

A WIRELESS POWER TRANSFER DEVICE**CROSS REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority to Singapore patent application no. 10202400647V which was filed on 8 March 2024, the contents of which are hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to a wireless power transfer device that comprises two sets of electrical coils that are arranged around a cubic-shaped housing to generate a uniform magnetic field within the housing when the two sets of electrical coils are energized. The arrangement of the electrical coils is such that the first set of electrical coils are disposed along a first central axis of the cubic-shaped housing and the second set of electrical coils are disposed along a second central axis of the cubic-shaped housing, where the first central axis and the second central axis are perpendicular to each other.

BACKGROUND

[0003] Due to advancements in technology, wireless power transfer systems have evolved from planar configurations to spatial configurations. Such a configuration is advantageous as it is able to alleviate the challenges introduced by issues such as misalignment, thermal dissipation, and complex driving circuits. In particular, spatial wireless power transfer systems provide a more robust solution by enabling energy transfer across three-dimensional spaces, thereby alleviating the need for precise alignment between transmitter and receiver.

[0004] One spatial wireless power transfer transmitter design that is widely adopted by those skilled in the art is the Helmholtz coil design and this design is commonly used in medical equipment, aerospace applications, and microrobots. The Helmholtz coil typically comprises coaxial circular coils that generate an evenly distributed magnetic flux density within a defined spatial region. Experimental prototypes proposed by those skilled in the art have demonstrated consistent flux distribution across multiple layers of space, showcasing the system's capability for uniform magnetic field generation.

[0005] Those skilled in the art have also proposed alternative spatial wireless power transfer designs such as a three-dimensional spherical transmitter structure that employs a rotational control method for the transmitter currents to homogenize the magnetic flux density. Similarly, bowl-shaped transmitter designs were also proposed and engineered to provide uniform magnetic field intensity near the surface of the transmitter. However, these curved-surface-based structures present manufacturing challenges due to the complexity of crafting the curved surfaces and winding the coils, limiting their practical applicability.

[0006] Another approach proposed by those skilled in the art are prismatic-based spatial wireless power transfer transmitters and these designs are preferred due to their ease of construction and coil winding. Such transmitters were found to be versatile and have been applied in diverse scenarios such as underwater vessels, automated lawnmowers, and room-scale wireless charging systems. One notable example of a prismatic-based spatial WPT design is the wireless charging room where in this configuration, a central pole, often constructed using a copper pillar with a tunable gap to form an LC resonator, compensates for weak magnetic flux generated by surface currents. It has also been suggested that aluminum sheets be used to direct surface currents and enhance magnetic field generation. However, while these designs may appear to be effective, these designs often require additional structural components, such as the central pole, to address flux distribution challenges.

[0007] As such, those skilled in the art are constantly striving to find ways to address the limitations of curved-surface and prismatic-based transmitters while optimizing spatial wireless power transfer system's performance for a broader range of applications.

SUMMARY

[0008] In one aspect, the present disclosure describes a wireless power transfer device comprising a first set of electrical coils disposed along a first central axis of a cubic-shaped housing. The first set of electrical coils comprises a first primary coil and a first electrical sub-coil, wherein the first electrical sub-coil is nested within the first primary coil in a same plane as the first primary coil, a second primary coil and a second electrical sub-coil, wherein the second electrical sub-coil is nested within the second primary coil in a same plane as the second primary coil, wherein the first and second primary coils are disposed on different planes that are parallel to each other, and whereby the first set of electrical coils is configured to generate

a first uniform magnetic field between the first primary coil and the second primary coil when the first set of electrical coils are electrically driven. The device also comprises a second set of electrical coils disposed along a second central axis of the cubic-shaped housing, the second central axis being perpendicular to the first central axis. The second set of electrical coils comprise a third primary coil and a third electrical sub-coil, wherein the third electrical sub-coil is nested within the third primary coil in a same plane as the third primary coil, a fourth primary coil and a fourth electrical sub-coil, wherein the fourth electrical sub-coil is nested within the fourth primary coil in a same plane as the fourth primary coil, wherein the third and fourth primary coils are disposed on different planes that are parallel to each other, and whereby the second set of electrical coils is configured to generate a second uniform magnetic field between the third primary coil and the fourth primary coil when the second set of electrical coils are electrically driven.

[0009] In a further embodiment of this aspect, the first set of electrical coils further comprises a first relay coil that is disposed on a different plane from the first and second primary coils, and wherein the first relay coil is positioned equidistant between the first and the second primary coils, and wherein the second set of electrical coils further comprises a second relay coil that is disposed on a different plane from the third and fourth primary coils, and wherein the second relay coil is positioned equidistant between the third and the fourth primary coils.

[0010] In a further embodiment of this aspect, the first set of electrical coils further comprises a first plurality of relay coils, each of the first plurality of relay coils being disposed on a plane different from each other and from the planes of the first and second primary coils, and wherein the first plurality of relay coils are positioned between the first and second primary coils such that all the coils in the first set of electrical coils are equidistant apart, and wherein the second set of electrical coils further comprises a second plurality of relay coils, each of the second plurality of relay coils being disposed on a plane different from each other and from the planes of the third and fourth primary coils, and wherein the second plurality of relay coils are positioned between the third and fourth primary coils such that all the coils in the second set of electrical coils are equidistant apart.

[0011] In a further embodiment of this aspect, the first primary coil is wound around edges of a first surface of the cubic-shaped housing, the second primary coil is wound around edges of a second surface of the cubic-shaped housing, the third primary coil is wound around edges of a third surface of the cubic-shaped housing, and the fourth primary coil is wound around edges of a fourth surface of the cubic-shaped housing.

[0012] In a further embodiment of this aspect, the first set of electrical coils further comprises a first U-shaped relay coil comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil; a second U-shaped relay coil comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil; wherein the second set of electrical coils further comprises: a third U-shaped relay coil comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil; a fourth U-shaped relay coil comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil.

[0013] In a further embodiment of this aspect, the first set of electrical coils further comprises a first plurality of sets of U-shaped relay coils, each set comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments

and parts of the first and second segments overlap with parts of the first primary coil, wherein the first and second segments of each of the first plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; a second plurality of sets of U-shaped relay coils, each set comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil; wherein the third and fourth segments of each of the second plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; wherein the second set of electrical coils further comprises: a third plurality of sets of U-shaped relay coils, each set comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil; wherein the fifth and sixth segments of each of the third plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; a fourth plurality of sets of U-shaped relay coils, each set comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil; and wherein the seventh and eighth segments of each of the fourth plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil.

[0014] In another aspect, the present disclosure describes a method for wirelessly transferring power using a device having a cubic-shaped housing, the method comprising the steps of providing a first set of electrical coils along a first central axis of the cubic-shaped housing, the first set of electrical coils comprising a first primary coil and a first electrical sub-coil, wherein the first electrical sub-coil is nested within the first primary coil in a same plane, a second primary coil and a second electrical sub-coil, wherein the second electrical sub-coil is nested within the second primary coil in a same plane, and wherein the first and second primary coils are disposed on different planes. The method then comprises the step of electrically driving the first set of electrical coils to generate a first uniform magnetic field

between the first primary coil and the second primary coil. The method then provides a second set of electrical coils along a second central axis of the cubic-shaped housing, the second central axis being perpendicular to the first central axis, the second set of electrical coils comprising a third primary coil and a third electrical sub-coil, wherein the third electrical sub-coil is nested within the third primary coil in a same plane, a fourth primary coil and a fourth electrical sub-coil, wherein the fourth electrical sub-coil is nested within the fourth primary coil in a same plane, wherein the third and fourth primary coils are disposed on different planes, and electrically driving the second set of electrical coils to generate a second uniform magnetic field between the third primary coil and the fourth primary coil.

[0015] In a further embodiment of this another aspect, the method further comprises the steps of connecting a first driving circuit to the first set of electrical coils, providing, using the first driving circuit, a sinusoidal current to drive the first set of electrical coils, connecting a second driving circuit to the second set of electrical coils, and providing, using the second driving circuit, a cosinusoidal current to drive the second set of electrical coils, wherein the sinusoidal and cosinusoidal currents are phase-shifted by 90 degrees such that a rotating magnetic field is generated within the cubic-shaped housing by the driven first and second sets of electrical coils.

[0016] In a further embodiment of this another aspect, the method further comprises the steps of connecting a first capacitor to the first set of electrical coils, wherein a value of the first capacitor is based on a self-inductance parameter of the first set of electrical coils and a resonant frequency, and connecting a second capacitor to the second set of electrical coils, wherein a value of the second capacitor is based on a self-inductance parameter of the second set of electrical coils and the resonant frequency.

[0017] In a further embodiment of this another aspect, the first set of electrical coils further comprises a first U-shaped relay coil comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil; a second U-shaped relay coil comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface

of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil; wherein the second set of electrical coils further comprises: a third U-shaped relay coil comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil; a fourth U-shaped relay coil comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil.

