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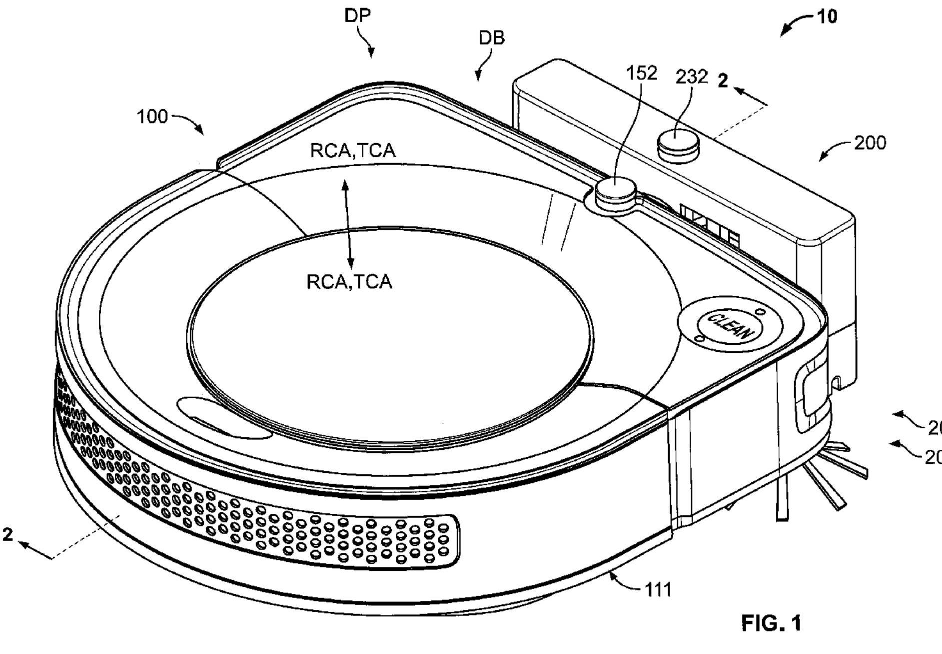

FIG. 1

(57) **Abstract:** A method for docking an autonomous mobile floor cleaning robot with a charging dock, the robot including a receiver coil and a structured light sensor, the charging dock including a docking bay and a transmitter coil, includes: positioning the robot in a prescribed docked position in the docking bay using the structured light sensor and by sensing a magnetic field emanating from the transmitter coil; and thereafter induction charging the robot using the receiver coil and the transmitter coil with the robot in the docked position.

[Continued on next page]

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AUTONOMOUS ROBOT AUTO-DOCKING AND ENERGY MANAGEMENT SYSTEMS AND METHODS

RELATED APPLICATION

[001] This application claims priority to U.S. Provisional Application Serial No. 62/361,881, filed July 13, 2016, the contents of which are hereby incorporated by reference in its entirety.

FIELD

[002] The present invention relates generally to robotic systems and, more specifically, to auto-docking and energy management systems for autonomous robots.

BACKGROUND

[003] Automated robots and robotic devices are used to perform tasks traditionally considered mundane, time-consuming, or dangerous. As the programming technology increases, so too does the demand for robots that require a minimum of human interaction for tasks such as robot refueling, testing, and servicing. A goal is a robot that could be configured a single time, which would then operate autonomously, without need for human assistance or intervention.

SUMMARY OF THE INVENTION

[004] According to embodiments of the invention, a method for docking an autonomous mobile floor cleaning robot with a charging dock, the robot including a receiver coil and a structured light sensor, the charging dock including a docking bay and a transmitter coil, includes: positioning the robot in a prescribed docked position in the docking bay using the structured light sensor and by sensing a magnetic field emanating from the transmitter coil; and thereafter induction charging the robot using the receiver coil and the transmitter coil with the robot in the docked position.

[005] In some embodiments, the dock includes an upstanding backstop, and the method further includes aligning the mobile floor cleaning robot with the charging dock using the structured light sensor by detecting the backstop using the structured light sensor.

[006] In some embodiments, when the robot is in the docked position, the receiver coil is located in a prescribed alignment with the transmitter coil.

[007] In some embodiments, the method includes: executing a cleaning mission using the robot; and using the structured light sensor to detect obstacles and/or voids proximate the robot during the cleaning mission.

[008] According to embodiments of the invention, an autonomous mobile floor cleaning robot for cleaning a surface includes a housing, a motive system, an induction charging system, and a cleaning system. The housing has a bottom. The motive system is operative to propel the robot across the surface. The induction charging system includes a receiver coil in the housing proximate the bottom of the housing, the receiver coil being configured to be inductively coupled to a transmitter coil in a charging dock during a charging operation. The cleaning system is operative to clean the surface as the robot traverses the surface. The cleaning system includes an evacuation port located in the bottom of the housing to release debris from the robot.

[009] In some embodiments, the receiver coil is offset from the center of the robot.

[0010] According to embodiments of the invention, an autonomous mobile robot includes a housing, a motive system, and an induction charging system. The housing has a bottom. The motive system is operative to propel the robot across a surface. The induction charging system includes a receiver coil in the housing proximate the bottom of the housing. The housing includes a bottom wall separating the receiver coil from the surface.

[0011] In some embodiments, the robot further includes a cleaning system operative to clean the surface as the robot traverses the surface. In some embodiments, the receiver coil is sealed from the environment and the cleaning system by the housing.

[0012] In some embodiments, the robot further includes a cutting element suspended from the bottom of the housing.

[0013] In some embodiments, the housing defines a coil chamber configured to receive the receiver coil, the coil chamber positioned at the bottom of the housing, and the receiver coil is disposed in the coil chamber. In some embodiments, the receiver coil is substantially planar and the coil chamber holds the receiver coil horizontal above the surface. According to some embodiments, a nominal thickness of the portion of the bottom wall defining the coil chamber is at least 2 mm, and a nominal thickness of a top wall defining the coil chamber is at least 2 mm.

[0014] According to some embodiments, the housing includes a chassis and a bottom cover, the chassis includes a chassis bottom wall covering the receiver coil and separating the receiver coil from a compartment of the robot, and the bottom cover separates the receiver coil from the surface.

[0015] In some embodiments, a center axis of the receiver coil is horizontally offset from a lateral centerline extending between front and rear edges of the robot by an offset distance. According to some embodiments, the offset distance is in the range of from about 2 cm to 8 cm.

[0016] In some embodiments, the autonomous mobile robot further includes a debris bin disposed at least partially above the receiver coil.

[0017] According to some embodiments, the autonomous mobile robot further includes an evacuation port located in the bottom of the housing at a position horizontally offset from a lateral centerline extending between the front and rear edges of the robot and located adjacent the coil.

[0018] In some embodiments, the front of the robot defines a square profile.

[0019] In some embodiments, the receiver coil is located a vertical distance from a lower outer surface of the bottom wall in the range of from about 1 mm to 5 mm. According to some embodiments, the receiver coil is located a vertical distance from a lower outer surface of the bottom wall of less than about 3mm.

[0020] According to some embodiments, windings of the receiver coil are mechanically fixed to an inside of a top surface of the bottom wall.

[0021] In some embodiments, the receiver coil is affixed to an inside top surface of the bottom wall by adhesive or fasteners.

[0022] According to some embodiments, the receiver coil is molded into the bottom wall or a top wall of the housing overlying the receiver coil.

[0023] In some embodiments, the receiver coil is encased by plastic on both its top and bottom sides.

[0024] Further features, advantages and details of the present invention will be appreciated by those of ordinary skill in the art from a reading of the figures and the detailed description of the embodiments that follow, such description being merely illustrative of the present invention.

BRIEF DESCRIPTIONS OF THE DRAWINGS

[0025] **FIG. 1** is a top, rear perspective view of an autonomous coverage robot system according to embodiments of the invention.

[0026] **FIG. 2** is a cross-sectional view of the robot system of **FIG. 1** taken along the line **2-2** of **FIG. 1**.

[0027] **FIG. 3** is a front, bottom perspective view of a robot forming a part of the robot system of **FIG. 1**.

[0028] **FIG. 4** is a top view of the robot of **FIG. 3**.

[0029] **FIG. 5** is a bottom view of the robot of **FIG. 3**.

[0030] **FIG. 6** is a fragmentary, cross-sectional view of the robot of **FIG. 3** taken along the line **2-2** of **FIG. 1**.

[0031] **FIG. 7** is a front perspective view of an image sensing device forming a part of the robot of **FIG. 3**.

[0032] **FIG. 8** is a front, top perspective view of a dock forming a part of the robot system of **FIG. 1**.

[0033] **FIG. 9** is a fragmentary, cross-sectional view of the dock of **FIG. 8** taken along the line **9-9** of **FIG. 8**.

[0034] **FIGS. 10** and **11** are schematic diagrams illustrating operations of a communications/guidance system forming a part of the robot system of **FIG. 1**.

[0035] **FIG. 12** is a schematic diagram representing electrical circuits forming parts of the robot system of **FIG. 1**.

[0036] **FIG. 13** is a front, top perspective view of an evacuation dock according to embodiments of the invention.

[0037] **FIG. 14** is a fragmentary, cross-sectional view of the dock of **FIG. 13** taken along the line **14-14** of **FIG. 13**.

[0038] **FIG. 15** is an exploded, top perspective view of an autonomous lawn mowing robot system according to embodiments of the invention.

[0039] **FIG. 16** is a fragmentary, bottom view of a lawn mowing robot forming a part of the robot system of **FIG. 15**.

[0040] **FIG. 17** is a front view of the lawn mowing robot system of **FIG. 15** wherein the lawn mowing robot is positioned over a dock of the lawn mowing robot system for charging of the lawn mowing robot.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0041] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which illustrative embodiments of the invention are shown. In the drawings, the relative sizes of regions or features may be exaggerated for clarity. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

[0042] It will be understood that when an element is referred to as being “coupled” or “connected” to another element, it can be directly coupled or connected to the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly coupled” or “directly connected” to another element, there are no intervening elements present. Like numbers refer to like elements throughout.

[0043] In addition, spatially relative terms, such as “under”, “below”, “lower”, “over”, “upper” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as “under” or “beneath” other elements or features would then be oriented “over” the other elements or features. Thus, the exemplary term “under” can encompass both an orientation of over and under. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0044] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. As used herein the expression “and/or” includes any and all combinations of one or more of the associated listed items.

[0045] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0046] The term “monolithic” means an object that is a single, unitary piece formed or composed of a material without joints or seams.

[0047] With reference to **FIGS. 1-14**, an autonomous coverage robot system **10** according to some embodiments is shown therein. The system **10** includes a vacuum cleaning robot **100** and a base station or dock **200**. The system **10** may include an evacuation dock **300** (**FIG. 13**) in addition to or in place of the dock **200**. The robot **100** is adapted to mate with the dock **200** and the evacuation dock **300**.

[0048] The system **10** also includes a charging or energy management system **205** and an auto-docking control system **201** each including cooperatively operating components of the robot **100** and the dock **200**. In some embodiments, the energy management system **205** includes an air gap transformer or induction charging circuit (including a primary or transmitter coil **244** in the dock **200** and a secondary or receiver coil **164** in the robot **100**) to enable wireless charging of the robot **100** by the dock **200**.

[0049] In the following description of the autonomous robot **100**, use of the terminology "forward/fore" refers generally to the primary direction of motion of the robot **100**, and the terminology fore-aft axis (see reference characters "**FA**" in **FIG. 4**) defines the forward direction of motion **F** (**FIG. 4**), which is coincident with the fore-aft diameter of the robot **100**.

[0050] The robot **100** further defines a lateral or left-right axis **LA** and a vertical axis **VA** that are perpendicular to one another and to the axis **FA**. The axes **FA** and **LA** define a plane that is substantially parallel to the plane defined by the points of contact of the wheels **132** and caster **134** (described below) or the support surface (*e.g.*, floor) on which the robot **100** rests.

[0051] The description also uses a frame of reference based on the dock **200** including X-, Y- and Z-axes, which are depicted in **FIG. 8**. The X-, Y- and Z-axes are perpendicular to one another and intersect at the center of the dock **200**. Movements, distances and dimensions along the Y-axis may be referred to as lateral, leftward or rightward. Movements, distances and dimensions along the X-axis may be referred to herein as depthwise, fore-aft, forward or rearward. Movements, distance and dimensions along the Z-axis may be referred to herein as vertical. The X- and Y-axes define a plane that is parallel to the support surface on which the dock **200** rests (*e.g.*, a floor).

[0052] In the embodiment depicted, the robot **100** includes a robot controller **102**, a body, housing infrastructure or housing (hereinafter, "housing") **111**, an electrical energy storage battery **126**, a motive system **130**, a cleaning system **140**, a detector system **150**, and an energy management or charging subsystem **160**. The detector system **150** forms a part of the auto-docking control system **201**.

[0053] The housing **111** has an undercarriage **115** (**FIG. 3**) and defines an internal main chamber **118** (**FIG. 2**). The undercarriage **115** forms the underside or bottom side of the housing **111** and the robot **100**. The housing **111** includes a chassis **110**, a top cover **112**, a bottom or undercarriage cover **114**, and a displaceable bumper **116**. The robot **100** may move in a forward direction **F** and a reverse drive direction **R**; consequently, the chassis **110** has corresponding forward and back ends, **110A** and **110B**, respectively.

[0054] The chassis **110** may be molded from a material such as plastic as a unitary or monolithic element that includes a plurality of preformed wells, recesses, and structural members for, *inter alia*, mounting or integrating elements of the various subsystems that operate the robot **100**. The covers **112, 114** may be molded from a material such as a polymeric material (plastic) as respective unitary or monolithic elements that are complementary in configuration with the chassis **110** and provide protection of and access to elements and components mounted to the chassis **110**. The chassis **110** and the covers **112, 114** are detachably integrated in combination by any suitable means (*e.g.*, screws). In some embodiments and as shown, the housing **111** has a front end defining a square profile. In some embodiments, the chassis **110** and covers **112, 114** form a structural envelope of minimal height having a generally D-shaped configuration that is generally symmetrical along the fore-aft axis **FA**.

[0055] An evacuation port **120** is defined in the undercarriage cover **114** and the bottom wall **110C** of the chassis **110**. The evacuation port **120** may be provided with a closure device or flap **120A** (**FIG. 5**).

[0056] A coil chamber **124** is defined between the undercarriage cover **114** and the bottom wall **110C** of the chassis **110** (**FIGS. 3** and **6**). The undercarriage cover **114** forms a bottom wall of the coil chamber **124**, and the bottom wall **110C** forms a top wall of the coil chamber **124**.

[0057] The displaceable bumper **116** has a shape generally conforming to that of the front end of the chassis **110** and is mounted in movable combination at the forward portion of the chassis **110** to extend outwardly therefrom (the "normal operating position"). The mounting configuration of the displaceable bumper **116** is such that it is displaced towards the chassis **110** (from the normal operating position) whenever the bumper **116** encounters a stationary object or obstacle of predetermined mass (the "displaced position"), and returns to the normal operating position when contact with the stationary object or obstacle is terminated (due to operation of a control sequence which, in response to any such displacement of the bumper **116**, implements a "bounce" mode that causes the robot **100** to evade the stationary object or obstacle and continue its task routine).

[0058] Installed along either lateral side of the chassis **110** are independent drive wheels **132** that mobilize the robot **100** and provide two points of contact with the floor surface. The drive wheels **132** may be spring loaded. The rear end **110B** of the chassis **110** includes a non-driven, multi-directional caster wheel **134** that provides additional support for the robot **100** as a third point of contact with the floor surface. One or more electric drive motors **136** are disposed in the housing **111** and operative to independently drive the wheels **132**. The motive components may include any combination of motors, wheels, drive shafts, or tracks as desired, based on cost or intended application of the robot **100**.

