(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
05 April 2018 (05.04.2018)

W!P O | PCT

(10) **International Publication Number**
WO 2018/060700 Al

(51) **International Patent Classification:**
G01B 7/00 (2006.01)

(21) **International Application Number:**
PCT/GB20 17/052891

(22) **International Filing Date:**
27 September 2017 (27.09.2017)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
20160100492 28 September 2016 (28.09.2016) GR
1618264.4 28 October 2016 (28.10.2016) GB

(71) **Applicant: OXFORD UNIVERSITY INNOVATION LIMITED** [GB/GB]; Buxton Court, 3 West Way, Oxford OX2 0JB (GB).

(72) **Inventors: KYPRIS, Orfeas;** c/o Oxford University Innovation Limited, Buxton Court, 3 West Way, Oxford OX2 0JB (GB). **MARKHAM, Andrew;** c/o Oxford University Innovation Limited, Buxton Court, 3 West Way, Oxford OX2 0JB (GB).

(74) **Agent: DEHNS;** St Bride's House, 10 Salisbury Square, London EC4Y 8JD (GB).

(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, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, 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,

(54) **Title:** MONITORING SYSTEM

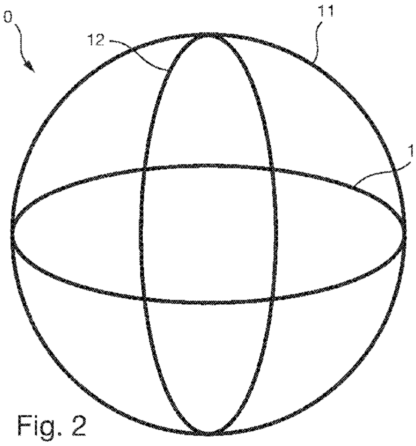
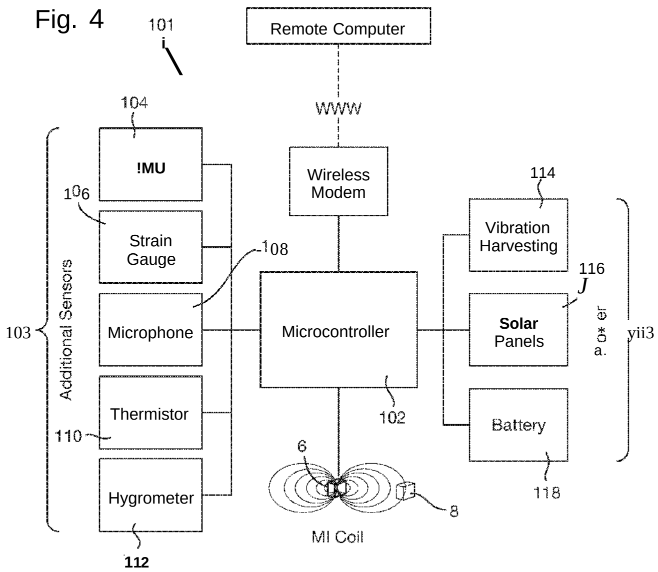


Fig. 2

Fig. 4



(57) **Abstract:** A system (101) for monitoring the structural health of a structure includes a transmitter (6) for transmitting a three-dimensional magnetic field, a receiver (8) for receiving the three-dimensional magnetic field transmitted by the transmitter to determine the relative three-dimensional positions of the transmitter (6) and the receiver (8), a sensor (103) for detecting an environmental property, and a control unit (102) arranged to receive data from the receiver (8) representative of the three- dimensional magnetic field received by the receiver (8) and to receive data from the sensor (103) representative of the environmental property detected by the sensor (103). The control unit (102) is arranged to communicate, and/or store for subsequent processing, the data received from the receiver (8) and the sensor (103).

WO 2018/060700 A1

[Continued on next page]

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))*

Monitoring System

This invention relates to a system for monitoring the structural health of a structure, in particular to a monitoring system for monitoring the displacements between points on the structure as a function of one or more environmental properties.

There are numerous structures, e.g. buildings, bridges, pavements, railway sleepers, for which it is desired to monitor their structural health, in order that stresses and failures may be identified promptly. This allows their causes to be addressed before significant damage to the structure occurs. Stresses and failures in a structure may be identified through the detection of anomalous behaviour of the structure. Typically this is done by monitoring the (e.g. relative) displacements of various points on the structure over time.

A number of techniques exist for monitoring displacements (e.g. between two points) in a structure, based, for example on radio frequency identification (RFID), ultrasonic, mechanical or optical fibre technology. However, a number of problems exist with such techniques.

RFID coils can only be attached to the surface of a structure (not embedded within) owing to the high frequencies used and are only able to measure displacements in one direction. Ultrasonic sensors require a line of sight (e.g. between a transmitter and a receiver), are only able to measure displacements in one direction and are affected by temperature and humidity changes. Mechanical systems, e.g. using linear variable differential transformer sensors, are unable to cope with large displacements (greater than a few centimetres) and their performance degrades over time, e.g. owing to stiction and non-linearities. Optical fibres also experience performance degradation over time, cannot cope with large displacements and are only able to measure displacements in one direction.

The aim of the present invention is to provide an improved system for monitoring the structural health of a structure.

When viewed from a first aspect the invention provides a system for monitoring the structural health of a structure comprising:

a transmitter for transmitting a three-dimensional magnetic field;

a receiver for receiving the three-dimensional magnetic field transmitted by the transmitter to determine the relative three-dimensional positions of the transmitter and the receiver;

a sensor for detecting an environmental property; and

a control unit arranged to receive data from the receiver representative of the three-dimensional magnetic field received by the receiver and to receive data from the sensor representative of the environmental property detected by the sensor;

wherein the control unit is arranged to communicate, and/or store for subsequent processing, the data received from the receiver and the sensor.

When viewed from a second aspect the invention provides a method of monitoring the structural health of a structure comprising:

transmitting a three-dimensional magnetic field from a transmitter;

receiving the three-dimensional magnetic field at a receiver;

detecting, using a sensor, an environmental property;

receiving data from the receiver representative of the three-dimensional magnetic field received by the receiver at a control unit, and receiving data from the sensor representative of the environmental property detected by the sensor; and

communicating from the control unit, and/or storing for subsequent processing in the control unit, the data received from the receiver and the sensor.

The present invention provides a monitoring system for monitoring the structural health of a structure. The system includes a transmitter arranged to transmit a three-dimensional magnetic field and a receiver arranged to receive the magnetic field transmitted by the transmitter. The transmission of the magnetic field between the transmitter and the receiver allows the positions of the transmitter and the receiver (relative to each other) to be determined (and thus preferably the method comprises determining the relative three-dimensional positions of the transmitter and the receiver from the three-dimensional magnetic field received by the receiver).

The system also includes a sensor for detecting an environmental property, e.g. experienced by the structure, and a control unit. The control unit receives data from the receiver (representative of the three-dimensional magnetic field as received by the receiver) and the sensor (representative of the environmental property detected by the sensor). The control unit communicates (e.g. transmits) the data received from the receiver and the sensor and/or stores the data received from the receiver and the sensor for further processing.

Thus the system of the present invention is able to use the three-dimensional magnetic field generated by the transmitter and detected by the receiver for the determination of the three-dimensional position and, e.g., orientation of the transmitter and the receiver relative to each other. Thus three-dimensional displacements over time (i.e. changes in the relative position) between the transmitter and receiver can be calculated using repeated determination of the three-dimensional position of the transmitter and receiver.

It will be appreciated that provision of three-dimensional position information of points in a structure (i.e. the locations of the transmitter and receiver) provides a large amount of information as to the type of displacements in the structure and therefore its structural health. In addition, as the transmitter and the receiver use a magnetic field to determine their relative positions, the operation is contactless (between the transmitter and receiver), it does not require a line of sight between the transmitter and receiver, the transmitter and receiver may be operated wirelessly, the magnetic field (and thus the determination of the positions of the transmitter and receiver) is unaffected by the presence of dielectric material (e.g. concrete, water or soil), and the transmitter and receiver can be embedded within a structure (e.g. concrete) during manufacture or retrofitted to an existing structure. This contrasts with previous devices for determining displacements in a structure (e.g. as discussed above) that suffer from one or more shortcomings.

Furthermore, the provision of a sensor, in addition to the transmitter and receiver, which is able to detect an environmental property, e.g. experienced by the structure being monitored, gives additional information that is able to be used along (e.g. in combination) with the position information determined from the transmitter and receiver to gain further insights as to the structural health of the structure. For example, as will be discussed further below, the data from the sensor may be used as a secondary measure of displacements in the structure and/or may be used to monitor how the position measurements determined from the transmitter and receiver depend upon the environmental property measured, e.g. to allow the displacement measurements to be correlated with the environmental property measurements, thus allowing the effect of the environmental property experienced by the structure on the displacement between the transmitter and the receiver to be understood and monitored.

The transmitter may be any suitable and desired transmitter arranged to (e.g. generate and) transmit a three-dimensional magnetic field (e.g. a magnetic field having non-zero components in three mutually perpendicular direction). Preferably the transmitter comprises a triaxial coil (e.g. comprising three mutually perpendicular coils each arranged to (e.g. generate and) transmit a three-dimensional magnetic field). Preferably the three-dimensional magnetic field comprises a time-varying (e.g. oscillating) three-dimensional magnetic field.

