

MAGNETIC INDUCTION TOMOGRAPHY-BASED FOD, LOD, AND ALIGNMENT**Introduction**

The present invention relates to an object detection system, particularly but not
5 exclusively for a wireless electric vehicle charging system, wherein the object
detection system uses magnetic induction tomography. In particular, the invention
relates to a foreign object detection ("FOD"), living object detection ("LOD") and/or
alignment detection system for wireless electric vehicle charging systems. The present
invention also relates, in certain embodiments, to methods of using an object detection
10 system of a wireless electric vehicle charging system and to use of a wireless electric
vehicle charging system comprising an object detection system in such methods. The
invention also relates to a ferrite assembly and a ferrimagnetic receptacle for a
wireless electric vehicle charging system, and to an electric vehicle comprising such
an object detection system.

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Background

FOD, LOD, and alignment systems for wireless electric vehicle charging systems are
known in the art. In fact, industry standards IEC 61980, IEC 61980-3, ISO 19363, and
SAE J2954 require wireless electric vehicle charging systems to include such systems.
20 It will be appreciated that at least the SAE standards also refer to living object detection
("LOD") as living object protection ("LOP"). However, the term "living object detection"
is used to refer to both LOD and LOP.

In a typical wireless electric vehicle charging system, an electric vehicle comprising a
25 vehicle assembly parks above (or in close proximity to) a ground assembly of a
wireless electric vehicle charging system. Power supplied in the form of alternating
current to a wireless power transfer ("WPT") coil of the ground assembly then induces
a magnetic field around the WPT coil, with that magnetic field then inducing an
alternating current in a corresponding WPT coil of the vehicle assembly. That current
30 is then used to charge the electric vehicle's battery.

In such systems, there is usually an air gap across which power is transmitted via a
magnetic field. Thus, for safety reasons, industry standards require wireless electric
vehicle charging systems to include object detection systems to detect the presence

of foreign objects (FOD) and/or living objects (LOD) so that a power supply to the ground assembly can be reduced or switched off altogether, or otherwise modified, when such an object is present to maximise the safety of the wireless electric vehicle charging system. In particular, FOD is typically used to prevent damage to the wireless electric vehicle charging system and/or the foreign object, whilst LOD is typically used to prevent injury and/or death of persons and/or animals in the proximity of the system. In cases of FOD, a particular safety consideration is that (foreign) metallic objects exposed to a magnetic field may heat up, which can be dangerous; thus, systems for detecting foreign metallic objects are used to ensure that such objects are removed from the area of WPT before WPT/charging is initiated. For this reason, industry standards typically require that FOD systems used in wireless electric vehicle charging systems need to be able to detect metal objects larger than 2 mm. Similarly, industry standards require wireless electric vehicle charging systems to have systems in place for determining the extent of alignment of the WPT coil of the ground assembly and the WPT coil of the vehicle assembly with each other, in order to maximise the efficiency of the charging process. It will be appreciated that more efficient charging occurs when greater alignment is achieved.

A problem with prior art FOD, LOD, and alignment systems is that these may be able to detect the presence of an object, but not characterise the object as a foreign object or a living object. In some cases where a foreign object, such as a leaf, is present, it may not be necessary to switch off the power supply to the WPT coil of the ground assembly, since there may not be any safety concerns associated with this. However, since the prior system cannot recognise the leaf as a leaf, and only recognises that an object is present more generally, the system may switch off the power supply to the WPT coil of the ground assembly when it does not need to. This may, for example, render the wireless electric vehicle charging system less convenient for users thereof than would otherwise be the case. Accordingly, it remains desirable to provide a wireless electric vehicle charging system having a FOD/LOD system which is able to characterise the object as a foreign (metal) object or a living object.

In some prior art wireless electric vehicle charging systems where the FOD/LOD system is able to distinguish between foreign and living objects, the system may nonetheless be imperfect. For example, a FOD, LOD, and/or alignment system that

relies on one or more optical cameras to image a particular area may be susceptible to dirt, rain, and/or snow obscuring the camera lens, for example. Accordingly, it is desirable to provide a FOD, LOD, and/or alignment system that is not affected (or is at least less affected than prior art systems) by adverse weather conditions.

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Another problem with prior art systems is that these are generally not able to determine the identity of a foreign or living object in the proximity of the system, and instead are limited to determining whether an object is present or not. Prior art systems that are able to identify such objects are often not very accurate and may inadvertently, for example, recognise a leaf as a small animal. Thus, it is desirable to provide object detection systems for wireless electric vehicle charging systems that are able to identify detected objects accurately, and preferably more accurately than prior art systems.

15 Another problem with prior art object detection systems is that these typically only provide details of the electromagnetic properties of the object. It is therefore desirable to provide object detection systems for electric vehicle charging systems that can obtain additional information about an object detected as being in the proximity thereof.

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Some prior art object detection systems need to be installed on the outside of an electric vehicle and/or in the form of large and/or bulky infrastructure at or near the ground assembly of the wireless electric vehicle charging system. This can be unattractive and render the systems vulnerable to accidental damage and/or vandalism. Thus, it is desired to provide object detection systems for wireless electric vehicle charging systems that are compact and are discrete once installed.

Another problem with some prior art object detection systems is that these may, if installed as part of a ground assembly of a wireless electric vehicle charging system and used to detect the extent of alignment of an electric vehicle with a ground assembly when the electric vehicle parks at (or near) the ground assembly, only be able to detect this for electric vehicles of a certain type, e.g. electric vehicles made by a particular manufacturer. Accordingly, it is desirable to provide an interoperable object

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detection system for e.g. alignment detection that can function successfully regardless of the type of electric vehicle involved in the wireless electric vehicle charging system.

Another problem with prior art object detection systems is that FOD systems typically
5 operate at a lower operating frequency than LOD systems. This is because FOD systems typically require operating frequencies that are sufficiently low to sensitively detect foreign objects, whilst LOD systems typically require much higher operating frequencies to successfully detect living objects (due to the inherently low electrical conductivity of living objects / biological material). This means separate FOD and LOD
10 systems often have to be installed as part of the same wireless electric vehicle charging system, which can be expensive and increases the amount of infrastructure that has to be installed as part of the wireless electric vehicle charging system. Thus, it is desirable to provide an object detection system capable of being used as both a FOD system and a LOD system.

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A known document, entitled "Simultaneous Metal Object Detection and Coil Alignment for Wireless EV Chargers Using Planar Coil Array" (Zhang et al, XP011888805) discloses use of a coil array before start of EV charging. First, a scan is performed for metal objects and any metal objects are imaged using magnetic induction tomography.
20 Provided no metal objects are present, coil alignment is then assessed by excitation of a receiving coil of the charging system and generation of a map representing voltage induced in the coils of the coil array. If the receiving coil is sufficiently well aligned based on the map, the planar coil array is then removed.

25 Another known document, CN113625353B, discloses in an EV charging system where detection of foreign objects uses a low frequency excitation signal for detection of metal objects and a high frequency excitation signal for detection of living objects imaging using magnetic induction tomography.

30 It is also desirable in general to provide alternative, and preferably improved, FOD, LOD, and alignment systems, as well as wireless electric vehicle charging systems and electric vehicles comprising such FOD, LOD, and alignment systems.

Summary of the Invention

The invention provides a magnetic induction tomography-based object detection system, such as a FOD and/or LOD system, particularly for inclusion in a wireless electric vehicle charging system where the object detection system may, additionally or alternatively, be part of an alignment system. The invention also provides a ferrite assembly and/or ferrimagnetic receptacle suitable for a wireless electric vehicle charging system, as well as an electric vehicle comprising a magnetic induction tomography-based object detection system.

The invention also provides several methods, including a method of determining whether an object is present in an area of magnetic field transmission / an imaging area of a wireless electric vehicle charging system, a method of modifying or managing a power supply to a WPT coil of a wireless electric vehicle charging system, and a method of identifying and/or characterising an object identified as present in an area of magnetic field transmission / an imaging area of a wireless electric vehicle charging system.

The invention also provides use of the wireless electric vehicle charging system of the invention in the methods of the invention.

According to a first aspect of the present invention, there is provided an object detection system for a wireless electric vehicle charging system, for producing data for foreign (e.g. metal) and/or living objects, using magnetic induction tomography at a frequency that is spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz to about 10 MHz.

The object detection system may be configured to operate at about 1 MHz to about 5 MHz. The object detection system may be configured to operate at at least 2 MHz and/or less than 4 MHz, for example about 3 MHz. The object detection system may be configured to operate at a single frequency, or within a range of frequencies greater than about 1 MHz or about 2 MHz, and/or less than about 10 MHz or about 5 MHz or about 4 MHz.

The object detection system may be configured to, using such data, produce a computationally generated profile and/or detect possible presence and/or determine

the identity and/or characteristics of a metal and/or living object in an area of magnetic field transmission and/or generate operational instructions.

5 An advantage of the wireless electric vehicle charging system is that the object detection system thereof may be installed in a ground assembly and/or vehicle assembly of the wireless electric vehicle charging system, rather than having to be installed on the outside of an electric vehicle or in the proximity of the ground assembly. Thus, the object detection system of the invention may be less vulnerable to accidental damage and/or vandalism than typical prior art systems.

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Yet another advantage of the wireless electric vehicle charging system of the invention relates to interoperability. Specifically, the object detection system of the wireless electric vehicle charging system of the invention can detect, for example, the extent of alignment between an electric vehicle and a ground assembly regardless of the type of electric vehicle parked at (or near) the ground assembly. Thus, the object detection system of the invention can readily be used with electric vehicles made by different electric vehicle manufacturers. Similarly, the wireless electric vehicle charging system of the invention may have an object detection system as part of a ground assembly and be interoperable in that the object detection system can work successfully to detect any kind of WPT coil of a vehicle assembly of the wireless electric vehicle charging system, regardless of whether that WPT coil has a different impedance value, sits at a different height above the ground assembly, is positioned in a different part of an electric vehicle, has a different shape/topology (suitable/example shapes/topologies including, for example, circular, solenoid, double-D, double-D circular, double-D quadrature, quad-D quadrature, bipolar, tripolar, and/or triple quadrature) etc to other types of vehicle assembly WPT coil(s).

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Another advantage of the wireless electric vehicle charging system of the invention is that the object detection system thereof can be used as both a FOD system and a LOD system, thereby reducing installation costs and the amount of infrastructure that has to be installed as part of the wireless electric vehicle charging system.

The charging system may operate at less than 1 MHz. The charging system may operate at less than 500 kHz. The charging system may operate at less than 100 kHz.

The computationally generated profile may be of and/or the object detection system may be configured to detect the possible presence and/or determine the identity and/or the characteristics of an object in an area or space of magnetic field transmission (that is, between a magnetic field transmitter and a magnetic field receiver) when the magnetic field transmitter and the magnetic field receiver are respectively located for charging. The area or space may include inductive coils of the magnetic field receiver. This enables information on alignment and/or type of coil to be determined.

