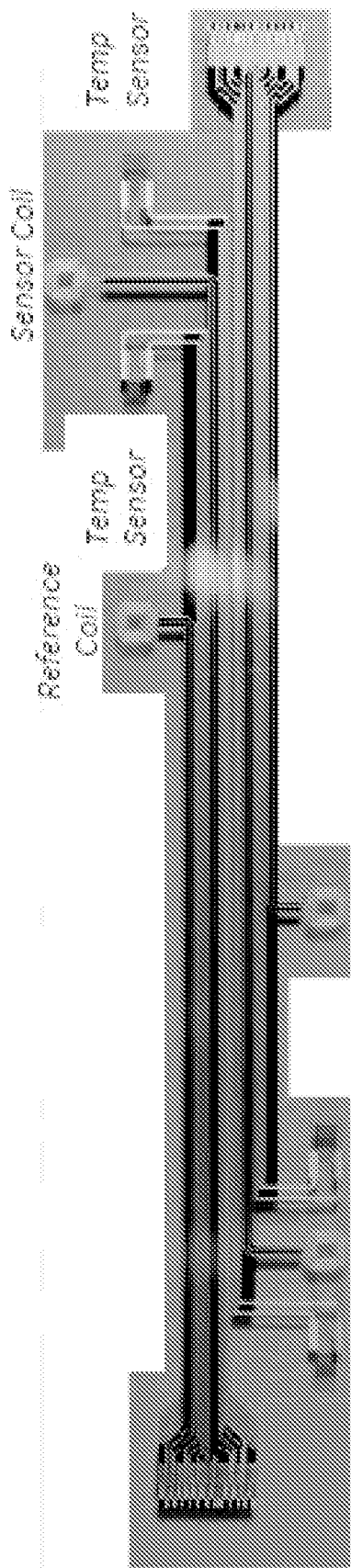


FIG. 6A

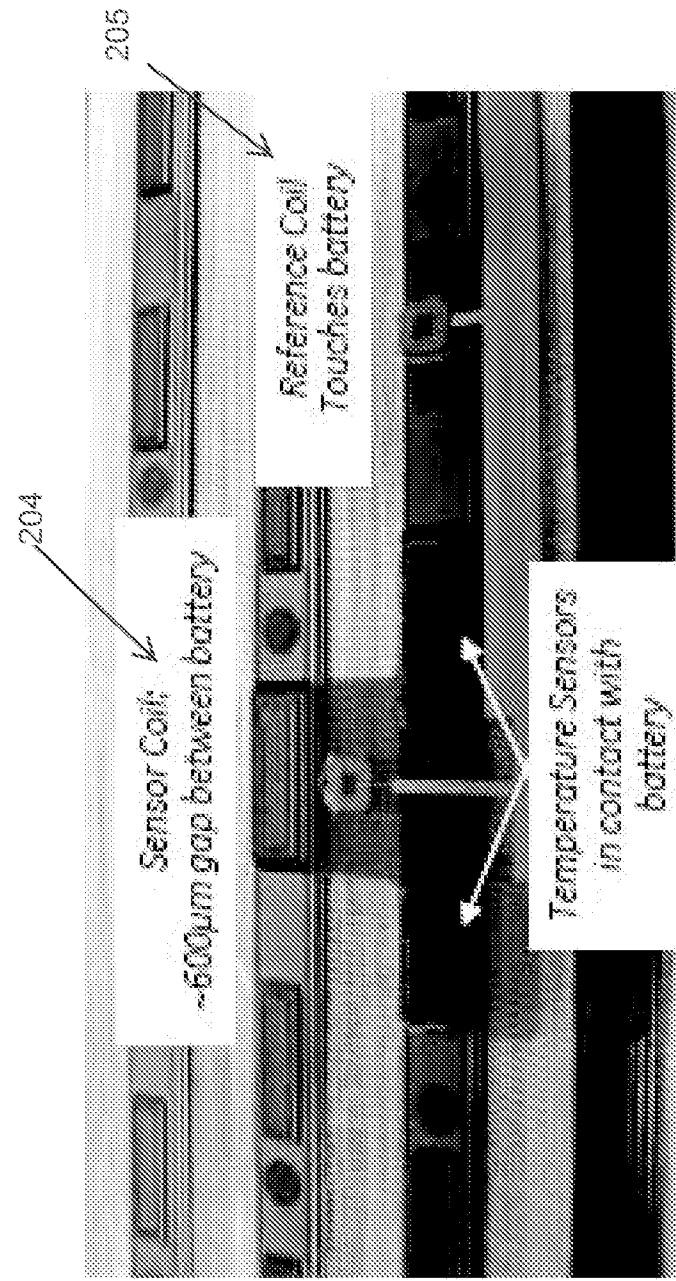


FIG. 6B

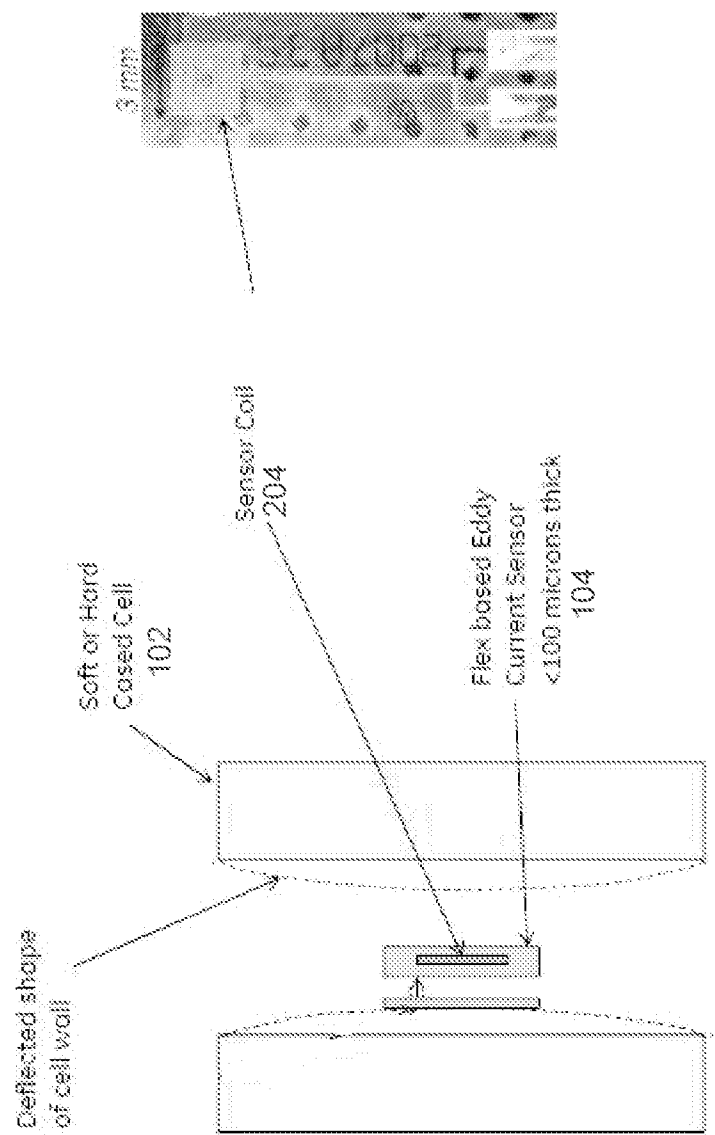


FIG. 7

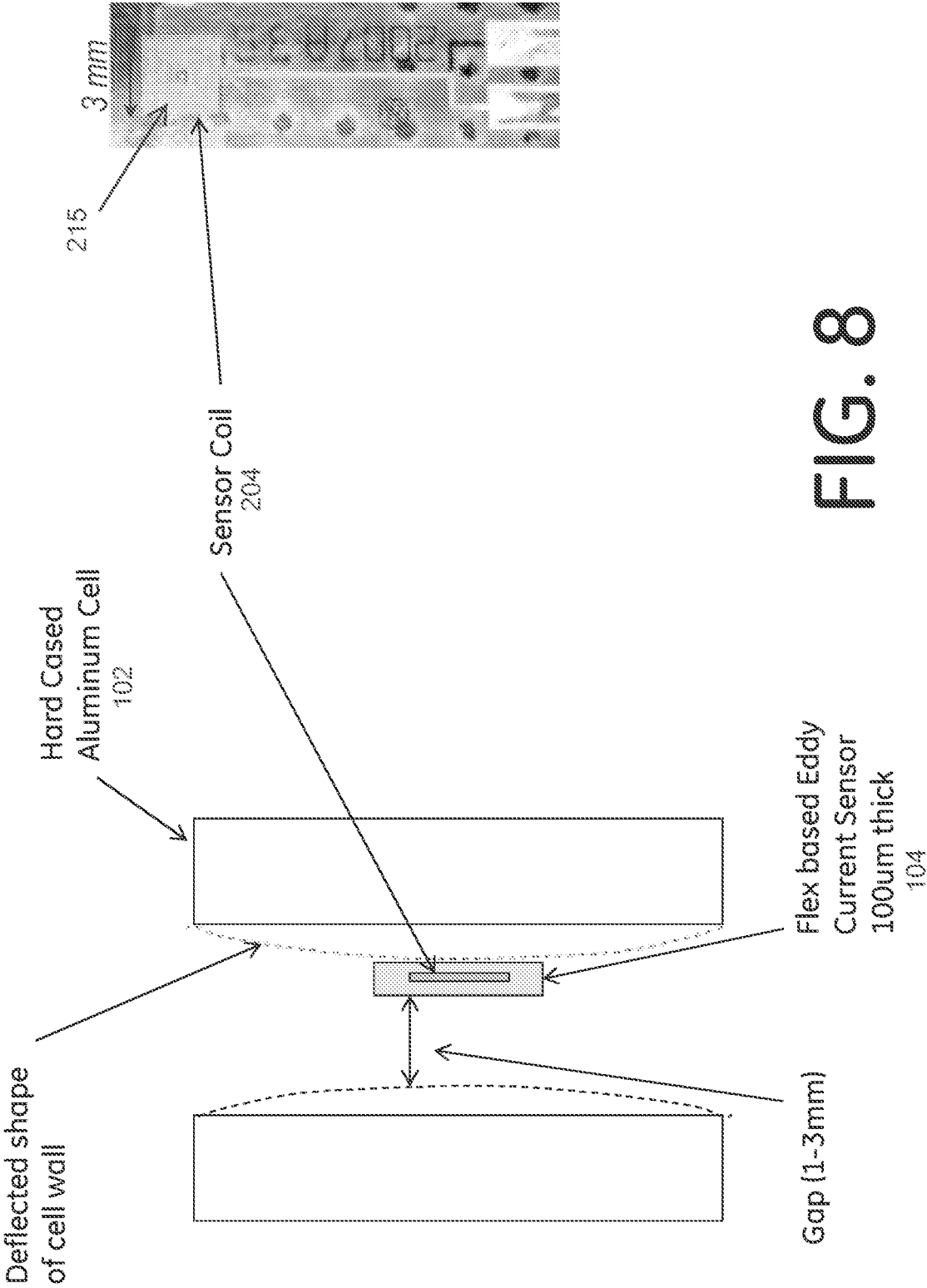


FIG. 8

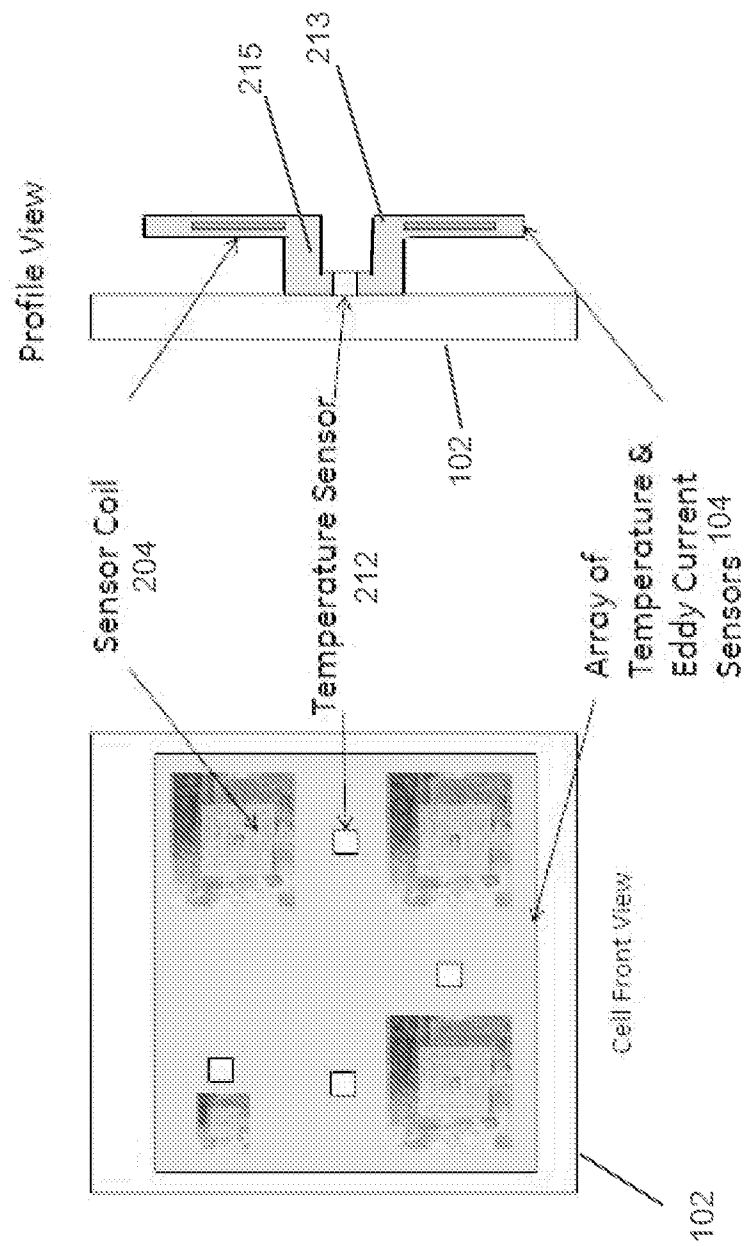


FIG. 9

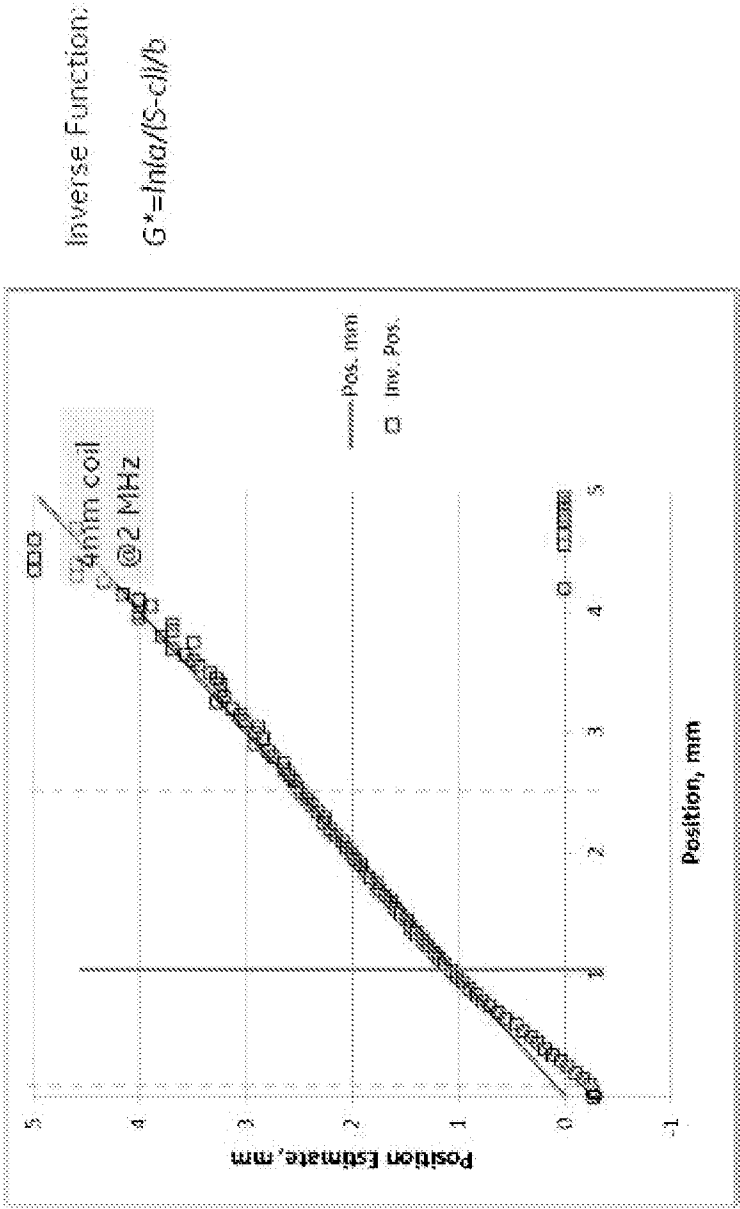


FIG. 10

Example of 0.4C Charge/Discharge Displacement Curve

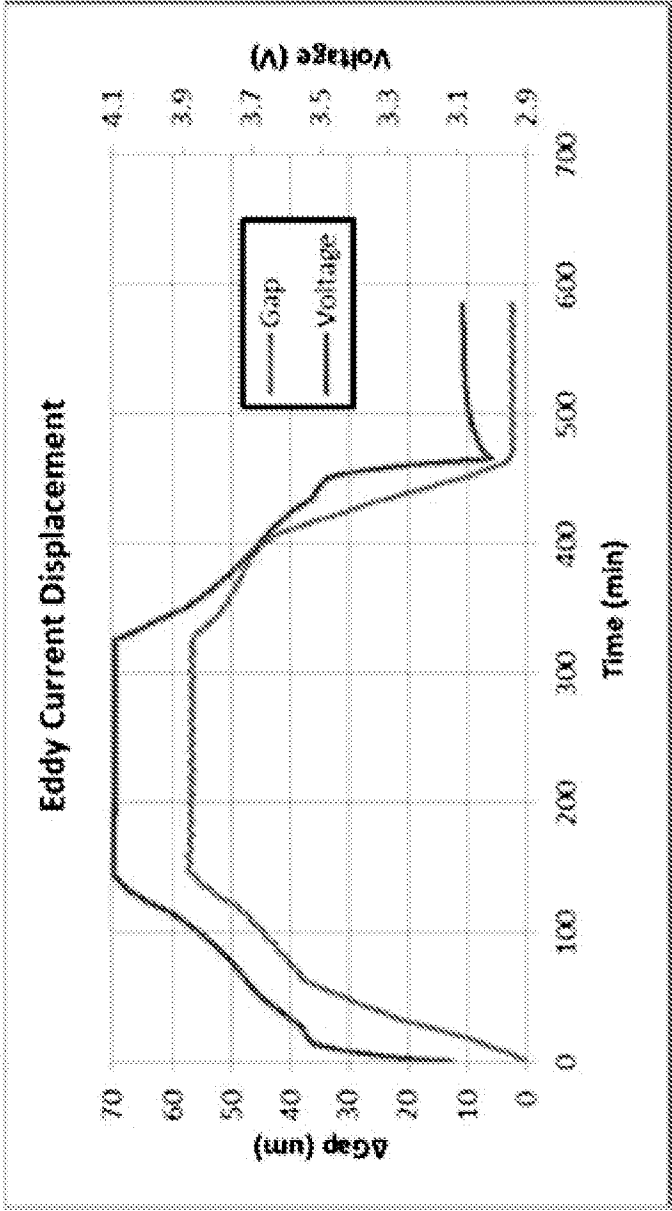