The transmitter may be arranged to (e.g. generate and) transmit the three-dimensional magnetic field at any suitable and desired frequency. In a preferred embodiment the frequency of the three-dimensional magnetic field is less than 200 kHz.

The transmitter may be arranged to (e.g. generate and) transmit the three-dimensional magnetic field at a single frequency. However in a preferred embodiment the transmitter is arranged to (e.g. generate and) transmit the three-dimensional magnetic field at a plurality of different frequencies. Preferably the plurality of frequencies of the three-dimensional magnetic field are between 1 kHz and 200 kHz.

The receiver may be any suitable and desired receiver arranged to receive (e.g. and detect) a three-dimensional magnetic field (e.g. a magnetic field having non-zero components in three mutually perpendicular direction). Preferably the receiver comprises a triaxial coil (e.g. comprising three mutually perpendicular coils each arranged to receive (e.g. and detect) a magnetic field).

Although in some embodiments the transmitter and/or the receiver may each simply be a single triaxial coil, in other embodiments the transmitter comprises a plurality of triaxial coils (e.g. each arranged to (e.g. generate and) transmit a three-dimensional magnetic field) and/or the receiver comprises a plurality of triaxial coils (e.g. each arranged to receive (e.g. and detect) a three-dimensional magnetic field). This helps to improve the accuracy of the relative positions and, e.g., orientations of the transmitter and the receiver that are determined.

The transmitter, receiver and sensor may be powered (if necessary) in any suitable and desired way. The receiver, transmitter and/or sensor may be connected to a power source either directly, e.g. through re-bars in a reinforced concrete structure, or wirelessly. In a preferred embodiment the transmitter is arranged to be powered wirelessly by a magnetic field, e.g. preferably the system comprises a magnetic field generator arranged to generate a magnetic field over a volume including the transmitter (e.g. over a volume of the structure containing the transmitter). Thus, e.g. when the transmitter comprises a triaxial coil, preferably the magnetic field for powering the transmitter induces a current in the transmitter which generates the three dimensional magnetic field transmitted by the transmitter.

The power source (e.g. for supplying power to the magnetic field generator or directly to the transmitter) may comprise any suitable and desired power source. In one embodiment the power source comprises vibration harvesting (e.g. from the structure), solar panels (e.g. positioned on the structure) or batteries.

It will be appreciated that the transmitter and the receiver may be interchangeable, e.g. in an embodiment when the receiver is arranged to (e.g. generate and) transmit a three-dimensional magnetic field, the transmitter is arranged to receive (e.g. and detect) the three-dimensional magnetic field transmitted by the receiver, and the control unit is arranged to receive data representative of the three-dimensional magnetic field received by the transmitter. Thus, in a preferred embodiment the system comprises a pair of transceivers (e.g. each) for transmitting and receiving a three-dimensional magnetic field to determine the relative three-dimensional positions of the pair of transceivers. Preferably each transceiver is arranged to generate and transmit a three-dimensional magnetic field. Preferably each transceiver is arranged to receive and detect the three-dimensional magnetic field (e.g. generated and) transmitted by the other transceiver of the pair of transceivers.

The transmitter and the receiver, and/or the sensor may be attached (e.g. retrofitted) to the exterior of the structure to be monitored. However preferably the transmitter and the receiver, and/or the sensor are embedded within a structure, e.g. during manufacture, erection or construction of the structure. When the structure comprises concrete, preferably the transmitter and the receiver, and/or the sensor are embedded within the concrete of the structure when the concrete is being poured.

It will be appreciated that preferably the transmitter, the receiver and the sensor are located on a structure (or a portion thereof) and thus when viewed from a further aspect the invention provides (at least a portion of) a structure comprising a system for monitoring the structural health of the structure according to any of the aspects or embodiments described herein.

In a preferred embodiment the system comprises an array of transmitters and receivers, and/or sensors, e.g. arranged throughout (e.g. on) the structure, for monitoring the structural health of the structure, e.g. as a whole. Preferably the transmitters, receivers and/or sensors are grouped into plurality of a transmitter, a receiver and a sensor. Thus preferably the transmitter, receiver and sensor in each group are located close to each other in a region of the structure, e.g. closer to each other than the nearest neighbouring group of a transmitter, receiver and sensor.

In another embodiment, when the system comprises an array of transmitters and receivers, and/or sensors, the transmitters, receivers and/or sensors may not be grouped together into sets of a transmitter, a receiver and a sensor. For example the transmitters, receivers and sensors may be arranged substantially evenly throughout the structure. Also, the system may not comprise the same number of transmitters, receivers and/or sensors, e.g. as described below.

When the system comprises a plurality of transmitters, receivers and/or sensors, but the transmitters and the receivers (and, e.g., the sensors) are grouped together, the relative displacement (and, e.g., orientation) between the transmitter and receiver in each group is determined, but the relative displacement (and, e.g., orientation) between other pairs of transmitters and receivers may not be determined. However, the system may be arranged (e.g. when the transmitters, receivers and/or sensors are arranged substantially evenly throughout the structure) such that the relative displacement (and, e.g., orientation) between any (e.g. each) pair of transmitters and receivers in the array is determined. This enables the displacement of the structure in many different directions to be determined.

In another embodiment the system comprises a plurality of transmitters and receivers (e.g. arranged in pairs) and a single sensor (or one of each type of sensor). This may be appropriate when the environmental property or properties being measured (e.g. temperature) may be able to be measured at a single location for the whole of the structure owing to it being unnecessary to measure it at multiple locations corresponding to each pair of transmitter and receiver (e.g. owing to the assumption that the environmental property or properties being measured is approximately constant throughout the structure).

Providing a plurality of pairs of transmitters and receivers, and, e.g., sensors enables a plurality of different displacements to be determined and these to be used with the environmental property to monitor the structural health of the structure over a range of space, i.e. at multiple different points on the structure. Furthermore, the plurality of different displacements and environmental property measurements may be used together, e.g. to cross check the displacements and measurements with each other, to improve the accuracy and alignment of the displacements and measurements.

When a plurality (e.g. of pairs) of transmitters and receivers are provided, preferably the transmitters are arranged to transmit their respective magnetic fields (and thus preferably the receivers are arranged to receive the magnetic fields from the respective transmitters) simultaneously. Alternatively, the transmitters may employ a multiplexing scheme (e.g. divided by time (time division multiple access (TDMA)), frequency (frequency division multiple access (FDMA)) or code (code division multiple access (CDMA))) to allow signals from respective transmitters to be separated.

The receiver and the transmitter (e.g. in each pair) may be arranged in any suitable and desired (e.g. initial) position with respect to each other in the structure. In a preferred embodiment the receiver (e.g. in each pair) is located (e.g. initially) within 10 cm of the transmitter (e.g. in each pair of a transmitter and a receiver), e.g. within 5 cm. Preferably the sensor is within 2 m of either the transmitter or the receiver (e.g. in each group of a transmitter, a receiver and a sensor), e.g. within 1 m. Preferably the transmitter and the receiver (e.g. in each pair) are arranged to be able to measure their relative three-dimensional position with an accuracy of better than 1 mm over a distance of 50 mm, e.g. better than 0.5 mm over a distance of 50 mm, e.g. approximately 0.4 mm over a distance of 50 mm.

In one embodiment the transmitter and/or receiver comprises a (e.g. metal) reflector, e.g. a reflecting plate. For the transmitter, the reflector is arranged to reflect the three-dimensional magnetic field transmitted by the transmitter towards the receiver. For the receiver, the reflector is arranged to reflect the three-dimensional magnetic field transmitted by the transmitter onto the receiver.

Providing the transmitter and/or the receiver with a reflector helps the transmitter and/or the receiver to be immune to the effect of metal in the structure that is located behind the transmitter and/or the receiver. The reflector also helps to improve the accuracy of the determination of the three-dimensional positions of the transmitter and/or the receiver owing to amplification of the transmitted and/or received three-dimensional magnetic field.

The reflector(s) may be positioned in any suitable and desired location to achieve this. Preferably the reflector(s) are arranged substantially in a plane perpendicular to a line between the transmitter and the receiver. Preferably the transmitter's reflector is arranged on the opposite side of the transmitter from the receiver. Preferably the receiver's reflector is arranged on the opposite side of the transmitter from the transmitter.

When the transmitter and/or the receiver comprises a triaxial coil, preferably the reflector is positioned from a closest edge of the respective triaxial coil by a distance that is less than twice the maximum diameter of the respective triaxial coil. When the transmitter and/or the receiver comprises a plurality of triaxial coils, each triaxial coil may be provided with its respective reflector. However in a preferred embodiment the transmitter and/or the receiver comprises a single reflector for the plurality of triaxial coils (e.g. one reflector for the plurality of triaxial coils in the transmitter and one reflector for the plurality of triaxial coils in the receiver).

When the monitoring system comprises a plurality of transmitters and receivers, e.g. grouped together into pairs of transmitters and receivers, preferably each pair of a transmitter and a receiver comprises a pair of reflectors (for the transmitter and receiver respectively).