[0059] In some embodiments, the cleaning system **140** includes a suction slot or opening **142A** defined in the undercarriage **115**. One or more motor driven rotating extractors (*e.g.*, brushes or rollers) **144** flank the opening **142A**. An electric vacuum fan **146** pulls air up through a gap between the extractors **144** to provide a suction force that assists the extractors in extracting debris from the floor surface. Air and debris that pass through the gap are routed through a plenum **142B** that leads to an opening of a cleaning or debris bin **145** disposed or encased in the chamber **118**. The opening leads to a debris collection cavity **145A** of the debris bin **145**. A filter **147** located above the cavity screens the debris from an air passage leading to the air intake of the vacuum fan **146**. Filtered air exhausted from the vacuum fan **146** is directed through an exhaust port **122**.

[0060] A side brush **148** is mounted along the sidewall of the chassis **110** proximate the forward end **110A** and ahead of the extractors **144** in the forward drive direction **F**. The side brush **148** rotatable about an axis perpendicular to the floor surface. The side brush **148** allows the robot **100** to produce a wider coverage area for cleaning along the floor surface. In particular, the side brush **148** may flick debris from outside the area footprint of the robot **100** into the path of the centrally located cleaning head assembly.

[0061] Other suitable configurations for the vacuum cleaning system are disclosed in U.S. Patent No. 9,215,957 to Cohen et al., U.S. Publication No. 2016/0166126 to Morin et al., and U.S. Patent No. 8,881,339 to Gilbert, Jr. et al. the disclosures of which are incorporated herein by reference.

[0062] The robot controller circuit **102** (depicted schematically) is carried by the chassis **110**. The robot controller **102** is configured (*e.g.*, appropriately designed and programmed) to govern over various other components of the robot **100** (*e.g.*, the extractors **144**, the side brush **148**, and/or the drive wheels **132**). As one example, the robot controller **102** may provide commands to operate the drive wheels **132** in unison to maneuver the robot

100 forward or backward. As another example, the robot controller **102** may issue a command to operate one drive wheel **132** in a forward direction and the other drive wheel **132** in a rearward direction to execute a clock-wise turn. Similarly, the robot controller **102** may provide commands to initiate or cease operation of the rotating extractors **144** or the side brush **148**. In some embodiments, the robot controller **102** is designed to implement a suitable behavior-based-robotics scheme to issue commands that cause the robot **100** to navigate and clean a floor surface in an autonomous fashion. The robot controller **102**, as well as other components of the robot **100**, may be powered by the battery **126** disposed on the chassis **110**.

[0063] The detector system **150** (**FIG. 4**) includes a top or communications/guidance signal receiver or detector **152**, proximity or wall following sensors **153**, cliff sensors **154**, a forward directional receiver or detector **156**, an optical mouse sensor **157**, a magnetic field sensor **155**, an image sensing device **158**, and a camera **159**. In some embodiments, each of these sensors or detectors is communicatively coupled to the robot controller **102**. The robot controller **102** implements the behavior-based-robotics scheme based on feedback received from the plurality of sensors distributed about the robot **100** and communicatively coupled to the robot controller **102**.

[0064] The proximity sensors **153** (depicted schematically) are installed along the periphery of the robot **100** proximate the front corners of the robot **100**. The proximity sensors **153** are responsive to the presence of potential obstacles that may appear in front of or beside the robot **100** as the robot **100** moves in the forward drive direction **F**.

[0065] The cliff sensors **154** are installed along the forward end **110A** of the chassis **110**. The cliff sensors **154** are designed to detect a potential cliff, or flooring drop, forward of the robot **100** as the robot **100** moves in the forward drive direction **F**. More specifically, the cliff sensors **154** are responsive to sudden changes in floor characteristics indicative of an edge or cliff of the floor surface (*e.g.,* an edge of a stair).

[0066] The communications/guidance signal detector **152** is mounted on the top front of the housing **111** of the robot **100**. The detector **152** is operable to receive signals projected from an emitter (*e.g.,* the avoidance signal emitter **232** and/or the homing and alignment emitters **234R**, **234L** of the dock **200**) and (optionally) an emitter of a navigation or virtual wall beacon. In some embodiments, the robot controller **102** may cause the robot **100** to navigate to and dock with the dock **200** in response to the communications detector **152** receiving a home signal emitted by the dock **200**.

[0067] In some embodiments and as shown, the detector **152** is mounted at the highest point on the robot **100** and toward the front of the robot **100** as defined by the primary traveling direction, as indicated by an arrow on axis **FA**. In alternative embodiments, multiple detectors can be used in place of the top signal detector **152**. Such an embodiment might include using multiple side-mounted sensors or detectors. Each of the sensors can be oriented in a manner so that a collective field of view of all the sensors corresponds to that of the single, top mounted sensor. Because a single, omni-directional detector is mounted at the highest point of the robot for optimal performance, it is possible to lower the profile of the robot by incorporating multiple, side mounted detectors.

[0068] The forward directional detector **156** is mounted on the front end of the robot **100** and may be mounted on or behind the bumper **116**. The forward directional detector **156** receives signals projected from the emitters **234R, 234L** on the dock **200**. In other embodiments, a pair of detectors receive signals from the emitters **234R, 234L** or more than two detectors may be used.

[0069] In some embodiments, the detectors **154, 156** are infrared ("IR") sensor or detector modules, that include a photodiode and related amplification and detection circuitry, in conjunction with an omni-directional lens, where omni-directional refers to a substantially single plane. Any detector, regardless of modulation or peak detection wavelength, can be used as long as the emitters **232, 234R, 234L** on the base dock **200** are adapted to match the detectors **152, 156** on the robot **100**. In another embodiment, IR phototransistors may be used with or without electronic amplification elements and may be connected directly to the analog inputs of a microprocessor. Signal processing may then be used to measure the intensity of IR light at the robot **100**, which provides an estimate of the distance between the robot **100** and the source of IR light.

[0070] As discussed hereinbelow, in some embodiments, a magnetic field sensing detector **155** is used in place of or in addition to the communications signal detector **152** and/or the directional detector **156**.

[0071] The camera **159** is a vision based sensor, such as a camera, having a field of view optical axis oriented in the forward drive direction of the robot **100**. In the illustrated embodiment, the camera **159** is located at the rear end **110A** of the robot with its line of sight angled forwardly and upwardly over the detector **152**. In some embodiments, the camera **159** is a video camera. In some embodiments, the camera **159** is used for detecting features and landmarks in the operating environment and building a map using Video Simultaneous Localization and Mapping (VSLAM) technology.

[0072] The optical mouse sensor **157** is located on the undercarriage **115** of the robot

100. The circle shown in the top view of **FIG. 4** shows relative placement of the optical mouse sensor **157**; however, the sensor **157** would not be visible in this view. The mouse sensor **157** tracks flooring and assists with drift compensation to keep the robot **100** moving in straight ranks.

[0073] The image sensing device **158** (**FIG.** 7) is mounted on the front end **110A** of the robot **100**. In some embodiments, the image sensor device **158** is mounted in or behind the bumper **116** and is protected by a transparent window **116A**. In some embodiments, the image sensing device **158** is a structured light sensor.

[0074] The image sensing device **158** includes a processor **158A**, a first light source **158L**, a second light source **158U**, and an image sensor **158D**, all of which may be integrated into a unitary module **158E**. The image sensor **158D** may be a CCD image sensor, an active pixel sensor, a CMOS image sensor or other suitable image sensor or camera. The light sources **158L**, **158U** may each be an LED, laser diode, or other suitable light source.

[0075] In use, the light sources **158U**, **158L** project light onto respective target or working surfaces **WSL**, **WSU** (**FIG. 11**), which light is reflected from the working surfaces onto the image sensor **158D**. The image sensor **158D** acquires a plurality or series of image frames. The image frames are processed by the processor **158A** to determine or calculate a depth, distance and/or displacement of the image sensor device **158** from or relative to each working surface **WSL**, **WSU**.

[0076] In some embodiments and as shown, the light source **158L** is configured to project its structured light beam **BL** (**FIG. 11**) at a downward oblique angle (relative to horizontal) to intersect a lower working surface **WSL**, and the light source **158U** is configured to project its structured light beam **BU** at an upward oblique angle (relative to horizontal) to intersect an upper working surface **WSU**. In operation, the lower surface **WSL** will typically be a floor or other support surface along which the robot **100** traverses, and the upper surface **WSU** may be objects in the environment of the robot **100** located above the floor or other support surface. In some embodiments, the image sensing device **158** determines the distance to each work surface based on the vertical location on the image sensor **158D** at which the beam **BU** or **BL** reflected off the working surface intersects the image sensor **158D** in the detection window of the image sensor **158D**.

[0077] Suitable structured light image sensing devices for use as the image sensing device **158** may include the Global Shutter Image Sensor available from PixArt Imaging, Inc. of Taiwan.

[0078] Various other types of sensors, though not shown in the illustrated examples, may also be incorporated in the robot **100** without departing from the scope of the present disclosure. For example, a tactile sensor responsive to a collision of the bumper **116** and/or a brush-motor sensor responsive to motor current of the brush motor may be incorporated in the robot **100**.

[0079] The robot **100** may further include a bin detection system for sensing an amount of debris present in the cleaning bin **122** (*e.g.,* as described in U.S. Patent Publication 2012/0291809, the entirety of which is hereby incorporated by reference).

[0080] The robot charging subsystem **160** includes a charging circuit **162** that includes a secondary or receiver coil **164**. The robot charging subsystem **160** forms a part of the energy management system **205**.

[0081] In some embodiments, the receiver coil **164** includes a wire **164A** that is concentrically, spirally wound to form radially superimposed segments or turns **164B**, and input and output ends **164C**. In some embodiments, the coil **164** is substantially planar or flat.

[0082] According to some embodiments, the coil **164** has a thickness **T1** (**FIG. 6**) of less than 1.25 mm and, in some embodiments, in the range of from about 0.2 mm to 1.5 mm.

[0083] The receiver coil **164** is mounted in the undercarriage **115** of the robot **100**, under the bin **145**. As shown in **FIG. 6**, the receiver coil **164** is contained or encased in the coil chamber **124**. In some embodiments, the coil **164** is secured to the housing **111** in the coil chamber **124**. In some embodiments, the windings of the coil are mechanically fixed to the inside (top) surface of the cover **114**. The coil **164** may be affixed to the cover **114** and/or the bottom wall **110C** of the chassis **110** by adhesive or fasteners, for example. In some embodiments, the coil **164** is molded into the cover **114** and/or the bottom wall **110C**. In some embodiments, the coil **164** is molded in plastic so that it is encased by plastic (*e.g.*, the cover **114**) on both its top and bottom sides (*i.e.*, fully encased).

[0084] In some embodiments, the coil chamber **124** is closed or sealed off from the environment exterior of the robot **100** and from the main chamber **118**. In some embodiments, the coil chamber **124** is substantially hermetically sealed off from the environment exterior of the robot **100** and from the main chamber **118**. In this way, the coil **164** is isolated from the environment and the remainder of the robot **100**. The coil **164** is thereby protected from contamination by dust or debris around the robot or present within the robot **100**.

[0085] The receiver coil **164** is located in the undercarriage **115** at a location corresponding to the location of the transmitter coil **244** of the dock **200**. Generally, the receiver coil **164** on the robot **100** mirrors the transmitter coil **244** on the dock **200**. According to some embodiments and as shown in **FIG. 5**, the center axis **RCA** of the coil **164** is horizontally offset from the lateral centerline **FA** of the robot **100** in order to provide room for the evacuation port **120**. In some embodiments, the offset distance **E1** (**FIG. 5**) between the axes **RCA** and **FA** (*i.e.,* the fore-aft midline of the robot **100**) is in the range of from about 2 cm to 8 cm.

[0086] In some embodiments, at least a portion of the debris bin is disposed above the receiver coil **164**. By locating the coil **164** at a location horizontally offset from the lateral centerline FA, room is provided on the undercarriage of the robot **100** to locate the evacuation port **120** laterally outside the outer diameter of the receiver coil **164**. As a result, the conduit or flow path from the debris bin **145** to the evacuation port **120** is located outside of the receiver coil **164** and not through the opening of the receiver coil **164** or through the coil chamber **124**.

[0087] In some embodiments, the coil **164** is oriented substantially parallel to the **FA-LA** plane of the robot **100**.

[0088] According to some embodiments, the receiver coil **164** is located a vertical distance **E2** (**FIG. 6**) from the lower outer surface of the bottom cover **114** of less than about 3 mm and, in some embodiments, in the range of from about 1 mm to 5 mm.

[0089] According to some embodiments, the nominal thickness **T2** (**FIG. 6**) of the portion of the bottom cover **114** defining the coil chamber **124** is at least 2 mm. According to some embodiments, the nominal thickness **T3** (**FIG. 6**) of the portion of the chassis bottom wall **110C** defining the coil chamber **124** (*i.e.*, the top wall defining the coil chamber **124**) is at least 2 mm.

[0090] Further details of embodiments of the receiver coil **164** and the robot charging subsystem **160** are provided hereinbelow.

[0091] The robot **100** may be modified to perform any suitable task(s). For example, the robot **100** may be used for floor waxing and polishing, floor scrubbing, ice resurfacing (as typically performed by equipment manufactured under the brand name Zamboni®), sweeping and vacuuming, unfinished floor sanding and stain/paint application, ice melting and snow removal, grass cutting, etc. In some embodiments, the robot is configured as a mobility base carrying a retractable mast on which a camera is mounted. Any number of components may be required for such tasks, and may each be incorporated into the robot **100**, as necessary. For simplicity, this application will describe vacuuming as the demonstrative predetermined task. The energy management and auto-docking functions disclosed herein have wide application across a variety of robotic systems.

[0092] **FIG. 8** is a schematic perspective view a dock **200** in accordance with one embodiment of the invention. The dock **200** includes a housing **211** including both a substantially horizontal base plate or platform **210** and a substantially vertical tower or backstop **220**. A docking bay **DB** is defined over the platform **210** and in front of the backstop **220**. The dock **200** may be any of a variety of shapes or sizes, providing sufficient space for the desired components and systems, described below.

[0093] The platform **210** includes a coil chamber **216** (**FIG. 9**) defined therein. A raised pad wall **212** overlies the coil chamber **216**. Tracks **214** are defined on either lateral side of the coil chamber **216** and pad wall **212**.

[0094] The platform **210** is generally parallel to the ground surface on which the dock **200** rests or may be slightly ramped to provide space for wiring. The height or thickness of the platform **210** can be sized to accommodate a transmitter induction coil **244**.

[0095] The dock **200** includes a dock charging subsystem **240**, a communications/guidance system **230**, a dock controller **222**, and a power input connector **224** (connected to a power supply, not shown). The dock charging system **240** forms a part of the energy management system **205**.

[0096] The dock controller circuit **222** (depicted schematically) is carried by the housing **211**. The dock controller **222** is configured (*e.g.*, appropriately designed and programmed) to govern over various other components of the dock **200**.

[0097] The communications/guidance system **230** (**FIG. 8**) includes a top signal emitter **232**, a first or right front homing/alignment emitter **234R**, a second or left front homing/alignment emitter **234L**, and a pair of horizontally spaced apart fine alignment emitters **238**.

[0098] The top signal emitter **232** is mounted on the top of the backstop **220**. The emitter **232** generates a first signal, such as an avoidance signal **BA** (**FIG. 8**), in a diffuse region near the dock **200** to prevent the robot from coming into inadvertent direct contact with the dock **200** while performing a task, such as vacuuming. The top signal emitter **232** may utilize a parabolic reflector to transmit the avoidance signal. In such an embodiment, the avoidance signal is emitted by a single LED directed at a lens whose geometry is determined by rotating a parabola about its focus. This parabolic reflector thus projects the avoidance signal **BA** out in a 360° pattern, without the necessity of multiple emitters. A similar configuration can be employed in the detector **156** on the robot, with a single receiver used in place of the single LED.

[0099] The homing/alignment emitters **234R**, **234L** are located on a front wall **220A** of the backstop **220**. In some embodiments, the emitters **234R**, **234L** are separated by a baffle **236**. The homing/alignment emitters **234R** and **234L** emit or project respective homing signals **BR** and **BQ** (**FIG. 10**) as discussed below. In some embodiments, the emitters **234R**, **234L** are LEDs. The emitters **234R**, **234L** serve as navigational buoys or fiducials. In some embodiments and as shown, the emitters **234R**, **234L** are laterally offset from the centerline **X-X** of the dock **200** and the directional detector **156B** is offset from the centerline **FA** of the robot **100** so that the detector **156B** is substantially centered between the emitters **234R**, **234L** when the robot **100** is in the docked position.