10 The object detection system may comprise: a probe for probing the area or space; a processor configured to: receive inputs from the probe, and produce data according to the inputs.

The processor may be configured to modify the operating frequency of the object detection system to reduce interference from a magnetic field of the charging system. The modified operating frequency may be spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz or from about 2 MHz, and/or to about 10 MHz or about 5 MHz or about 4 MHz. The processor may be configured to determine that the extent of interference is above a threshold and to modify the operating frequency based on a result of that determination. The modified frequency may be selected by the processor on a random basis.

The processor may include a filter configured to remove signal components of frequency corresponding to the operating frequency of the charging system and optionally higher order harmonics thereof.

The probe may be stationary with respect to a ground assembly comprising the magnetic field transmitter or a vehicle assembly comprising the magnetic field receiver.

30 The object detection system may further comprise an analyser for processing the data to determine whether an object is present in the area or space and/or to determine the identity and/or the characteristics of an object.

The object detection system may further comprise an analyser for processing the data to determine whether an object is present in the area or space and/or to determine the identity and/or the characteristics of an object.

- 5 The analyser may be configured to process the data to generate the profile, and to process the profile to detect possible presence and/or determine the identity and/or characteristics of an object in the area or space.

- 10 The object detection system may further comprise an imager as well as an analyser, wherein the imager is configured to receive data from the processor, and produce an image of the area or space according to the data. In this case, the computationally generated profile is the image, the imager is configured to produce the image using magnetic induction tomography, and the analyser is configured to analyse the image or image data to determine whether an object is present in the imaging area and/or to
15 determine the identity of and/or characteristics of the object.

The analyser may be configured to analyse the image using an artificial intelligence algorithm.

- 20 The object detection system may additionally comprise a computational modeller configured to receive data from the processor and to evaluate electromagnetic properties of an object present in the imaging area according to the data.

- 25 The object detection system may further comprise a power manager configured to manage a power supply to a wireless power transfer coil of the wireless electric vehicle charging system according to whether an object is determined as present in the imaging area and/or according to identification and/or characterisation of the object.

- 30 The power manager may be configured to manage the power supply by reducing the power supply while continuing to supply power for charging and/or modifying the power supply by focussing or localising the power supply, e.g. to parts of the wireless electric vehicle charging system at which an object is not detected as present.

The invention also relates to a wireless electric vehicle charging system comprising an object detection system in accordance with the first aspect or any optional feature thereof. The invention also relates to an electric vehicle charging system comprising an object detection system in accordance with the first aspect or any optional feature
5 thereof, or the wireless electric vehicle charging system.

According to a second aspect, there is provided a method comprising producing data for a foreign (e.g. metal) or living object in an area of magnetic field transmission in a wireless electric vehicle charging system, using magnetic induction tomography at a
10 frequency that is spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz to about 10 MHz to detect presence of, identify and/or characterise the object.

The method may be to detect presence of, identify and/or characterise the object
15 and/or to generate an operational instruction.

An advantage of the object detection system is that the system may be less affected by adverse weather conditions than prior art systems. This is because the object detection system is magnetic induction tomography-based, and thus may not, for
20 example, rely on visual data, for example camera lenses that can be covered by dirt, rain, and/or snow.

Another advantage is that the presence of and/or one or more characteristic(s) of and/or feature(s) about the object can be detected, including of both foreign (e.g.
25 metal) and living objects, unlike a simple system in which only the presence or absence of either a metal or a living object may be detected. For example, the identity of the object (e.g. a leaf or other part of a plant or a metal/metallic object, in cases of FOD, or pet or animal such as a cat, in cases of LOD) may be determined. Similarly, characteristics such as the object's size, the object's electromagnetic properties, the
30 object's density, and/or dynamic characteristics (such as the object's trajectory) may be determined. These effects are made possible by using magnetic induction tomography in the object detection system of the invention.

Since the frequencies used for wireless power transmission and for object detection are sufficiently spaced, interference is unproblematic. This also means that object detection and charging can be performed contemporaneously.

- 5 Further, unlike the system described in CN113625353B, there is no need for separate tomography-based processes for detection of foreign (e.g. metal) and living objects using different frequencies. The object detection system of the first or second aspects may use a single magnetic field frequency for object detection, for example at about 1 MHz to 5 MHz, especially at about 3 MHz.

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A further advantage of a wireless electric vehicle charging system including the object detection system of the first and second aspects is that the accuracy with which the object detection system thereof may identify an object detected as present can be high. Additionally, the accuracy with which the system is able to do this may improve
15 over time.

Yet another advantage of the object detection system is that it may produce a profile, such as an image or a dataset, of an object or an area containing the object, and/or additionally determine/quantify electromagnetic properties of the object, thereby
20 providing more detail about the detected object than is typically achieved in prior art systems. The profile may include information enabling determining presence and/or determining identity and/or determining characteristics of the object by further processing of the profile in a computational model.

- 25 The method of the second aspect may make use of and/or take place within the object detection system and/or the wireless charging system of the first aspect.

According to a third aspect, there is provided a method of modifying a power supply to a wireless power transfer coil of a wireless electric vehicle charging system, the
30 method comprising using magnetic induction tomography to make a determination, about whether an object is present and/or about characteristics and/or identity of an object or to produce a profile of the object, in an area of magnetic field transmission in the wireless electric vehicle charging system, and modifying and/or varying the power supply suitably according to the determination or the profile.

The modifying and/or varying the power supply may comprise reducing the power supply while continuing to supply power for charging.

- 5 The modifying and /or varying the power supply may comprise focussing or localising the power supply, e.g. to parts of the wireless electric vehicle charging system at which an object is not detected as present.

10 According to a fourth aspect, there is provided an object detection system for modifying a power supply to a wireless power transfer coil of a wireless electric vehicle charging system, configured to use magnetic induction tomography to make a determination, about whether an object is present and/or about characteristics and/or identity of an object or to produce a profile of the object, in an area of magnetic field transmission in the wireless electric vehicle charging system, and to suitably modify
15 and/or vary the power supply, suitably according to the determination or the profile.

An advantage of the wireless electric vehicle charging system of the third and fourth aspects is that the power supply to a WPT coil of the system can be managed in response to an object being detected, identified or characterised. Unlike typical prior
20 art systems, the object detection system of the invention may identify the object accurately, and thus the power supply can be appropriately varied, for example reduced while charging is continued, or otherwise managed accordingly.

The method of the fourth aspect may make use of and/or take place within the object
25 detection system of the third aspect.

According to a fifth aspect, there is provided an object detection system comprising at least one coil printed on a circuit board, the at least one coil being for use in magnetic field generation and/or impedance change detection in a magnetic induction
30 tomography process.

Such an at least one coil on a circuit board is compact and inexpensive to make. Field of view of the detection system may be increased relative to conventional coils wherein the at least one coil comprises a plurality of coils.

The invention also provides a wireless electric vehicle charging system comprising an object detection system in accordance with the fifth (or other) aspect, in which the printed circuit board is in a fixed position in a ground assembly for use in object
5 detection in an area of magnetic field transmission.

The coils may be located between the transmitting coils and a ferrite assembly.

The ferrite assembly may at least partially enclose the at least one coil on the circuit
10 board.

The ferrite assembly may comprise a concave receptacle comprising a ferrimagnetic material, for focussing and/or directing a magnetic field generated around or by a magnetic field transmitter.
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According to a sixth aspect, there is provided a method in a detection process using magnetic induction tomography, comprising using at least one coil printed on a circuit board in magnetic field generation and/or impedance change detection.

20 The method may use the objection detection system of the fifth aspect and optional features thereof, and/or take place in the wireless electric vehicle charging system for object detection in an area of magnetic field transmission by a transmitter of the charging system.

25 According to a seventh aspect, there is provided a computer-implemented method comprising: receiving at a machine learning ("ML") model one or more datasets comprising values representing magnitude and phase of impedance or changes thereof at a probe used in a magnetic induction tomography based process for probing a space; processing of the values by the ML model to output information indicative of
30 or a prediction for presence, identity and/or at least one characteristic of an object in the space.

In this method, an image or image data for display of an image is preferably not generated. The values are processed directly by the ML model. The values may be received directly at the input layer of a neural network-based model.

- 5 According to an eighth aspect, there may be provided apparatus comprising: a probe; and a computing component comprising processing means and a memory storing computer program code, wherein the processing means and the memory with the code is configured to perform the method of the seventh aspect and any optional step thereof, wherein the data sets are from signals generated at the probe.

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According to a ninth aspect, there may be provided a computer program product comprising computer program code which, when executed by a computer, is configured to cause the computer to carry out the method of the seventh aspect and any optional step thereof.

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According to a tenth aspect, there is provided a ferrite assembly suitable for a wireless electric vehicle charging system, the assembly comprising a concave receptacle comprising a ferrimagnetic material, for focussing and/or directing a magnetic field generated around or by a magnetic field transmitter.

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According to an eleventh aspect, there is provided a ferrimagnetic receptacle at least partially enclosing a probe of an object detection system for a wireless electric vehicle charging system.

- 25 According to a twelfth aspect, there is provided an object detection system for a wireless charging system comprising a processor configured to: cause magnetic field generation at a first frequency for a magnetic induction tomography-based process; make a determination about extent of interference in a signal received from a probe used in the magnetic induction tomography-based process; and cause magnetic field
30 generation at a second frequency different from the first frequency for the magnetic induction tomography-based process dependent on the determination.

The first frequency and the second frequency may be greater than 1 MHz or greater than 2 MHz and/or less than 10 MHz or less than 5 MHz or less than 4 MHz. The

interference may arise from the magnetic field of a magnetic field transmitter of the charging system.

5 The magnetic field generation at the first and second frequencies is at the probe. The probe may comprise a plurality of probing devices. The object detection system may cause one or more, but not all, of the probing devices to generate a magnetic field at the second frequency, while the other probing devices are caused to generate a magnetic field at the first frequency.

10 The invention may provide a wireless electric vehicle charging system comprising the object detection system.

According to a thirteenth aspect, there is provided a method comprising: causing magnetic field generation at a first frequency for a magnetic induction tomography-based process; making a determination about extent of interference in a signal
15 received from a probe used in the magnetic induction tomography-based process; and cause magnetic field generation at a second frequency different from the first frequency for the magnetic induction tomography-based process dependent on the determining.

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According to a fourteenth aspect, there is provided a wireless electric vehicle charging system, comprising an object detection system which is configured to produce a computationally generated profile (or detect the possible presence of an object) using magnetic induction tomography.

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The computationally generated profile may be of an area or space between a magnetic field transmitter and a magnetic field receiver.

The computationally generated profile may be an image.

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The object detection system may comprise (one of more of):

- (a) an imaging area,
- (b) a probe for probing the imaging area,
- (c) a processor configured to:

- (i) receive one or more input(s) from the probe, and
 - (ii) produce data according to the one or more input(s); and/or
 - (d) an imager configured to:
 - (i) receive data from the processor, and
 - (ii) produce an image of the imaging area according to the data,
- wherein the imager is configured to produce the image using magnetic induction tomography.