The relative three-dimensional positions of the transmitter and the receiver may be determined in any suitable and desired way, i.e. using the three-dimensional magnetic field received by the receiver. In a preferred embodiment the three dimensional (vector) magnetic field (e.g. generated and) transmitted by the transmitter (e.g. generated by a current through the triaxial coil) induces a signal (e.g. current) in the receiver (e.g. current in the triaxial coil) which is measured, from which the three-dimensional magnetic field at the receiver may be determined and from which the relative three-dimensional positions of the transmitter and the receiver may be determined.

Preferably the three-dimensional position is determined from the current induced in the receiver (and thus preferably determined from the magnetic field (determined from the current measured) to have been received by the receiver) using a model (e.g. simulation) of the three-dimensional magnetic field transmitted by the transmitter in the structure. Thus preferably the method comprises (and preferably the system is arranged to) modelling the magnetic field (e.g. generated and) transmitted by the transmitter. The magnetic field in the structure may be modelled in any suitable and desired way, e.g. using numerical methods such as finite element analysis and/or analytical methods.

Preferably the measured current induced in the receiver (and thus preferably the magnetic field (determined from the current) to have been received by the receiver) is used with the model of the three-dimensional magnetic field to determine the relative three-dimensional positions of the transmitter and the receiver (e.g. the three-dimensional position vector between the transmitter and the receiver). Thus, in preferred embodiments, the magnetic field measured by the receiver is compared against the model of the magnetic field distribution (based on the magnetic field transmitter from, e.g. from the current supplied to, the transmitter), to extract the relative three-dimensional positions of the transmitter and the receiver.

At least in preferred embodiments, owing to the six degrees of freedom from the three-dimensional vector magnetic field transmitted by the transmitter, both the relative (three-dimensional) positions and orientations of the transmitter and the receiver may be determined.

When the three-dimensional magnetic field comprises multiple different frequencies, preferably orthogonal frequency division multiplexing (OFDM) is used, e.g. on the three-dimensional magnetic field received by the receiver, to extract information from each of the different frequency components of the magnetic field. Also, e.g. in addition to OFDM, a method of cross-correlation can be used, in which a predicted (e.g. template) signal (for the magnetic field) is compared with the received signal (for the magnetic field). The relative displacement between the transmitter and the receiver may then be determined using the template signal and the received signal, e.g. using the difference is the signal amplitude between the template signal and the received signal. This may be done in conjunction with the model of the magnetic field.

As well as using the transmitter and the receiver to determine their relative three-dimensional positions, the three-dimensional magnetic field (e.g. detected by and) received by the receiver may be used to make other measurements as is suitable and desired. In a preferred embodiment the three-dimensional magnetic field received by the receiver is used (when the structure comprises reinforced concrete) to determine when the re-bars in the reinforced concrete have at least partially corroded. Preferably this is done by comparing the three-dimensional magnetic field received by the receiver with the model of the magnetic field, e.g. to identify distortions of the magnetic field owing to corrosion of the re-bars (e.g. in addition to the normal distortion expected from uncorroded re-bars).

When modelling the magnetic field (e.g. generated and) transmitted by the transmitter and (e.g. detected by and) received by the receiver, the magnetic field may be modelled in any suitable and desired way, e.g. using a dipole model. However preferably the magnetic field is modelled using a coil model based on the shape of the (e.g. triaxial coil in the) transmitter and/or the receiver. Thus a rectangular or a circular (or the appropriate shape of the coil) coil model may be used.

This helps to better represent the magnetic field in the model, e.g. compared to a dipole model, as it takes into account the dimensions and geometry of the transmitter and/or the receiver. This is particularly important when modelling the magnetic field at small distances from the transmitter and/or the receiver, e.g. at distances from the transmitter and/or the receiver that are of the order of the size of the transmitter and/or the receiver, as it helps to allow an accurate determination of the relative positions of the transmitter and the receiver from the measurement of the magnetic field by the receiver.

The sensor for detecting an environmental property experienced by the structure may be any suitable and desired sensor arranged to detect any suitable and desired environmental property. In a preferred embodiment the sensor is arranged to make a quantitative measurement (i.e. measure the value) of an environmental property (e.g. a parameter, variable, quantity or characteristic) experienced by the structure.

Preferably the sensor is arranged to detect the environmental property substantially simultaneously with the receiver receiving the three-dimensional magnetic field from the transmitter. This simultaneous measurement helps the relative positions of the transmitter and the receiver to be correlated accurately with the environmental property measured by the sensor.

In a preferred embodiment the sensor comprises one or more of: an inertial measurement unit (for measuring the acceleration of the structure), a thermistor (for measuring the temperature of the structure), a microphone (for measuring acoustic signals in the structure), an optical fibre (e.g. containing a fibre Bragg grating, for measuring the temperature and/or strain of the structure), a camera (for measuring visual information from the structure), a hygrometer (for measuring the humidity of the structure) and a strain gauge (for measuring the strain of the structure).

In one embodiment the system comprises a plurality of sensors, e.g. two or more of: an inertial measurement unit, a thermistor, a microphone, an optical fibre (e.g. containing a fibre Bragg grating), a camera, a hygrometer and a strain gauge. This allows the displacements between the transmitter and the receiver to be characterised and monitored as a function of a plurality of environmental properties as measured by the plurality of sensors respectively.

It will be appreciated that by taking one or, preferably, more measurements from sensors of environmental properties associated with the structure enables a model of the relative three-dimensional positions of a pair or pairs of transmitters and receivers (and thus the displacements therebetween), as a function of the one or more environmental properties measured by the sensors, to be built. A model such as this then helps to allow the relative position measurements of the transmitter and the receiver, and the environmental property measured by the sensor to be compared against a prediction from the model, e.g. the model may predict that for a particular value of an environmental property, a particular value for the relative positions of the transmitter and receiver are to be expected.

Thus preferably the method comprises (and preferably the system is configured to) building a model of the displacements between a pair or pairs of transmitters and receivers, as a function of the one or more environmental properties measured by the sensors. Preferably the model is built in a setup phase of the system, e.g. the system is installed in the structure and operated to collect data (e.g. from repeated measurements) from the receiver(s) and the sensor(s) so that this data can be used (e.g. by the control unit or a processor remote from the control unit) to build the model. The model may also be built using further data, e.g. one or more of: the time of day, the time of year, the weather (e.g. temperature), the traffic level (e.g. when the structure is a bridge), etc.. Thus the recorded data (displacements, environmental properties, etc.) may be used to determine correlations between the data to make predictions about the state of the structure. The building of the model may use an artificial intelligence or machine learning algorithm.

An expected measurement (based on the model, given the measurement of the environmental property by the sensor) for the relative positions of the transmitter and receiver confirms that the structure is intact and operating as expected. An unexpected measurement (e.g. indicating that the displacement of the receiver relative to the transmitter is not wholly owing to the environmental property) may indicate that something detrimental has happened to the structure, leading to it not behaving as expected. This may then indicate that further investigation (e.g. a visual inspection) of the structure needs to be performed. Preferably the system is arranged to determine (and preferably the method comprises determining) when the measured relative three-dimensional positions of the transmitter and the receiver do not agree with the model, given the (e.g. value of the) environmental property or properties measured by the sensor(s). The agreement (or lack thereof) between the measured data and the model may be determined in any suitable and desired way, e.g. by determining when the measured relative three-dimensional positions of the transmitter and the receiver are within (or outside) a particular (e.g. predetermined) deviation from the expected positions given by the model (based on the environmental property or properties measured by the sensor(s)).

It will be appreciated that the system is suited to (and thus preferably is configured to) monitor the structure over time. Preferably, e.g. over a period of time, the transmitter is arranged to transmit periodically a three-dimensional magnetic field, the receiver is arranged to receive the three-dimensional magnetic field transmitted periodically by the transmitter to determine periodically the relative three-dimensional positions of the transmitter and the receiver, the sensor is arranged to detect periodically an environmental property experienced by the structure, the control unit is arranged to receive data (e.g. periodically) from the receiver representative of the three-dimensional magnetic field received by the receiver and to receive data (e.g. periodically) from the sensor representative of the environmental property detected by the sensor, and the control unit is arranged to communicate (e.g. periodically), and/or store (e.g. periodically) for subsequent processing, the data received from the receiver and the sensor.

Preferably the method comprises transmitting periodically a three-dimensional magnetic field from a transmitter; receiving periodically the three-dimensional magnetic field at a receiver; detecting periodically, using a sensor, an environmental property experienced by the structure; receiving (e.g. periodically) data from the receiver representative of the three-dimensional magnetic field received by the receiver at a control unit, and receiving (e.g. periodically) data from the sensor representative of the environmental property detected by the sensor; and communicating (e.g. periodically) from the control unit, and/or storing (e.g. periodically) for subsequent processing in the control unit, the data received from the receiver and the sensor.

Thus the system and the method are arranged to take repeated measurements of the relative positions of the transmitter and the receiver, and of the environmental property, over time. The repeated measurements may be used to calibrate (e.g. automatically) the system, e.g. the dependence of the relative position measurements on the environmental parameter, so, e.g., that the model may be updated over time to refine the characterisation of the relative positions of the transmitter and receiver as a function of the environmental parameter(s). As with the building of the model, this (e.g. continual) updating of the model, may use an artificial intelligence or machine learning algorithm.