[00100] The fine alignment emitters **238** are located on the front wall **220A**. The fine alignment emitters **238** are spaced apart a prescribed distance **E3** (**FIG. 8**). In some embodiments, the distance **E3** is in the range of from about 1 cm to 3 cm. The fine alignment emitters **238** emit or project respective near alignment signals **BN** as discussed below. In some embodiments, the fine alignment emitters **238** are LEDs. The emitters **238** serve as navigational beacons or fiducials.

[00101] The dock charging subsystem **240** includes a charging circuit **242**, which includes a primary or transmitter coil **244**.

[00102] In some embodiments, the transmitter coil **244** includes a wire **244A** that is concentrically, spirally wound to form radially superimposed segments or turns **244B**, and input and output ends **244C**. In some embodiments, the coil **244** is substantially planar or flat.

[00103] According to some embodiments, the coil **244** has a thickness **T4** (**FIG. 9**) of less than 1.25 mm and, in some embodiments, in the range of from about 0.2 mm to 1.5 mm.

[00104] The transmitter coil **244** is mounted in the platform **210** of the dock **200**. In some embodiments and as shown in **FIG. 9**, the transmitter coil **244** is contained in the coil chamber **216**. In some embodiments, the coil **244** is secured to the platform **210** in the coil chamber **216**. The coil **244** may be affixed to the pad wall **212** and/or a bottom wall **210A** of the platform **210** by adhesive or fasteners, for example. In some embodiments, the coil **244** is molded into the pad wall **212** and/or the bottom wall **217**.

[00105] In some embodiments, the coil chamber **216** is closed or sealed off from the environment exterior of the dock **200**. In some embodiments, the coil chamber **216** is substantially hermetically sealed off from the environment exterior of the dock **200**. In this way, the coil **244** is isolated from the environment and protected from contamination by the robot **100**.

[00106] The transmitter coil **244** is located in the platform **210** in a location corresponding to the location of the receiver coil **164** of the robot **100**.

[00107] In some embodiments, the coil **244** is oriented substantially parallel to the floor.

[00108] According to some embodiments, the transmitter coil **244** is located a vertical distance **E5** (**FIG. 9**) from the upper outer surface of the pad wall **212** of less than about 7 mm and, in some embodiments, in the range of from about 3 mm to 20 mm.

[00109] According to some embodiments, the nominal thickness **T5** (**FIG. 9**) of the portion of the pad wall **212** defining the coil chamber **216** is at least 2 mm.

[00110] Further details of embodiments of the transmitter coil **244** and the dock charging subsystem **240** are provided hereinbelow.

[00111] The robot **100** uses a variety of behavioral modes to effectively vacuum a working area. Behavioral modes are layers of control systems that can be operated in parallel. The robot controller **102** (*e.g.*, microprocessor) is operative to execute a prioritized arbitration scheme to identify and implement one or more dominant behavioral modes for any given scenario, based upon inputs from the sensor system. The robot controller **102** is also operative to coordinate avoidance, homing, and docking maneuvers with the dock **200**.

[00112] Generally, the behavioral modes for the described robot **100** can be characterized as: (1) coverage behavioral modes; (2) escape behavioral modes, and (3) safety behavioral modes. Coverage behavioral modes are primarily designed to allow the robot **100** to perform its operations in an efficient and effective manner, while the escape and safety behavioral modes are priority behavioral modes implemented when a signal from the sensor system indicates that normal operation of the robot **100** is impaired (*e.g.*, obstacle encountered), or is likely to be impaired (*e.g.*, drop-off detected).

[00113] Representative and illustrative coverage behavioral modes (for vacuuming) for the robot **100** include: (1) a Spot Coverage pattern; (2) an Obstacle-Following (or Edge-Cleaning) Coverage pattern, and (3) a Room Coverage pattern. The Spot Coverage pattern causes the robot **100** to clean a limited area within the defined working area, *e.g.*, a high-traffic area. In a certain embodiments the Spot Coverage pattern is implemented by means of a spiral algorithm (but other types of self-bounded area algorithms, such as polygonal, can be used). The spiral algorithm, which causes outward or inward spiraling movement of the robot **100**, is implemented by control signals from the microprocessor to the motive system to change the turn radius/radii thereof as a function of time or distance traveled (thereby increasing/decreasing the spiral movement pattern of the robot **100**).

[00114] The foregoing description of typical behavioral modes for the robot **100** are intended to be representative of the types of operating modes that can be implemented by the robot **100**. One skilled in the art will appreciate that the behavioral modes described above can be implemented in other combinations and other modes can be defined to achieve a desired result in a particular application.

[00115] A navigational control system may be used advantageously in combination with the robot **100** to enhance the cleaning efficiency thereof, by adding a deterministic component (in the form of a control signal that controls the movement of the robot **100**) to the motion algorithms, including random motion, autonomously implemented by the robot **100**. The navigational control system operates under the direction of a navigation control algorithm. The navigation control algorithm includes a definition of a predetermined triggering event.

[00116] Broadly described, the navigational control system, under the direction of the navigation control algorithm, monitors the movement activity of the robot **100**. In one embodiment, the monitored movement activity is defined in terms of the "position history" of the robot **100**, as described in further detail below. In another embodiment, the monitored movement activity is defined in terms of the "instantaneous position" of the robot **100**.

[00117] The predetermined triggering event is a specific occurrence or condition in the movement activity of the robot **100**. Upon the realization of the predetermined triggering event, the navigational control system operates to generate and communicate a control signal to the robot **100**. In response to the control signal, the robot **100** operates to implement or execute a conduct prescribed by the control signal, *i.e.,* the prescribed conduct. This prescribed conduct represents a deterministic component of the movement activity of the robot **100**.

[00118] The image sensing device **158** can be used to acquire information for guidance and operation of the robot during various operations of the robot **100**. In some embodiments, the image sensing device **158** is used to detect obstacles and hazards about the robot **100** so that those obstacles and hazards can be avoided or otherwise addressed. Within the operational range of the image sensor device **158**, the downwardly directed beam **BL** can be used to detect obstacles at or near the floor level as well as cliffs or depressions in the floor. The upwardly directed beam **BU** can be used to detect obstacles at or above the top of the robot **100** in order to detect and avoid obstacles under which the robot may become wedged.

[00119] In some embodiments, the image sensing device **158** is operative to effectively detect objects and voids up to at least 10 inches forward of the robot **100** and, in some embodiments, up to at least 12 inches.

[00120] The camera **159** can be used to navigate the robot and acquire images for other operational use. In some embodiments, the camera **159** is a VSLAM camera and is used to detect features and landmarks in the operating environment and build a map.

[00121] While the robot **100** is vacuuming, it will periodically approach the stationary dock **100**. Contact with the dock **200** could damage or move the dock **100** into an area that would make docking impossible. Therefore, avoidance functionality is desirable. To avoid inadvertent contact, the dock **200** may generate an avoidance signal **BA**, as depicted in **FIG. 10**. The avoidance signal **BA** is shown being transmitted from the emitter **232** on the top of the backstop **220**. The radial range of the avoidance signal **BA** from the dock **200** may vary, depending on predefined factory settings, user settings, or other considerations. At a minimum, the avoidance signal **BA** need only project a distance sufficient to protect the dock **200** from unintentional contact with the robot **100**. The avoidance signal **BA** range can extend from beyond the periphery of the dock **200**, to up to and beyond several feet from the dock **200**, depending on the application.

[00122] The avoidance signal **BA** may be an omni-directional (*i.e.*, single plane) infrared beam, although other signals are contemplated, such as a plurality of single stationary beams or signals. If stationary beams are used, however, a sufficient number could provide adequate coverage around the dock **200** to increase the chances of the robot **100** encountering them. When the detector **152** of the robot **100** receives the avoidance signal **BA** from the emitter **232**, the robot **100** can alter its course, as required, to avoid the dock **200**. Alternatively, if the robot **100** is actively or passively seeking the dock **200** (for recharging or other docking purposes), it can alter its course toward the dock **200**, such as by circling the dock **200**, in such a way to increase the chances of encountering the homing signals as described below.

[00123] Generally, the avoidance signal **BA** is modulated and coded, as are the homing signals **BR**, **BQ**. The bit encoding method as well as binary codes are selected such that the robot **100** can detect the presence of each signal, even if the robot **100** receives multiple codes simultaneously.

[00124] Whenever measurable level of IR radiation from the avoidance signal **BA** strikes the detector **152**, the robot's IR avoidance behavior is triggered. In one embodiment, this behavior causes the robot **100** to spin in place to the left until the IR signal falls below detectable levels. The robot **100** then resumes its previous motion. In one embodiment, the detector **152** acts as a gradient detector. When the robot **100** encounters a region of higher IR intensity, the robot **100** spins in place. Because the detector **152** is mounted at the front of the robot **100** and because the robot **100** does not move backward, the detector **152** always "sees" the increasing IR intensity before other parts of the robot **100**. Thus, spinning in place causes the detector **152** to move to a region of decreased intensity. When the robot **100** next moves forward, it necessarily moves to a region of decreased IR intensity—away from the avoidance signal **BA**.

[00125] In other embodiments, the dock **200** includes multiple coded emitters at different power levels or emitters that vary their power level using a system of time multiplexing. These create concentric coded signal rings which enable the robot **100** to navigate towards the dock **200** from far away in the room. Thus, the robot **100** would be aware of the presence of the dock **200** at all times, facilitating locating the dock **200**, docking, determining how much of the room has been cleaned, etc. Alternatively, the robot **100** uses its motion through the IR field to measure a gradient of IR energy. When the sign of the gradient is negative (*i.e.,* the detected energy is decreasing with motion), the robot **100** goes straight (away from the IR source). When the sign of the gradient is positive (energy increasing), the robot **100** turns. The net effect is to implement a "gradient descent algorithm," with the robot **100** escaping from the source of the avoidance signal **BA**. This gradient method may also be used to seek the source of emitted signals. The concentric rings at varying power levels facilitate this possibility even without a means for determination of the raw signal strength.

[00126] In some embodiments, in order to dock, the system **10** executes a docking procedure including the following sequential steps: a) a seeking or discovery step; b) a homing or far approach step; and c) a near approach step. In some embodiments, the system **10** may also execute a fine approach step. The robot **100** may adopt corresponding modes in which it executes each of these steps (*i.e.,* a seeking mode, a far approach mode, a near approach mode, and a fine approach mode). The docking procedure terminates with the robot **100** in a final, prescribed docked position **DP (FIG. 1)** within the docking bay **DB**. The docked position **DP** may include permitted tolerances or deviation from a precise target docked position.

[00127] In the seeking step, the robot **100** in the seeking mode seeks and discovers the presence and general location of the dock **200** with respect to the robot **100**.

[00128] Then, in the far approach step, the robot **100** in the far approach mode coarse or gross aligns with the docking bay **DB** of the dock **200** and progressively moves toward the docked position **DP**. The robot **100** may progress toward the dock **200** through an intermediate distance, after which the near approach step and mode take over.

[00129] Then, in the near approach step, the robot **100** in the near approach mode more closely aligns with the docking bay **DB** and further progressively moves toward the docked position **DP**. In this step, the robot **100** reduces the distance between the front end **110A** of the robot **100** and the front wall **220A** of the backstop **220**. The robot **100** may also adjust its lateral alignment or rotational orientation with respect to the platform **210**. In some embodiments, the robot **100** may turn and drive rearwardly into the docking bay **DB** (*i.e.*, dock backwards).

[00130] Then, in the fine approach step, the robot **100** in the fine approach mode further progressively moves toward the target docked position and may terminate the approach upon reaching the docked position **DP**. In this step, the robot **100** fine tunes the distance between the front end **110A** of the robot **100** and the front wall **220A** of the backstop **220**. The robot **100** may also fine tune its lateral alignment or rotational orientation with respect to the platform **210**.

[00131] In some embodiments, the robot **100** performs its docking with the dock **200** accurately and repeatably, without the need for gross mechanical guidance features.

[00132] The robot **100** may assume its seeking mode and seek the dock **200** when it detects the need to recharge its battery, or when it has completed vacuuming the room. As described above, once the robot **100** detects or discovers the presence of the avoidance signal **BA** (and therefore the dock **200**), which in this mode serves as a discovery signal, it can assume the far approach mode and move as required to detect the homing signals **BR**, **BL**.

[00133] In the far approach step, the robot **100** uses the homing signals **BR**, **BQ** (**FIG. 10**) and its directional detector **156** to guide the robot **100**. As with the avoidance signal **BA** above, the projected range and orientation of the homing signals **BR**, **BQ** may be varied, as desired. It should be noted however, that longer signals can increase the chance of the robot **100** finding the dock **200** efficiently. Longer signals can also be useful if the robot **100** is deployed in a particularly large room, where locating the dock **200** randomly could be inordinately time consuming. Homing signal **BR**, **BQ** ranges that extend from approximately six inches beyond the front of the platform **210**, to up to and beyond several feet beyond the platform **210** are contemplated, depending on application. The angular width of the homing signals **BR**, **BQ** may vary depending on application, but angular widths in the range of 5° to up to and beyond 60° are contemplated. The angular width of each homing signal **BR, BQ** may be the area covered by the beam or sweep of the homing signal **BR, BQ** and, in some embodiments, is generally or substantially frusto-conical. A gradient behavior as described above can also be used to aid the robot in seeking out the dock **200**.

[00134] The two homing signals **BR, BQ** are distinguishable by the robot **100**, for example as a first or lateral right homing signal **BR** and a second or lateral left homing signal **BQ**. IR beams are generally used to produce the signals and, as such, are not visible. The IR beams may be modulated. Any signal bit pattern may be used, provided the robot **100** recognizes which signal to orient to a particular side. Alternatively, the signals **BR, BQ** may be distinguished by using different wavelengths or by using different carrier frequencies (*e.g.*, 380 kHz versus 38 kHz, etc.).

[00135] Thus, when the robot **100** wants or needs to dock, if the detector **156** receives the right signal **BR** transmitting from the dock **200**, it moves to keep the right signal **BR** on the robot's right side; if it detects the left signal **BQ** transmitting from the dock **200**, it moves to keep the left signal **BQ** on the robot's left side. Where the two signals overlap (the overlap zone **BO**), the robot **100** knows that the dock **200** is nearby and may then dock. Such a system may be optimized to make the overlap zone **BO** as thin as practicably possible, to ensure proper orientation and approach of the robot **100** and successful docking. Alternatively, the right signal **BR** and left signal **BQ** may be replaced by a single signal, which the robot **100** would follow until docked.

[00136] **FIG. 10** depicts an exemplary path **RP** the robot **100** may traverse during a docking procedure utilizing the homing signals. When the detector **156** is in the left signal **156** field, the robot **100** will move towards the right, in direction **MR** in an effort to keep that left signal **BQ** to the left of the robot **100.** When the detector **156** is in the right signal **BR** field, thus the robot **100** will move towards the left, in direction **ML** in an effort to keep that right signal **BR** to the right of the detector **156.** Last, when the detector **156** encounters the overlap zone **BO**, the robot **100** will move in direction **MD** directly towards the dock **100.**

[00137] While approaching the dock **200**, the robot **100** may slow its speed of approach and/or discontinue vacuuming, or perform other functions to ensure trouble-free docking. These operations may occur when the robot **100** detects the avoidance signal **BA**, thus recognizing that it is close to the dock **200**, or at some other predetermined time, *e.g.*, upon a change in the signal from the emitters **234R, 234L.**

[00138] With reference to **FIG. 11**, in the near approach mode, the robot **100** uses the image sensor device **158** to guide the robot **100** in the near approach step. Data from the image sensor device **158** can be used to guide both lateral alignment of the robot **100** with respect to the backstop **220** and depth alignment (*i.e.*, proximity) of the robot **100** with respect to the backstop **200** (*i.e.*, the image sensor device **158** operates as a depth or distance detector). The image sensor device **158** uses the structured light beams **BL**, **BU** to detect the presence and relative location of the dock **200** relative to the front end **110A** of the robot **100**. In some embodiments, the image sensor device **158** detects the location of the backstop front wall **220A** as the robot **100** enters the docking bay **DB**.