The object detection system may additionally comprise an analyser configured to analyse the image to determine whether an object is present in the imaging area and/or to identify and/or characterise the object.

The analyser may be configured to analyse the image using an artificial intelligence algorithm.

The object detection system may additionally comprise a computational modeller configured to receive data from the processor and to evaluate electromagnetic properties of an object present in the imaging area according to the data.

The object detection system may additionally comprise a power manager configured to manage a power supply to a wireless power transfer coil of the wireless electric vehicle charging system according to whether an object is determined as present in the imaging area by the analyser and/or according to identification and/or characterisation of the object by the analyser.

The object detection system may additionally comprise a ferrite assembly.

The invention may also provide a wireless electric vehicle charging system, wherein the probe is part of a magnetic field transmitter or a magnetic field receiver. The ferrite assembly may at least partially encloses the probe.

The wireless electric vehicle charging system may comprise a plurality of ground assemblies and a probe is configured as part of each ground assembly and/or the processor is configured to receive one or more input(s) from each probe.

According to a fifteenth aspect, there is provided an electric vehicle comprising an object detection system configured to produce a computationally generated profile, or to detect the possible presence of an object, using magnetic induction tomography.

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According to a sixteenth aspect, there is provided method of determining whether an object is present (or not) in an area of magnetic field transmission in a wireless electric vehicle charging system, the method comprising using magnetic induction tomography to determine whether the object is present (or not).

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According to a seventeenth aspect, there is provided a method of identifying or characterising an object in an area of magnetic field transmission in a wireless electric vehicle charging system, the method comprising using magnetic induction tomography to identify and/or characterise the object.

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Optional and/or preferred features and/or steps of the twelfth aspect are applicable to the thirteenth aspect.

Preferred and/or optional features and/or characteristics of one aspect of the invention are equally applicable to another aspect *mutatis mutandis*.

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Brief Description of Figures

Embodiments of the invention are now illustrated by way of the following examples, which are not intended to be limiting, with reference to the accompanying drawings, in which:

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Fig. 1 shows a schematic block diagram of a wireless electric vehicle charging system according to an embodiment of the first aspect of the invention;

Fig. 2 shows a schematic block diagram of the wireless electric vehicle charging system of Figure 1 with two probes shown;

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Fig. 3 shows a schematic block diagram of the ground assembly probe of Figure 2;

Fig. 4 shows a schematic block diagram of an alternative ground assembly probe to that shown in Figure 3;

Fig. 5 shows a schematic block diagram of the mode of action of the probe of Figure 4;

Fig. 6 shows a schematic block diagram (top view) of a probe comprising a plurality of probing devices arranged in a 4x4 array;

5 Fig. 7 shows a schematic block diagram (top view) of a probe comprising a plurality of probing devices arranged in a 5x5 array;

Fig. 8 shows a schematic block diagram (top view) of a probe comprising a plurality of probing devices arranged in an 8x8 array;

10 Fig. 9 shows a schematic block diagram of an object detection system of a wireless electric vehicle charging system according to an embodiment of the first aspect of the invention comprising one ground assembly;

Fig. 10 shows a schematic block diagram of an object detection system of a wireless electric vehicle charging system according to an embodiment of the first aspect of the invention comprising a plurality of ground assemblies;

15 Fig. 11 shows a schematic block diagram of the processor of the object detection systems of Figures 9 and 10;

Fig. 12 shows an example of a two-dimensional magnetic induction tomography image obtainable using the imager of the object detection systems of Figures 9 and 10;

20 Fig. 13 shows a graph of magnitude of impedance against distance plotted during a simulation-based investigation into an object detection system of a wireless electric vehicle charging system according to an embodiment of the first aspect of the invention; and

25 Fig. 14 shows a graph of phase against distance for the simulation-based investigation of Figure 13;

Fig. 15 is schematic block diagram of an object detection system in accordance with another embodiment, in a wireless electric vehicle charging system comprising one ground assembly;

30 Fig. 16 is a schematic illustration of architecture of a computational model in accordance with embodiments;

Fig. 17 is a flowchart comprising steps occurring at the computing component; and

Fig. 18 is a schematic illustration of a computer system on which the computational modeller and the computational component may be implemented.

Detailed Description of the Invention

Embodiments of the invention relate to an object detection system for a wireless electric vehicle charging system. Embodiments are not limited to use with such charging systems. For example, object detection systems described herein may be used with wireless charging systems other than for use with electric vehicles. Further, object detection systems described herein may be used other than with wireless charging systems, for example in object detection, identification and/or characterisation in manufacturing or in medical scenarios. For example, the object detection system may be used for testing for object integrity in manufacturing (e.g. eddy current testing).

The object detection systems and associated methods described herein use magnetic induction tomography ("MIT"). Herein, MIT refers to a process of generating a varying magnetic field in a space (or area) to induce eddy currents in objects in the space, measuring changes in impedance in a probe caused by magnetic fields generated by the eddy currents, and processing of measurements indicative of the changes to yield information on presence, identity and/or characteristics of objects in which the eddy currents have been generated. The systems and methods may include image construction, but embodiments are not limited to such. Object detection systems herein described and associated methods may interpret collected data directly without an image being constructed to yield predictions for or information indicative of presence, identity or characteristics of any objects in a probed space and/or operational instructions relating to such objects.

In some embodiments, the object detection system may be suitably configured to produce a computationally (or digitally) generated profile using magnetic induction tomography. Using magnetic induction tomography is advantageous because this allows a profile, such as an image, of the object detected to be prepared, which is not always possible in prior art systems. A user may be presented with such a profile on a display where the profile is an image or the image may be processed by an analyser to provide the user with additional information that may be useful to, for example, help the user decide whether the object needs to be removed before WPT should be initiated and/or whether the vehicle assembly is sufficiently aligned with the ground

assembly for efficient charging to occur. In some embodiments, a profile may be produced within a model, for example an algorithmic model, that may not be an image. Such a profile may be used to indicate or predict presence of, to identify and/or to characterise an object in the probed space. For example, the profile may be in the

5 form of a data structure of one or more dimensions including numerical values carrying information on features of any objects in the space, the information being generated and interpreted within the model. Alternatively, in some embodiments no such profile may be produced in generation or updating of outputs by the model. The term “imaging area” may be used herein to refer to the area or space that is probed regardless of

10 whether an image is generated.

It will be appreciated that the terms “ground assembly” and “vehicle assembly” are terms of art used in at least the industry standard SAE J2954. However, for the avoidance of doubt, the term “ground assembly” as used herein is intended to mean

15 the component(s) of the wireless electric vehicle charging system, typically found in close proximity to the electric vehicle during charging, which are used to supply power to the electric vehicle during charging. These components may receive power from the electric vehicle if/when the electric vehicle discharges excess power it does not need to the grid.

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Similarly, the term “vehicle assembly” as used herein is intended to mean the component(s) of the wireless electric vehicle charging system typically found in the electric vehicle. Like the ground assembly, these are involved in charging and/or discharging, as applicable. It will be appreciated that the ground assembly and the

25 vehicle assembly typically each comprise a WPT coil, and that a “WPT coil” means a coil used for the purposes of charging (and/or discharging) power to (and/or from) an electric vehicle.

The term “central assembly” is also used to describe additional components of the

30 ground-side apparatus (the ground-side apparatus being all components of the electric vehicle charging system not present in/on the electric vehicle). Thus, the central assembly may typically include a power supply and a control unit, such as a cabinet, used to supply power to one or more ground assemblies as required. The central

assembly and the one or more ground assemblies may thus collectively constitute the ground-side apparatus.

5 The computationally (or digitally) generated profile is of an area between a magnetic field transmitter and a magnetic field receiver. Generating a profile of this area is advantageous because this is the area in which one or more magnetic field(s) may be present during WPT, and thus the area that is ideally free from objects during WPT. Additionally, the magnetic field transmitter and the magnetic field receiver may be the components of the wireless electric vehicle charging system involved in WPT, and thus
10 usually the components that need to be adequately aligned with each other, for efficient WPT/charging to occur. Since the WPT coils are a type of object in this detection process, determining of information for or generating of a profile of this area can enable this alignment to be detected.

15 The computationally generated profile may be any type of computationally generated profile; the computationally generated profile may be a dataset, a digital map, a graphic, an image, a model, a scan, or a spatial profile. Generating such a profile is advantageous because this profile can then be analysed to determine details of the object. The profile may be analysed by a user if the computationally generated profile
20 is an image, as this can be visually presented to a user of the system. In this case, the object detection system may comprise a display for displaying an image. The profile may be generated in a first set of algorithms (or first sub-model) in a model and the profile processed by a second set of algorithms (or second sub-model) in the model to output information indicative of or a prediction of presence of, identity of and/or
25 characteristics of an object in the space.

The object detection system may comprise: a probe for probing/imaging an imaging area, and a processor configured to: receive one or more input(s) from the probe, and produce data according to the one or more input(s). The object detection system may
30 further comprise a computing component, which in some embodiments comprises an imager configured to: receive data from the processor, and produce an image of the imaging area according to the data, wherein the imager is configured to produce the image using magnetic induction tomography.

As already indicated, in embodiments, the imaging area may be an area between a magnetic field transmitter and a magnetic field receiver. The imaging area may comprise an area between a WPT coil (of a ground assembly of the wireless electric vehicle charging system) and a WPT coil (of a vehicle assembly of the wireless electric vehicle charging system). Detection in this area is advantageous because this is where WPT occurs. It is thus the area of most use and of concern, for FOD, LOD and/or alignment. The imaging area may be a combination of an area between and including a WPT coil of a ground assembly of the wireless electric vehicle charging system and a WPT coil of a vehicle assembly of the wireless electric vehicle charging system and an area immediately adjacent thereto. Expanding the imaging area to include an area adjacent to and/or surrounding the area where WPT occurs is advantageous because this allows the detection of object(s) that may be about to enter the area where WPT occurs, thereby allowing action to be taken (if required), such as switching off or varying the power supply to a WPT coil, e.g. before those objects enter the area where WPT occurs. This can increase the safety of the wireless electric vehicle charging system.

The display may be available to a driver or other user of an EV. The display may be configured to display the image or information identifying or characterising an object in the detection area. This may allow the image to be visually displayed/presented, e.g. to a user of the wireless electric vehicle charging system. This may help the user determine whether an object is present in the imaging area (and identify the object if so).

The computing component may comprise an analyser. In embodiments where a profile is generated in the form of an image, the analyser is configured to analyse the image. In other embodiments, the analyser may be configured to receive data directly from the processor, without an image being generated. The analyser may be configured to analyse the image or image data to determine whether an object is present in the imaging area. The analyser may be additionally configured to identify and/or characterise the object. The analyser may be configured to characterise the object as a WPT coil of the wireless electric vehicle charging system, a foreign object, or a living object. Including an analyser is advantageous because this prevents the user from having to analyse the image, which may otherwise be susceptible to human error.