The time period of the measurements (i.e. duration between successive measurements) may be of any suitable and desired duration. It will be appreciated that the time period of the measurements of the relative positions of the transmitter and the receiver may or may not be the same as the time period of the measurements of the environmental parameter by the sensor. Furthermore, when the system comprises a plurality of sensors, the different sensors may or may not be arranged to take their respective periodic measurements with the same time period. Instead, as will be described below, some measurements will be more suited to being taken at a higher frequency than other measurements.

In one embodiment the sensor comprises an inertial measurement unit (IMU) for measuring the acceleration of the sensor (and therefore, for example, the acceleration of the structure at the location of the sensor on the structure). Preferably the inertial measurement unit comprises an accelerometer (for measuring the linear acceleration of the inertial measurement unit) and a gyroscope (for measuring rotational acceleration of the inertial measurement unit). Preferably the inertial measurement unit comprises a magnetometer (for measuring the earth's magnetic field experienced by the inertial measurement unit).

An IMU measures the acceleration of the IMU and therefore the forces acting on the IMU (and therefore, for example, the forces acting on the structure at the location of the sensor on the structure). Thus it will be appreciated that an IMU is able to determine the relative displacement (e.g. compared to its previous position) of the IMU (and therefore, for example, the relative displacement of the structure at the location of the sensor on the structure) which may be obtained by calculating the second anti-derivative of the acceleration measurement from the IMU.

As an IMU is able to determine relative displacements, e.g. over short timescales, the monitoring system is (in preferred embodiments) therefore able to measure displacements of a structure over both short and long timescales. This is because preferably the position and displacement measurements determined from the transmitter and receiver are able to be measured over a long timescale (e.g. relative to the short timescales over which the IMU measurements may be made).

Preferably the IMU has a sampling rate of greater than 100 Hz, e.g. approximately 1 kHz. Thus the IMU is able to measure displacements, e.g. owing to impacts or impulses on the structure, at a fine temporal resolution. The IMU may suffer from noise and may drift over time, so it may not be as suitable for performing long term measurements (e.g. over a period of time greater than a few seconds). Preferably the position measurements determined from the transmitter and receiver, e.g. using the data received from the receiver by the control unit, are used to (e.g. periodically) calibrate (e.g. reset) the measurements determined from the IMU. Preferably the position measurements determined from the transmitter and receiver are taken at a sampling rate of between 5 Hz and 100 Hz, e.g. approximately 20 Hz.

Preferably the system (e.g. the control unit or a processor remote from the control unit) is arranged to perform frequency domain analysis of the measurements determined from the IMU. This may help to provide more detailed information on the displacements experienced by the structure.

The system may comprise any suitable and desired number of IMUs, e.g. a plurality at different positions on the structure to perform a plurality of relative displacement measurements of different parts of the structure. Preferably the system comprises an IMU for each (or each pair) of a transmitter and a receiver, e.g. the (or each) IMU is grouped together with a transmitter and a receiver, e.g. in a region of the structure. Preferably the (or each) IMU is located within a metre of the (or a respective) transmitter or the receiver.

As the transmitter and the receiver, and the IMU, are both arranged to provide data for determining position measurements, preferably the data received by the control unit from the receiver and the IMU is combined, e.g. the system (e.g. the control unit or a processor remote from the control unit) is arranged to combine the data received by the control unit from the receiver and the data received by the control unit from the IMU. This allows more detailed information, e.g. owing to correlations between the relative positions of the transmitter and the receiver, and the displacement of the IMU, to be extracted.

The data from the receiver and the data from the IMU may be combined in any suitable and desired way. Preferably the data from the receiver and the data from the IMU are combined using a Kalman filter, a particle (e.g. Monte Carlo) method or a neural network (e.g. a data driven design).

In one embodiment the sensor comprises a thermistor for measuring the temperature (e.g. of the structure) at the location of the sensor. Measuring the temperature (e.g. the ambient temperature) allows (at least some of) the displacements between the transmitter and the receiver (e.g. owing to the volume of the material therebetween) to be characterised as a function of temperature, such that these displacements can be correlated with the measured temperature and monitored accordingly.

For example, the temperature measurement(s) may be used (e.g. in a model) to determine the expected relative positions of the transmitter and the receiver, owing to the thermal load, and to compare this to the measured relative positions of the transmitter and the receiver.

In one embodiment the sensor comprises a microphone for measuring acoustic signals (e.g. from the structure) at the location of the sensor. Measuring acoustic signals (e.g. owing to vehicles travelling over the structure, or even from the formation of cracks in the structure) allows (at least some of) the displacements between the transmitter and the receiver to be characterised as a function, such that these displacements can be correlated with the measured acoustic signals and monitored accordingly. The acoustic signals may be used to characterise the conditional of the structure (e.g. the condition of the expansion joint on a bridge), by analysing the (time-domain and/or frequency content of the) signal as a function of temperature, humidity, displacement and/or acceleration.

For example, the acoustic signal measurement(s) may be used (e.g. in a model) to determine the expected relative positions of the transmitter and the receiver (and/or the expected displacement of an IMU), owing to the cause of the acoustic signal, and to compare this to the measured relative positions of the transmitter and the receiver (and/or the measured displacement of an IMU), e.g. does the displacement match the noise?

In one embodiment the sensor comprises, e.g. instead of or in addition to an IMU, a thermistor and/or a microphone, one or more of: an optical fibre (e.g. containing a fibre Bragg grating, for measuring the temperature and/or strain of the structure), a camera (for measuring visual information from the structure), a hygrometer (for measuring the humidity of the structure) and a strain gauge (for measuring the strain of the structure).

As with the IMU, the thermistor and/or the microphone (when provided), preferably the measurements from each of any other sensors that are provided are used (e.g. in a model) to determine the expected relative positions of the transmitter and the receiver (and/or the expected displacement of an IMU), owing to the environmental property measured by the respective sensor, and to compare this to the measured relative positions of the transmitter and the receiver (and/or the measured displacement of an IMU).

Also as with the IMU, preferably the data received by the control unit from each of any other sensors that are provided is combined with the data received by the control unit from the receiver (and, e.g., any of the data from any of the other sensors) is combined, e.g. by the control unit or a processor remote from the control unit.

As the system, at least in preferred embodiments, is able to use the data received by the control unit (from the receiver(s) and the sensor(s)) to compare against expected values for the relative three-dimensional positions of the transmitter(s) and the receiver(s), preferably the system (e.g. the control unit or a processor remote from the control unit) is arranged to signal (e.g. raise an alarm) when the measured relative three-dimensional positions of the transmitter and the receiver do not agree with the model, given the environmental property or properties measured by the sensor(s). This helps to indicate when the structure may not be behaving as expected and thus may require further investigation, e.g. an inspection to check for problems such as damage to the structure.

The various processing steps described above using the data received by the control unit (e.g. to determine the relative three-dimensional positions of the transmitter and the receiver, to combine the data from the receiver and the sensor, to build a model of displacements of the structure as a function of one or more environmental parameters, etc.) may be performed by any suitable and desired component in the system, e.g. depending whether the data received by the control unit (from the receiver(s) and the sensor(s)) is communicated from the control unit or stored by the control unit for subsequent processing.

The control unit could be arranged to perform one or more of these processing steps. However, in a preferred embodiment the system comprises a processor (e.g. remote from the control unit) arranged to receive data (e.g. the data from the receiver(s) and the sensor(s)) from the control unit. Thus preferably the control unit is arranged to communicate the data it receives to the processor.

When the control unit is arranged to communicate the data it receives, e.g. to a processor, preferably the system (e.g. the control unit) comprises a transmitter (e.g. a modem) arranged to communicate data (e.g. via a wired or a wireless connection) from the control unit, e.g. to the remote processor. When the control unit is arranged to store the data it receives (for subsequent processing), preferably the system (e.g. the control unit) comprises a memory, e.g. any suitable and desired storage device (such as a data logger).

The control unit may comprise any suitable and desired component for receiving the data from the receiver(s) and the sensor(s), and for communicating and/or storing the data it receives for subsequent processing. In a preferred embodiment the control unit comprises a micro-controller.

The control unit may receive the data from the receiver(s) and the sensor(s) in any suitable and desired way, e.g. via respective wired or wireless connections.

The system may be implemented in any suitable and desired structure. For example, the structure may comprise a bridge and thus the system may be used to measure the displacement across (and thus the portion of the structure may comprise) an expansion joint. Thus preferably the transmitter and the receiver are located on either side of the expansion joint.

In another example, the structure may comprise a pre-fabricated concrete structure and thus the system may be used to measure the displacement between different (e.g. adjacent) structural blocks. Thus preferably the transmitter and the receiver are located on different (e.g. adjacent) structural blocks.