[00139] The image sensor device **158** can thus gauge the distance between the front end **110A** of the robot **100** and the backstop **220** and thereby the position of the robot **100** relative to the dock **200** on the X-axis. The robot controller **102** can then use this information to control movement of the robot **100**.

[00140] In some embodiments, the near approach mode is assumed before the wheels **132** engage the tracks **214**. In some embodiments, the near approach mode is assumed when the robot **100** is in the range of from about 8 to 16 inches from the backstop **220**.

[00141] In some embodiments, the robot controller **102** will use the image sensor device **158** alone to determine the final position of the robot **100**. However, the desired docked position **DP** may be such that the spacing **E7** (**FIG. 2**) between the front wall **220A** and the image sensor **158D** is less than the specified or effective minimum range **E8** (**FIG. 11**) of the image sensor device **158** (*i.e.*, the image sensor device **158** is too close to the front wall **220A** to accurately determine the distance). For example, the minimum range **E8** of the image sensor device **158** may be 3 cm and the spacing **E7** may be less than 5 mm. For this reason, the robot **100** may further execute a fine approach step. The fine approach step may be accomplished using different techniques/devices, as discussed below.

[00142] In some embodiments, in the fine approach step, the robot **100** uses the image sensor device **158** and the fine alignment emitters **238** to guide the robot **100** into its final docked position. The emitters **238** are spaced apart a known distance **E3** from one another. The modulated signal beams **BN** (**FIG. 11**) emitted from the emitters **238** are received directly at the image sensor **158B**. As the robot **100** approaches the backstop wall **220A**, the perceived distance between the emitters **238** shrinks, and when the perceived distance equals an expected value for the desired spacing **E7** of the robot **100** to the backstop wall **220A**, the robot **100** halts. From this, the image sensor device **158** can determine the distance to the backstop wall **220A** with sufficient accuracy within a range less than the effective minimum range of the image sensor device **158** (using structural light sensing).

[00143] If the effective minimum range provided by this method is insufficient to guide the robot **100** to the final position, the robot controller **102** can guide the robot **100** the remaining distance to the docked position **DP** using odometry or dead reckoning. That is, the robot **100** uses the image sensor **158D** and emitters **238** to guide the robot **100** to a distance within the effective minimum range, calculates the gap distance from the detected position to the docked position **DP**, and then drives the robot **100** forward the gap distance.

[00144] In other embodiments, in the fine approach step, the robot **100** uses odometry or dead reckoning as described above without using the emitters **238**. That is, the robot **100** uses the image sensor device **158** to guide the robot **100** to a distance within the effective minimum range of the image sensor device **158**, calculates the gap distance from the detected position to the docked position **DP**, and then drives the robot **100** forward the gap distance.

[00145] In another embodiment, the robot **100** uses the magnetic coils **164, 244** to dock. By sensing the magnetic field of the dock side coil **244** upon approaching the dock **200**, the robot **100** can determine alignment of the dock side transmit coil **244** and robot side receiver coil **164**.

[00146] In other embodiments, in the fine approach step, the robot **100** uses an onboard bump sensor (*e.g.*, a contact sensor or displacement sensor) to detect when the front end **110A** of the robot **100** has made contact with the front wall **220A**. Upon detecting contact, the robot **100** may stop or reverse a prescribed distance to position the robot **100** in the docked position **DP**.

[00147] In other embodiments, the camera **159** (*e.g.*, a VSLAM camera) is used to detect the dock **200** in order to guide the robot **100** in the far approach step. The camera **159** may also be used to build and use a map using VSLAM technology as discussed above. For example, in some embodiments, the camera **159** is aimed upward (*e.g.*, to view locations 3-8 feet above the floor) to view objects or features (*e.g.*, picture frames and doorway frames and edges) for mapping and localizing the robot **100** relative to these landmarks (*i.e.*, groupings of features).

[00148] In addition to operating as navigational beacons, homing signals **BR, BQ**, the avoidance signal **BA**, and/or the image sensor signals **BL, BU** may also be used to transmit information, including programming data, fail safe and diagnostic information, docking control data and information, maintenance and control sequences, etc. In such an embodiment, the signals can provide the control information, dictating the robot's reactions, as opposed to the robot **100** taking certain actions upon contacting certain signals from the dock **200**. In that case, the robot **100** functions as more of a slave to the dock **200**, operating as directed by the signals sent.

[00149] In each of the far approach step, the near approach step, and the fine approach step, the robot **100** may use the navigational aids described herein to adjust the lateral alignment of the robot **100** with respect to the dock **200**, the angular orientation of the robot **100** with respect to the dock **200**, and/or the depthwise position of the robot **100** into the dock **200** (*i.e.*, proximity to the backstop **220**).

[00150] Generally, the control sequence for vacuuming can include three subsequences based on the measured energy level of the robot **100**. Those are referenced generally as a high energy level, a medium energy level, and a low energy level. In the high energy level subsequence, the robot **100** performs its predetermined task, in this case, vacuuming (utilizing various behavioral modes as described above), while avoiding the dock **200**. When avoiding the dock **200**, the robot **100** performs its avoidance behavior and continues to operate normally. This process continues while the robot **100** continually monitors its energy level. Various methods are available to monitor the energy level of the power source, such as coulometry (*i.e.*, the measuring of current constantly entering and leaving the power source), or simply measuring voltage remaining in the power source. Other embodiments of the robot **100** may simply employ a timer and a look-up table stored in memory to determine how long the robot **100** can operate before it enters a different energy level subsequence. Still other embodiments may simply operate the robot **100** for a predetermined time period before recharging, without determining which energy level subsequence it is operating in. If the robot **100** operates on a liquid or gaseous fuel, this level may also be measured with devices currently known in the art.

[00151] Once the energy remaining drops below a predetermined high level, the robot **100** enters its medium energy level sequence. The robot **100** continues to vacuum and monitor its energy level. In the medium energy level, however, the robot **100** "passively seeks" the dock **200**. While passively seeking the dock **200**, the robot **100** does not alter its travel characteristics; rather, it continues about its normal behavioral mode until it detects the avoidance signal **BA** or a homing signal **BR**, **BQ**, each of which may be followed until the robot **100** ultimately docks with the dock **200**. In other words, if the robot detects the avoidance signal **BA** while passively seeking, rather than avoiding the dock **200** as it normally would, it alters its travel characteristics until it detects the homing signal **BR** or **BQ**, thus allowing it to dock.

[00152] Alternatively, the robot **100** continues operating in this medium energy level subsequence until it registers an energy level below a predetermined low level. At this point, the robot **100** enters the low level subsequence, characterized by a change in operation and travel characteristics. To conserve energy, the robot **100** may discontinue powering all incidental systems, and operations, such as vacuuming, allowing it to conserve as much energy as possible for "actively searching" for the dock **200**. While actively searching, the robot **100** may alter its travel characteristics to increase its chances of finding the dock **200**. It may discontinue behavioral modes such as those employing a spiral movement, which do not necessarily create a higher chance of locating the dock **200**, in favor of more deliberate modes, such as wall-following. This deliberate seeking will continue until the robot **100** detects the presence of the dock **200**, either by detecting the avoidance signal **BA** or the homing signals **BR**, **BQ**. Clearly, additional subsequences may be incorporated which sound alarms when the power remaining reaches a critical level, or which reconstruct the route the robot **100** has taken since last contacting the dock **200** to aid in relocating the dock **200**.

[00153] The robot **100** may also dock because it has determined that it has completed its assigned task (*e.g.,* vacuuming a room) or its bin needs to be emptied. The robot **100** may make this determination based on a variety of factors, including considerations regarding room size, total run time, total distance traveled, dirt sensing, etc. Alternatively, the robot may employ room-mapping programs, using the dock **200** and/or walls and large objects as points of reference. Upon determining that it has completed its task, the robot **100** will alter its travel characteristics in order to find the dock **200** quickly. The dock **200** may include a charging system only (*i.e.*, a charging dock) or may include both a charging system and an evacuation system or station operative to empty debris from the bin of the robot **100**.

[00154] Once the robot **100** is in the docked position, it can recharge itself autonomously. Circuitry within the dock **200** detects the presence of the robot **100** and then switches on the charging voltage to the transmitter coil **244**.

[00155] While docked with the dock **200**, the robot **100** can also perform other maintenance or diagnostic checks. In certain embodiments, the robot **100** can completely recharge its power source or only partially charge it, based on various factors. Other behaviors while in the docking position such as diagnostic functions, internal mechanism cleaning, communication with network, or data manipulation functions may also be performed.

[00156] As discussed, herein, the energy management system **205** uses electromagnetic induction charging to charge the robot **100**. The use of induction charging can provide a number of advantages as compared to direct electrical contact charging.

[00157] The use of induction charging eliminates electrical contacts as points of failure in the system **10**. The induction charging system makes docking easier and more reliable.

[00158] Greater flexibility is provided for industrial design. Induction charging allows for a completely sealed dock.

[00159] As discussed herein, in some embodiments the magnetic field from the transmitter coil can be used as a dock avoidance signal to the robot, in which case the dock avoidance sensor of the robot can be omitted.

[00160] The induction charging system does not require explicit communication from the charge receiving circuit (on the robot) to the charge transmitter circuit (on the dock) for staying in regulation.

[00161] By encasing the receiver coil **164** and the transmitter coil **244** in the coil chambers **124** and **216** (and, likewise encasing the transmitter coil **344** in the coil chamber **316** as described below), the coils **164, 244, 344** are isolated from the environment and the interior of the robot **100**. As a result, people and pets and internal components of the robot **100** are protected from the voltage of the coils and the coils are protected from damage. Additionally, the transmitter coils **244, 344** are prevented from contacting the receiver coil **164**. In some embodiments, each coil **164, 244, 344** is encased on each of its top and bottom sides by plastic having a thickness in the range of from about 1 to 3 mm.

[00162] Various parameters may affect the coupling factor between the receiver and transmitter coils and can be adjusted to improve the coupling factor. The coupling factor is increased by a smaller separation gap, larger coil areas, and more precise alignment. Good alignment is less critical for larger coils. Thicker coil wire improves efficiency.

[00163] In some embodiments, the coils are operated at frequencies in the 160-270 kHz range.

[00164] The electromagnetic induction charging system **205** is schematically shown in **FIG. 12** and includes the robot charging subsystem **160** and the dock charging subsystem **240**. When the robot **100** is docked in the docking bay **DB** as described, the receiver coil **164** is superimposed over the transmitter coil **244** with a vertical or axial gap **GC** therebetween. In this manner, the coils **164, 244** form an air gap transformer. The circuit **242** applies an alternating current through the transmitter coil **244**, thereby creating an alternating magnetic field (flux) emanating from the transmitter coil **244**. The flux is received and converted into an electrical current by the receiver coil **164**. This electrical current is used by the circuit **162** to charge the battery **126** or otherwise provide energy to the robot **100**.

[00165] The efficiency of the induction charging (both energy transfer rate and power loss) is dependent on the alignment and spacing between the coils **164, 244**. The docking modes, methods, structures and sensors as described herein can ensure that the robot **100** is consistently properly docked in the docked position **DP**, and the coils **164**, **244** are thereby properly aligned.

[00166] In some embodiments, when the robot **100** is in the docked position **DP**, the coils **164**, **244** lie in substantially parallel planes. In some embodiments, the coil **164** defines a receiver coil plane **PRC** (**FIG. 2**), and the coil **244** defines a transmitter coil plane **PTC**, and the planes **PRC** and **PTC** are parallel or form an angle with respect to one another no greater than 10 degrees.

[00167] When the robot **100** is in the prescribed docked position **DP** (**FIGS. 1** and **2**), the coil **164** is located in a prescribed vertical alignment position with respect to the coil **244**. In some embodiments, the central axis **RCA** of the coil **164** is substantially coaxial with the central axis **TCA** of the coil **244**. In some embodiments, the axis **RCA** is disposed within 5 mm of the axis **TCA** in the receiver coil plane **PRC** and, in some embodiments, within 30 mm.

[00168] In other embodiments, when the robot **100** is in the docked position **DP**, the transmitter coil axis **TCA** intersects the receiver coil plane **PRC** at a location that is offset a prescribed offset distance from the receiver coil axis **RCA**, and the transmitter coil **244** vertically overlaps the receiver coil **164**. In some embodiments, the prescribed distance is no greater than about 5 mm and, in some embodiments, is in the range of from about 5 mm to 30 mm.

[00169] Notably, the transmitter coil **244** is horizontally located in the platform **212** such that the transmitter coil center axis **TCA** is offset from the center or midline of the platform **212** in order to more closely align the center axes **RCA**, **TCA** of the receiver coil **164** and the transmitter coil **244** when the robot **100** is in the docked position **DP**.

[00170] The offset of the receiver coil **164** accommodates the evacuation port **318** of the dock **300**.

[00171] Moreover, the placement of the receiver coil **164** in the undercarriage **115** of the robot **100** and the placement of the transmitter coil **244** in the platform **212** can provide a relatively small axial gap **GC** (**FIG. 2**) between the coils **164**, **244**. Nonetheless, the coils **164**, **244** are each protected from the environment by being enveloped in the coil chambers **124**, **216**. A smaller gap enables improved energy transfer efficiency. In some embodiments, the gap **GC** has a height **E10** of 7 mm or less.

[00172] According to some embodiments, the robot charging subsystem **160** and the dock charging subsystem **240** operate as follows. The dock charging circuit ("transmitter firmware") **242** assumes the following main states: Ping, Handshaking, and Charging.

Generally, the dock charging circuit **242** "pings" periodically (*e.g.*, approximately every 1/3 second) to determine whether the robot **100** is on the dock **200**, confirms the presence of the robot **100**, and determines whether to send a full charge.

[00173] In Ping mode, the dock charging circuit **242** starts the coil **244** oscillating, and measures how long it takes to stop oscillation to detect when a real robot is present, when there is a foreign object absorbing power ("snow shovel" detection), and when there is nothing near the dock.

[00174] In Handshake mode, the dock charging circuit **242** listens for an authentication word from the robot **100** by observing differences in power consumed when running power for a short duration.

[00175] In Charging mode, the power sent is controlled by the dock charging circuit **242** for efficiency and to keep the electronics in valid operating regions (current and voltage). In particular, in Charging mode the dock charging circuit **242** sends power using voltage-feedback-current-control until the dock charging circuit **242** detects the receiver (*i.e.,* the robot charging circuit **162**) detuning, and then stops sending power for a variable amount of time. The amount of time that power is off is dynamically adjusted based on how long the receiver consumed power before detuning.

[00176] Cycle-by-cycle control of the dock charging circuit **242** may be performed in an interrupt handler that runs on every cycle of the transmit coil (in some embodiments, approximately 200KHz or every 5μs). Every cycle the interrupt handler determines what current to send to the transmitter coil **244** on the next cycle by adjusting the current limit (called "limit" in the diagrams) or completely turning off adding energy the next cycle (called enabling the "dead" signal in the diagrams). The high level control code described determines which of these interrupt handlers should run to manage the transmitter coil **244** depending on the high level state of the dock charging circuit **242**.

[00177] The "Charging Resonant Tank" state is the main mode when sending power to the robot **100**. In this mode, the dock charging circuit **242** adjusts the current limit until the dock charging circuit **242** detects the robot charging circuit **162** detune. When it does, it enters the "Idle" state which triggers the background code to measure the amount of time the receiver coil **164** was drawing power and sleep for the calculated amount of time.

[00178] The "Hard Start" state and "Decaying" state are transient states while transferring power. The dock charging circuit **242** initially enters "Hard Start" state, and will move between "Charging Resonant Tank" state and "Decaying" state while transferring power until it enters "Idle" state when the robot charging circuit **162** detunes.