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/12707

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01B 7/06, 7/02, 7/00 (2015.01)

CPC - G01B 7/06, 7/02, 7/00

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)

IPC(8): G01B 7/06, 7/02, 7/00 (2015.01)

CPC: G01B 7/06, 7/02, 7/00

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 practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google Patent, Google Scholar, IEEE, ProQuest, Total Patent; Google Patent, Google Scholar, IEEE, ProQuest, Total Patent

Search terms used: battery, eddy, current, monitoring, sensor, detector, processor, controller, lithium-ion, algorithm

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — Y	US 2011/0039137 A1 (ENGLE, B et al.) February 17, 2011; abstract, figures 1-4, 7, 8, 9, 12, paragraphs [0032], [0034], [0038], [0039], [0043], [0061], [0062], [0066], [0077]	1-7, 19-25 — 8-18, 26, 27
Y	US 2012/0119746 A1 (MACRIS, E) May 17, 2012; abstract, figure 2, paragraphs [0032], [0034]-[0036]	8, 10, 12-18, 27
Y	US 2013/0344355 A1 (ROBERT BOSCH GMBH) December 26, 2013; paragraph [0023]	9, 11, 13-18
Y	US 2013/0154652 A1 (RICE, M et al.) June 20, 2013; figure 4, paragraphs [0050], [0051], claim 1	17
Y	US 2007/0103150 A1 (TADA, M et al.) May 10, 2007; paragraph [0086]	26

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"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

29 March 2015 (29.03.2015)

Date of mailing of the international search report

09 APR 2015

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
Facsimile No. 571-273-3201

Authorized officer

Shane Thomas

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774