In another example, the structure may comprise a pavement or a railway track and thus the system may be used to measure the displacement of a crack in the pavement or in a railway sleeper. Thus preferably the transmitter and the receiver are located on the same paving stone and railway sleeper (e.g. either side of a crack to be monitored) or on different (e.g. adjacent) paving stones or on different (e.g. adjacent) components of a railway track.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 shows a reinforced concrete structure having an array of transmitters and receivers embedded therein in accordance with an embodiment of the present invention;

Figure 2 is a schematic diagram of a triaxial coil in accordance with an embodiment of the present invention;

Figure 3 is schematic diagram of a pair of a transmitter and a receiver in accordance with an embodiment of the present invention;

Figure 4 is schematic diagram of a monitoring system in accordance with an embodiment of the present invention; and

Figure 5 shows an expansion joint having a transmitter and a receiver arranged either side thereof in accordance with an embodiment of the present invention.

There are numerous structures, e.g. buildings, bridges, pavements, railway sleepers, for which it is desired to monitor their structural health, in order that stresses and failures may be identified promptly. This allows their causes to be addressed before significant damage to the structure occurs. Stresses and failures in a structure may be identified through the detection of anomalous behaviour of the structure.

A preferred embodiment of a system for monitoring the structural health of a structure will now be described. Figure 1 shows a reinforced concrete structure 1 that includes a monitoring system in accordance with an embodiment of the present invention. The reinforced concrete structure 1 includes a mass of concrete 2 within which a grid of reinforcement bars ("re-bars") 4 are arranged. The structure 1 also contains an array of transmitters 6 and receivers 8 that are embedded in the concrete 2 for use as part of the monitoring system.

Each transmitter 6 and receiver 8 is formed from a triaxial (magnetic inductance (MI)) coil having three mutually perpendicular coils.

Figure 2 shows a schematic diagram of a triaxial coil 10 in accordance with an embodiment of the present invention. The triaxial coil 10 has three mutually perpendicular circular coils 11, 12, 13 that are each wound around a support structure.

Also arranged in the structure 1 are a number of other sensors that are arranged to detect various respective environmental properties that are experienced by the structure 1. These sensors, along with other components of the monitoring system are described below with reference to Figure 4.

Figure 3 is schematic diagram of a pair of a transmitter 51 and a receiver 52 in accordance with an embodiment of the present invention. In this embodiment the transmitter 51 includes multiple triaxial coils 54 and the receiver 52 also includes multiple triaxial coils 56. The transmitter 51 and the receiver 52 also include a respective reflecting plate 53, 54 arranged to reflect the three-dimensional magnetic field generated and transmitted by the transmitter triaxial coils 54 onto the receiver triaxial coils 56.

Figure 4 shows a schematic diagram of a monitoring system 101 for a structure (e.g. the reinforced concrete structure 1 shown in Figure 1) in accordance with an embodiment of the present invention. The system 101 includes a pair of triaxial MI coils that act as a transmitter 6 and a receiver 8. The receiver 8 is connected (e.g. wirelessly) to a micro-controller 102, with the micro-controller 102 arranged to receive data from the receiver 8 representative of the three-dimensional magnetic field detected and received by the receiver 8 from the transmitter 6.

Along with the pair of MI coils 6, 8, the monitoring system 101 includes a number of other sensors 103: an inertial measurement unit (IMU) 104, a strain gauge 106, a microphone 108, a thermistor 110 and a hygrometer 112. These sensors 103 are arranged to measure respective environmental properties experienced by the structure: the IMU 104 is arranged to measure the acceleration of (e.g. impulses on) the structure, the strain gauge 106 is arranged to measure the strain of the structure, the microphone 108 is arranged to measure acoustic signals in the structure, the thermistor 110 is arranged to measure the temperature of the structure and the hygrometer 112 is arranged to measure the humidity of the structure.

Each of these sensors 103 is arranged in proximity to the pair of MI coils 6, 8 and is connected (e.g. wirelessly) to the micro-controller 110 and the hygrometer 112 representative of the respective environmental parameter being measured. 102. As with the receiver 8, the micro-controller 102 is arranged to receive data from each of the IMU 104, the strain gauge 106, the microphone 108, the thermistor 110 and the hygrometer 112.

The system 101 also includes a power generation sub-system 113 that comprises a vibration harvesting device 114, solar panels 116 and a battery 118. Each of the vibration harvesting device 114, the solar panels 116 and the battery 118 is connected, via the micro-controller 102, to the rest of the system 101 to deliver power to the various components, e.g. the sensors 103 and the pair of MI coils 6, 8.

Finally, the system 101 includes a wireless modem 120, connected (e.g. wirelessly) to the micro-controller 102, for receiving data from the micro-controller 102 (e.g. from the sensors 103 and the pair of MI coils 6, 8). The wireless modem 120 is also connected to, and arranged to send data to, an computer 122 that is remote from the structure.

Operation of the system 101 will now be described with reference to Figures 1, 2 and 3.

During construction of the structure, e.g. a reinforced concrete structure 1 as shown in Figure 1, pairs of MI coils 6, 8 (each arranged as a triaxial coil 10 as shown in Figure 2, to act as pairs of receivers and transmitters), along with an inertial measurement unit (IMU) 104, a strain gauge 106, a microphone 108, a thermistor 110 and a hygrometer 112 are embedded in the concrete 2, along with the re-bars 4. The reinforced concrete 2 is then used to construct the structure 1, e.g. a building or bridge, and the monitoring system 101 (as shown in Figure 4) is assembled on the structure 1. Thus a micro-controller 102, a wireless modem 120, a vibration harvesting device 114, solar panels 116 and a battery 118 are arranged on the structure 1, and the necessary connections are arranged between each of the MI coils 6, 8, the various sensors 103, the power generation sub-system 113, the wireless modem 120 and the micro-controller 120, as well a connection between the wireless modem 120 and a computer 122 remote from the structure 1.

Once the structure 1 has been constructed, and the monitoring system 101 assembled, the monitoring system 101 is operated in a setup phase. In this setup phase, the power generation sub-system 113 is used to supply a time-varying current to the transmitter coils 6. This current causes the transmitter coils 6 to each generate and transmit a three-dimensional time-varying magnetic field at multiple different frequencies through the structure 1. This magnetic field induces a current in the respective receiver coils 8 in each of the pairs of MI coils 6, 8. These currents are read out by the micro-controller 102 and then communicated from the micro-controller 102 to the remote computer 122 via the wireless modem 120. This process is repeated to obtain multiple measurements from the pair of MI coils 6, 8 over a period of time.

Over the same period of time, the IMU 104 measures accelerations of the structure (e.g. owing to impacts on the structure), the strain gauge 106 measures the strain in the structure, the microphone 108 measures acoustic signals in the structure, the thermistor 110 measures the temperature of the structure and the hygrometer 112 measures the humidity of the structure 1. These measurements, which are also taken repeatedly over the period of time, are read out by the micro-controller 102 and then communicated from the micro-controller 102 to the remote computer 122 via the wireless modem 120.

The computer 122 is then used to determine, from the measurements from the pairs of MI coils 6, 8, the relative positions of the transmitters 6 and the receivers 8, and thus their displacements over the period of time during the setup phase. This is done by using orthogonal frequency division multiplexing to extract information relating to each of the different frequency components of the magnetic field and comparing the measured components against those from a model of the magnetic field in the structure to determine the relative positions of the transmitters 6 and the receivers 8.

The data from the IMU 104 is also used by the computer 122 to determine the displacements of the IMU 104. The displacements of the pairs of MI coils 6, 8 are then combined with the displacements of the IMU 104 by the computer, using a

Kalman filter. This gives refined information about the relative positions of the transmitters 6 and the receivers 8.

The computer 122 then uses these combined displacements with the measurements from the strain gauge 106, the microphone 108, the thermistor 110 and the hygrometer 112 to build a model that characterises the displacements of the MI coils 6, 8 and the IMU 104 in the structure as a function of the measured strain, the measured acoustic signals, the measured temperature and the measured humidity, along with the time of day and the traffic levels (when the structure 1 is, e.g., a bridge).

Once the model has been built, the monitoring system 101 can then be used to monitor the structural health of the structure 1. Similar to in the setup phase, a time-varying current is supplied from the power generation sub-system 113 to the transmitter coils 6 in order to generate and transmit a three-dimensional time-varying magnetic field from each of the transmitter coils 6. As before, this magnetic field induces a current in the respective receiver coils 8 in each of the pairs of MI coils 6, 8 and these currents are read out by the micro-controller 102, then communicated from the micro-controller 102 to the remote computer 122 via the wireless modem 120. This process is repeated to obtain multiple measurements from the pair of MI coils 6, 8 over a period of time that the structure 1 is to be monitored.

Over the same period of time, measurements are obtained from the IMU 104, the strain gauge 106, the microphone 108, the thermistor 110 and the hygrometer 112. These measurements, which are also taken repeatedly over the period of time, are read out by the micro-controller 102 and then communicated from the micro-controller 102 to the remote computer 122 via the wireless modem 120.

The computer 122 again determines the displacements from the pairs of MI coils 6, 8 and the IMU 104 and then combines these determined displacements using the Kalman filter to refine these displacements. Using the model that was built during the setup phase of the system 101, the measurements from the IMU 104, the strain gauge 106, the microphone 108, the thermistor 110 and the hygrometer 112 are input to obtain a prediction for the expected displacements for the pairs of MI coils

6, 8 (i.e. given the measurements from the respective sensors 103). The computer 122 then compares the predicted displacements against those determined from the combination of the displacements from the pairs of MI coils 6, 8 and the IMU 104.