[00179] After starting and sending the authentication code, the robot charging circuit **162** checks that power is coming in. Assuming it is, the robot charging circuit **162** enters the main loop where it detunes when the system voltage exceeds some threshold. How long it takes for this to happen will depend on the power being drawn from the robot charging circuit **162** (*i.e.*, whether it is charging a battery, and how much power is being sent to the battery). The robot charging circuit **162** then detunes briefly, which the dock charging circuit **242** will detect, and then retunes to accept power when the dock charging circuit **242** next decides to send it.

[00180] In some embodiments, the magnetic field emitted from the transmitter coil **244** and the tank circuit of the dock charging circuit **242** is also used in the navigation control of the robot **100**. The robot **100** will detect the magnetic charge that accompanies the "ping" generated by the dock charging circuit **242**. The robot **100** can use that detection to avoid the dock **200** (*e.g.,* while the robot is moving about on its cleaning mission) or discover the dock **200** (to initiate docking). According to some embodiments, the detection radius is in the range of from about 6 to 18 inches from the dock **200** and, in some embodiments, 10 to 14 inches.

[00181] In some embodiments, the magnetic field sensor **155** on the robot **100** is used to detect the ping signals. The sensor **155** may be used to detect the ping signals independently of the robot's receiver coil **164** and charging circuit **162**. The magnetic field sensor **155** may include a first magnetic sensing circuit **155A** and a second magnetic sensing circuit **155B**. The magnetic sensing circuits **155A**, **155B** may each be small LC circuits with high gain amplifiers. The inductor coil of the first magnetic sensing circuit **155A** may be oriented in the Z-direction (vertically) so that it provides a signal roughly proportional to the distance to the transmitter coil **244**. The inductor coil of the second magnetic sensing circuit **155B** may be oriented in the X- or Y-direction (left-to-right, fore-aft, or horizontally) so that it provides a signal roughly proportional to the orientation to the transmitter coil **244**.

[00182] The magnetic field sensor **155** may also be used to determine where the robot **100** is located in the magnetic field of the dock transmitter coil **244** during docking. In this manner, detection from the magnetic field sensor **155** can be used to execute the far approach step in place of or in addition to data provided by the front directional detector **156**.

[00183] The magnetic field sensor **155** may also be used to confirm that the coils **164**, **244** are sufficiently well-aligned once the robot **100** is fully docked. This can enable improved alignment between the coils **164**, **244**, and thereby guarantee good efficiency in the coupling to achieve good power transfer.

[00184] In some embodiments, the robot **100** is aligned with the dock **200**, and thereby the coil **164** is aligned with the coil **244**, along the X-axis and along the Y-axis with a tolerance of +/- 25 mm or less, in some embodiments, +/- 5 mm or less and, in some embodiments, about +/- 1 mm. In some embodiments, the tolerance for alignment of the coils **164, 244** along the Z-axis is 20 mm or less (*i.e.,* the coil **164** is not spaced above the coil **244** more than 20 mm, and the coils **164, 244** are as close together as feasible).

[00185] FIGS. 13 and **14** show an evacuation dock **300** in accordance with one embodiment of the invention. The evacuation dock **300** includes a housing **311** including both a substantially horizontal base plate or platform **310** and a substantially vertical tower or backstop **320**. A docking bay **DB** is defined over the platform **310** and in front of the backstop **320**. The evacuation dock **300** may be any of a variety of shapes or sizes, providing sufficient space for the desired components and systems, described below.

[00186] The platform **310** includes a coil chamber **316** defined therein. The coil chamber **316** is defined by the wall **312** and a lower wall **315**. A raised pad wall **312** overlies the coil chamber **316**. Parallel tracks **314** are defined on either lateral side of the coil chamber **316** and the pad wall **312**. An evacuation suction port **318** is defined in the pad wall **312**. The evacuation suction port **318** is offset from the lateral centerline of the platform **310** and the midpoint between the tracks **314**.

[00187] The platform **310** is sloped at an upwards angle toward the backstop **320**. In some embodiments, the platform **310** angle of rise is in the range of from 6 to 10 degrees, in some embodiments, 8 to 10 degrees and, in some embodiments, about 8.6 degrees.

[00188] The evacuation dock **300** includes a charging subsystem **340**, a communications/guidance system **330**, a dock controller **322**, and a power input connector **324** (connected to a power supply, not shown) corresponding to and operative in the same manner as the charging subsystem **240**, the communications/guidance system **230**, the dock controller **222**, and the power input connector **224**, respectively, except as discussed below. The evacuation dock **300** includes an avoidance emitter **332**, directional emitters **334R, 334L**, and a pair of fine alignment emitters **338** corresponding to the avoidance emitter **232**, the directional emitters **234R, 234L**, and the emitters **238**, respectively.

[00189] The charging subsystem **340** includes a charging circuit **342** and a transmitter coil **344** corresponding to the charging circuit **242** and the transmitter coil **244**. The coil **344** is encased in the coil chamber **316** in the same manner as described above with regard to the coil chamber **216** and the coil **244**. The coil **344** is tilted or oriented at an oblique angle **A1** (**FIG. 14**) with respect to the floor toward the backstop **320**. In some embodiments, the angle

A1 is in the range of from about 6 to 10 degrees, in some embodiments, 8 to 10 degrees and, in some embodiments, about 8.6 degrees. The central axis **RCA** of the coil **344** is offset from the midline **X-X** of the platform **310** to match the offset of the coil **164**.

[00190] The evacuation dock **300** further includes a debris evacuation system **350**. The evacuation system **350** includes a debris bin **352** (which may be removable) in the tower **320**, an evacuation port **318** located in the platform **310**, a duct or ducts fluidly connecting the port **318** to the bin **352**, and a suction fan **354** configured to draw debris from the evacuation port **318** and into the bin **352**.

[00191] The wheel tracks **314** are designed to receive the robot's drive wheels **132** to guide the robot **100** onto the platform **310** in proper alignment with the evacuation suction port **318**. Each of the wheel tracks **314** includes a depressed wheel well **319** that holds a drive wheel **132** in place to positively align and locate the robot **100** relative to the platform **310**, and to prevent the robot **100** from unintentionally sliding down the inclined platform **310** once docked.

[00192] The robot **100** can dock with the evacuation dock **300** by advancing onto the platform **310** and into the docking bay **DB** of the evacuation station **300** as described above with regard to the dock **200**. Once the evacuation dock **300** receives the robot **100**, the suction fan **354** generates a vacuum that draws debris from the cleaning bin **145** of the robot **100**, through the platform **310**, and into the debris bin **352**.

[00193] When the robot **100** is docked in the prescribed docked position in the docking bay **DB**, the coils **164** will be superimposed over and suitably vertically aligned with the coil **344**. Additionally, the evacuation port **120** of the robot **100** will be aligned with and in contact with or in close proximity to the evacuation port **318** of the evacuation dock **300**.

[00194] The robot **100** can avoid, discover, far approach, near approach, and fine approach the evacuation dock **300** in the same manner as described above with regard to the dock **200**. It is also contemplated that the fine alignment emitters **338** may be omitted. The robot may rely on the wheel wells **319** to capture the wheels **132**, thereby positively aligning and positioning the robots and ensuring that the robot is properly aligned in the final portion of the docking approach. The image sensor device **158** can be used to ensure that the wheels **132** do not over- or under-run the wheel wells.

[00195] The magnetic field sensor **155** may also be used to detect magnetic ping signals from the coil **344** to guide the robot **100** as described above for the dock **200**.

[00196] In some embodiments, the robot **100** is aligned with the evacuation dock **300**, and the coil **164** is thereby aligned with the coil **344**, along the X-axis and along the Y-axis with a tolerance of about +/- 1 mm. The evacuation dock **300** requires close alignment of the evacuation port **120** of the robot with the suction port **318** of the evacuation dock **300**, and therefore the tolerance for misalignment may be very small and less than the tolerance permitted for the dock **200**. In some embodiments, the tolerance for alignment of the coils **164**, **344** along the Z-axis is about +/- 20 mm.

[00197] With reference to **FIGS. 15-17**, a lawn mowing robot system **20** according to embodiments of the invention is shown therein. The system **20** includes a lawn mower robot and a charging dock **500**. The robot **400** includes a robot charging subsystem **460** and the dock **500** includes a dock charging subsystem **560**, which together form an induction charging system **505**.

[00198] The robot **400** further includes a robot controller **402**, a chassis **410**, a cutting deck **414**, a cover **412**, a battery **426**, a motive system **430**, and a cutting system **440**. The chassis **410**, the cutting deck **414**, and the cover **412** form a robot body, housing infrastructure or housing.

[00199] The motive system **430** includes a pair of independently driven wheels **434**, a pair of caster wheels **435**, a motor **434A** to drive the wheels **434**, and an automatic height adjuster **436**.

[00200] The cutting system **440** includes at least one cutting element suspected from the bottom of the body of the robot **100**. As shown, the cutting system **440** includes a pair of rotary cutting blades **444** suspended from the bottom of the cutting deck **414** and an electric motor **442** to drive the blades **444**.

[00201] The robot charging subsystem **460** includes a charging circuit **462** and a receiver coil **464** generally corresponding to the charging circuit **162** and a receiver coil **164**.

[00202] The coil **464** is contained in a receiver coil chamber **424** defined in the cutting deck **414**. The cutting deck **414** or chassis **410** includes a bottom wall **410C** defining a portion of the receiver coil chamber **424**. In some embodiments, the bottom wall **410C** has a nominal thickness of at least 2 mm. The bottom wall **410C** separates the coil **464** from the underlying surface (*e.g.*, the ground or objects). In some embodiments, the center axis **RCA-RCA** is centered on the fore-aft central axis **FA-FA** of the robot **400**.

[00203] The dock **500** includes a housing **511**, ground anchors or spikes **512**, the dock charging subsystem **540**, a homing system **530**, and a dock controller **522**.

[00204] The housing **511** includes a base **510** and a cover **514**. The base **510** and the cover **514** collectively form an enclosed chamber **516**.

[00205] The dock charging subsystem **540** includes a charging circuit **542** and a transmitter coil **544** generally corresponding to the charging circuit **242** and a transmitter coil **244**. The transmitter coil **544** is contained in the chamber **516**. The cover **514** includes a top wall **514A** defining a portion of the chamber **516**. The top wall **514A** separates the coil **544** from the robot **400** or other overlying objects. In some embodiments, the top wall **514A** has a nominal thickness of at least 2 mm.

[00206] The robot **400** can be used to autonomously mow a lawn. When the robot **400** has completed its mowing session or requires a recharge, it will seek the dock **500**.

[00207] In some embodiments, the robot **400** uses localization beacons about the lawn to triangulate into the vicinity of the dock **500**. In some embodiments, the robot **400** is configured to align with the dock **500** using the magnetic charge emitted by a periodic pinging of the dock charging circuit **542**, such as described above with regard to the magnetic field sensor **155** and the dock charging circuit **242**. In some embodiments, the robot **400** includes a Hall Effect sensor which is used to sense the magnetic charge ping, enabling the robot controller **402** to align the robot **400** with the dock **500** as the robot **400** approaches its prescribed docked position over the dock **500**.

[00208] When the robot **400** is in its prescribed docked position over the dock **500**, the receiver coil **464** and the transmitter coil **544** will be substantially vertically aligned, overlapping or in near proximity. In some embodiments, the robot **400** is positioned over the dock **500** such that the central axis **RCA-RCA** of the receiver coil **464** is aligned or brought into close proximity to the central axis **TCA-TCA** of the transmitter coil **544**. The robot **400** may lower the cutting deck **414** relative to the chassis **510** and the wheels **435**, and thereby the coil **464**, using the height adjuster **436**. In this manner, the receiver coil **464** is brought into closer proximity to the transmitter coil **544**. In some embodiments, the cutting deck **414** is lowered into contact with the dock **500**.

[00209] The robot charging subsystem **460** and the dock charging subsystem **540** can thereafter cooperate to inductively charge the robot **400** in the same manner as described above with regard to the robot charging subsystem **160** and the dock charging subsystem **240**.

[00210] The coils **164, 244, 344, 464, 544** may be formed of any suitable material and construction. In some embodiments, one or more of the coils is/are formed of wound copper wire. In some embodiments, one or more of the coils is/are formed of stamped copper. In some embodiments, one or more of the coils is/are formed of wound aluminum wire. In some embodiments, one or more of the coils is/are formed of wound Litz wire (copper or aluminum).

[00211] In some embodiments, the vertical spacing distance between the coils **164**

and **244** and between the coils **164** and **344** when the robot is docked us less than 20 mm.

[00212] In some embodiments, the coil **164** is 1.25 mm thick, has 22 windings, an inner diameter of 58 mm, and an outer diameter of 117 mm.

[00213] In some embodiments, the receiver coil **164** ("Rx Coil") and the transmitter coils **244**, **344** ("Tx Coil") have the following characteristics:

Tx Coil (dock/evacuation station)
OD: 110-120mm
12-15 turns
Induction of 30 microhenries
The front runner embodiment is a Litz Wire coil.

Rx Coil (robot)
OD: 110-120mm, currently ~114mm
18-26 turns, currently 22 turns
Induction of 30-65 uH, currently 50 microhenries
The front runner embodiment is copper magnet wire coil.

Representative measured data for Copper Magnetic Coil:

Magnet Coil 1: 22 Turns	Resistance	Inductance:
0Hz:	150.323mΩ	47.217uH
100kHz:	650.055mΩ	46.538uH
200kHz:	1.359Ω	46.208uH
300kHz:	2.271Ω	46.038uH
Magnet Coil 3: 23 Turns	Resistance	Inductance:
0Hz:	161.146mΩ	56.777uH
100kHz:	798.030mΩ	55.819uH
200kHz:	1.630Ω	55.398uH
300kHz:	2.640Ω	55.183uH

Litz wire coils are also contemplated, with representative measured data as follows:

Litz Wire Coil 1: 23 Turns	Resistance	Inductance:
0Hz:	234.934mΩ	61.536uH
100kHz:	683.445mΩ	60.350uH
200kHz:	1.575Ω	60.168uH
300kHz:	2.912Ω	60.060uH
Litz Wire Coil 2: 23 Turns	Resistance	Inductance:
0Hz:	163.450mΩ	58.556uH
100kHz:	376.530mΩ	58.358uH
200kHz:	907.549mΩ	58.278uH
300kHz:	1.736Ω	58.220uH

Stamped copper coils are also contemplated, with representative measured data as follows:

Stamped Copper Coil 60uH:	Resistance	Inductance:
0Hz:	426.396mΩ	60.527uH
100kHz:	1.100Ω	59.789uH
200kHz:	2.145Ω	59.622uH
300kHz:	3.452Ω	59.891uH
Stamped Copper Coil 32 uH:	Resistance	Inductance:
0Hz:	293.873mΩ	33.672uH
100kHz:	627.671mΩ	33.191uH
200kHz:	1.117Ω	33.024uH
300kHz:	1.743Ω	32.981uH

Stamped aluminum coils are also contemplated, with representative measured data as follows:

Stamped Aluminum Coil 60uH 0.4mm:	Resistance	Inductance:
0Hz:	537.804mΩ	60.448uH
100kHz:	1.194Ω	59.494uH
200kHz:	2.424Ω	59.829uH
300kHz:	3.936Ω	60.130uH

Stamped Aluminum Coil 60uH 0.3mm:	Resistance	Inductance:
0Hz:	559.495mΩ	60.596uH
100kHz:	1.211Ω	60.098uH
200kHz:	2.370Ω	59.940uH
300kHz:	3.790Ω	60.229uH
Stamped Aluminum Coil 32 uH 0.3mm	Resistance	Inductance:
0Hz:	369.833mΩ	33.720uH
100kHz:	669.292mΩ	33.488uH
200kHz:	1.217Ω	33.342uH
300kHz:	1.910Ω	33.326uH

In some embodiments, the receiver coil **164** ("Rx Coil") and the transmitter coils **244**, **344** ("Tx Coil") are stamped aluminum coils having the following characteristics:

Rx Coil:
Outer Diameter: 114 mm
Inner Diameter: 30 mm
Turns: 30
Trace Width: 1.2 mm
Space between traces: 0.2mm
Estimated inductance: 58 uH (microhenries)

Tx Coil:
Outer Diameter: 114 mm
Inner Diameter: 72 mm
Turns: 15
Trace Width: 1.2 mm
Space between traces: 0.2mm
Estimated inductance: 32 uH (microhenries)

In some embodiments, the receiver coil **464** ("Rx Coil") and the transmitter coil **544** ("Tx Coil") of the robotic lawn mower system **20** have the following characteristics:

Tx Coil (charging dock)
4 turns
Induction of 10-20uH, currently 15 microhenries
Need to charge 300W battery

Rx Coil (robot)
9 turns
#16AWG (American wire gauge)
Nominal diam 300mm
Induction of 40-60 uH, currently 50 microhenries
(Data measured on 8 turns of #18 AWG: 100kHz frequency, 56.uH, 0.499 ESR)

[00214] The foregoing is illustrative of the present invention and is not to be construed as limiting thereof. Although a few exemplary embodiments of this invention have been described, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention. Therefore, it is to be understood that the foregoing is illustrative of the present invention and is not to be construed as limited to the specific embodiments disclosed, and that modifications to the disclosed embodiments, as well as other embodiments, are intended to be included within the scope of the invention.