The analyser may be configured to characterise the object as a metal/metallic foreign object. Preferably, the analyser is configured to determine the degree to which an object identified as a metal/metallic foreign object is metallic and/or to determine the extent to which an object identified as a metal/metallic foreign object differs to a WPT coil of the wireless electric vehicle charging system, such as a WPT coil of the vehicle assembly of the wireless electric vehicle charging system. Thus, the analyser may be configured to distinguish between one or more foreign metal object(s) and one or more WPT coil(s) of the wireless electric vehicle charging system.

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In embodiments wherein the analyser is configured to characterise the object as a WPT coil of the wireless electric vehicle charging system, the analyser may be configured to determine the extent of alignment between the WPT coil and the probe. This is advantageous because this allows the user to determine whether there is sufficient alignment for efficient WPT/charging to occur, and/or whether the alignment needs to be adjusted before WPT/charging can (or should be) initiated.

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The analyser may be configured to determine the extent of alignment between an electric vehicle and a ground assembly of the wireless electric vehicle charging system. In this respect, the analyser may be configured to determine the extent of alignment between at least one component of a ground assembly of the wireless electric vehicle charging system and at least one component of a vehicle assembly of the wireless electric vehicle charging system. Preferably, the at least one component of the ground assembly is a WPT coil of the ground assembly and/or the at least one component of the vehicle assembly is a WPT coil of the vehicle assembly. More preferably, the analyser is configured to determine the extent of alignment between a WPT coil of a ground assembly of the wireless electric vehicle charging system and a WPT coil of a vehicle assembly (and/or an electric vehicle) of the wireless electric vehicle charging system by comparing a set/known position of the WPT coil of the ground assembly with a (relative) position of the WPT coil of the vehicle assembly (and/or electric vehicle). It will be appreciated that alignment between the ground assembly and the electric vehicle / vehicle assembly may be determined by analysing the extent of alignment between one or more other component(s) of the ground assembly, electric vehicle, and/or vehicle assembly, as well. Analysing and/or

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determining the extent of alignment is advantageous because more efficient WPT/charging generally occurs when greater alignment is achieved.

5 In embodiments where the analyser analyses an image, the analyser may be configured to analyse the image using an algorithm, which may be an artificial intelligence algorithm. Preferably, the artificial intelligence algorithm is a machine learning algorithm and/or a deep learning algorithm. Using an algorithm / artificial intelligence algorithm may allow the analysis to be performed much faster and/or more accurately than if the analysis is instead performed by a human or person.

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The analyser may be configured to use an output of an analysis labelled as correct or otherwise to train the artificial intelligence algorithm. This is advantageous because this can improve the accuracy of the analysis performed by the analyser in the future. A suitable training dataset comprising inputs and labelled outputs may be produced
15 by labelling of outputs by a human, or by labelling in an automated process using a camera-based object detection system and known image processing techniques that record images of objects for which the image generating object detection system takes frames, and classifies the objects using the image processing techniques.

20 The object detection system may additionally comprise a computational modeller. Preferably, the computational modeller is configured to receive data from the processor and to evaluate electromagnetic properties of an object present in the imaging area according to the data. The computational modeller may be configured to produce an output detailing the electromagnetic properties of the object. For example,
25 the computational modeller may additionally be configured to produce a report on the electromagnetic properties of the object. Examples of electromagnetic properties of the object the computational modeller may be able to determine include the distance between the object (or different parts of the same object) and the probe, the object's dimensions and depth (i.e. shape), the density of the object, the conductivity of the
30 object, and the permittivity of the object. It will be appreciated that other electromagnetic properties may also be determined by the computational modeller. The output of the computational modeller may be associated with the output image.

The object detection system may additionally comprise a power manager. Preferably, the power manager is configured to manage a power supply to a WPT coil of the wireless electric vehicle charging system. More preferably, the power manager is additionally configured to manage the power supply, e.g. according to whether an
5 object is determined as present in the imaging area by the analyser and/or according to identification and/or characterisation of the object by the analyser. Including a power manager may allow the power supplied to WPT coils of the wireless electric vehicle charging system to be controlled in response to the presence/absence of an object in the imaging area or the object's identification and/or characterisation. In particular, the
10 power manager may be configured to reduce power supply to the charging system while charging is continued.

The object detection system may be a dynamic system. Thus, in embodiments in which the object detection system is configured to produce images, a plurality of
15 images may be produced, e.g. over a period of time. This may be advantageous because this allows the movement of an object in or through the imaging area to be tracked (or otherwise monitored) over time. This can provide additional information which could be useful for identifying and/or characterising the object. For example, the artificial intelligence algorithm may have been trained to recognise a specific
20 movement pattern enabling it to identify the object as a leaf, with a cat having a different specific movement that can be recognised by the algorithm to enable it to identify the object as a cat.

The probe may be any probe suitable for probing the imaging area. The probe may be
25 or comprise one or more probing device(s). In such embodiments, the one or more input(s) to the processor may be values indicative of one or more impedance(s), or change of impedance due to the magnetic fields from induced eddy currents in any objects in the area. Measuring the impedances of the probing device(s) in this manner may be advantageous because this information can be used to quantify
30 electromagnetic properties of an object in the imaging area, and/or because such information is useful as an input for magnetic induction tomography-based imaging and/or a computing component for predicting presence, identity and/or characteristics of any objects.

The/each probing device may comprise a coil. This is advantageous because the coil(s) can be used to generate one or more magnetic field(s), which can be used to probe the imaging area. Preferably, there is a plurality of probing devices. This is advantageous because this allows a larger imaging area to be probed than in
5 embodiments wherein only one probing device is used and/or for greater resolution. This may allow additional information about any object(s) present in the imaging area to be obtained. The plurality of probing devices may be arranged, e.g. in an array or grid. This is advantageous because this allows the imaging area to be uniformly probed, thereby increasing the likelihood of an object in the imaging area being
10 detected and, if such an object is detected, enabling several parts of the object to be probed, thereby increasing the amount of information obtained about the object. The array may be, for example, a grid arrangement of 4x4 coils, 5x5 coils, or 8x8 coils. It will be appreciated that the exact structure of the array may depend on factors such as the desired coverage area and/or the required granularity/accuracy. Thus, the exact
15 structure of the array may be decided on a case-by-case basis.

The object detection system may be configured to cause the/each probe to generate magnetic fields for the magnetic induction tomography process of at a frequency of at least about 1 MHz or at least about 2 MHz and/or at less than about 10 MHz or less
20 than about 5 MHz or less than about 4 MHz. The object detection system may be configured to cause the/each probe to generate magnetic fields at about 3 MHz, for example. The/each probing device may be operated at such frequencies. This is advantageous because this (relatively high) frequency is sufficiently high to avoid interference from WPT between the WPT coils of the wireless electric vehicle charging
25 system. This is because industry standards currently approve WPT in such charging systems at a frequency of about 85 kHz, which is much lower than the operating frequency of the object detection system; thus, object detection signals can be readily distinguished/isolated/filtered from WPT signals. In general, the object detection system may be comprised in a wireless charging system, which may be an inductive
30 charging system and/or which may not be for EVs, in which the operating frequency is spectrally spaced from the operating frequency of the object detection system.

Using said operating frequencies is advantageous because it facilitates use of the object detection system for both FOD and LOD. This is because prior art FOD systems

typically operate at a frequency of about 5 kHz to about 100 kHz in order to maximise their sensitivity to foreign objects. However, FOD systems having an operating frequency of about 1 MHz to about 10 MHz may nonetheless be sufficiently sensitive to (successfully) detect foreign objects. In contrast, prior art LOD systems typically
5 require a higher operating frequency to (successfully) detect living objects due to the generally low electrical conductivity of living objects / biological material. Using an operating frequency of about 1 MHz to about 10 MHz, preferably less than about 5 MHz, results in successful detection of living objects by the object detection system. Thus, the object detection system of the invention may be used as both a foreign
10 objection detection system and a living object detection system.

A further advantage of using an operating frequency of about 1 MHz to about 10 MHz, preferably less than about 5 MHz, is that this may shorten the time taken for the object detection system to detect foreign objects, compared to prior art FOD systems having
15 an operating frequency of about 5 kHz to about 100 kHz. This is because data is acquired faster when a higher frequency is used.

The object detection system may additionally comprise a transimpedance circuit, which may be for maintaining one or more impedance(s) of the probe, for example at
20 about 50 Ω . Maintaining the impedance(s) at about 50 Ω is advantageous because this improves signal quality of the probe and avoids instability issues associated with the probe.

The object detection system may additionally or alternatively comprise a matching
25 network. This facilitates maintenance of system impedance to improve stability and signal-to-noise ratio ("SNR"), particularly where the object detection uses high frequencies, whilst also allowing for a wide range of designs of probe.

The object detection system may additionally employ shifting of operating frequency
30 of probing devices (e.g. coils) (known as "frequency agility").

The object detection system may additionally comprise a ferrite assembly. Including a ferrite assembly is advantageous because this can be used to direct a magnetic field generated by the probe in a particular direction, such as into the imaging area. This

may increase the efficiency of the object detection system and may reduce the likelihood of the object detection system detecting objects outside the imaging area which are of no concern for the purposes of FOD, LOD, and/or alignment.

- 5 The probe may be part of a magnetic field transmitter or a magnetic field receiver. This is advantageous because this may result in the probe being concealed inside of (or in close proximity to) other components of the wireless electric vehicle charging system, which can be visually more attractive than would otherwise be possible and which may reduce the likelihood of the probe being accidentally damaged and/or vandalised.

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The magnetic field transmitter or magnetic field receiver may be a ground assembly of the wireless electric vehicle charging system. Preferably, in such embodiments, the probe is positioned beneath a WPT coil of the ground assembly. Positioning the probe in this manner can be advantageous to facilitate minimisation of the distance between
15 the WPT coil of the ground assembly and a corresponding WPT coil of a vehicle assembly compared to, for example, positioning the probe above the WPT coil of the ground assembly. This is advantageous because this increases the efficiency of WPT between the WPT coils.

- 20 In embodiments wherein the probe is part of a ground assembly of the wireless electric vehicle charging system, the ferrite assembly may at least partially enclose the probe. Preferably, the ferrite assembly is positioned at least partly beneath and/or adjacent to the probe. Positioning the ferrite assembly in this way may be advantageous because this can help direct one or more magnetic field(s) generated by the probe(s)
25 into the imaging area, which may be above the ground assembly. Alternatively or additionally, the ferrite assembly may be positioned at least partly above the probe.

- Alternatively or additionally, the magnetic field transmitter or magnetic field receiver may be a vehicle assembly of the wireless electric vehicle charging system. Preferably,
30 in such embodiments, the probe is positioned above a WPT coil of the vehicle assembly. Positioning the probe in this manner can be advantageous because this minimises the distance between the WPT coil of the vehicle assembly and a corresponding WPT coil of a ground assembly compared to, for example, positioning

the probe beneath the WPT coil of the vehicle assembly. This is advantageous because this increases the efficiency of WPT between the WPT coils.