If the measured displacements agree with the expected displacements as predicted by the model (within an error tolerance) this indicates that the structure 1 is behaving as expected. If the measured displacements disagree with the expected displacements predicted by the model, this indicates that the structure 1 is not behaving as expected, and thus may have developed a fault. In this latter situation, the computer 122 raises an alarm which signals that the structure 1 needs to be investigated further, e.g. through a visual inspection.

In this way, the structural health of the structure 1 may be monitored using the monitoring system 101.

Figure 5 shows an example of a structure in which the system of an embodiment of the present invention may be used. Figure 5 shows an expansion joint 201 (e.g. in a bridge) having a transmitter 206 and a receiver 208 arranged either side of the joint 201 in accordance with an embodiment of the present invention.

The transmitter 206 and the receiver 208 are attached to the concrete 202 on either side of the joint 201. The structure (including the expansion joint 201) as a whole will also include sensors for measuring environmental properties experienced by the structure, e.g. as shown in Figure 4.

Operation of the system shown in Figure 5 is the same as for the system described above with reference to Figure 4, and thus it can be used to monitor the displacements of the expansion joint 201 over time to check that it is behaving as expected.

It will be seen that at least in preferred embodiments, the invention provides a system that is able to monitor the structural health of a structure. The provision of three-dimensional position information of points in a structure provides a large amount of useful information as to the type of displacements in the structure and therefore its structural health. In addition, as the transmitter and the receiver use a magnetic field to determine their relative positions, the operation is contactless, it does not require a line of sight between the transmitter and receiver, the transmitter and receiver may be operated wirelessly, the magnetic field is unaffected by the presence of dielectric material, and the transmitter and receiver can be embedded within a structure during manufacture or retrofitted to an existing structure.

Furthermore, the provision of a sensor, in addition to the transmitter and receiver, which is able to detect an environmental property, gives additional information that is able to be used along with the position information determined from the transmitter and receiver to gain further insights as to the structural health of the structure.

Claims

1. A system for monitoring the structural health of a structure comprising:

a transmitter for transmitting a three-dimensional magnetic field;

a receiver for receiving the three-dimensional magnetic field transmitted by the transmitter to determine the relative three-dimensional positions of the transmitter and the receiver;

a sensor for detecting an environmental property; and

a control unit arranged to receive data from the receiver representative of the three-dimensional magnetic field received by the receiver and to receive data from the sensor representative of the environmental property detected by the sensor;

wherein the control unit is arranged to communicate, and/or store for subsequent processing, the data received from the receiver and the sensor.

2. A system as claimed in claim 1, wherein the transmitter and the receiver each comprises a triaxial coil.

3. A system as claimed in claim 1 or 2, wherein the transmitter and/or the receiver comprises a reflector arranged to reflect the three-dimensional magnetic field towards the receiver.

4. A system as claimed in claim 1, 2 or 3, wherein the transmitter is arranged to transmit a time-varying three-dimensional magnetic field and the receiver is arranged to receive the time-varying three-dimensional magnetic field.

5. A system as claimed in any one of the preceding claims, wherein the frequency of the three-dimensional magnetic field is less than 200 kHz.

6. A system as claimed in any one of the preceding claims, wherein the transmitter is arranged to transmit the three-dimensional magnetic field at a plurality of different frequencies and the receiver is arranged to receive the three-dimensional magnetic field at a plurality of different frequencies.

7. A system as claimed in any one of the preceding claims, wherein the system comprises a magnetic field generator arranged to generate a magnetic field for powering the transmitter over a volume including the transmitter.

8. A system as claimed in claim 7, wherein the system comprises a power source for supplying power to the magnetic field generator, wherein the power source comprises a vibration harvesting device, a solar panel or a battery.

9. A system as claimed in any one of the preceding claims, wherein the transmitter and the receiver each comprises a transceiver for transmitting and receiving a three-dimensional magnetic field to determine the relative three-dimensional positions of the pair of transceivers.

10. A system as claimed in any of the preceding claims, wherein the transmitter and the receiver, and/or the sensor are arranged to be embedded within a structure.

11. A system as claimed in any one of the preceding claims, wherein the system comprises an array of transmitters and receivers, and/or sensors for monitoring the structural health of the structure.

12. A system as claimed in claim 11, wherein the transmitters, receivers and/or sensors are grouped into plurality of a transmitter, a receiver and a sensor.

13. A system as claimed in any one of the preceding claims, wherein the relative three-dimensional positions of the transmitter and the receiver are determined from the current induced in the receiver using a model of the three-dimensional magnetic field transmitted by the transmitter in the structure.

14. A system as claimed in any one of the preceding claims, wherein the sensor comprises one or more of: an inertial measurement unit, a thermistor, a microphone, an optical fibre, a camera, a hygrometer and a strain gauge.

15. A system as claimed in claim 14, wherein the system is arranged to combine the data received by the control unit from the receiver and the data received by the control unit from the inertial measurement unit.

16. A system as claimed in any one of the preceding claims, wherein the system is arranged to determine when the relative three-dimensional positions of the transmitter and the receiver do not agree with a model of the relative three-dimensional positions of the transmitter and the receiver as a function of the one or more environmental properties measured by the sensors, given the environmental property measured by the sensor.

17. A system as claimed in claim 16, wherein the system is arranged to signal when the measured relative three-dimensional positions of the transmitter and the receiver do not agree with the model, given the environmental property measured by the sensor.

18. A system as claimed in any one of the preceding claims, wherein the transmitter is arranged to transmit periodically a three-dimensional magnetic field, the receiver is arranged to receive the three-dimensional magnetic field transmitted periodically by the transmitter to determine periodically the relative three-dimensional positions of the transmitter and the receiver, the sensor is arranged to detect periodically an environmental property experienced by the structure, the control unit is arranged to receive data periodically from the receiver representative of the three-dimensional magnetic field received by the receiver and to receive data periodically from the sensor representative of the environmental property detected by the sensor, and the control unit is arranged to communicate periodically, and/or store periodically for subsequent processing, the data received from the receiver and the sensor.

19. A system as claimed in any one of the preceding claims, wherein the system comprises a processor arranged to receive data from the control unit.

20. A structure comprising a system for monitoring the structural health of the structure as claimed in any one of the preceding claims.

21. A method of monitoring the structural health of a structure comprising:

transmitting a three-dimensional magnetic field from a transmitter;

receiving the three-dimensional magnetic field at a receiver;

detecting, using a sensor, an environmental property;

receiving data from the receiver representative of the three-dimensional magnetic field received by the receiver at a control unit, and receiving data from the sensor representative of the environmental property detected by the sensor; and

communicating from the control unit, and/or storing for subsequent processing in the control unit, the data received from the receiver and the sensor.

22. A method as claimed in claim 21, further comprising determining the relative three-dimensional positions of the transmitter and the receiver from the three-dimensional magnetic field received by the receiver.

23. A method as claimed in claim 21 or 22, further comprising modelling the magnetic field transmitted by the transmitter

24. A method as claimed in claim 21, 22 or 23, further comprising building a model of the three-dimensional positions of the transmitter and the receiver as a function of the environmental property measured by the sensor.

25. A method as claimed in any one of claims 21 to 24, further comprising transmitting periodically a three-dimensional magnetic field from a transmitter; receiving periodically the three-dimensional magnetic field at a receiver; detecting periodically, using a sensor, an environmental property experienced by the structure; receiving periodically data from the receiver representative of the three-dimensional magnetic field received by the receiver at a control unit, and receiving periodically data from the sensor representative of the environmental property detected by the sensor; and communicating periodically from the control unit, and/or storing periodically for subsequent processing in the control unit, the data received from the receiver and the sensor.