THAT WHICH IS CLAIMED IS:

1. A method for docking an autonomous mobile floor cleaning robot with a charging dock, the robot including a receiver coil and a structured light sensor, the charging dock including a docking bay and a transmitter coil, the method comprising:

positioning the robot in a prescribed docked position in the docking bay using the structured light sensor and by sensing a magnetic field emanating from the transmitter coil; and thereafter

induction charging the robot using the receiver coil and the transmitter coil with the robot in the docked position.

2. The method of Claim 1 wherein:

the dock includes an upstanding backstop; and

further comprising aligning the mobile floor cleaning robot with the charging dock using the structured light sensor by detecting the backstop using the structured light sensor.

3. The method of Claim 1 wherein, when the robot is in the docked position, the receiver coil is located in a prescribed alignment with the transmitter coil.

4. The method of Claim 1 including:

executing a cleaning mission using the robot; and

using the structured light sensor to detect obstacles and/or voids proximate the robot during the cleaning mission.

5. An autonomous mobile floor cleaning robot for cleaning a surface, the robot comprising:

a housing having a bottom;

a motive system operative to propel the robot across the surface;

an induction charging system including a receiver coil in the housing proximate the bottom of the housing, the receiver coil being configured to be inductively coupled to a transmitter coil in a charging dock during a charging operation; and

a cleaning system operative to clean the surface as the robot traverses the surface, the cleaning system including an evacuation port located in the bottom of the housing to release debris from the robot.

6. The robot of Claim 5 wherein the receiver coil is offset from the center of the robot.

7. An autonomous mobile robot, comprising:
a housing having a bottom;
a motive system operative to propel the robot across a surface; and
an induction charging system including a receiver coil in the housing proximate the bottom of the housing;
wherein the housing includes a bottom wall separating the receiver coil from the surface.

8. The robot of Claim 7 further including a cleaning system operative to clean the surface as the robot traverses the surface.

9. The robot of Claim 8 wherein the receiver coil is sealed from the environment and the cleaning system by the housing.

10. The robot of Claim 7 further including a cutting element suspended from the bottom of the housing.

11. The robot of Claim 7 wherein:
the housing defines a coil chamber configured to receive the receiver coil, the coil chamber positioned at the bottom of the housing; and
the receiver coil is disposed in the coil chamber.

12. The robot of Claim 11, wherein the receiver coil is substantially planar and the coil chamber holds the receiver coil horizontal above the surface.

13. The robot of Claim 11, wherein:
a nominal thickness of the portion of the bottom wall defining the coil chamber is at least 2 mm; and

a nominal thickness of a top wall defining the coil chamber is at least 2 mm.

14. The robot of Claim 7 wherein:

the housing includes a chassis and a bottom cover;

the chassis includes a chassis bottom wall covering the receiver coil and separating the receiver coil from a compartment of the robot; and

the bottom cover separates the receiver coil from the surface.

15. The robot of Claim 7, wherein a center axis of the receiver coil is horizontally offset from a lateral centerline extending between front and rear edges of the robot by an offset distance.

16. The robot of Claim 15, wherein the offset distance is in the range of from about 2 cm to 8 cm.

17. The robot of Claim 7, further comprising a debris bin disposed at least partially above the receiver coil.

18. The robot of Claim 7, further comprising an evacuation port located in the bottom of the housing at a position horizontally offset from a lateral centerline extending between the front and rear edges of the robot and located adjacent the coil.

19. The robot of Claim 7, wherein the front of the robot defines a square profile.

20. The robot of Claim 7, wherein the receiver coil is located a vertical distance from a lower outer surface of the bottom wall in the range of from about 1 mm to 5 mm.

21. The robot of Claim 20, wherein the receiver coil is located a vertical distance from a lower outer surface of the bottom wall of less than about 3mm.

22. The robot of Claim 7, wherein windings of the receiver coil are mechanically fixed to an inside of a top surface of the bottom wall.

23. The robot of Claim 7, wherein the receiver coil is affixed to an inside top

surface of the bottom wall by adhesive or fasteners.

24. The robot of Claim 7, wherein the receiver coil is molded into the bottom wall or a top wall of the housing overlying the receiver coil.

25. The robot of Claim 7, wherein the receiver coil is encased by plastic on both its top and bottom sides.

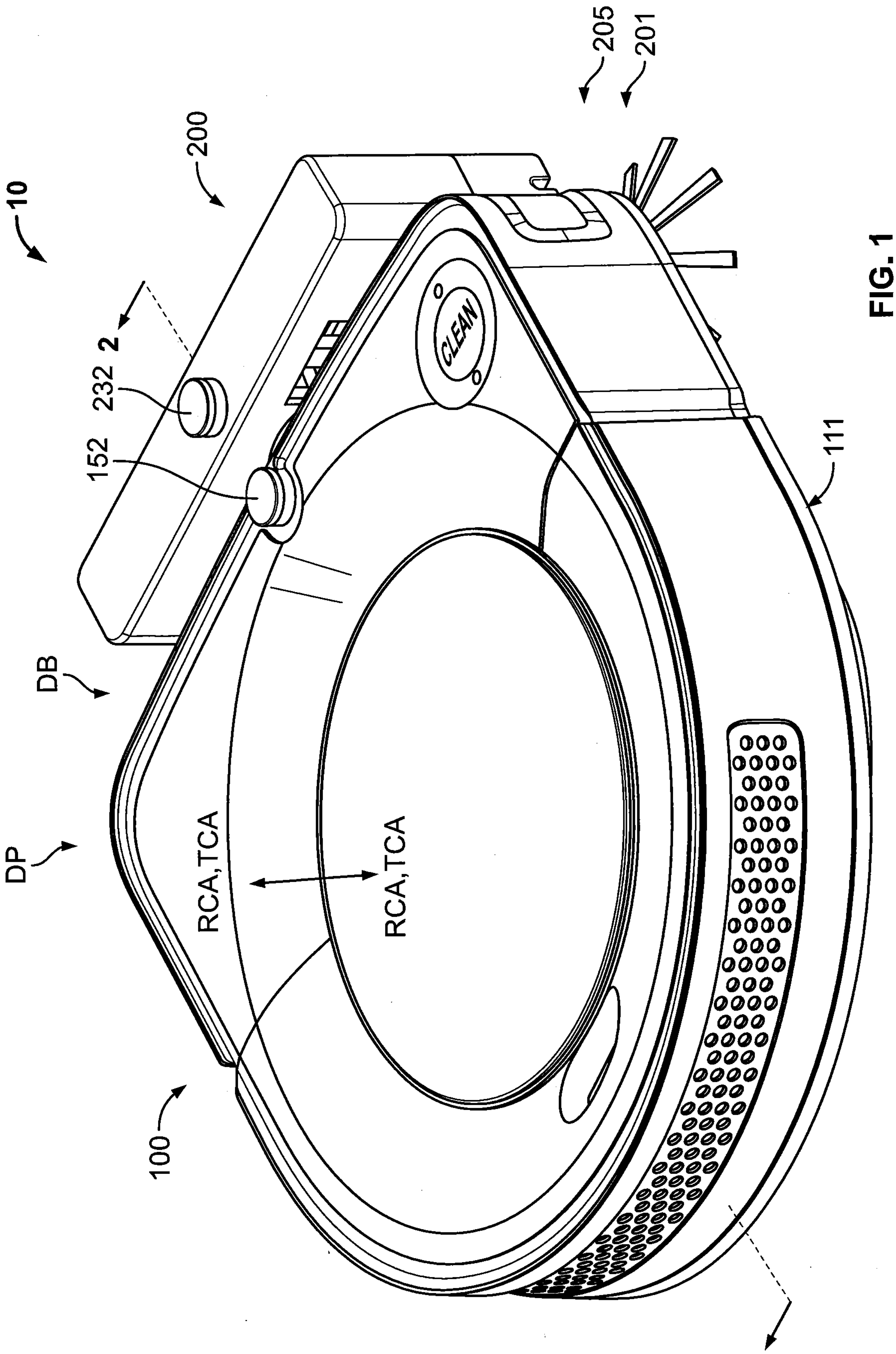

FIG. 1

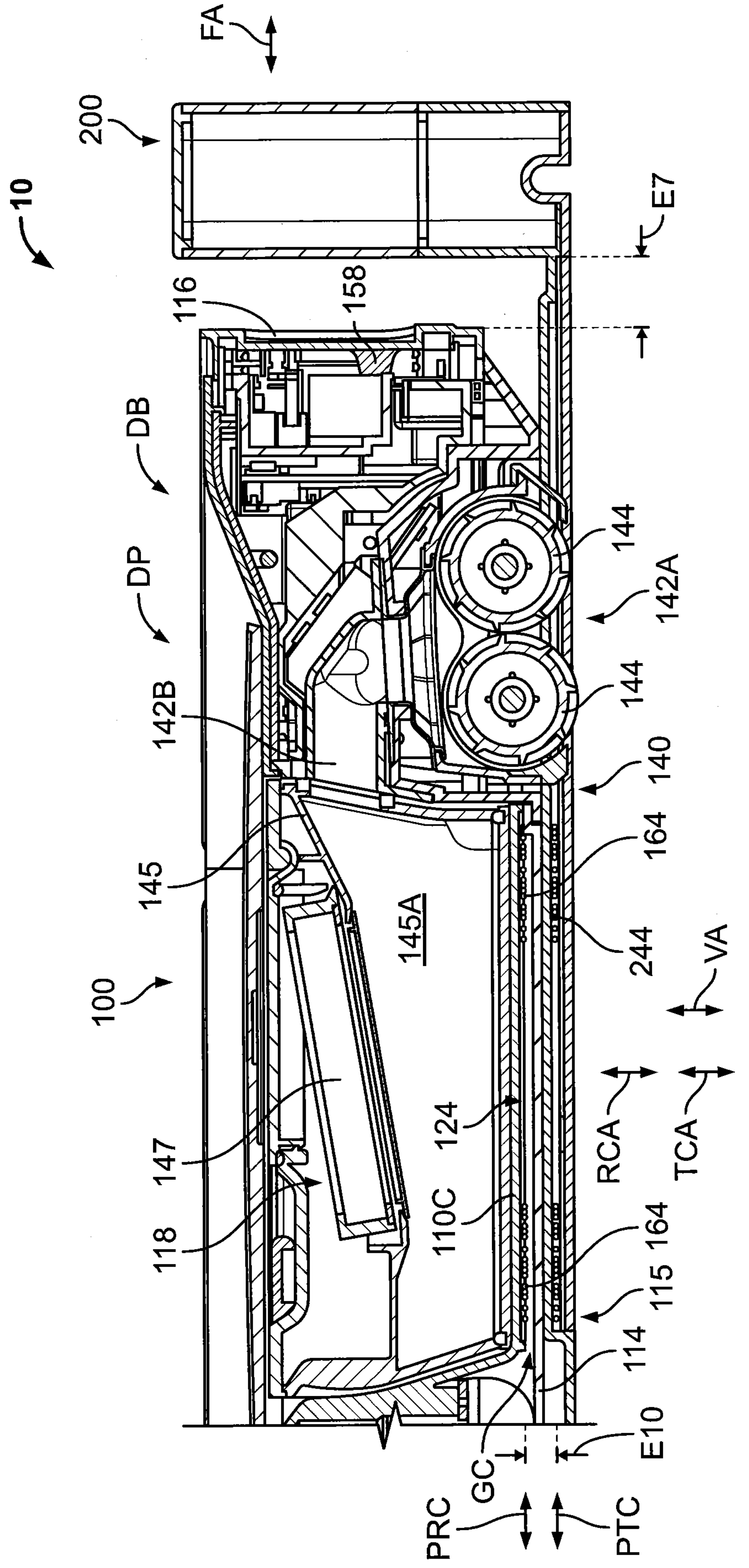
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FIG. 2

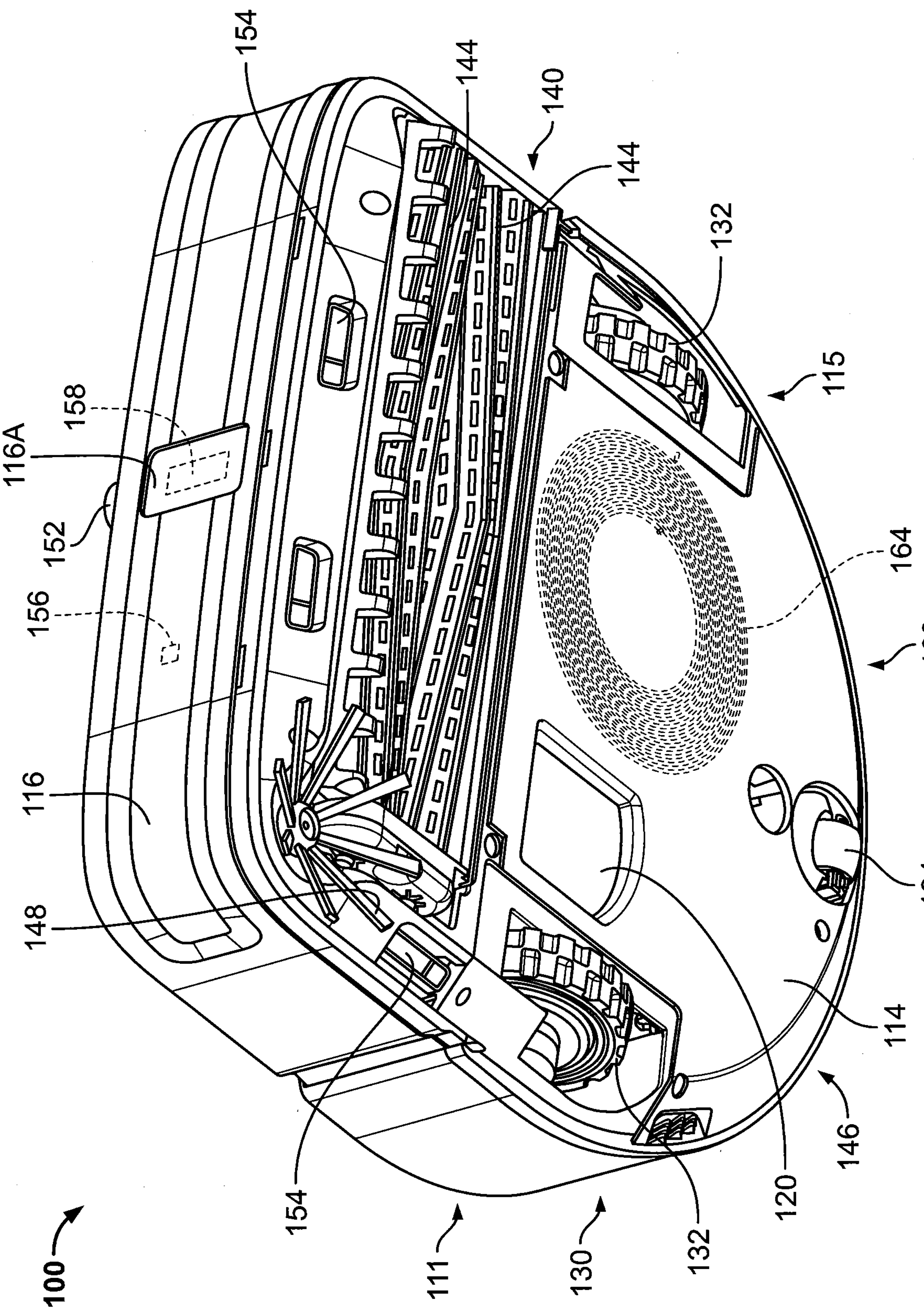
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FIG. 3