[0018] In a further embodiment of this another aspect, the first set of electrical coils further comprises a first plurality of sets of U-shaped relay coils, each set comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil, wherein the first and second segments of each of the first plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; a second plurality of sets of U-shaped relay coils, each set comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil; wherein the third and fourth segments of each of the second plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; wherein the second set of electrical coils further comprises: a third plurality of sets of U-shaped relay coils, each set comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil;

wherein the fifth and sixth segments of each of the third plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil; a fourth plurality of sets of U-shaped relay coils, each set comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil; and wherein the seventh and eighth segments of each of the fourth plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Various embodiments of the present disclosure are described below with reference to the following drawings:

Figure 1 illustrates a structural diagram illustrating the windings of the electrical coils of a wireless power transfer device in accordance with embodiments of the present disclosure;

Figure 2a illustrates a structural diagram illustrating the labels of the electrical coils of a wireless power transfer device along a central y-axis of the housing of the device in accordance with embodiments of the present disclosure;

Figure 2b illustrates a structural diagram illustrating the labels of the electrical sub-coils nested within a corresponding electrical coil of a wireless power transfer device along a central y-axis of the housing of the device in accordance with embodiments of the present disclosure;

Figure 3a illustrates a structural diagram illustrating the labels of the electrical coils of a wireless power transfer device along a central x-axis of the housing of the device in accordance with embodiments of the present disclosure;

Figure 3b illustrates a structural diagram illustrating the labels of the electrical sub-coils nested within a corresponding electrical coil of a wireless power transfer device along a central x-axis of the housing of the device in accordance with embodiments of the present disclosure;

Figure 4 illustrates a structural diagram illustrating the windings of the electrical coils of the wireless power transfer device when a plurality of electrical coils are positioned between the first and second electrical coils that are disposed along a central y-axis of the housing of the device in accordance with embodiments of the disclosure;

Figure 5 illustrates a structural diagram illustrating the windings of the electrical coils of the wireless power transfer device when a plurality of electrical coils are positioned between the

first and second electrical coils that are disposed along a central x-axis of the housing of the device in accordance with embodiments of the disclosure;

Figure 6 illustrates four structural diagrams illustrating the windings of the electrical coils of the wireless power transfer device for four variations of winding structures in accordance with embodiments of the disclosure;

Figure 7 illustrates an image of an exemplary three-dimensional cubic-shaped housing in accordance with embodiments of the disclosure;

Figure 8 illustrates a winding structure of a continuous electrical coil that make up three different electrical coils with key points on the continuous electrical coil being labeled;

Figure 9 illustrates label key points on the continuous electrical coil when the continuous electrical coil is laid out as a single continuous wire;

Figure 10a illustrates a first part of a table that illustrates the simulated magnetic flux densities in three dimensions;

Figure 10b illustrates a second part of the table that illustrates the simulated magnetic flux densities in three dimensions;

Figure 10c illustrates a final part of the table that illustrates the simulated magnetic flux densities in three dimensions;

Figure 11a illustrates a plot of the coefficient of variation (CoV) for various electrical coil configurations and various sizes of nested electrical sub-coils;

Figure 11b illustrates a plot of the coefficient of variation (CoV) for various electrical coil configurations;

Figure 12 illustrates an image of an exemplary wireless power transfer device in accordance with embodiments of the disclosure;

Figure 13 illustrates an experimental setup in accordance with embodiments of the disclosure;

Figure 14 illustrates areas that were scanned in accordance with the experimental setup shown in Figure 13;

Figure 15 illustrates a schematic diagram of the testing points and testing areas in each layer that was scanned as shown in Figure 14;

Figure 16 illustrates a magnetic field distribution of the four layers illustrated in Figure 14;

Figure 17a illustrates an image of a cubic wireless charging container based on a Helmholtz coil;

Figure 17b illustrates an image of a cubic wireless charging container based on a conventional optimal folded coil design;

Figure 18a illustrates measured voltages at a $z=40\text{mm}$ plane for the cubic wireless charging container design based on the Helmholtz coil as shown in Figure 17a and for the cubic wireless charging container design based on the conventional folded coil design as shown in Figure 17b; Figure 18b illustrates measured voltages at a $z=40\text{mm}$ plane for a wireless power transfer device in accordance with embodiments of the disclosure;

Figure 19 illustrates a bar chart showing the differences between the coefficient of variation (CoV) for the cubic wireless charging container design based on the Helmholtz coil as shown in Figure 17a, for the cubic wireless charging container design based on the conventional folded coil design as shown in Figure 17b and for a wireless power transfer device in accordance with embodiments of the disclosure, when the z plane is varied between 40mm and 160mm;

Figure 20 illustrates a flowchart showing the process for wirelessly transferring power using a device having a cubic-shaped housing in accordance with embodiments of the disclosure;

Figure 21 illustrates an embodiment of the wireless power transfer device comprising U-shaped relay coils;

Figure 22 illustrates an embodiment of the wireless power transfer device having one set of U-shaped relay coils along a central y -axis of the housing of the device and a top view of the device;

Figure 23 illustrates a plot of the coefficient of variation (CoV) for various U-shaped relay coil configurations;

Figure 24 illustrates a flowchart of a two-stage multi-objective process for optimizing the U-shaped relay coil configuration based on a Simulated Annealing (SA) algorithm;

Figure 25 illustrates the optimization results for minimal CoV and the corresponding average magnetic flux density is maximized;

Figure 26a illustrates the results when total coil length L_{total} is minimized;

Figure 26b illustrates the results when a low uniformed CoV is achieved;

Figure 26c illustrates the results when average magnetic flux density μ is maximized;

Figure 27a illustrates a perspective view of an embodiment of the wireless power transfer device with three sets of U-shaped relay coils;

Figure 27b illustrates a top view of the embodiment illustrated in Figure 27a, along the x - y plane;

Figure 27c illustrates a front view of the embodiment illustrated in Figure 27a, along the x - z plane;

Figure 27d illustrates a vector of the magnetic field at a time instant of $\omega t = 0$;

Figure 27e illustrates a vector of the magnetic field at a time instant of $\omega t = \pi/4$;

Figure 27f illustrates a vector of the magnetic field at a time instant of $\omega t = \pi/2$;

Figure 27g illustrates a vector of the magnetic field at a time instant of $\omega t = 3\pi/4$;

Figure 27h illustrates a vector of the magnetic field at a time instant of $\omega t = \pi$;

Figure 28a illustrates a cubic wireless charging container based on a Helmholtz coil configuration;

Figure 28b illustrates a wireless power transfer device comprising three sets of U-shaped relay coils in accordance with embodiments of the disclosure;

Figure 29a illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 100 mm from the base of the container;

Figure 29b illustrates the measured magnetic field distribution for the wireless power transfer device comprising three sets of U-shaped relay coils as illustrated in Figure 28b when the measurement was carried out at a height of 100 mm from the base of the device;

Figure 29c illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 133 mm from the base of the container;

Figure 29d illustrates the measured magnetic field distribution for the wireless power transfer device comprising three sets of U-shaped relay coils as illustrated in Figure 28b when the measurement was carried out at a height of 133 mm from the base of the device;

Figure 29e illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 166 mm from the base of the container; and

Figure 29f illustrates the measured magnetic field distribution for the wireless power transfer device comprising three sets of U-shaped relay coils as illustrated in Figure 28b when the measurement was carried out at a height of 166 mm from the base of the device.

DETAILED DESCRIPTION

[0020] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as

described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0021] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0022] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0023] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0024] As used herein, “comprising” means including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0025] As used herein, “consisting of” means including, and limited to, whatever follows the phrase “consisting of”. Thus, use of the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0026] In the context of various embodiments, the directional terms mentioned herein, such as “top” and “bottom” or “upper” and “lower” refer to directions as described with reference to the drawings. Therefore, the directional terms are only used for illustration and are not meant to limit the present disclosure.

[0027] In the context of various embodiments, the arrangements of the central axes mentioned herein, such as a first central refers to an imaginary straight line that extends along one principal direction of a cubic-shaped housing. This axis is typically chosen to coincide with one of the orthogonal edges of the cubic structure (e.g., the Z-axis, X-axis or Y-axis). A second central axis is another imaginary straight line that is perpendicular to the first central axis and aligned with another principal direction of the cubic-shaped housing. Together, these axes may

be used to define the spatial orientation of electrical coils that may be wrapped around the cubic-shaped housing.

[0028] It should be noted that although the terms first, second and third are used herein to describe various elements, these elements should not be limited by these terms as these terms are meant to only distinguish one element from another element. Thus, the first element described herein could be termed as a second element without departing from this disclosure.