Fig. 1

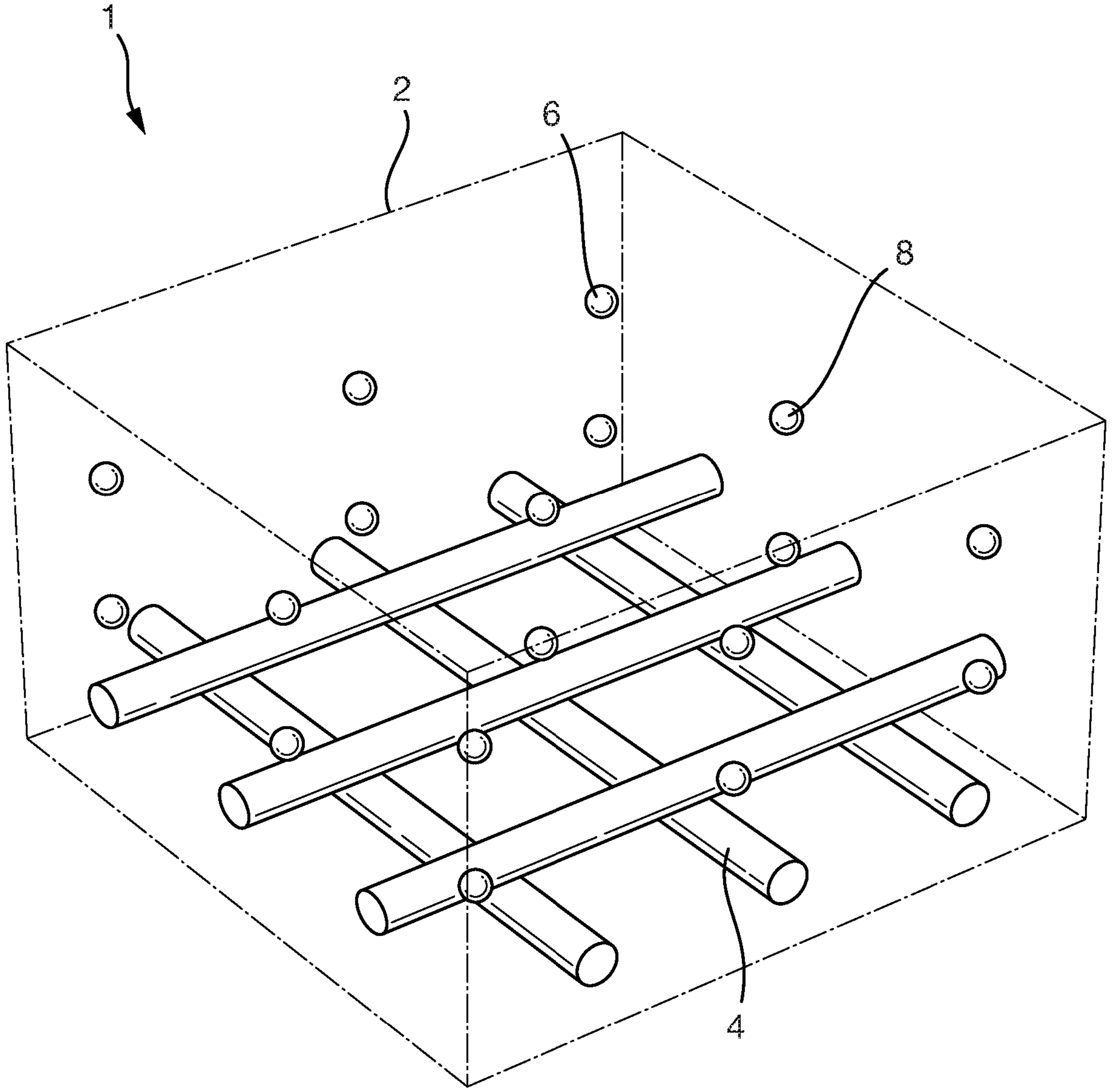


Fig. 2

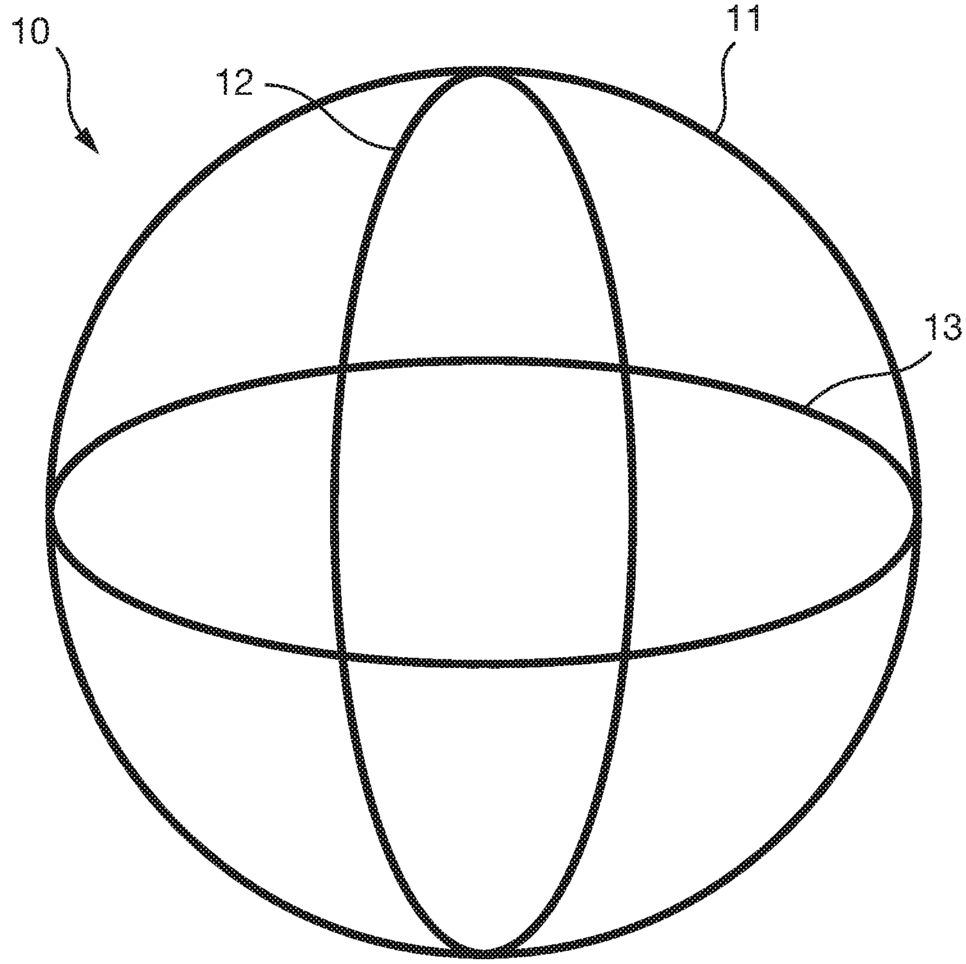
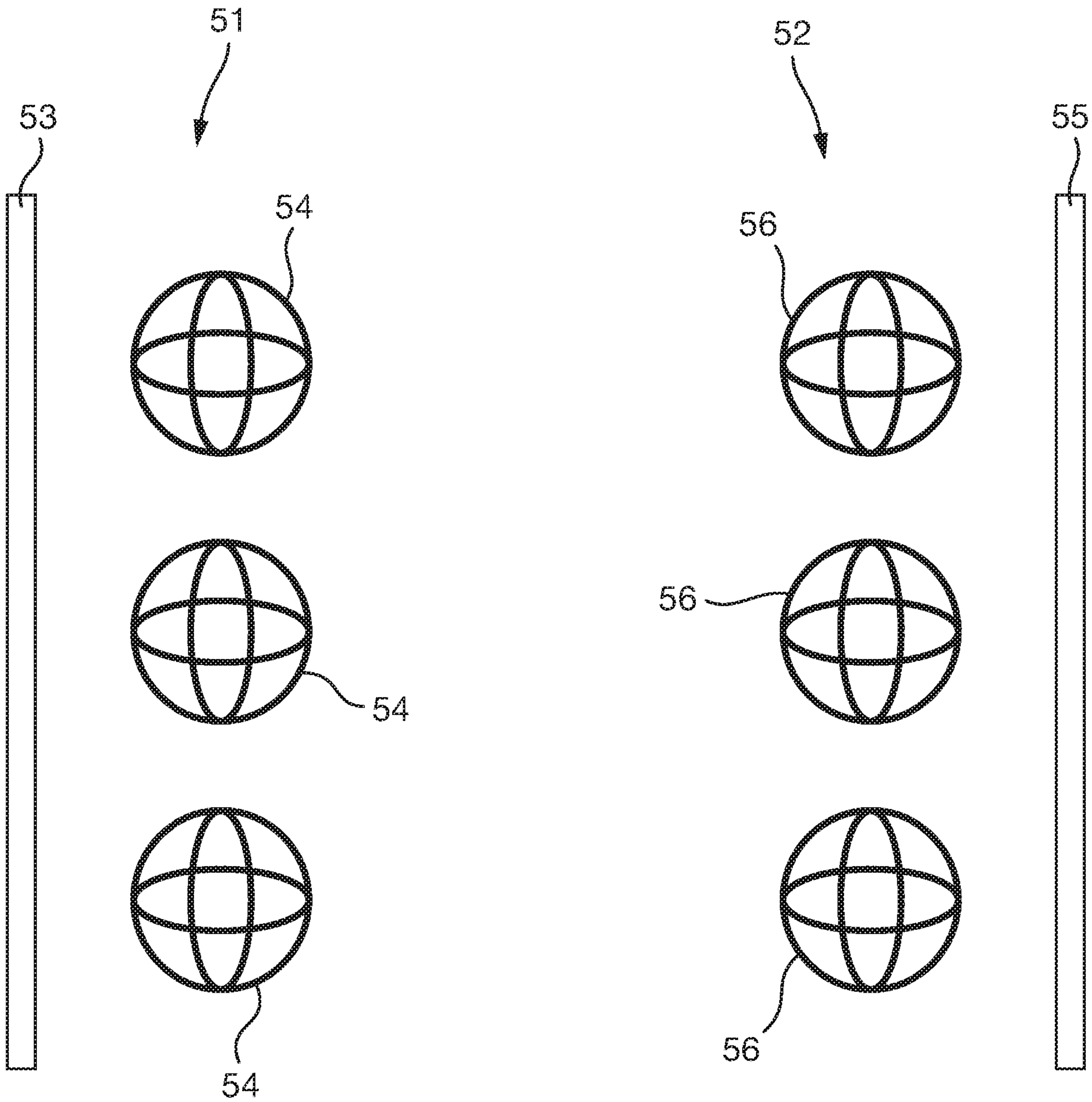