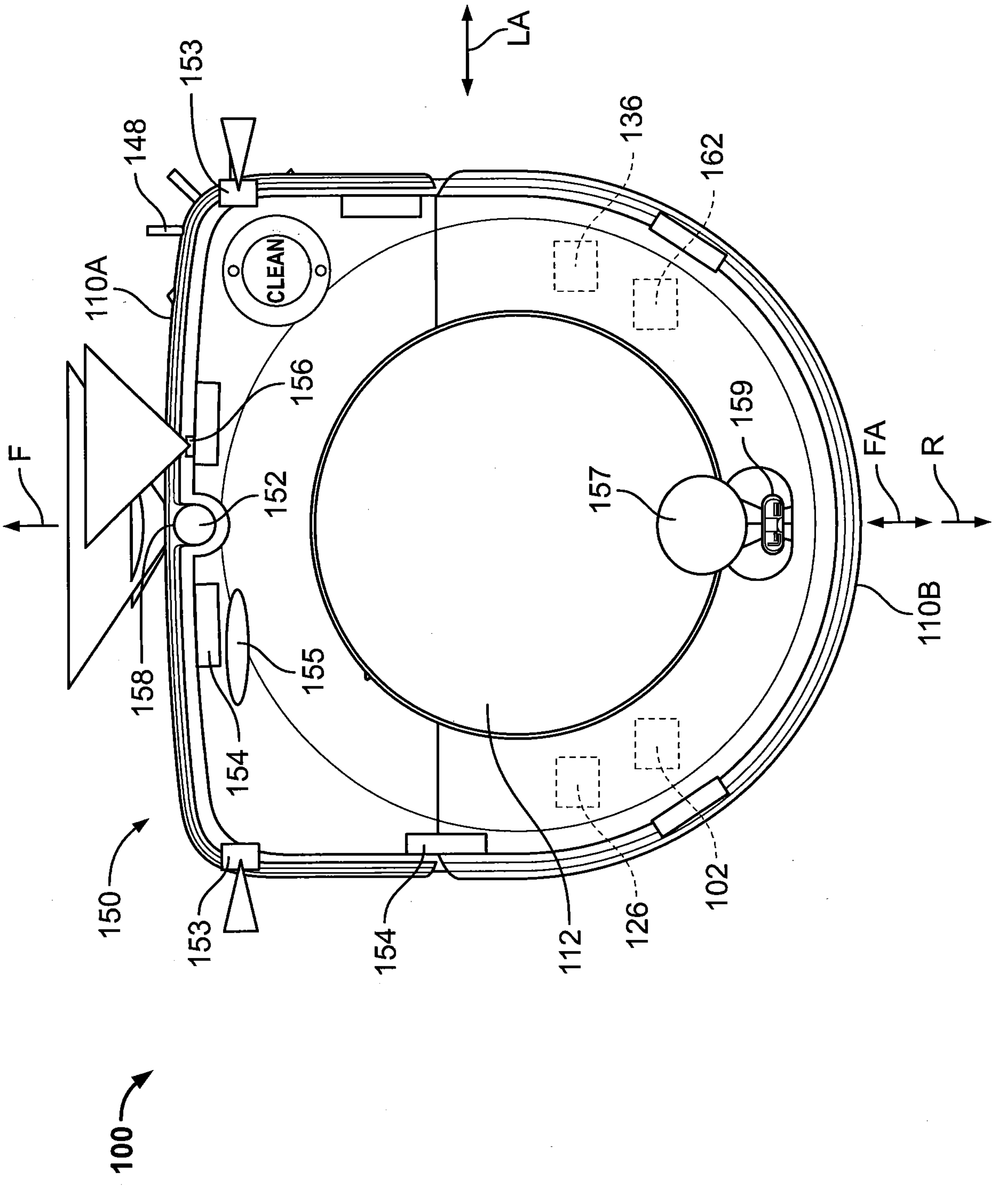
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FIG. 4

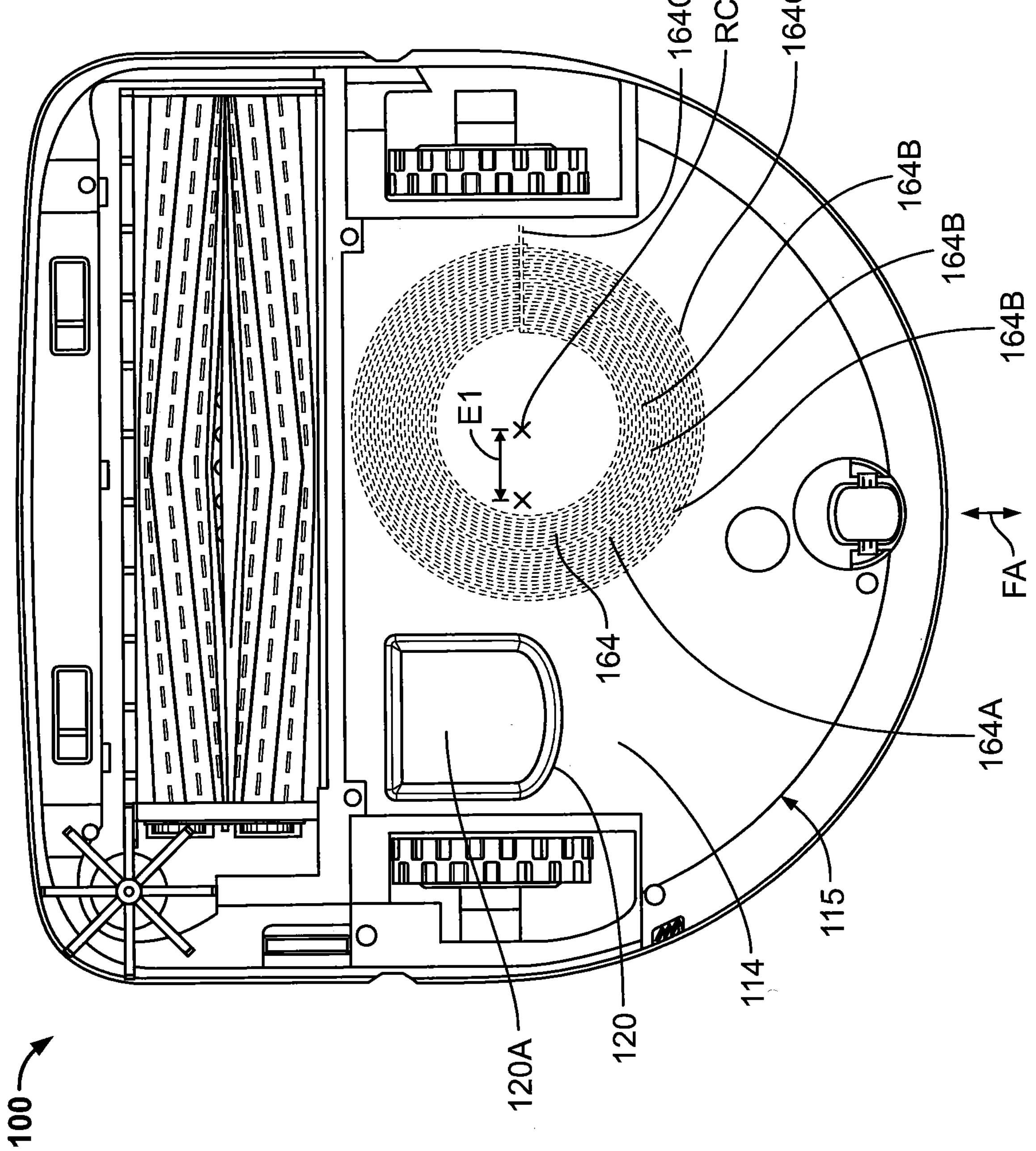
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FIG. 5

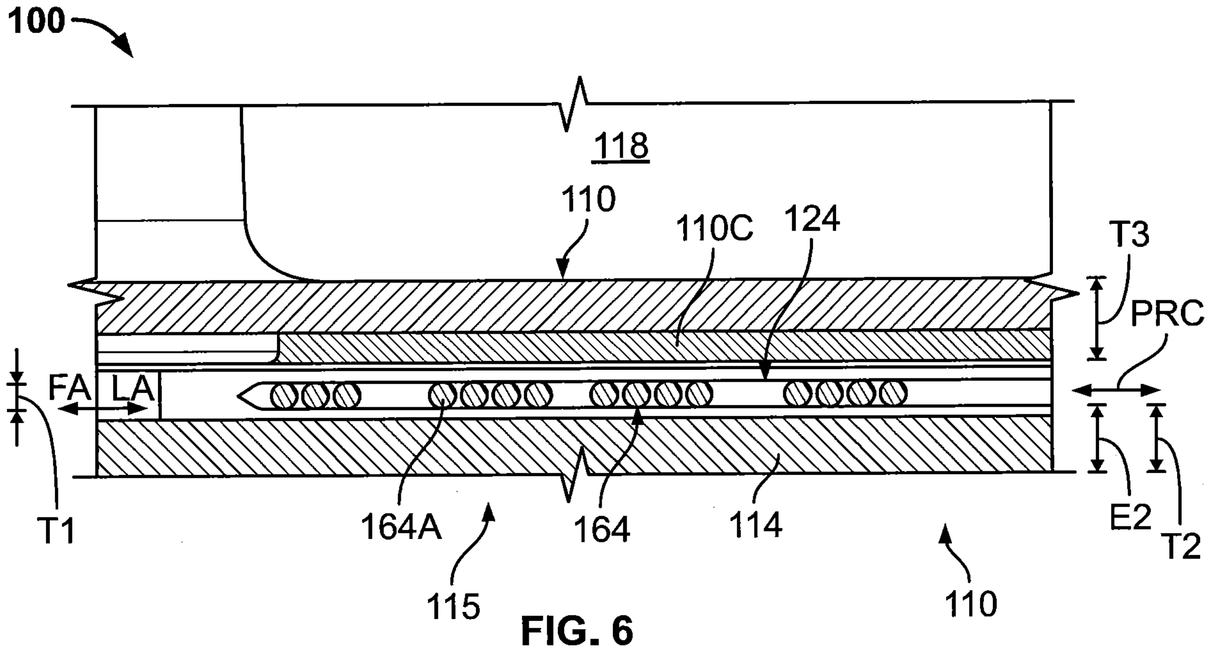
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FIG. 6

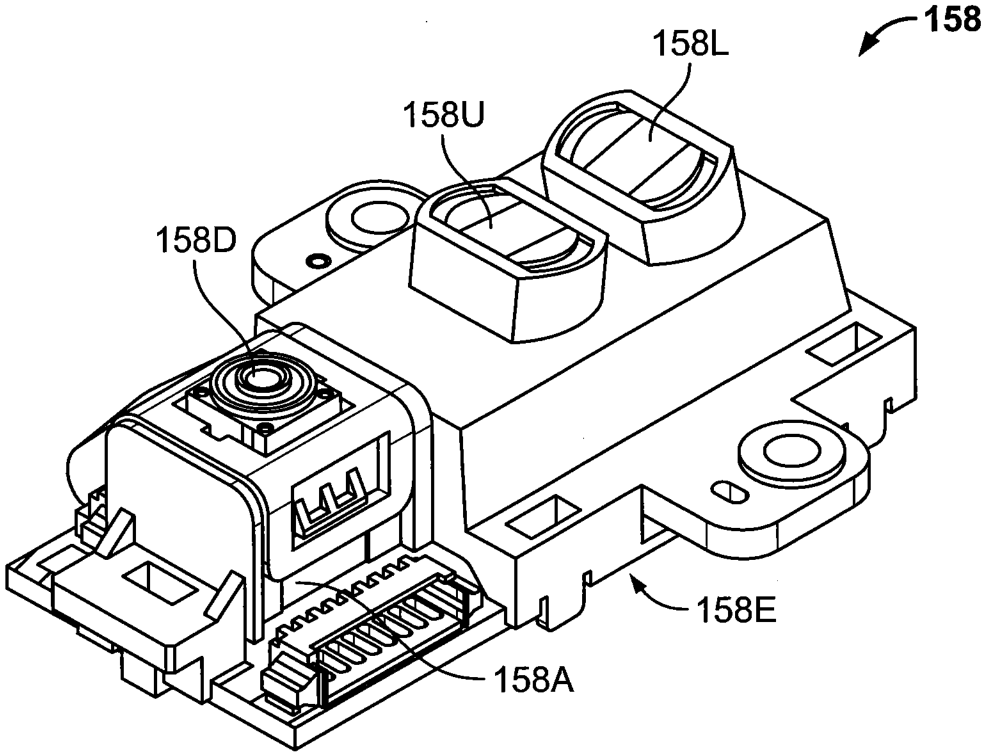
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FIG. 7

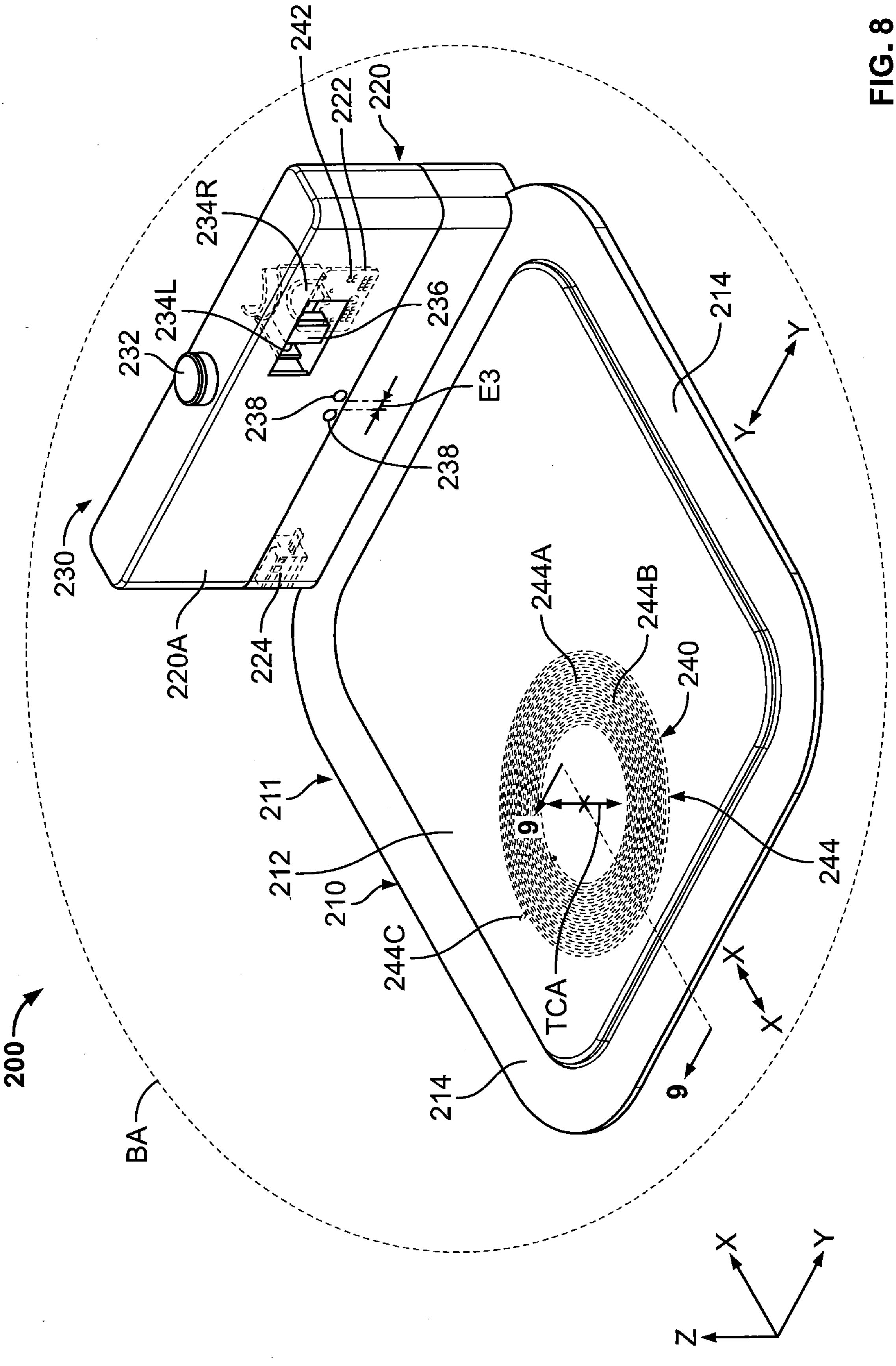
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FIG. 8