5 In embodiments wherein the probe is part of a vehicle assembly of the wireless electric vehicle charging system, the ferrite assembly may at least partially enclose the probe. Preferably, the ferrite assembly is positioned at least partly above and/or adjacent to the probe. Positioning the ferrite assembly in this way may be advantageous because this can help direct one or more magnetic field(s) generated by the probe(s) into the imaging area, which may be beneath the vehicle assembly. Alternatively or
10 additionally, the ferrite assembly may be positioned at least partly beneath the probe.

All components of the object detection system may be part of the ground assembly of the wireless electric vehicle charging system. The wireless electric vehicle charging system may similarly be configured such that no components of the object detection
15 system are part of the vehicle assembly. Such arrangements are advantageous because these enhance interoperability of the wireless electric vehicle charging system with electric vehicles made by different manufacturers. This is because those manufacturers are not required to install any components of the object detection system in their electric vehicles for the object detection system to work successfully
20 therewith.

The object detection may be any type of object detection system. However, the object detection system preferably is one or more or all of a foreign object detection system, a living object detection system, and/or an alignment detection system. Thus, the
25 object detection system may be for one or more or all of foreign object detection, living object detection, and/or alignment detection.

The wireless electric vehicle charging system may comprise a plurality of ground assemblies. Preferably, a probe is configured as part of each ground assembly and/or
30 the processor is configured to receive one or more input(s) from each probe. This is advantageous because this allows FOD, LOD, and/or alignment to be performed across a plurality of ground assemblies of the same wireless electric vehicle charging system simultaneously. Thus, if an object is present at one ground assembly, but no object is present at another ground assembly, then a driver of an electric vehicle may

be directed to the other ground assembly to charge their electric vehicle while a person removes the object(s) detected at the one ground assembly. This can maximise the efficiency of the wireless electric vehicle charging system because this reduces the likelihood of the driver having to wait for an operator of the wireless electric vehicle charging system to remove an object from an area in the proximity of a ground assembly before it can charge its electric vehicle.

In some embodiments, as indicated above, a ferrite assembly is provided for a wireless electric vehicle charging system. The ferrite assembly may comprise a concave receptacle, comprising a ferrimagnetic material suitable for focussing and/or directing a magnetic field generated around (or by) a magnetic field transmitter. It will be appreciated that "concave" is one of several shapes the ferrite assembly may suitably adopt. Other suitable shapes include, for example, an inverted pyramid which has been hollowed out, or a bowl shape. Ferrite assemblies having such shapes are advantageous because these can readily be used to direct one or more magnetic field(s) generated by the probe(s), e.g. into the imaging area.

The invention also provides a ferrimagnetic receptacle, at least partially enclosing a probe of an object detection system, suitable for a wireless electric vehicle charging system. This is advantageous because this ferrimagnetic receptacle can readily be used to direct and/or focus one or more magnetic field(s) generated by the probe(s), e.g. into the imaging area.

In some embodiments, there is provided an electric vehicle comprising an object detection system, suitably configured to produce a computationally (or digitally) generated profile using magnetic induction tomography. Using magnetic induction tomography in an electric vehicle is advantageous because this allows a profile, such as an image, of the object detected to be prepared, which is not always possible in prior art systems. Having such a profile available means that a user or driver of the system can be provided with additional information that may be useful to, for example, help the user decide whether the object needs to be removed before WPT can / should be initiated and/or whether the vehicle assembly is sufficiently aligned with the ground assembly for efficient WPT/charging to occur.

In some embodiments, there is provided a method of modifying a power supply to a WPT coil of a wireless electric vehicle charging system. The method may comprise using magnetic induction tomography to make a determination about whether an object is present or identity or characteristics of the object, such as in an area of magnetic field transmission in the wireless electric vehicle charging system, and modifying or varying the power (supply), according to the determination. The modification made to the power supply may be any suitable modification. However, preferably the power supply is modified by reducing (or switching off) the power supply, e.g. in the event that an object is detected as present. Alternatively or additionally, the power supply may be modified by focussing/localising the power supply, e.g. to parts of the wireless electric vehicle charging system at which an object is not detected as present.

The invention also provides a method of managing a power supply to a WPT coil of a wireless electric vehicle charging system, the method comprising (one or more of):

- (a) providing a wireless electric vehicle charging system having an object detection system, e.g. according to the first aspect of the invention,
- (b) using the probe to probe/image the imaging area,
- (c) providing one or more input(s) from the probe to the processor,
- (d) using the processor to produce data according to the one or more input(s),
- (e) providing data from the processor to the imager, or (directly) to the analyser,
- (f) using the imager to produce the image,
- (g) using the analyser to analyse the image or the data from the processor directly to determine whether an object is present in the imaging area, and/or to identify and/or characterise the object;
- (h) using the power manager to manage the power supply according to whether an object is determined as present in the imaging area by the analyser and/or according to identification and/or characterisation of the object by the analyser.

Using magnetic induction tomography in these methods is advantageous for the same reasons as given above in respect of other aspects of the invention.

The invention also provides a method of identifying or characterising an object in an imaging area in a wireless electric vehicle charging system, the method comprising (one or more of):

- 5 providing a wireless electric vehicle charging system comprising an object detection system, e.g. according to the first aspect of the invention, using the probe to probe/image the imaging area, providing one or more input(s) from the probe to the processor, using the processor to produce data according to the one or more input(s),
- 10 providing data from the processor to the imager, which is then used to produce the image, or (directly) to an analyser.

- Where the data is provided to the imager, then the analyser may be used to analyse the image to determine whether an object is present in the imaging area, and/or the
- 15 analyser may be used to identify and/or characterise the object. Where the data is provided directly to the analyser, the analyser may be used to determine whether an object is present in the imaging area, and/or the analyser may be used to identify and/or characterise the object.

- 20 According to embodiments, there is provided a method of determining the extent of alignment of an electric vehicle (or vehicle assembly) with a ground assembly of a wireless electric vehicle charging system. The method may comprise using magnetic induction tomography to determine the extent of alignment.

- 25 In embodiments, there is also provided a method of determining the extent of alignment of an electric vehicle (or vehicle assembly) with a ground assembly of a wireless electric vehicle charging system, the method comprising (one or more of):

- providing a wireless electric vehicle charging system having an object detection system, e.g. according to the first aspect of the invention,
 - 30 using the probe to probe/image the imaging area,
 - providing one or more input(s) from the probe to the processor,
 - using the processor to produce data according to the one or more input(s),

providing data from the processor to the imager, which is then used to produce the image, or (directly) to an analyser.

Where the data is provided to the imager, then the imager may be used to produce the image, and the analyser may be used to analyse the image to determine whether the electric vehicle (or vehicle assembly) is sufficiently aligned with the ground assembly, e.g. by comparing an actual alignment to a (predetermined) threshold value. Where the data is provided to the analyser directly, then the analyser may be used to analyse the image to determine whether the electric vehicle (or vehicle assembly) is sufficiently aligned with the ground assembly, e.g. by comparing an actual alignment to a (predetermined) threshold value.

If the alignment is determined as insufficient, then this determination may be communicated to a driver of the electric vehicle (e.g. by displaying a message on a screen of (or inside) the electric vehicle), optionally with guidance on how to improve the alignment. Preferably, if the alignment is determined as sufficient, then this determination is communicated to a driver of the electric vehicle (e.g. by displaying a message on a screen of (or inside) the electric vehicle). Communicating the determination to the driver in these manners is advantageous because this can help the driver determine whether or not it needs to move the electric vehicle to improve the alignment.

Referring to Figure 1, a wireless electric vehicle charging system 1 comprises a power source 2 positioned in a central assembly (not shown in Figure 1) for supplying alternating current to a WPT coil 3 of a ground assembly. When alternating current is supplied to the WPT coil of the ground assembly, a magnetic field is generated around the WPT coil. The magnetic field induces an alternating current in a corresponding WPT coil 4 of a vehicle assembly of an electric vehicle 5 parked at the ground assembly. That alternating current is then used to charge the battery of the electric vehicle. In this manner, power is transferred from the ground-side power source to the electric vehicle by WPT (indicated by the dashed lines in Figure 1).

In Figure 1, an area between a magnetic field transmitter (the WPT coil of the ground assembly) and a magnetic field receiver (the WPT coil of the vehicle assembly), which is an imaging area 6, is indicated by dotted lines.

- 5 It will be appreciated that not all components of the central assembly, ground assembly, and vehicle assembly of this wireless electric vehicle charging system are shown in Figure 1 to facilitate clarity of this drawing.

- 10 Referring to Figures 2 to 5, the wireless electric vehicle charging system of Figure 1 comprises an object detection system. Installed as part of the ground assembly is a probe comprising a single coil 7 as a probing device which is supplied with alternating current by a power source 2. The probe is positioned beneath the WPT coil of the ground assembly (not shown in Figures 3, 4, and 5).

- 15 It will be appreciated that alternatively the probe may comprise a plurality of probing devices in the form of coils 8, as shown in Figure 4.

- 20 When alternating current passes through the coil(s) 7, 8 constituting the probe, a magnetic field 10 is generated around each coil constituting the probe (only one magnetic field shown in Figure 5). If an object 11 is present in the imaging area and is conductive, then the magnetic field will induce an eddy current 12 in the object. The eddy current flowing through the object in turn generates a magnetic field 13 around the object, which affects the impedance of the coil(s) constituting the probe.

- 25 To direct the magnetic field generated around each coil constituting the probe into the imaging area, a ferrite assembly 9 is included as part of the ground assembly. It will be appreciated that the ferrite assembly shown in Figures 2 to 5 has the shape of an inverted pyramid which has been hollowed out.

- 30 In embodiments of the invention, there is no requirement for a probe or any part of an object detection system to be included in the vehicle assembly. However, a similar setup to that described above relating to a ferrite assembly may additionally or alternatively be included in the vehicle assembly of the electric vehicle and this is illustrated in Figure 2.

Referring to Figure 6, in an embodiment a probe comprises a plurality of probing devices which are coils 8 on a plate 14. The probing devices are arranged in a grid arrangement of 4x4 coils.

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Referring to Figure 7, a probe comprises a plurality of probing devices which are coils 8 on a plate 14. The probing devices are arranged in a grid arrangement of 5x5 coils.

Referring to Figure 8, a probe comprises a plurality of probing devices which are coils 8 on a plate 14. The probing devices are arranged in grid arrangement of 8x8 coils.

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Generally, the probing devices may be arranged in a grid arrangement of n by n coils. Embodiments are not limited to any number or arrangement of coils and are not limited to arrangement in a grid; a grid of n x m coils may be used or a plurality of coils may be arranged irregularly in embodiments where an image is not generated, provided they remain in a fixed position relative to one another.