[0029] A cubic-shaped wireless power transfer (WPT) device 100 is illustrated in Figure 1. WPT device 100 comprises two orthogonally arranged sets of electrical coils. The first set of electrical coils, depicted with solid lines, comprises electrical coil set 102 that is aligned along a first central axis of a cubic-shaped housing (not shown) of WPT device 100. The second set of electrical coils, depicted with dashed lines, comprises electrical coil set 104 that is aligned along a second central axis of the cubic-shaped housing such that the second central axis is perpendicular to the first central axis. To provide clarity and to avoid electrical coil sets 102 and 104 from obscuring the central axes lines, the first central axis of the cubic-shaped housing is illustrated in Figure 2a as axis 201 and the second central axis of the cubic-shaped housing is illustrated in Figure 3a as axis 301. The cubic-shaped housing (which is not shown in Figure 1) is structured such that it facilitates efficient and uniform magnetic field generation within the enclosed space when the electrical coil sets 102 and 104 are driven and energized.

[0030] As illustrated in Figure 1, electrical coil set 102 is arranged such that the two electrical coils of electrical coil set 102 reside in the Z-X planes of the cubic-shaped housing, i.e., the first and second primary coils. In this embodiment, electrical coil set 102 comprises two electrical coils, i.e., two primary coils, that are positioned on different Z-X planes and these two coils are parallel to each other, with one coil wrapped around a front surface of the cubic-shaped housing and the other wrapped around a rear surface of the cubic-shaped housing, ensuring they are spatially separated along the Y-axis. Similarly, electrical coil set 104 is arranged in the Z-Y planes and comprise of two separate coils that reside on different Z-Y planes, i.e., the third and fourth primary coils, with these two coils being parallel to one another and spatially separated along the X-axis. This arrangement causes the magnetic fields generated by electrical coil sets 102 and 104 to interact orthogonally when these electrical coil sets are energized.

[0031] Figure 2a and Figure 2b illustrate the configuration of electrical coil set 102 in WPT device 100 where it is shown that electric coil set 102 is provided along first central axis 201. In embodiments of the disclosure, electrical coil set 102 comprises a first primary coil formed by segments 202a, 202b, 202c, 202d, and 202e, which together define a square-shaped loop in the Z-X plane. The first primary coil has a square shape as it is wrapped around the edges of the front surface of the cubic-shaped housing of WPT device 100.

[0032] Electrical coil set 102 also comprises a second primary coil formed by segments 212a, 212b, 212c, 212d, and 212e, which together also define a square-shaped loop in the Z-X plane. The second primary coil also has a square shape as it is wrapped around the edges of the rear surface of the cubic-shaped housing of WPT device 100. It should be noted that the first and second primary coils are designed to have similar areas and align with each other to ensure that a consistent and uniform magnetic field may be generated along first central axis 201, i.e., along the y-axis, between these two coils. Electrical coil set 102 also includes segment 212f that is electrically coupled to an end of segment 212e. The open ends (or unconnected ends) of segments 212f and 202a may be used to connect electrical coil set 102 to a driving circuit so that current may be excited through electrical coil set 102. In embodiments of the disclosure, segment 212f may be omitted, in which case the open ends of segments 212e and 202a may be directly connected to the driving circuit to achieve the same functionality.

[0033] Figure 2b focuses on a first electrical sub-coil which is nested within or confined within the first primary coil. The first electrical sub-coil comprises of segments 204, 205, 206 and 207, which together define a rectangular-shaped loop in the Z-X plane. A second electrical sub-coil which is nested within the second primary coil is also shown in Figure 2b. The second electrical sub-coil comprises of segments 214, 215, 216 and 217, which together define a rectangular-shaped loop in the Z-X plane. The dimensions of segments 205, 207, 215 and 217 may be varied, with these segments having a maximum length that is defined by the length of segments 202e and 212e as shown in Figure 2a.

[0034] The electrical sub-coils that are nested within the first and second primary coils enhance the performance and flexibility of the WPT device 100 by improving magnetic field uniformity along first central axis 201. These nested electrical sub-coils, defined by segments

204, 205, 206, 207 and segments 214, 215, 216, 217 that are confined within the first and second primary coils respectively, generate supplementary magnetic fields that complement the primary fields generated by the electrical coils, resulting in a denser and more uniform magnetic flux. Further, the adjustable dimensions of the sub-coil segments allow fine-tuning of the field strength, making WPT device 100 adaptable to different receiver configurations.

[0035] Figure 3a and Figure 3b illustrate the configuration of electrical coil set 104 in WPT device 100 where it is shown that electric coil set 104 is provided along second central axis 301 which is perpendicular to first central axis 201. In embodiments of the disclosure, electrical coil set 104 comprises a third primary coil formed by segments 302a, 302b, 302c, 302d, and 302e, which together define a square-shaped loop in the Z-Y plane. The third primary coil has a square shape as it is wrapped around the edges of a side surface of the cubic-shaped housing of WPT device 100.

[0036] Electrical coil set 104 also comprises a fourth primary coil formed by segments 312a, 312b, 312c, 312d, and 312e, which together also define a square-shaped loop in the Z-Y plane. The fourth primary coil also has a square shape as it is wrapped around the edges of another side surface of the cubic-shaped housing of WPT device 100. It should be noted that the third and fourth primary coils are also designed to have similar areas and align with each other to ensure that a consistent and uniform magnetic field may be generated along second central axis 301, i.e., along the x-axis. Electrical coil set 104 also includes segment 312f that is electrically coupled to an end of segment 312e. The open ends of segments 312f and 302a may be used to connect electrical coil set 104 to a driving circuit so that current may be excited through electrical coil set 104. In embodiments of the disclosure, segment 312f may be omitted, in which case the open ends of segments 312e and 302a may be directly connected to the driving circuit to achieve the same functionality.

[0037] Figure 3b illustrates a third electrical sub-coil which is nested within or confined within the third primary coil. The third electrical sub-coil comprises of segments 304, 305, 306 and 307, which together define a rectangular-shaped loop in the Z-Y plane. A fourth electrical sub-coil which is nested within the fourth primary coil is also shown in Figure 3b. The fourth electrical sub-coil comprises of segments 314, 315, 316 and 317, which together define a rectangular-shaped loop in the Z-Y plane. The dimensions of segments 305, 307, 315 and 317

may be varied, with these segments having a maximum length that is defined by the length of segments 302e and 312e as shown in Figure 3a.

[0038] The electrical sub-coils that are nested within the third and fourth primary coils similarly enhance the performance and flexibility of the WPT device 100 by improving magnetic field uniformity along second central axis 301 by allowing fine-tuning of the field strength and making WPT device 100 adaptable to different receiver configurations.

[0039] Figure 4 illustrates an embodiment whereby an additional electrical coil, i.e., a relay coil, is provided between the two primary (i.e., a first and a second) coils with all three electrical coils aligned along a central y-axis of the cubic-shaped housing of WPT device 100. Each of the square-shaped electrical coils have sides of length l and the primary electrical coils overlap with their respective nested electrical sub-coils with a length d , where $0 \leq d \leq l$. It can be seen that relay coil 404 is centrally positioned between primary coils 402 and 406 ensuring that relay coil 404 is equidistant between primary coils 402 and 406. Specifically, the distance between primary coil 402 and relay coil 404 may be defined as l/n where n is defined as a division factor which represents a total number of gaps or spacings between the two primary coils.

[0040] Figure 5 illustrates a similar embodiment whereby an additional electrical coil, i.e., a relay coil, is provided between the two primary (i.e., a third and a fourth) coils with all three electrical coils aligned along a central x-axis of the cubic-shaped housing of WPT device 100. Each of the square-shaped electrical coils have sides of length l and the primary coils overlap with their respective nested electrical sub-coils with a length d , where $0 \leq d \leq l$. It can be seen that relay coil 504 is centrally positioned between primary coils 502 and 506 ensuring that relay coil 504 is equidistant between primary coils 502 and 506. Specifically, the distance between primary coil 502 and relay coil 504 may be defined as l/n where n is defined as the division factor between the two primary coils.

[0041] Figure 6 illustrates various configurations of electrical coils aligned along a central axis such as the y-axis within a cubic-shaped WPT device 100 with each configuration being associated with a different division factor, n . Specifically, the configurations 602, 604, 606 and 608 illustrates how the number of relay coils between the primary coils affects the spacing and arrangement of the coils.

[0042] In configuration 602, no relay coils are present as such, the division factor for this configuration is 1, i.e., $n = 1$ and the two electrical coils are separated by the length l . In configuration 604, one relay coil is positioned equidistantly between the primary coils, dividing the total spacing into two equal segments of $l/2$ as the divisional factor for this configuration is 2, i.e., $n = 2$.

[0043] In configuration 606, two relay coils are introduced between the primary coils, resulting in three equal segments of $l/3$ as the divisional factor for this configuration is 3, i.e., $n = 3$. In configuration 608, three relay coils are introduced between the primary electrical coils, resulting in four equal segments of $l/4$ as the divisional factor for this configuration is 4, i.e., $n = 4$.