Fig. 3



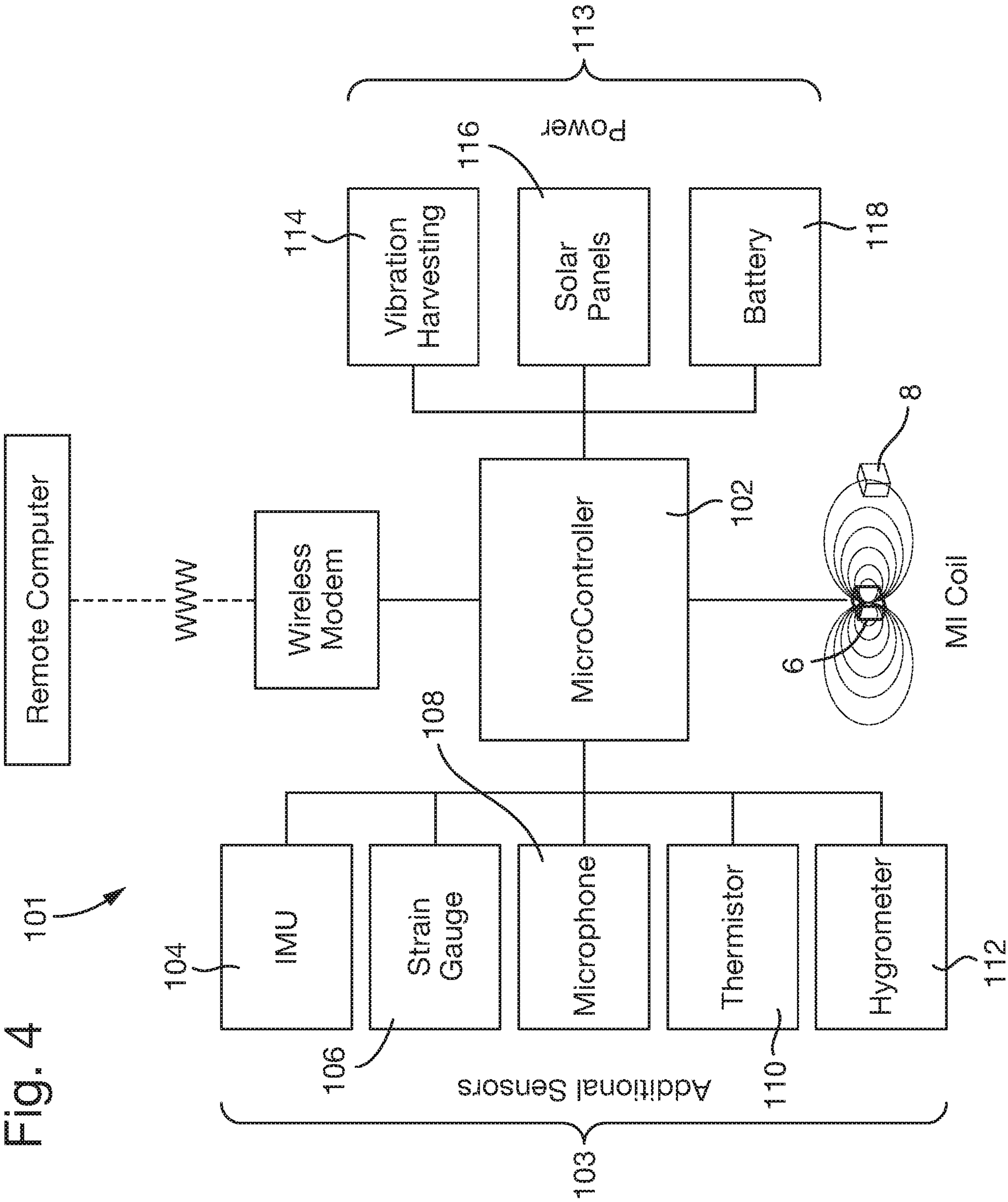
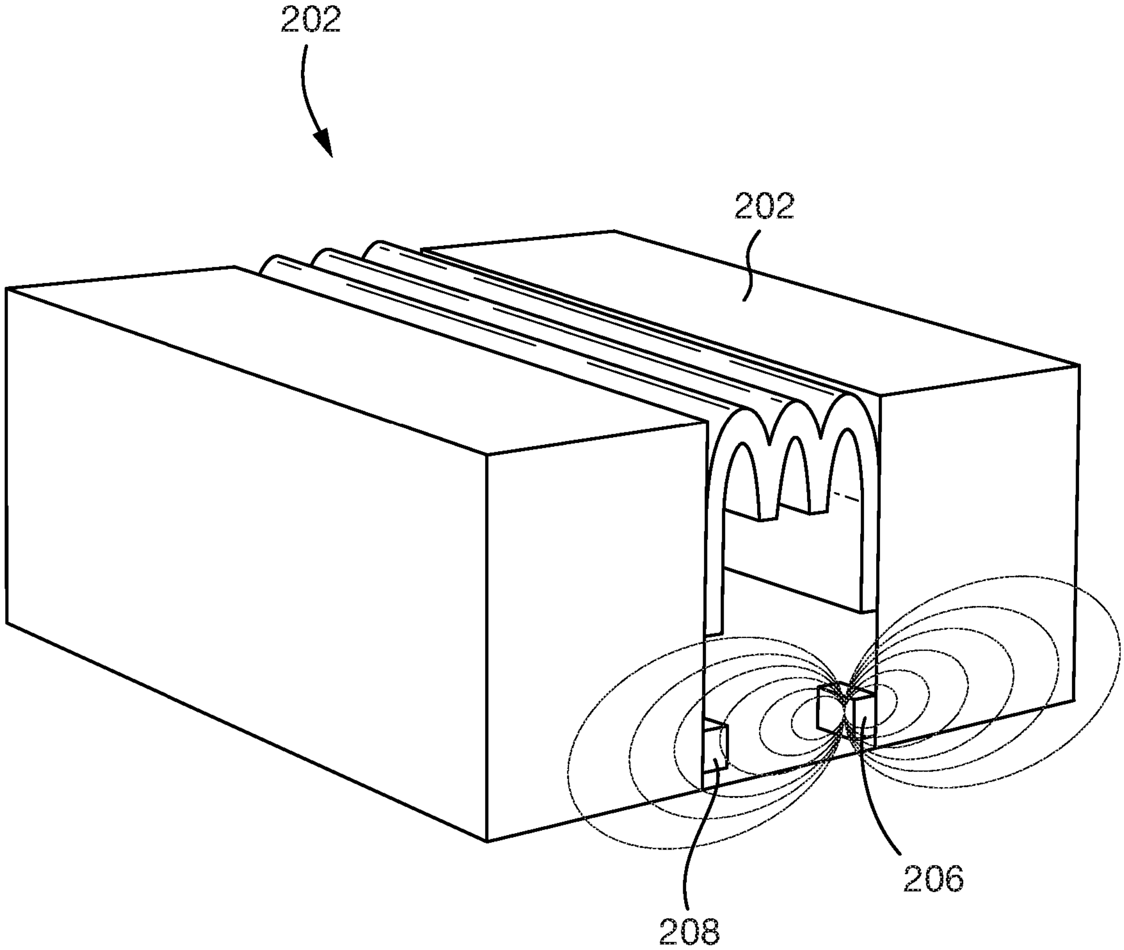

Remote Computer
WWW
Wireless Modem
MicroController
102
Vibration Harvesting
114
Solar Panels
116
Battery
118
Power
113
MI Coil
6
8
IMU
104
Strain Gauge
106
Microphone
108
Thermistor
110
Hygrometer
112
Additional Sensors
103
101

Fig. 4

Fig. 5



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/052891

A. CLASSIFICATION OF SUBJECT MATTER
INV. GO1B7/Q0
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

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)

EPO-Internal , WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 789 043 Bl (NELSON CARL V [US] ET AL) 7 September 2004 (2004-09-07) column 2, line 60 - column 10, line 14; figures 1-4 -----	1-25
A	US 2010/271012 Al (PATTERSON WILLIAM R [US] ET AL) 28 October 2010 (2010-10-28) figures 1-17 -----	1-25
A	WO 2016/047603 Al (NEJI LAW INC [JP]) 31 March 2016 (2016-03-31) the whole document -----	1-25

☐ 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) orwhich 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	Date of mailing of the international search report
29 November 2017	15/12/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Mai coci , Andrei

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2017/052891

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6789043 BI	07-09-2004	NONE	
US 2010271012 AI	28--10--2010	US 2010271012 AI	28--10--2010
		US 2014043017 AI	13--02--2014
Wo 2016047603 AI	31--03--2016	JP 6042854 B2	14--12--2016
		JP 2016065754 A	28--04--2016
		Wo 2016047603 AI	31--03--2016