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The probing devices in the form of coils 8 may be provided in a conventional form for magnetic induction tomography. Alternatively, in embodiments, the coils may be implemented as one or a plurality of traces, for example of copper, printed onto a circuit board or a plurality of circuit boards. This reduces costs versus provision of conventional coils. Embodiments are not limited to such an object detection system for or in a wireless EV charging system. Embodiments may be implemented in an object detection system for other purposes, for example for use in medical/healthcare scenarios or in manufacturing and product testing (e.g. testing known as eddy current testing), or in liquid flow monitoring.

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In embodiments the probing devices may be implemented as dual coils, where one coil is used for magnetic field generation and the other is used for detection of impedance variation.

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Referring to Figures 9, 11, and 12, an example object detection system 15 comprises a probe 16, a processor 17, an imager 18, an analyser 19, and a computational modeller 20.

The probe 16 comprises a plurality of probing devices. The probing devices are coils arranged in a grid arrangement of 8x8 coils. Each coil provides an input (illustrated by the dashed lines in Figure 11) to the processor 17.

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The processor 17 (or processing circuitry) comprises a selector in the form of a multiplexor 21, a first amplifier 22, a filter 23, a controller in the form of a field-programmable gate array (FPGA) 24, a voltage controlled current source 25 and a second amplifier 26.

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The multiplexor 21 is electrically coupled to each of the coils 8 and controllable to permit an excitation signal to be provided to each of the coils 8 and to select each of the coils 8 sequentially to receive an AC signal from. Thus, there are 64 inputs in total to the multiplexor 21. The multiplexor 21 is electrically connected to the first amplifier 22 and is configured to pass the signal received from a selected coil to the first amplifier 22. The first amplifier 22 is configured to amplify the received input. The first amplifier 22 is electrically connected to the filter 23 and is configured to pass the amplified input to the filter 23. The filter 23 is electrically connected to the FPGA 24 and is configured to remove errant frequencies from the amplified alternating current signal. In particular, the filter 23 is configured to remove low frequency components of the AC signal corresponding to the operating frequency (e.g. 85 kHz) of the charging system and higher order harmonics thereof. The filtered signal is then passed onto the FPGA 24. The controller may be implemented as a microcontroller rather than an FPGA in variant embodiments.

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The FPGA 24 includes an impedance measurer, which is configured to sample the magnitude and/or phase of impedance at each of the coils using received signals. The FPGA 24 is configured to pass samples onto the imager 18 (not shown in Figure 11).

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The FPGA 24 is electrically coupled to the voltage controlled current source (VVCS) 25. The VVCS 25 is connected to the second amplifier 26. The FPGA 24 is configured to control the VVCS 25 to provide an AC signal to the second amplifier 26. The second amplifier 26 is also electrically connected to the multiplexor 21 and is configured to amplify the signal received from the VVCS 25 and to provide the

amplified signal to the multiplexor 21. The multiplexor 21 is configured to permit the amplified signal to excite all of the coils 8 for which impedance measurements are to be taken. The coils 8 may be excited continuously or at intervals.

- 5 The FPGA 24 is also connected directly to the multiplexor 21. The FPGA 24 is configured to provide control signals (indicated by a dotted line in Figure 11) to the multiplexor 21 so that the multiplexor 21 selects each of the inputs in turn to enable a return signal from each coil 8 to the FPGA 24 via the first amplifier 22 and the filter 23. The multiplexor 21 is configured to select each of the 64 inputs in response to the control signals to enable the signal from each coil to pass to the first amplifier 22. Thus, samples for each coil can be obtained and forwarded to the imager 18.

Optionally, in some embodiments the FPGA may be configured to determine if greater interference than is acceptable is present in the signal received at the FPGA 24 from the probe 7, 8, which may derive from a magnetic field of the charging system. In this case, the FPGA is determined to modify the frequency used in the MIT. Like the previous frequency used, the modified frequency may be spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz or from about 2 MHz, and/or to about 10 MHz or about 5 MHz or about 4 MHz. The modified frequency may be selected by the FPGA on a random basis. As will be appreciated, the likelihood of interference is greater where the frequency used is closer to the operating frequency of the charging system. Accordingly, in object detection systems using MIT in wireless charging systems where the magnetic field of the charging system interferes with a signal from which magnetic induction data (magnitude and phase) is sampled, frequency modification may be used without limitation to EV charging system. Such frequency modification is known as frequency agility in the art.

Optionally, in some embodiments, a transimpedance circuit may additionally be provided that includes the second amplifier 26. This circuit is for maintaining impedances of the probing devices (e.g. coils).

Optionally, in some embodiments, a matching circuit may be provided for each probing device (e.g. coil). This is to compensate for the power provided to probing devices not being constant because of the effect of eddy currents. Thus, the matching circuit may

comprise inductive and resistive components positioned before each probing device, which is configured to adjust effective inductance and resistance to align input impedance to the probe with a predetermined value.

- 5 Once the inputs have been processed, the imager 18 produces an image 27 of the imaging area probed by the probe 16 using magnetic induction tomography. An example of a two-dimensional image which may be produced by the imager is shown in Figure 12 (although it will be appreciated that three-dimensional images may alternatively or additionally be produced). Specifically, each coil of the probe
- 10 corresponds to one pixel 28 in the image, with darker colouring indicating a greater change in impedance relative to the applied signal. Thus, in Figure 12, it can be seen that an object has been detected close to the coils corresponding to the pixels at the top-left of the image.
- 15 It will be appreciated that, in practice, each coil may correspond to more than one pixel, and thus the image produced by the imager 18 may have more, possibly many more, than 64 pixels in total when a grid arrangement of 8x8 coils is used for the probe.

The relationship between the voltage induced in the probe coil by the magnetic field

20 generated around the object by the eddy current flowing therein and the material properties of the object is non-linear. Accordingly, the imager linearises the relationship between the change in voltage as a function of changes in conductivity or permittivity using a Taylor expansion. This results in equations $\Delta V = J\Delta\sigma$ and $\Delta V = J\Delta\mu$, where ΔV is the change in voltage (in volts), $\Delta\sigma$ is the change in conductivity (in Siemens per metre), $\Delta\mu$ is the change in permittivity (in m^2), and J is the Jacobian matrix

25 determinant. By using the Tikhonov Regularisation, two more equations can be derived for calculating changes in conductivity and permittivity as well. These are $\Delta\sigma = (J^T J + \alpha^2 I)^{-1} J^T \Delta V$ and $\Delta\mu = (J^T J + \alpha^2 I)^{-1} J^T \Delta V$, where α is the regularisation parameter and I is the identity matrix. These equations can thus be used to facilitate

30 production of an image based on the impedances of the probe coils measured by the impedance measurer.

Referring now to Figure 10, an object detection system similar to that described above in relation to Figures 9, 11, and 12 is shown. However, in the object detection system

shown in Figure 10, the wireless electric vehicle charging system comprises a plurality of ground assemblies and a probe is configured as part of each ground assembly, with the processor being configured to receive an input from each probe. The rest of the system is the same as that described above in relation to Figures 9, 11, and 12.

5

In both embodiments, the object detection system additionally comprises a computational modeller 20 configured to receive data from the processor 17 and to evaluate electromagnetic properties of an object present in the imaging area according to the data. This evaluation is performed on the basis of the following equation:

$$10 \quad \nabla \times \frac{1}{\mu} \nabla \times A + j\omega\sigma A = J_s$$

where μ is the permittivity of the object (in m^2), ω is the field angular frequency (in degrees per second), σ is the electrical conductivity (in Siemens per metre), A is the magnetic vector potential (calculated according to the equation $B = \text{curl}(A)$, where B is the magnetic flux density in teslas), J_s is the excitation current density (in amps per m^2), and j is the imaginary operator. In this context, it will be appreciated that $\nabla \times$ means “curl of”. If low frequency excitation of the probe coils is used, then wave propagation effects can be ignored during this evaluation process; this results in an eddy current modelling problem, which is solved using an edge-based finite element model in three dimensions. Since the coils are in close proximity with each other in the 8x8 grid, the magnetic field generated around one coil when alternating current is passed therethrough affects the electromagnetic properties of neighbouring coils within the magnetic field of the one coil. Pairs of coils coupled in this way are said to have mutual inductance. Mutual inductance between pairs of coils in the 8x8 grid is accounted for using the following equation:

$$25 \quad V_R = -j\omega \int A \times J_0 dv$$

where V_R is the induced voltage of the one coil (in volts), j is the imaginary operator, ω is the field angular frequency (in degrees per second), A is the magnetic vector potential (calculated according to the equation $B = \text{curl}(A)$, where B is the magnetic flux density in teslas), J_0 is the current density in the receiving coil (in amps per m^2) and v is the volume of the other coil in the pair (in volts). The alternating current supplied to the probe coils is supplied at a fixed voltage, which means J_0 is known when calculations are performed using this equation.

30

Accordingly, by applying the above equations, the computational modeller is able to calculate various electromagnetic properties of an object detected in the imaging area.

5 As mentioned above, the object detection systems of Figures 9 and 10 each comprise an analyser 19 for analysing the image produced by the imager 18. The analyser uses an artificial intelligence algorithm, such as a U-net convolutional neural network implemented with programming tools such as MATLAB or Python™. The artificial intelligence algorithm is used by the analyser to determine whether an object is
10 present in the imaging area and, if so, to identify the object, i.e. to determine what the object is, and to characterise the object as a WPT coil of the wireless electric vehicle charging system (in cases where this object detection system is used for alignment detection), a foreign object, or a living object.

15 A user may then manually check the accuracy of the identification and/or characterisation by the artificial intelligence algorithm and inform the analyser whether this/these was/were correct. In this manner, the artificial intelligence algorithm is able to be trained using the results of its own analysis, meaning that the algorithm will improve in accuracy over time.

20

It will be appreciated that communication between the various components of these object detection systems are indicated by the arrows in Figures 9 and 10.

A simulation-based investigation was performed to determine whether an object
25 detection system of a wireless electric vehicle charging system of the invention could successfully detect a foreign object, a living object, and the extent of alignment of the WPT coil of the ground assembly and the WPT coil of the vehicle assembly with each other, and whether the object detection system could successfully distinguish between the foreign object, the living object, and the vehicle assembly.

30

The simulation was performed using “Eddy Current NDE Scenario Simulator”, this being an application written for MATLAB and developed by K. Brinker, based on the following research article:

Dodd, C. V. & Deeds, W. E., 1968. *Analytical Solutions to Eddy-Current Probe-Coil Problems*. Journal of Applied Physics, 39(6), p. 2829–2838.S.

5 The foreign object the simulation was performed based on was copper having a conductivity of $58e^6$ S/m and a permeability constant of 1. The living object the simulation was performed based on was biological material having a conductivity of 2 S/m and a permeability constant of 1.