[0044] Regardless of the number of relay electrical circuits, it can be seen that each of the primary coils maintain a consistent overlap length d to ensure uniform magnetic field generation while the coil arrangement may be adapted for specific operational requirements or spatial configurations. One skilled in the art will also recognize that the configurations illustrated in Figure 6 may be applied to electrical coils aligned along a central axis perpendicular to the y-axis, e.g., the x-axis or z-axis, without departing from this disclosure as the coils along either axis are identical in design and configuration.

[0045] Figure 7 illustrates an image of a three-dimensional cubic-shaped housing for WPT device 100 in accordance with embodiments of the present disclosure. Housing 700 comprises open square frames on all six sides with each frame or surface providing support and alignment for the coils. The corners of the cube are shown to be reinforced with vertical and horizontal ridges to add structural stability and to ensure precise positioning of the coils. The central region of housing 700 is designed to allow the placement of wireless power receivers, enabling the penetration of magnetic fields within the housing.

[0046] Figure 8 illustrates a detailed structure and configuration of a set of electrical coils within WPT device 100 as previously illustrated in Figure 4 when the set of electrical coils comprise a single continuous electrical wire. Specifically, critical points P_1 - P_{24} are illustrated

in Figure 8, whereby each of these critical points show the positions where the continuous electrical wire is bent to form a segment of an electrical coil.

[0047] Figure 9 illustrates a flattened, two-dimensional representation of the coil layout for additional clarity. This linearized view highlights the relationships between the labelled points, the segment lengths, and the overlap regions within the coil structure. The distances between the points, such as $l, \frac{l+d}{2}$, and d , are clearly annotated, emphasizing the geometric precision and symmetry in the coil's design. This representation is particularly useful for understanding the spatial distribution and alignment of the wire within the cubic-shaped housing. One skilled in the art will also recognize that the configurations illustrated in Figures 8 and 9 may be applied to any number of electrical coils and may be applied to electrical coils aligned along a central axis perpendicular to the central axis adopted in Figures 8 and 9 without departing from this disclosure as the coils along either axis are identical in design and configuration.

[0048] A compensated scheme for inductive resonance may be applied to WPT device 100 to improve the efficiency of this device by addressing the effects of leakage inductances in the electrical coils. In inductive-resonant mode operation, series capacitances may be connected to the sets of electrical coils to neutralize these leakage inductances. The value of the compensating capacitance, C , may be determined by:

$$C = \frac{1}{4\pi^2 f^2 L} \quad \dots \text{equation (1)}$$

where f is the desired resonant frequency, L is the self-inductance of an electrical coil set (i.e., along a specific central axis of the housing). Through the use of this compensating capacitance, the inductive reactance of the coil may then be effectively balanced resulting in a resonance condition that minimizes power losses and maximizes energy transfer efficiency.

[0049] In embodiments of the disclosure, a control scheme for enhancing the system's functionality by enabling omnidirectional wireless charging for planar receivers may be adopted as well. The driving currents for the electrical coil sets in the respective central axes of the cubic-shaped housing of WPT device 100 may be defined as follows:

$$i_Y = I_m \sin(2\pi f t) \quad \dots \text{equation (2)}$$

$$i_x = I_m \cos(2\pi ft) \quad \dots \text{equation (3)}$$

where i_x and i_y are defined as the driving currents for the electrical coil sets along the x-axis and y-axis of WPT device 100, f is defined as the operating frequency, t is defined as the time, and I_m is defined as the amplitude of the driving current. The 90-degree phase difference between these currents ensures the generation of a rotating magnetic field within the cubic-shaped housing, which is crucial for charging receivers in any orientation.

[0050] Simulation:

[0051] Simulations were performed using Ansys Maxwell 2023R1 to evaluate the magnetic flux density in WPT device 100 under varying configurations. The currents flowing through the two sets of electrical coils were set to 1A, with a maximum of 10 adaptive passes in the finite element analysis (FEA) and a percentage error threshold of 1%. The cubic-shaped housing of WPT device 100 was set to have a length of 20 cm, and the overlap parameter d was varied between 0 cm, 4 cm, 8 cm, 12 cm, 14 cm, 16 cm and 20 cm and this corresponded to d/l values of 0, 0.2, 0.4, 0.6, 0.8 and 1.0, respectively. The division factor n was set to be 1, 2, 3, 4, 5, 6, 7 and 8, respectively.

[0052] Based on the above, the magnetic flux densities were then simulated across three dimensions—on the yx-plane with $z = l/2 = 10\text{cm}$; zx-plane with $y = l/2 = 10\text{cm}$; and zy-plane with $x = l/2 = 10\text{cm}$ and the results are illustrated in Figures 10a, 10b and 10c.

[0053] Based on the results obtained, it can be seen that magnetic flux density becomes increasingly uniform as the overlap parameter d (or d/l) increases. Similarly, as the division factor n increases incrementally from 1 to 8, the magnetic flux density exhibits a progressive improvement in uniformity across the cubic charging space.

[0054] In order to quantify the distribution of the magnetic flux densities inside the cubic charging space, the average magnetic flux density (i.e., strength of B-field, $\bar{B}$) and the coefficient of variation (CoV) of the magnetic flux density (i.e., $\text{CoV}(\bar{B})$) inside the chamber were estimated based on the measured 226981(=61*61*61) magnetic flux density (B) from 1

cm to 19 cm with an interval of 3mm on each dimension. The results obtained from this simulation is illustrated in Table 1 below.

n	d/l											
	0		0.2		0.4		0.6		0.8		1.0	
	$\bar{B}(\mu T)$	CoV	$\bar{B}(\mu T)$	CoV	$\bar{B}(\mu T)$	CoV	$\bar{B}(\mu T)$	CoV	$\bar{B}(\mu T)$	CoV	$\bar{B}(\mu T)$	CoV
1	4.36	0.356	5.81	0.378	7.08	0.303	8.07	0.267	8.62	0.328	8.59	0.351
2	8.49	0.223	9.56	0.336	10.61	0.288	11.61	0.194	12.33	0.166	12.42	0.185
3	12.37	0.151	13.34	0.173	14.28	0.213	15.17	0.177	15.97	0.112	16.17	0.119
4	16.11	0.110	17.10	0.146	17.99	0.139	18.82	0.142	19.61	0.091	19.88	0.086
5	19.90	0.086	20.82	0.114	21.68	0.117	22.70	0.093	23.45	0.072	23.60	0.070
6	23.63	0.071	24.53	0.092	25.38	0.102	26.19	0.088	26.95	0.068	27.28	0.058
7	27.35	0.065	28.22	0.084	29.03	0.086	29.87	0.078	30.63	0.060	30.67	0.052
8	31.07	0.059	31.92	0.075	32.75	0.079	33.56	0.072	34.31	0.055	34.67	0.050

TABLE 1

[0055] The results shown in Table 1 are then plotted in Figure 11a. As can be seen from Figure 11a, when the overlap parameter comprises $d/l = 0.6$, this results in the minimum CoV for $n = 1$. When the overlap parameter comprises $d/l = 0.8$, this results in the minimum CoV for $n = 2$ and $n = 3$. When the overlap parameter comprises $d/l = 1.0$, this results in the minimum CoV for $n = 4$ to $n = 8$.

[0056] Figure 11b illustrates the minimum CoV for various division factors n . From the plot shown in Figure 11b, it can be seen that the CoV is close to 0.1 when $n = 4$, which is determined to be a sufficiently acceptable CoV for most applications. In a preferred embodiment of the disclosure, the overlap parameter was set to $d/l = 1.0$, and the division factor was set to $n = 4$ for the WPT device 100.

[0057] Experiments:

[0058] Experiments were conducted on an exemplary WPT device with an overlap parameter $d/l = 1.0$ and a division factor $n = 4$, as illustrated in Figure 12. The magnetic flux density inside the chamber was indirectly measured using an electromagnetic compatibility (EMC) scanner, c.g., Model: SCN-500. The scanner directly measured voltages in dB μ V, and these measurements were used to determine the strength of the magnetic flux density within

the WPT device. Further, the CoVs of the measured voltages were verified to correspond to those of the magnetic flux density inside the chamber.

[0059] To facilitate the tests, two pure sinusoidal currents with a 90° phase difference angle were generated using power amplifiers, e.g., Models: ATA-1220D and HSA 4101, and these currents were used to drive the two sets of electric coils thereby exciting a magnetic field within the WPT device. A spectrum analyzer, e.g. Model: RSA306B, was then used to measure the induced electromotive force at 200 kHz. The setup used in the tests is illustrated in Figure 13.

[0060] The scanning area was tested across four distinct layers, corresponding to z -levels of 40 mm, 80 mm, 120 mm, and 160 mm, as illustrated in Figure 14. Within each layer, the specific testing points and the corresponding testing areas are detailed in Figure 15, providing a comprehensive visualization of the measurement setup.

[0061] Figure 16 illustrates the measured voltages from the experiments in dB μ V with the corresponding average values and their CoVs summarized in Table 2 below. For fair comparisons, additional experiments were also conducted on two conventional coil designs, both employing the same transmitter current control scheme as defined in Equations (2) and (3) above. The first design was based on the conventional Helmholtz coil as illustrated in Figure 17a. The second design was based on folded coils, as illustrated in Figure 17b. In this design, the folded ratio is fixed at its optimal value of 33.3% to ensure even distribution of magnetic flux density within the chamber.

	Average of the measured voltage (dB μ V)	CoV
$z = 40$ mm	62.10	0.00661
$z = 80$ mm	62.09	0.00613
$z = 120$ mm	62.23	0.00570
$z = 160$ mm	62.22	0.00453
Total	62.16	0.00586

TABLE 2

[0062] The comparative measured results at the $z = 40$ mm plane are illustrated in Figures 18a and 18b, demonstrating the superior performance of the proposed coil design method compared to conventional designs. Specifically, plot 1802 illustrates the results obtained for

the conventional Helmholtz coil design, plot 1804 illustrates the results obtained for the folded coil design and plot 1806 illustrates the results obtained for the WPT device designed in accordance with embodiments of the disclosure.

[0063] The coefficients of variation (CoVs) for the conventional Helmholtz coil design 1902, the folded coil design 1904 and the WPT device design 1906 are further analysed and plotted as bar charts in Figure 19. From these plots, it can be seen that the WPT device design 1906 was able to achieve an approximately 80% reduction in CoV compared to the folded coil design 1904. Additionally, when compared to the conventional Helmholtz coil design 1902, the WPT device design 1906 achieved an even greater reduction in CoV, of approximately 86%.

[0064] A process for wirelessly transferring power using a device having a cubic-shaped housing in accordance with embodiments of this disclosure is illustrated in Figure 20.

[0065] Process 2000 begins at step 2002 by providing a first set of electrical coils along a first central axis of the cubic-shaped housing. In this embodiment, the first set of electrical coils comprises a first primary coil and a first electrical sub-coil, wherein the first electrical sub-coil is nested within the first primary coil in a same plane, a second primary coil and a second electrical sub-coil, wherein the second electrical sub-coil is nested within the second primary coil in a same plane, wherein the first and second primary coils are disposed on different planes.

[0066] Process 2000, at step 2004, then proceeds to electrically drive the first set of electrical coils to generate a first uniform magnetic field between the first primary coil and the second primary coil.

[0067] At step 2006, process 2000 then provides a second set of electrical coils along a second central axis of the cubic-shaped housing, the second central axis being perpendicular to the first central axis. In this embodiment, the second set of electrical coils comprises a third primary coil and a third electrical sub-coil, wherein the third electrical sub-coil is nested within the third primary coil in a same plane, a fourth primary coil and a fourth electrical sub-coil, wherein the fourth primary coil is nested within the fourth electrical sub-coil in a same plane, wherein the third and fourth primary coils are disposed on different planes.

[0068] Process 2000 then electrically drives the second set of electrical coils to generate a second uniform magnetic field between the third primary coil and the fourth primary coil. This takes place at step 2008.

[0069] In other embodiments of the disclosure, the first set of electrical coils may further comprise a first relay coil that is provided on a different plane from the first and second primary coils, and wherein the first relay coil is positioned equidistant between the first and the second primary coils, and the second set of electrical coils may further comprise a second relay coil that is provided on a different plane from the third and fourth primary coils, wherein the second relay coil is positioned equidistant between the third and the fourth primary coils.

[0070] In other embodiments of the disclosure, the first set of electrical coils may further comprise a first plurality of relay coils, each of the first plurality of relay coils being provided on a plane different from each other and from the planes of the first and second primary coils, wherein the first plurality of relay coils are positioned between the first and second primary coils such that all the coils in the first set of electrical coils are equidistant apart; and the second set of electrical coils may further comprise a second plurality of relay coils, each of the second plurality of relay coils being provided on a plane different from each other and from the planes of the third and fourth primary coils, wherein the second plurality of relay coils are positioned between the third and fourth primary coils such that all the coils in the second set of electrical coils are equidistant apart.

[0071] In other embodiments of the disclosure, process 2000 may connect a first driving circuit to the first set of electrical coils, process 2000 may then provide, using the first driving circuit, a sinusoidal current to drive the first set of electrical coils, connect a second driving circuit to the second set of electrical coils, and process 2000 may then provide, using the second driving circuit, a cosinusoidal current to drive the second set of electrical coils, wherein the sinusoidal and cosinusoidal currents are phase-shifted by 90 degrees such that a rotating magnetic field is generated within the cubic-shaped housing by the driven first and second sets of electrical coils.

[0072] In other embodiments of the disclosure, process 2000 may connect a first capacitor to the first set of electrical coils, wherein a value of the first capacitor is based on a self-inductance parameter of the first set of electrical coils and a resonant frequency and connect a second capacitor to the second set of electrical coils, wherein a value of the second capacitor is based on a self-inductance parameter of the second set of electrical coils and the resonant frequency.

[0073] **Embodiment: Wireless power transfer device with U-shaped relay coils**

[0074] Another embodiment of the disclosure is illustrated as U-shaped WPT device 2102 in Figure 21 and this embodiment was introduced to address the limitation that the access to and removal of charging devices from WPT device 2101 is difficult due to the multiple relay coils that are wound around all the surfaces, i.e., around all six surfaces of WPT device 2101. Figure 21 illustrates WPT device 2101 (as described in the previous sections) having two relay coils provided between primary coils 2103a and 2103b. Figure 21 also illustrates another embodiment of the WPT device having U-shaped relay coils, i.e., U-shaped WPT device 2102, disposed between primary coils 2104a and 2104b.

[0075] As can be seen from Figure 21, U-shaped WPT device 2102 comprises two U-shaped relay coils, i.e., one set of U-shaped relay coils, and that the windings of the U-shaped relay coils do not pass directly through the top and bottom surfaces of the cubic-shaped housing. Instead, these coils are arranged in a U-shape around the planes of primary coils 2104a and 2104b, along the Y-axis of the cubic-shaped housing. This design preserves the free space on the top and bottom surfaces of the cubic-shaped housing, enabling greater flexibility in device placement.

[0076] Specifically, U-shaped WPT device 2102 has a U-shaped relay coil comprising segment 2106 arranged in a U-shape around edges of a top surface of the cubic-shaped housing, and segment 2107 arranged in a U-shape around edges of a bottom surface of the cubic-shaped housing. The ends of segment 2106 are connected to the ends of segment 2107 by connecting segments 2108 and 2109. Additionally, as can be seen from Figure 21, parts of segments 2106 and 2107 overlap with parts of primary coil 2104b, on a plane of primary coil 2104b.

[0077] U-shaped WPT device 2102 also has another U-shaped relay coil comprising segment 2110 arranged in a U-shape around edges of the top surface of the cubic-shaped housing, and segment 2111 arranged in a U-shape around edges of the bottom surface of the cubic-shaped housing. The ends of segment 2110 are connected to the ends of segment 2111 by connecting segments 2112 and 2113 and as can be seen from Figure 21, parts of segments 2110 and 2111 overlap with parts of primary coil 2104a, on a plane of primary coil 2104a.

[0078] Figure 21 illustrates the embodiment whereby the primary coils and the U-shaped relay coils are provided in the Z-X planes of the cubic-shaped housing, i.e., along the Y-axis of the housing. In accordance with the previous embodiment, it is understood that primary coils and U-shaped relay coils may be similarly provided in the Z-Y planes of the cubic-shaped housing, i.e., along the X-axis of the housing, or in the X-Y planes of the cubic-shaped housing, i.e., along the Z-axis of the housing. This arrangement causes the magnetic fields generated by the various electrical coil sets to interact orthogonally when these electrical coil sets are energized.

[0079] In other words, although it is not shown in Figure 21, it is understood that U-shaped WPT device 2102 may also include a set of U-shaped relay coils, i.e., a pair of U-shaped relay coils, arranged along the X-axis of the cubic-shaped housing, where each U-shaped relay coil comprises a segment arranged in a U-shape around edges of a top surface of the cubic-shaped housing, and a segment arranged in a U-shape around edges of a bottom surface of the cubic-shaped housing. The ends of the segment arranged in the U-shape around edges of the top surface are connected to the ends of the segment arranged in a U-shape around edges of the bottom surface by connecting segments, where parts of the segments that are arranged in the U-shape overlap with parts of a primary coil residing in a Z-Y plane of the housing. It should also be noted that although the embodiment in Figure 21 only illustrates one set of U-shaped relay coils, one skilled in the art will recognize that WPT device 2102 may comprise a plurality of sets of U-shaped relay coils where the segments of each set of the plurality of U-shaped relay coils are configured to have lengths specific to the set of U-shaped relay coil.

[0080] In embodiments of the disclosure, a set of U-shaped relay coils may be defined as two relay coils that are symmetrical about the center of the cubic-shaped housing. The number of sets of U-shaped relay coils may be denoted by N_{set} , and the folded length of each set of U-

shaped relay coil is denoted by l_i (where $i = 1, 2, \dots, N_{\text{set}}$). For example, when $N_{\text{set}} = 1$, and $l_1 = l/3$ and no nested sub-coils are present, the structure and parameters for one set of electrical coils as provided along the Y-axis of the cubic-shaped housing is as illustrated in Figure 22.