10 To determine the extent of alignment of the WPT coil of the ground assembly and the WPT coil of the vehicle assembly with each other, the object detection system may need to detect at least one feature of the vehicle assembly. Accordingly, the simulation was performed based on detection of a ferrite (PC95) forming part of the vehicle assembly and having a conductivity of $167e^{-3}$ S/m and a permeability constant of 3300.

15 The simulation was used to determine changes in magnitude of impedance and phase through each of the copper, the biological material, and the ferrite. Magnitude of impedance measurements and phase measurements were initially simulated based on detection of the surface of each of these objects. Corresponding measurements based on detection of material at different distances into each of these objects were
20 then simulated, such that 20 measurements (per object) were simulated in total between a depth of 0 mm (i.e. at the surface) and 300 mm.

The simulation was performed based on a probe comprising a single coil having an external diameter of 85 mm, an internal diameter of 10 mm, a height of 1 mm, and
25 20 turns. The coil was simulated as having an inductance of 14.73 μ H and an operating frequency of 3 MHz, and was simulated as being positioned on the upper surface of the ground assembly, i.e. above the WPT coil of the ground assembly.

30 Once all measurements had been simulated, two graphs were produced showing magnitude of impedance and phase profiles for each of the copper, the biological material, and the ferrite. The graph of magnitude of impedance against distance into the material is shown in Figure 13 and the graph of phase against distance into the material is shown in Figure 14.

Referring to Figure 13, the biological material exhibited a unique impedance profile, but the copper and the ferrite (PC95) had very similar impedance profiles. However, referring to Figure 14, the copper, the biological material, and the ferrite all exhibited different phase profiles to each other, meaning that each of these three objects could
5 be distinguished from each other based on their phase profiles using the object detection system.

Thus, the simulation confirmed that an object detection system of a wireless electric vehicle charging system of the invention may be able to detect foreign objects and
10 living objects and to identify and/or characterise such objects.

Referring to Figure 15, in another embodiment an object detection system comprises the probe 16 and the processor 17 described above. Further, the computing component does not include an imager, but instead is in the form of an analyser
15 configured to process the values to determine useful outputs without generation of image or image data.

The processor 17 is configured to provide sampled magnitude and phase values for input to the analyser, which comprises a machine learning ("ML") model. A dataset of
20 values for each coil 7, 8 is provided sequentially, in line with the order in which signals from coils are passed by the multiplexor 21.

The impedance measurer may, each time the multiplexor 21 is controlled to allow a signal from a particular coil 7, 8 to pass to the FPGA 24, sample the signal one or more
25 times to produce a corresponding number of pairs of values for magnitude and phase. These values are all included in a dataset that is provided by the processor 17 to the analyser. For example, a received signal may be sampled 120 times to produce 120 values for magnitude, each having a corresponding phase value. The dataset provided by the processor to the analyser may thus comprise 240 values. The dataset may be
30 provided in a manner or data structure from which the ML model can infer identity of the coil, for example from location of the values in the data structure, or an identifier can be included explicitly in the data structure.

According to embodiments, the ML model may be configured to predict or indicate one or more classes relating to whether an object present in an area of magnetic field transmission has one or more identities and/or characteristics. The identified classes may be a profile. The classes may be or relate to, by way of example only and without
5 limitation, any one, more or all of: the object is formed of metal; the object is formed of biological matter; the object has a minimum dimension greater than a predetermined threshold (e.g. greater than 2 mm); the object has a width and/or length and/or depth above a predetermined threshold or within a predetermined range; the object has a conductivity that is greater and/or lesser than a predetermined threshold value and/or
10 with a predetermined range; the object has permittivity that is greater and/or lesser than a predetermined threshold value or within a predetermined range; the object has permeability that is greater and/or lesser than a predetermined threshold value or within a range; the object is charging coils; the object is charging coils of a particular type (according, for example, to types defined in standards IEC 61980 and SAE
15 J2954); charging coils of a receiver are misaligned with coils of the transmitter by greater than a threshold distance for charging to be permitted; charging coils of a receiver are misaligned with coils of the transmitter by greater than a threshold distance for charging to be permitted in a forward or backwards and/or left or right direction; position of object (e.g. relative to coils). Notably, WPT coils can be
20 recognised by the ML model due to continuous impedance values across them and their specific shapes.

In some embodiments, the object detection system may include a control module (not illustrated in the Figures) that uses stored algorithms to determine further information
25 based on indicated or predicted classes. For example, direction of movement of any object can be determined from change in position. In the same way as described above in relation to a computing component having an imager and an analyser, the outputs of the model may be used by a power manager and/or further processed to indicate to the driver on the display any action required to improve alignment before
30 charging can begin and/or whether an object must be removed from the space before charging can begin.

Further, according to embodiments, the ML model may be configured to predict or indicate one or more classes in the form of operational instructions for the transmitter

of the charging system. The classes may be or relate to, by way of example only and without limitation, any one, more or all of: charging must be stopped; power of charging must be reduced to a predetermined level; power of charging is permitted at normal power; charging must be localised and/or focussed. Further, according to
5 embodiments, the ML model may be configured to predict or indicate one or more classes in the form of operational instructions for the object detection system (or the processor thereof). Such classes may be or relate to: the frequency used in MIT for the coil is to be modified (that is, whether the frequency should be changed to reduce interference); or whether alignment instructions should be provided for a user of the
10 EV.

An ML model in accordance with embodiments, which includes a convolutional neural network ("CNN"), is described below. Embodiments are not limited to this and alternative forms of ML model may be used. In embodiments, the object detection
15 system may include more than one ML model, such models processing the same datasets in parallel to indicate or predict the same or different classes. Such alternative models may include or be based on: an artificial neural network ("ANN"), particularly a feedforward neural network; a nearest centroid model; a k-nearest neighbour model; decision tree-based model; a tree-based ensemble machine learning model (for
20 example random forest); or a support vector machine model. Such models are known to persons skilled in the art. In such an ANN, for example, the input layer is configured to receive the sampled (measured) data provided by the processor 17, together with an identifier of the relevant coil as an index. For example, the ANN may receive 240 values for magnitude and phase as inputs.

25 The ML model that includes a CNN includes a first sub-model (or first set of algorithms) comprising a feature extraction stage and a second sub-model (or second set of algorithms comprising a classification stage. The feature extraction stage comprises the CNN, which comprises a first convolution layer, followed by a first pooling layer,
30 followed by a second convolution layer, which is followed by a second pooling layer. The model includes first and second convolution filters (kernels of size 5x5 with no padding), to extract features from the input data set and the data received by the second convolution layer, respectively. In variant embodiment different sizes of filters may be used, for example 3x3. The first and second pooling layers are each configured

to reduce the amount of data generated by the corresponding convolution layer, while preserving some of the extracted features. The model includes a pooling window size for each of the pooling layers of 2x2. In variant embodiments different window sizes may be used. The first and second pooling layers each use a max pooling technique
5 to select the maximum value from each of the 2x2 regions.

The model is configured to flatten the data output from the second pooling layer so that the data is in a single column. This column (or vector) is a profile for the space. The data is then received as an input to the classification stage which includes a first
10 fully-connected layer, followed by a rectified linear unit (ReLU) layer (not shown) followed by a second fully-connected layer. Each of the first and second fully-connected layers is configured to perform matrix multiplications on the input data. The ReLU layer is configured to provide nonlinear characteristics. Finally, at the output of the second FC layer, the model is configured to apply a softmax function so that
15 indication / predictions made by the model sum to 1 for particular classes.

The model is configured to output predictions or indications regarding presence of, identity of and characteristics of an object between a ground assembly and a vehicle assembly, each prediction relating to a predetermined class. The model is shown as
20 having 10 classes, but embodiments are not limited in this respect.

Referring to Figure 17, in use a dataset comprising values for magnitude and phase is received at the computing component (in the form of the analyser) from the processor 17. The values are received in the analyser at the input layer of the ML
25 model at step 40 in a data structure from which an identifier of the coil is interpretable and also with an indication of the time of the samples. At step 42, the data is processed by the first sub-model to generate a vector for the probed space (and any objects in the space), that is, the vector is processed at the first convolutional layer, the first pooling layer, the second convolutional layer, the second pooling layer and the output
30 of the second pooling layer is flattened to form the vector. At step 44, the vector is processed by the second sub-model, that is, by the fully-connected layer and the model then updates an output value for each class, the output value being indicative of whether that class is true or false. The model will then receive a dataset of values for a next coil from the processor 17 and repeat steps 40 to 44, such that the profile

and outputs of the model are updated repeatedly. After a dataset has been received from all coils, the process is repeated and the processor 17 supplies datasets again for all the coils in turn.

- 5 The model (or an alternative thereto) is trained using a training data. The training data comprises sets (or frames) comprising a dataset for each coil associated with classes known to be correct that were generated when different objects were present and/or when transmitting and receiving WPT coils are in various states of alignment/misalignment and/or when different WPT coils of a receiver were present.
- 10 Each frame is able to be processed by the CNN-based model (or alternative models) to generate predictions / indications in relation to the known objects. Such a dataset enables the model to be trained using conventional backpropagation techniques.

- Such a training dataset can be produced by use of the image generating object
- 15 detection system described herein, which may, for data collection, be deployed in a real-world scenario or in a laboratory where various objects are located in the imaging area. Further, the quality of such a training dataset can be improved by use of a camera-based object classification system that records images of objects for which the image generating object detection system takes frames, and classifies the objects
- 20 using conventional image processing techniques known to the skilled person outside the scope of this disclosure.

- It should be noted that embodiments in which magnitude and phase values are input to an ML model are not limited to use in an objection detection system using magnetic
- 25 induction tomography at any particular operating frequency – there is no requirement for the system to be used at from about 1 MHz to about 10 MHz, for example. Embodiments may be used at higher or lower frequencies, particularly where there is no requirement to capture information on both LOD, and FOD and alignment. Further, embodiments are also not limited to use of an ML model in accordance with
- 30 embodiments in a charging scenario.

An example implementation of the computational component is now described with reference to Figure 18. Such a computational component may be implemented by a computing system implemented in any other suitable hardware, software, and/or

firmware, or a combination thereof. Such a computer system may be implemented locally to the probe, remotely, or functionality may be distributed with some located locally and some remotely, or functionally distributed across a plurality of remote locations.

5

The computing system 100 may comprise various hardware components including one or more single or multi-core processors represented by a processor 102, a computer readable information storage medium such as a solid-state drive 104, another computer readable information storage medium such as a ROM/RAM 106 and
10 a communications (input/output) interface 108. The computing system 100 may be an "off the shelf" generic computing system. Some embodiments including a neural network may benefit from a processor such as an NUC by Intel, RAM of at least 16 gigabytes and a memory 106 capable of storing large amounts of data.

15 Communication between the various components of the computing system 100 may be enabled by one or more buses 110 (e.g. a PCI bus, universal serial bus), to which the various hardware components are electronically coupled.