[0081] Figure 22 illustrates an embodiment of U-shaped WPT device 2202 when $N_{\text{set}} = 1$, and $l_1 = l/3$ and no nested sub-coils are present, and when the set of electrical coils are provided along the Y-axis of the cubic-shaped housing. A top view of WPT device 2202 is illustrated as device-view 2204, where the segments of the U-shaped relay coils that are arranged in a U-shape around the edges of the top surface of the cubic-shaped housing are illustrated as segments 2205 and 2206. Although it can't be seen from this diagram, it should be noted that U-shaped relay coils would also be arranged in a U-shape around the edges of the bottom surface of the cubic-shaped housing in device-view 2204.

[0082] As the primary coils and the U-shaped relay coils that are provided in the Z-X planes of the cubic-shaped housing, i.e., along the Y-axis of the housing, share the same structure as the primary coils and the U-shaped relay coils that are provided in the Z-Y planes of the cubic-shaped housing, i.e., along the X-axis of the housing, it should be noted that magnetic field simulations performed for primary coils and the U-shaped relay coils along the Y-axis of the housing may be similarly applied to primary coils and the U-shaped relay coils along the X-axis or Z-axis of the housing.

[0083] Simulations were then performed using Ansys Maxwell 2023R1 to evaluate the magnetic flux density in U-shaped WPT device 2102 under varying configurations. The currents flowing through the two sets of electrical coils were set to 1A, with a maximum of 10 adaptive passes in the finite element analysis (FEA) and a percentage error threshold of 1%. The cubic-shaped housing of WPT device 100 was set to have a length of 20 cm, and the number of sets of U-shaped relay coils N_{set} was varied between 0 and 4 with the length l_i being defined as $l_i = i(\frac{l}{2N_{\text{set}}+1})$. The simulated coefficient of variation (CoV) for the various sets of U-shaped relay coils N_{set} is plotted in Figure 23.

[0084] In further embodiments, in order to optimize the lengths l_i of the different U-shaped relay coils, a Simulated Annealing (SA) algorithm may be adopted to determine the optimal

lengths l_i that are to be used for each set of the U-shaped relay coils. The optimization parameters for the SA algorithm are set out in Table 3 below.

Terms	Specifications
Coil parameters	Number of sets of U-shaped relay coils $N_{set} \in [1, 4]$
	Length of each U-shaped relay coil $l_i \in [5\text{ mm}, 95\text{ mm}]$, $i = 1, \dots, N_{set}$
Design objectives	Minimize CoV with acceptable average magnetic flux density, μ and total coil length L_{total}
Simulated annealing	Initial temperature = 5230°C
	Factor for acceptance distribution = -5
	Factor for visiting distribution = 2.62
	Maximal epochs = 1500

TABLE 3

[0085] The SA algorithm is configured to achieve a uniform magnetic field by minimizing the coefficient of variation (CoV) of the device. Additionally, the optimization performed by the SA algorithm takes into consideration the average magnetic flux density, μ , and total coil length, L_{total} , for one set of U-shaped relay coils for the cubic-shaped housing, as reducing the total coil L_{total} results in lower system costs and losses. In this optimization process, CoV is prioritized, while ensuring that μ and L_{total} remain within acceptable ranges.

[0086] The average magnetic flux density and the CoV inside the cubic-shaped housing are estimated based on measurements taken at 753,571 test points (91×91×91), spaced at 2 mm intervals from 10 mm to 190 mm along each dimension. The optimization process, as illustrated in Figure 24, involves two nested algorithmic loops that employ design automation techniques. In the outer loop, the number of the set of U-shaped relay coils is enumerated, while in the inner loop, the optimal lengths l_i are determined using the SA algorithm.

[0087] Process 2400, as illustrated in Figure 24, begins at step 2402 where process 2400 begins the outer loop iteration process by proposing a new number of sets of U-shaped relay coils N_{set} for evaluation. Process 2400 then proceeds to step 2404, which is the first step of the inner loop iteration. At this step, process 2400 proceeds to generate the initial fold lengths, $\{l_i\}_{ini}$

for the U-shaped relay coils for the current number of sets of U-shaped relay coils N_{set} . At step 2406, process 2400 then triggers the provision of the information generated at step 2404 to the Ansys Maxwell software so that the software may evaluate the objectives, i.e., the uniformity of the magnetic flux density, using FEM for the initial fold lengths. Specifically, at step 2408, process 2400 creates the proposed U-shaped relay coil configurations using the Ansys Maxwell software based on the assigned materials and excitations. Process 2400 then initializes an objective function for the average magnetic flux density, μ , for evaluation and process 2400 performs the evaluation step using finite element models (FEMs) for the initial fold lengths and the enumerated set of U-shaped relay coil, N_{set} . Process 2400 then proceeds to generate new fold lengths for the U-shaped relay coils using a distorted Cauchy-Lorentz visiting distribution to explore possible solution spaces and this takes place at step 2410. At step 2412, process 2400 then triggers the provision of the information generated at step 2410 to the Ansys Maxwell software so that the software may evaluate the objectives, i.e., the uniformity of the magnetic flux density, using FEM for the new fold lengths. Process 2400 then obtains the difference in objective function values, ΔO , at step 2414.

[0088] If process 2400 determines at step 2420 that the new lengths may be accepted, process 2400 proceeds to step 2416 to update the fold lengths of the U-shaped relay coils with the new lengths. Process 2400 then proceeds to step 2422. At this step, process 2400 determines if a maximum number of iterations have been reached and if process 2400 determines that the maximum number of iterations have been reached, it will proceed to step 2424 where the optimal fold lengths for the enumerated set will be saved. Process 2400 will then proceed to construct the Pareto Frontier for the multi-objective design at step 2426 and if process 2400 determines that the objectives have not been met, process 2400 will then return to step 2402.

[0089] Conversely, at step 2422, if process 2400 determines that the maximum number of iterations have not been reached, process 2400 will decrease a temperature parameter, T , before proceeding to step 2410. Process 2400 then proceeds to generate new fold lengths for the U-shaped relay coils using the distorted Cauchy-Lorentz visiting distribution and the new temperature parameter. Process 2400 then repeats steps 2412 to 2422 until a maximum number of iterations is achieved and this then ends the iteration of the inner loop.

[0090] Returning to step 2420, if process 2400 determines that the new lengths may not be accepted, process 2400 then determines if the new lengths may be accepted probabilistically using the Metropolis Rule. If accepted, process 2400 will update the fold lengths of the U-shaped relay coils with the new lengths and will then proceed to step 2422. Else, the initial lengths will still be maintained. Like the description above, process 2400 then determines at step 2422 if a maximum number of iterations have been reached and if process 2400 determines that the maximum number of iterations have been reached, it will proceed to steps 2424 and 2426 accordingly.

[0091] Based on process 2400, the optimal lengths of the U-shaped relay coils for various values of N_{set} are set out in Table 4 below.

	l_1 (mm)	l_2 (mm)	l_3 (mm)	l_4 (mm)	L_{total} (mm)
$N_{set} = 1$	78.2				3829
$N_{set} = 2$	56.2	87.7			5963
$N_{set} = 3$	42.5	72.1	91.2		8070
$N_{set} = 4$	7	52.6	77.8	90	9860

TABLE 4

[0092] The optimization results for different values of N_{set} with minimal CoV and the corresponding average magnetic flux density are plotted in Figure 25. When the number of sets of U-shaped relay coils is 0, i.e., $N_{set} = 0$, such a configuration would be similar to a conventional Helmholtz coil design. For such a design, it was found that the CoV value was notably higher at 0.413, and the magnetic flux density was at 5.18 μ T.

[0093] When the sets of U-shaped relay coils were used in the design, i.e., $N_{set} = 1, 2, 3, 4$, it can be seen from Figure 25 that this resulted in lower CoV values as N_{set} increases. Additionally, when the plot in Figure 25 is compared with the plot in Figure 23, it can be seen that the proposed optimized design results in a reduction in the CoV values when the number of relay coils are increased. Specifically, it is observed that when the number of sets of U-shaped relay coils N_{set} are increased to 2 and 3, this results in a substantial improvement in the CoV values, with the CoV values decreasing by 30.8% and 32.5% respectively, and magnetic

flux density μ increasing by 10.3% and 11.9% respectively. When the number of sets of U-shaped relay coils N_{set} was increased to 4, i.e., $N_{\text{set}} = 4$, the device was able to achieve optimal uniformity and magnetic flux density however, the improvements over $N_{\text{set}} = 3$ (0.632% for CoV and 19.1% for μ) were found to be marginal, considering that there was a 22.2% increase in total coil length when $N_{\text{set}} = 4$. As a result, it was determined that for this embodiment, the optimum number of sets of U-shaped relay coils N_{set} was to be 3.

[0094] Figure 26 illustrates all the candidate solutions and the corresponding Pareto frontiers that were obtained during the optimization search process for $N_{\text{set}} = 3$. Specifically, from Figure 26a, it can be seen on the Pareto frontier that there was a conflict in the objective when the total coil length L_{total} was minimized, from Figure 26b that there was a conflict when a low CoV for uniformity was to be achieved, and from Figure 26c that there was a conflict when average magnetic flux density μ was to be maximized. The selected design, highlighted on the Pareto frontier, was able to achieve a minimal CoV of 0.188 and a strong magnetic flux density of 26.9 μT , albeit at the cost of increased total coil length.

[0095] A 3D perspective view of the optimized coil structure for $N_{\text{set}} = 3$ is illustrated in Figure 27a. A top view, i.e., along the X-Y plane, of the optimized coil structure for $N_{\text{set}} = 3$ is illustrated in Figure 27b and a front view, i.e., along the Z-X plane, of the optimized coil structure for $N_{\text{set}} = 3$ is illustrated in Figure 27c. The excitation currents for the two sets of coils are set with a 90-degree phase difference so that a rotational magnetic field may be generated within the wireless power transfer device. Figures 27d-27h illustrate top views of the magnetic field vectors at layer $z = 100$ mm at various time instants. Specifically, Figure 27d illustrates the vector of the magnetic field at a time instant of $\omega t = 0$, Figure 27e illustrates the vector of the magnetic field at a time instant of $\omega t = \pi/4$, Figure 27f illustrates the vector of the magnetic field at a time instant of $\omega t = \pi/2$, Figure 27g illustrates the vector of the magnetic field at a time instant of $\omega t = 3\pi/4$ and Figure 27h illustrates the vector of the magnetic field at a time instant of $\omega t = \pi$. From these figures, it can be seen that although the direction of the magnetic field rotates over time, the magnitudes of the magnetic field remain nearly uniform across the various time intervals.

[0096] Figure 28a illustrates a 3D perspective view of the conventional Helmholtz coil design and Figure 28b illustrates a 3D perspective view of the U-shaped relay coil WPT device

with $N_{\text{set}} = 3$. For case of construction, the lengths of each set of the U-shaped relay coils were fixed as follows: $l_1 = 40$ mm, $l_2 = 70$ mm and $l_3 = 90$ mm with these dimensions deviating slightly from the optimized simulation values of $l_1 = 42.5$ mm, $l_2 = 72.1$ mm and $l_3 = 91.2$ mm. The simulation results for the structure shown in Figure 28b show that the average magnetic flux density μ and CoV for the U-shaped relay coil WPT device with $N_{\text{set}} = 3$ were $26.7 \mu\text{T}$ and 0.189 respectively, closely matching the optimized values of $26.9 \mu\text{T}$ and 0.188 . To ensure that the device shown in Figure 28a and the optimized device shown in Figure 28b have identical total wire lengths, the device shown in Figure 28a was wound with 5 turns of wire and the design shown in Figure 28b was wound with 1 turn of wire, whereby the cubic-shaped housing comprised of 3D-printed cubic containers made of epoxy resin.

[0097] The magnetic flux densities inside the structures shown in Figures 28a and 28b are then measured using a spectrum analyzer (Model: FPL1007) equipped with a near-field magnetic probe (Model: SinnoRally type II). The probe is configured to detect the magnetic fields within the structures before converting the detected magnetic fields into electrical signals, which are then measured by a spectrum analyzer. During the measurement process, the excitation currents that are provided to the electrical coils of these two structures are set to a frequency of 200 kHz with an RMS value of 0.5 A, and an angular phase difference between the two excitation currents is set to be 90° .

[0098] Measurements were conducted at three layers, at heights of 100 mm, 133 mm, and 166 mm, respectively for each of these two structures. Each layer employed a measurement area defined as $\{(x, y): -70 \text{ mm} \leq x \leq 70 \text{ mm} \text{ and } -70 \text{ mm} \leq y \leq 70 \text{ mm}\}$, with a measurement step of 28 mm per point. At each measurement point, the probe was rotated from 0 to 180 degrees in 18-degree intervals, and the amplitudes of the sensed voltages were recorded by the spectrum analyzer. The average values of the sensed voltage across all degrees for both designs are plotted in Figures 29a-f. Specifically, Figure 29a illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 100 mm from the base of the container, Figure 29b illustrates the measured magnetic field distribution for the wireless power transfer device illustrated in Figure 28b when the measurement was carried out at a height of 100 mm from the base of the device, Figure 29c illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 133 mm from the

base of the container, Figure 29d illustrates the measured magnetic field distribution for the wireless power transfer device illustrated in Figure 28b when the measurement was carried out at a height of 133 mm from the base of the device, Figure 29e illustrates the measured magnetic field distribution for the cubic wireless charging container in Figure 28a when the measurement was carried out at a height of 166 mm from the base of the container, and Figure 29f illustrates the measured magnetic field distribution for the wireless power transfer device illustrated in Figure 28b when the measurement was carried out at a height of 166 mm from the base of the device.

[0099] Table 5 below sets out the average and CoV values of the sensed voltages for the structures illustrated in Figures 28a and 28b.

	Conventional Helmholtz coil design		U-shaped relay coil WPT device with $N_{set} = 3$	
	Avg. (dBμV)	CoV	Avg. (dBμV)	CoV
Height = 100 mm	70.61	0.0084	72.49	0.0038
Height = 133 mm	70.37	0.0137	71.89	0.0058
Height = 166 mm	69.16	0.0215	70.57	0.0101
Total	70.05	0.0178	71.65	0.0132

TABLE 5

[00100] Based on the results shown in Table 5, it can be seen that the U-shaped relay coil WPT device exhibits a more robust and evenly distributed magnetic field compared to the conventional Helmholtz coil design. Across the three layers, the average sensed voltage in the U-shaped relay coil WPT device increased by 2.28% as compared to the average sensed voltage of the conventional Helmholtz coil design. Furthermore, the average CoV for the U-shaped relay coil WPT device is reduced by 25.84% compared to the conventional Helmholtz coil design.

[00101] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations and modifications as falling within the scope of the appended claims.

CLAIMS:

1. A wireless power transfer device comprising:

a first set of electrical coils disposed along a first central axis of a cubic-shaped housing, the first set of electrical coils comprising:

a first primary coil and a first electrical sub-coil, wherein the first electrical sub-coil is nested within the first primary coil in a same plane as the first primary coil,

a second primary coil and a second electrical sub-coil, wherein the second electrical sub-coil is nested within the second primary coil in a same plane as the second primary coil,

wherein the first and second primary coils are disposed on different planes that are parallel to each other;

whereby the first set of electrical coils is configured to generate a first uniform magnetic field between the first primary coil and the second primary coil when the first set of electrical coils are electrically driven,

a second set of electrical coils disposed along a second central axis of the cubic-shaped housing, the second central axis being perpendicular to the first central axis, the second set of electrical coils comprising:

a third primary coil and a third electrical sub-coil, wherein the third electrical sub-coil is nested within the third primary coil in a same plane as the third primary coil,

a fourth primary coil and a fourth electrical sub-coil, wherein the fourth electrical sub-coil is nested within the fourth primary coil in a same plane as the fourth primary coil,

wherein the third and fourth primary coils are disposed on different planes that are parallel to each other;

whereby the second set of electrical coils is configured to generate a second uniform magnetic field between the third primary coil and the fourth primary coil when the second set of electrical coils are electrically driven.

2. The wireless power transfer device according to claim 1,

wherein the first set of electrical coils further comprises a first relay coil that is disposed on a different plane from the first and second primary coils, and wherein the first relay coil is positioned equidistant between the first and the second primary coils; and

wherein the second set of electrical coils further comprises a second relay coil that is disposed on a different plane from the third and fourth primary coils, and wherein the second relay coil is positioned equidistant between the third and the fourth primary coils.

3. The wireless power transfer device according to claim 1,
wherein the first set of electrical coils further comprises a first plurality of relay coils, each of the first plurality of relay coils being disposed on a plane different from each other and from the planes of the first and second primary coils, and wherein the first plurality of relay coils are positioned between the first and second primary coils such that all the coils in the first set of electrical coils are equidistant apart; and
wherein the second set of electrical coils further comprises a second plurality of relay coils, each of the second plurality of relay coils being disposed on a plane different from each other and from the planes of the third and fourth primary coils, and wherein the second plurality of relay coils are positioned between the third and fourth primary coils such that all the coils in the second set of electrical coils are equidistant apart.
4. The wireless power transfer device according to claim 3,
wherein the first and second plurality of relay coils each comprise two relay coils.
5. The wireless power transfer device according to claim 3,
wherein the first and second plurality of relay coils each comprise three relay coils.
6. The wireless power transfer device according to claim 1,
wherein the first primary coil is wound around edges of a first surface of the cubic-shaped housing, the second primary coil is wound around edges of a second surface of the cubic-shaped housing, the third primary coil is wound around edges of a third surface of the cubic-shaped housing, and the fourth primary coil is wound around edges of a fourth surface of the cubic-shaped housing.
7. The wireless power transfer device according to any one of claims 1 to 6,
wherein segments of the first electrical sub-coil overlaps with segments the first primary coil and segments of the second electrical sub-coil overlaps with segments the second primary coil.
8. The wireless power transfer device according to any one of claims 1 to 7,

wherein segments of the third electrical sub-coil overlaps with segments the third primary coil and segments of the fourth electrical sub-coil overlaps with segments the fourth primary coil.