The input/output interface 108 may allow networking capabilities such as wire or
20 wireless access. As an example, the input/output interface 108 may comprise a networking interface such as, but not limited to, a network port, a network socket, a network interface controller and the like. Multiple examples of how the networking interface may be implemented will become apparent to the person skilled in the art of the present technology. The solid-state drive 104 may store program instructions, such
25 as those part of suitable for being loaded into the memory 106 and executed by the processor 102 for the methods described herein.

MIT is well known for use in non-destructive inspection where conductivity or permeability distributions can yield relevant information, for example in biomedical
30 imaging, manufacturing, fields of oil and gas. The probe is intended for location in a ground assembly and the model is trained to indicate presence and/or characteristics of objects between a ground assembly and a vehicle assembly and/or alignments of coils for WPT, but embodiments of the invention are not limited to such.

Parts List

- | | |
|-------|--|
| 1 | wireless electric vehicle charging system |
| 2 | power source |
| 3 | WPT coil of ground assembly |
| 5 4 | WPT coil of vehicle assembly |
| 5 | electric vehicle |
| 6 | imaging area |
| 7 | single coil |
| 8 | plurality of coils |
| 10 9 | ferrite assembly |
| 10 | magnetic field generated around probe |
| 11 | object |
| 12 | eddy current |
| 13 | magnetic field generated around eddy currents flowing through object |
| 15 14 | plate |
| 15 | object detection system |
| 16 | probe |
| 17 | processor |
| 18 | imager |
| 20 19 | analyser |
| 20 | computational modeller |
| 21 | multiplexor |
| 22 | amplifier for amplifying received input |
| 23 | filter |
| 25 24 | field-programmable gate array / microcontroller |
| 25 | voltage controlled current source |
| 26 | amplifier for amplifying transmitted signal |
| 27 | image |
| 28 | pixel |
| 30 29 | computing component |
| 102 | processor |
| 104 | storage medium |
| 106 | ROM/RAM |
| 108 | communications interface |

110 buses

Claims

1. An object detection system for a wireless electric vehicle charging system, for generating of data for foreign and/or living objects, using magnetic induction tomography at a frequency that is spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz to about 10 MHz.
2. The object detection system of claim 1, wherein the object detection system is configured to operate at about 1 MHz to about 5 MHz.
3. The object detection system of claim 1 or claim 2, configured to, using such data, produce a computationally generated profile and/or detect possible presence and/or determine the identity and/or characteristics of a metal and/or living object in an area of magnetic field transmission and/or generate operational instructions.
4. The object detection system of any one of the preceding claims, comprising:
a probe for probing the area or space; and
a processor configured to:
(i) receive inputs from the probe, and
(ii) produce the data according to the inputs.
5. The object detection system of claim 4, wherein the processor includes a filter configured to remove from the input signals components of frequency corresponding to the operating frequency of the charging system and optionally higher order harmonics thereof.
6. The object detection system of claim 4 or claim 5, wherein the processor is configured to modify the operating frequency of the object detection system to reduce interference from a magnetic field of the charging system, wherein the modified operating frequency is spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz and to about 10 MHz.

7. The object detection system of any one of claims 4 to 6, wherein the probe is stationary with respect to a ground assembly comprising a magnetic field transmitter or a vehicle assembly comprising a magnetic field receiver.
- 5 8. The object detection system of any one of claims 4 to 7, further comprising an analyser for determining, based on processing of the data, whether an object is present in the area and/or the identity and/or the characteristics of an object and/or an operational instruction.
- 10 9. The object detection system of claim 8, wherein the analyser includes a machine learning model configured to receive the data at an input layer and to process the data to determine, based on processing of the data, whether an object is present in the area and/or the identity and/or the characteristics of an object and/or an operational instruction.
- 15 10. The object detection system of claim 8, further comprising an imager, wherein the imager is configured to receive data from the processor, and produce an image of the area according to the data, wherein the computationally generated profile is the image, wherein the imager is configured to produce the image using magnetic induction tomography, and wherein the analyser is configured to analyse the image to determine whether an object is present in the area and/or the identity and/or the characteristics of an object and/or an operational instruction.
- 20 11. The object detection system of claim 10, wherein the analyser is configured to analyse the image using an artificial intelligence algorithm.
- 25 12. The object detection system of claim 10 or claim 11, wherein the object detection system additionally comprises a computational modeller configured to receive data from the processor and to evaluate electromagnetic properties of an object present in the imaging area according to the data.
- 30 13. The object detection system of any one of the preceding claims, further comprising a power manager configured to manage a power supply to a wireless power transfer coil of the wireless electric vehicle charging system according to

whether an object is determined as present in the imaging area and/or according to identification and/or characterisation of the object.

14. The object detection system of claim 13, wherein the power manager is
5 configured to manage the power supply by reducing the power supply while continuing to supply power for charging and/or modifying the power supply by focussing or localising the power supply.

15. The object detection system of any one of the preceding claims, wherein the
10 object detection system is configured to produce a computationally generated profile and/or detect possible presence and/or determine the identity and/or characteristics of an object while the charging system performs charging.

16. The object detection system of claim 15, wherein the charging system operates
15 at less than 500 kHz.

17. A charging system comprising the object detection system of any one of the preceding claims.

20 18. An electric vehicle comprising an object detection system of any one of claims 1 to 16.

19. A method of producing data for a foreign or living object in an area of magnetic field transmission in a wireless electric vehicle charging system, the method
25 comprising using magnetic induction tomography at a frequency that is spectrally distanced from an operating frequency of the charging system and/or from about 1 MHz to about 10 MHz.

20. A method of modifying a power supply to a wireless power transfer coil of a
30 wireless electric vehicle charging system, the method comprising using magnetic induction tomography to make a determination, about whether an object is present and/or about characteristics and/or identity of an object or to produce a profile of the object, in an area of magnetic field transmission in the wireless electric vehicle

charging system, and modifying and/or varying the power supply suitably according to the determination or the profile.

21. The method of claim 20, wherein the modifying and/or varying the power supply
5 comprises reducing the power supply while continuing to supply power for charging.

22. An object detection system for modifying a power supply to a wireless power
transfer coil of a wireless electric vehicle charging system, configured to use magnetic
induction tomography to make a determination, about whether an object is present
10 and/or about characteristics and/or identity of an object or to produce a profile of the
object, in an area of magnetic field transmission in the wireless electric vehicle
charging system, and to suitably modify and/or vary the power supply, suitably
according to the determination or the profile.

15 23. An object detection system comprising at least one coil printed on a circuit
board, the at least one coil being for use in magnetic field generation and/or impedance
change detection in a magnetic induction tomography process.

24. The object detection system of claim 23, wherein the at least one coil comprises
20 a plurality of coils.

25. A wireless electric vehicle charging system comprising the object detection
system of claim 23 or claim 24, wherein the printed circuit board is in a fixed position
in a ground assembly for use in object detection in an area of magnetic field
25 transmission.

26. The wireless electric vehicle charging system of claim 25, wherein the coils are
located on a side of transmitting coils of the ground assembly remote from where an
electric vehicle is located when located for charging.

30 27. The wireless electric vehicle charging system of claim 26, wherein the coils are
located between the transmitting coils and a ferrite assembly.

28. The charging system of claim 27, wherein the ferrite assembly at least partially encloses the at least one coil on the circuit board.

29. The charging system of claim 28, wherein the ferrite assembly comprises a concave receptacle comprising a ferrimagnetic material, for focussing and/or directing a magnetic field generated around or by a magnetic field transmitter.

30. A method in a detection process using magnetic induction tomography, comprising using at least one coil printed on a circuit board in magnetic field generation and/or impedance change detection.

31. A computer-implemented method comprising:
receiving at a machine learning ("ML") model one or more datasets comprising values representing magnitude and phase of impedance or changes thereof at a probe used in a magnetic induction tomography-based process for probing a space;
processing of the values by the ML model to generate or update information indicative of or a prediction for presence, identity and/or at least one characteristic of an object in the space and/or an operational instruction.

32. The method of claim 31, wherein the one or more datasets are received at an input layer of the ML model.

33. The method of claim 32, where the one or more data sets comprise a plurality of the datasets, values in each dataset relating to impedance at one of a plurality of probing devices of the probe.

34. The method of claim 33, wherein the probing devices are in fixed relative positions, and each dataset uniquely identifies the probing device to which its values relate.

35. The method of claim 33 or claim 34, wherein each dataset comprises a plurality of values representative of a plurality of values for magnitude and corresponding values for phase for impedance of the respective probing device.

36. The method of any one of claims 33 to 35, where the receiving comprises receiving the datasets sequentially from each of the probing devices, wherein the processing comprises processing each received data set and updating the information
5 or prediction based on the respective data set.

37. The method of any one of claims 33 to 36, wherein each dataset includes information indicative of sampling time of the values in the dataset.

10 38. The method of any one of claims 33 to 37, wherein the ML model comprises a trained deep learning model, wherein the receiving comprises receiving the datasets at an input layer of the deep learning algorithm.

39. The method of claim 38, wherein the deep learning model comprises first and
15 second portions, wherein the processing comprises: processing each dataset by the first portion to generate a data structure for the space or an object in the space; and processing the data structure to generate or update the output information.

40. The method of claim 39, wherein the first portion includes a neural network sub-
20 model, wherein the processing of each dataset by the first portion comprises processing of each dataset by the neural network.

41. The method of claim 40, wherein the neural network based sub-model comprises a convolutional neural network ("CNN"), wherein the processing of each
25 dataset by the first portion comprises processing of each dataset by the CNN.

42. The method of any one of claims 39 to 41, wherein the second portion is a classification sub-model, wherein the processing of the data structure by the classification sub-model includes processing the data structure to provide the
30 information, wherein the information is indicative of or a prediction of at least one class.

43. The method of any one of claims 31 to 42, wherein the information or prediction is indicative of and/or based on inference by the model of relative position, shape, size, conductivity, permittivity and/or permeability.

44. The method of any one of claims 31 to 43, wherein the operational instruction is at least one of:

- a control instruction for the power supply to the WPT coil;
- 5 alignment instruction for communication to the driver.

45. The method of any one of claims 31 to 44, further comprising:
determining, based on the information or prediction for presence, identity and/or
at least one characteristic, an operational instruction.

10

46. Apparatus comprising:

- a probe;
- a computing component comprising processing means and a memory storing
computer program code, wherein the processing means and the memory with the code
15 is configured to perform the method of any one of claims 31 to 45, wherein the datasets
are from signals generated at the probe.

47. A computer program product comprising computer program code which, when
executed by a computer, is configured to cause the computer to carry out the method
20 of any one of claims 31 to 45.

48. An object detection system for a wireless charging system comprising a
processor configured to:

- cause magnetic field generation at a first frequency for a magnetic induction
tomography-based process;
- 25 make a determination about extent of interference in a signal received from a
probe used in the magnetic induction tomography-based process; and
- cause magnetic field generation at a second frequency different from the first
frequency for the magnetic induction tomography-based process dependent on the
30 determination.