9. The wireless power transfer device according to any one of claims 1 to 8,

wherein the first set of electrical coils comprise a first continuous electrical wire and the second set of electrical coils comprise a second continuous electrical wire.

10. The wireless power transfer device according to any one of claims 1 to 9 further comprising:

a first driving circuit electrically connected to the first set of electrical coils, the first driving circuit configured to provide a sinusoidal current to drive the first set of electrical coils; and

a second driving circuit electrically connected to the second set of electrical coils, the second driving circuit configured to provide a cosinusoidal current to drive the second set of electrical coils,

wherein the sinusoidal and cosinusoidal currents are phase-shifted by 90 degrees such that a rotating magnetic field is generated within the cubic-shaped housing by the driven first and second sets of electrical coils.

11. The wireless power transfer device according to any one of claims 1 to 10, further comprising:

a first capacitor electrically connected to the first set of electrical coils, wherein a value of the first capacitor is based on a self-inductance parameter of the first set of electrical coils and a resonant frequency; and

a second capacitor electrically connected to the second set of electrical coils, wherein a value of the second capacitor is based on a self-inductance parameter of the second set of electrical coils and the resonant frequency.

12. The wireless power transfer device according to claim 6,

wherein the first set of electrical coils further comprises:

a first U-shaped relay coil comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil;

a second U-shaped relay coil comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil;

wherein the second set of electrical coils further comprises:

a third U-shaped relay coil comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil;

a fourth U-shaped relay coil comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil.

13. The wireless power transfer device according to claim 6,

wherein the first set of electrical coils further comprises:

a first plurality of sets of U-shaped relay coils, each set comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil,

wherein the first and second segments of each of the first plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

a second plurality of sets of U-shaped relay coils, each set comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth

connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil;

wherein the third and fourth segments of each of the second plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

wherein the second set of electrical coils further comprises:

a third plurality of sets of U-shaped relay coils, each set comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil;

wherein the fifth and sixth segments of each of the third plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

a fourth plurality of sets of U-shaped relay coils, each set comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil; and

wherein the seventh and eighth segments of each of the fourth plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil.

14. A method for wirelessly transferring power using a device having a cubic-shaped housing, the method comprising:

providing a first set of electrical coils along a first central axis of the cubic-shaped housing, the first set of electrical coils comprising:

a first primary coil and a first electrical sub-coil, wherein the first electrical sub-coil is nested within the first primary coil in a same plane as the first primary coil,

a second primary coil and a second electrical sub-coil, wherein the second electrical sub-coil is nested within the second primary coil in a same plane as the second primary coil,

wherein the first and second primary coils are disposed on different planes that are parallel to each other;

electrically driving the first set of electrical coils to generate a first uniform magnetic field between the first primary coil and the second primary coil;

providing a second set of electrical coils along a second central axis of the cubic-shaped housing, the second central axis being perpendicular to the first central axis, the second set of electrical coils comprising:

a third primary coil and a third electrical sub-coil, wherein the third electrical sub-coil is nested within the third primary coil in a same plane as the third primary coil,

a fourth primary coil and a fourth electrical sub-coil, wherein the fourth electrical sub-coil is nested within the fourth primary coil in a same plane as the fourth primary coil,

wherein the third and fourth primary coils are disposed on different planes that are parallel to each other; and

electrically driving the second set of electrical coils to generate a second uniform magnetic field between the third primary coil and the fourth primary coil.

15. The method according to claim 14,

wherein the first set of electrical coils further comprises a first relay coil that is provided on a different plane from the first and second primary coils, and wherein the first relay coil is positioned equidistant between the first and the second primary coils; and

wherein the second set of electrical coils further comprises a second relay coil that is provided on a different plane from the third and fourth primary coils, and wherein the second relay coil is positioned equidistant between the third and the fourth primary coils.

16. The method according to claim 14,

wherein the first set of electrical coils further comprises a first plurality of relay coils, each of the first plurality of relay coils being provided on a plane different from each other and from the planes of the first and second primary coils, and wherein the first plurality of relay coils are positioned between the first and second primary coils such that all the coils in the first set of electrical coils are equidistant apart; and

wherein the second set of electrical coils further comprises a second plurality of relay coils, each of the second plurality of relay coils being provided on a plane different from each other and from the planes of the third and fourth primary coils, and wherein the second plurality of

relay coils are positioned between the third and fourth primary coils such that all the coils in the second set of electrical coils are equidistant apart.

17. The method according to claim 16,

wherein the first and second plurality of relay coils each comprise two relay coils.

18. The method according to claim 16,

wherein the first and second plurality of relay coils each comprise three relay coils.

19. The method according to claim 14,

wherein the first primary coil is wound around edges of a first surface of the cubic-shaped housing, the second primary coil is wound around edges of a second surface of the cubic-shaped housing, the third primary coil is wound around edges of a third surface of the cubic-shaped housing, and the fourth primary coil is wound around edges of a fourth surface of the cubic-shaped housing.

20. The method according to any one of claims 14 to 19,

wherein segments of the first electrical sub-coil overlaps with segments of the first primary coil and segments of the second electrical sub-coil overlaps with segments of the second primary coil.

21. The method according to any one of claims 14 to 20,

wherein segments of the third electrical sub-coil overlaps with segments the third primary coil and segments of the fourth electrical sub-coil overlaps with segments the fourth primary coil.

22. The method according to any one of claims 14 to 21,

wherein the first set of electrical coils comprise a first continuous electrical wire and the second set of electrical coils comprise a second continuous electrical wire.

23. The method according to any one of claims 14 to 22 further comprising the steps of:

connecting a first driving circuit to the first set of electrical coils;

providing, using the first driving circuit, a sinusoidal current to drive the first set of electrical coils;

connecting a second driving circuit to the second set of electrical coils; and
providing, using the second driving circuit, a cosinusoidal current to drive the second set of electrical coils,

wherein the sinusoidal and cosinusoidal currents are phase-shifted by 90 degrees such that a rotating magnetic field is generated within the cubic-shaped housing by the driven first and second sets of electrical coils.

24. The method according to any one of claims 14 to 23, further comprising:

connecting a first capacitor to the first set of electrical coils, wherein a value of the first capacitor is based on a self-inductance parameter of the first set of electrical coils and a resonant frequency; and

connecting a second capacitor to the second set of electrical coils, wherein a value of the second capacitor is based on a self-inductance parameter of the second set of electrical coils and the resonant frequency.

25. The method according to claim 19,

wherein the first set of electrical coils further comprises:

a first U-shaped relay coil comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil;

a second U-shaped relay coil comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil;

wherein the second set of electrical coils further comprises:

a third U-shaped relay coil comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil;

a fourth U-shaped relay coil comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil.

26. The method according to claim 19,

wherein the first set of electrical coils further comprises:

a first plurality of sets of U-shaped relay coils, each set comprising a first segment arranged in a U-shape around edges of a fifth surface of the cubic-shaped housing, and a second segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the first and second segments are connected by first and second connecting segments and parts of the first and second segments overlap with parts of the first primary coil,

wherein the first and second segments of each of the first plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

a second plurality of sets of U-shaped relay coils, each set comprising a third segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a fourth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the third and fourth segments are connected by third and fourth connecting segments and parts of the third and fourth segments overlap with parts of the second primary coil;

wherein the third and fourth segments of each of the second plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

wherein the second set of electrical coils further comprises:

a third plurality of sets of U-shaped relay coils, each set comprising a fifth segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and a sixth segment arranged in a U-shape around edges of a sixth surface of the cubic-shaped housing, wherein the fifth and sixth segments are connected by fifth and sixth connecting segments and parts of the fifth and sixth segments overlap with parts of the third primary coil;

wherein the fifth and sixth segments of each of the third plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil;

a fourth plurality of sets of U-shaped relay coils, each set comprising a seventh segment arranged in a U-shape around edges of the fifth surface of the cubic-shaped housing, and an eighth segment arranged in a U-shape around edges of the sixth surface of the cubic-shaped housing, wherein the seventh and eighth segments are connected by seventh and eighth connecting segments and parts of the seventh and eighth segments overlap with parts of the fourth primary coil; and

wherein the seventh and eighth segments of each of the fourth plurality of sets of U-shaped relay coils are configured to have lengths specific to the respective U-shaped relay coil.