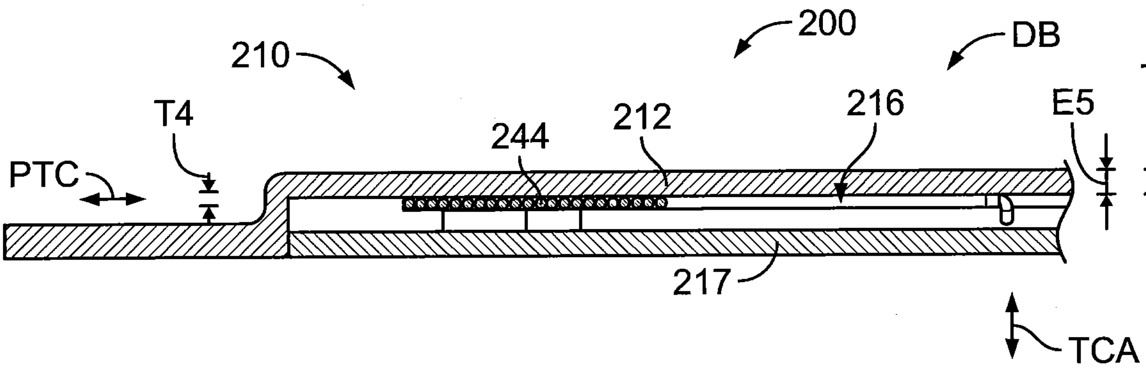
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FIG. 9

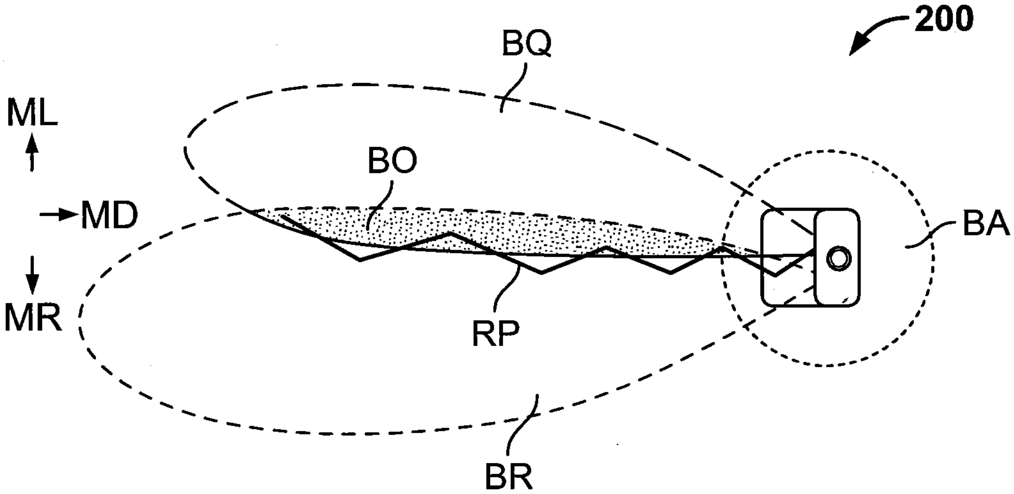
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FIG. 10

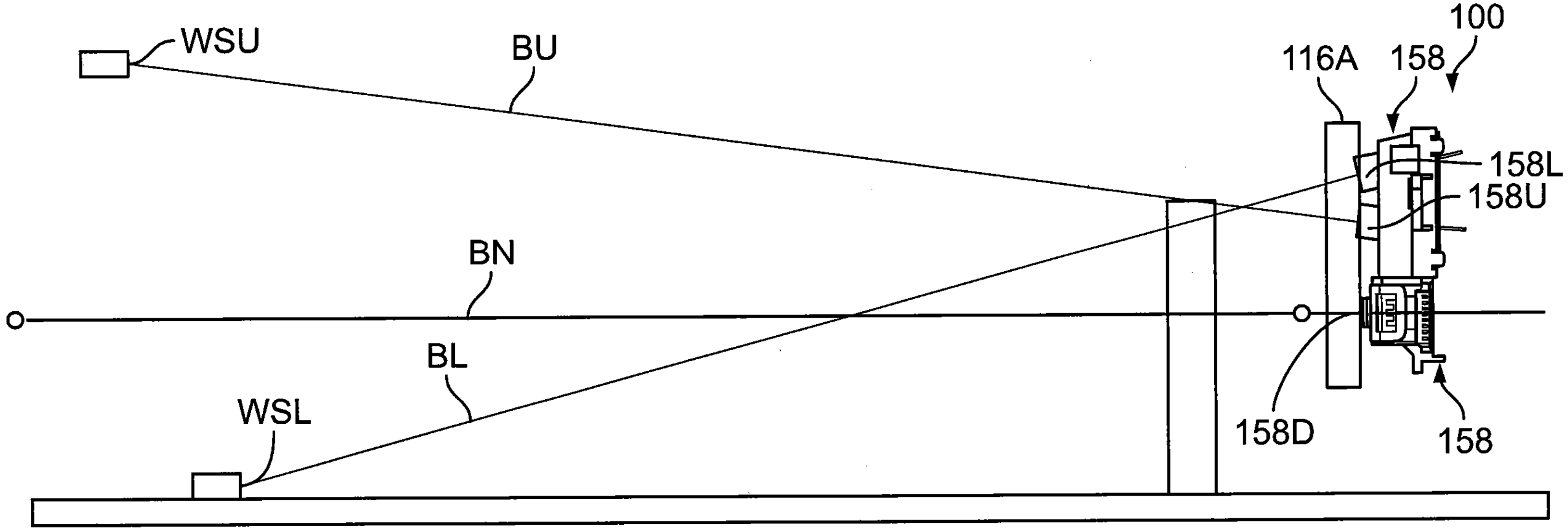
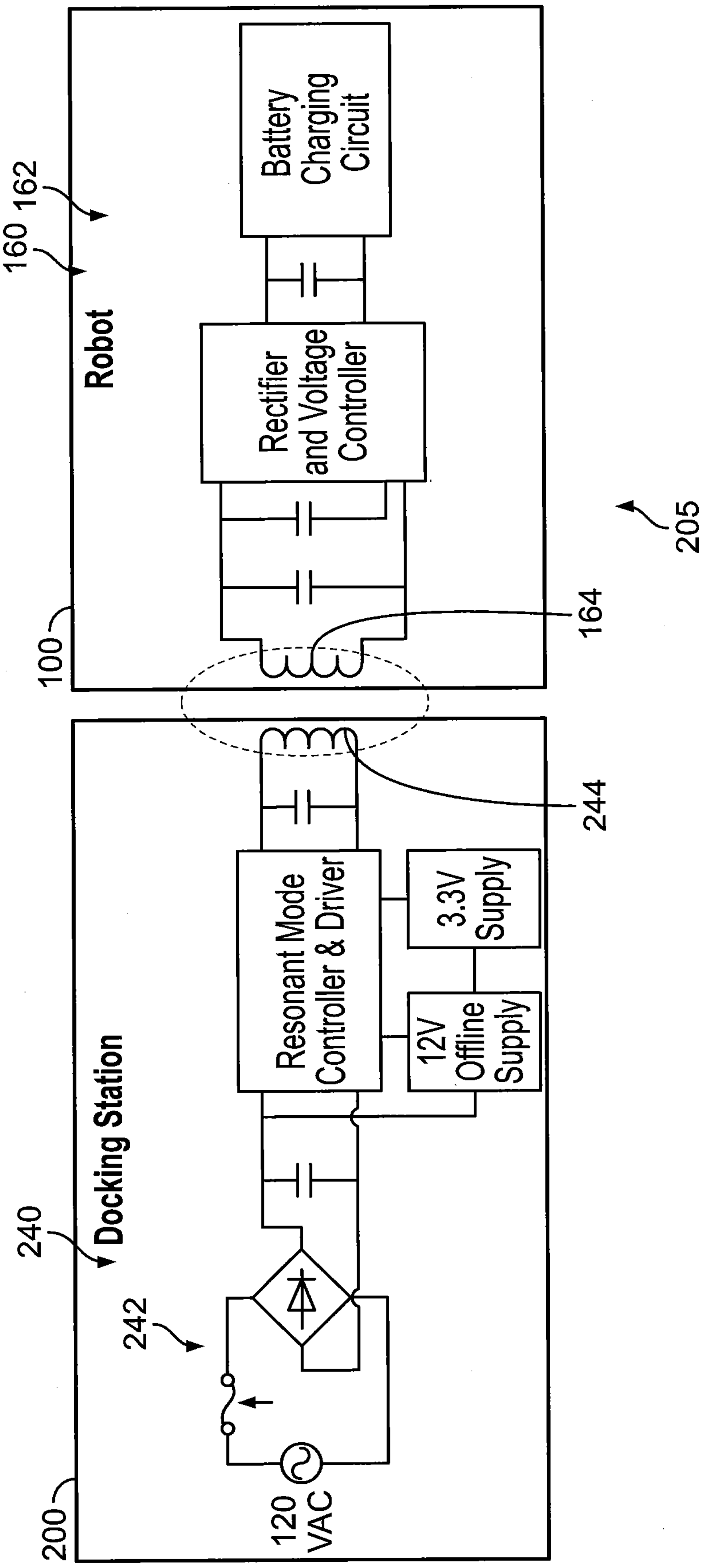


FIG. 11


Robot
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Battery Charging Circuit
Rectifier and Voltage Controller
100
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Docking Station
240
242
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120 VAC
Resonant Mode Controller & Driver
3.3V Supply
12V Offline Supply
244

FIG. 12

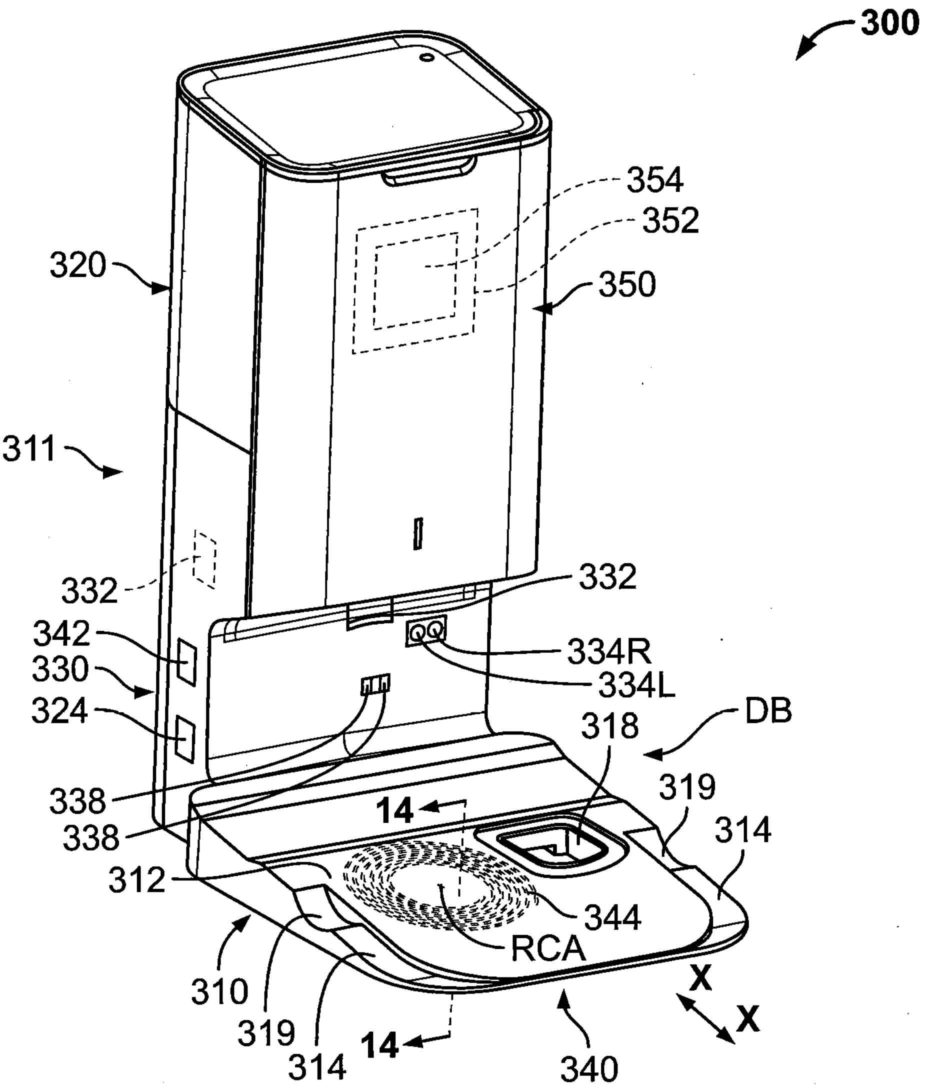
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FIG. 13

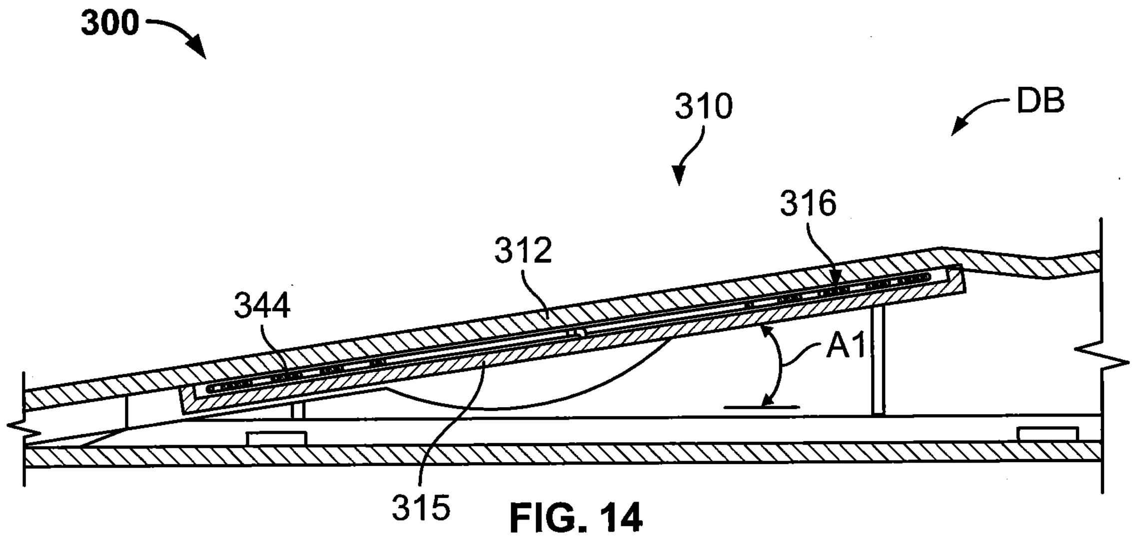
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FIG. 14

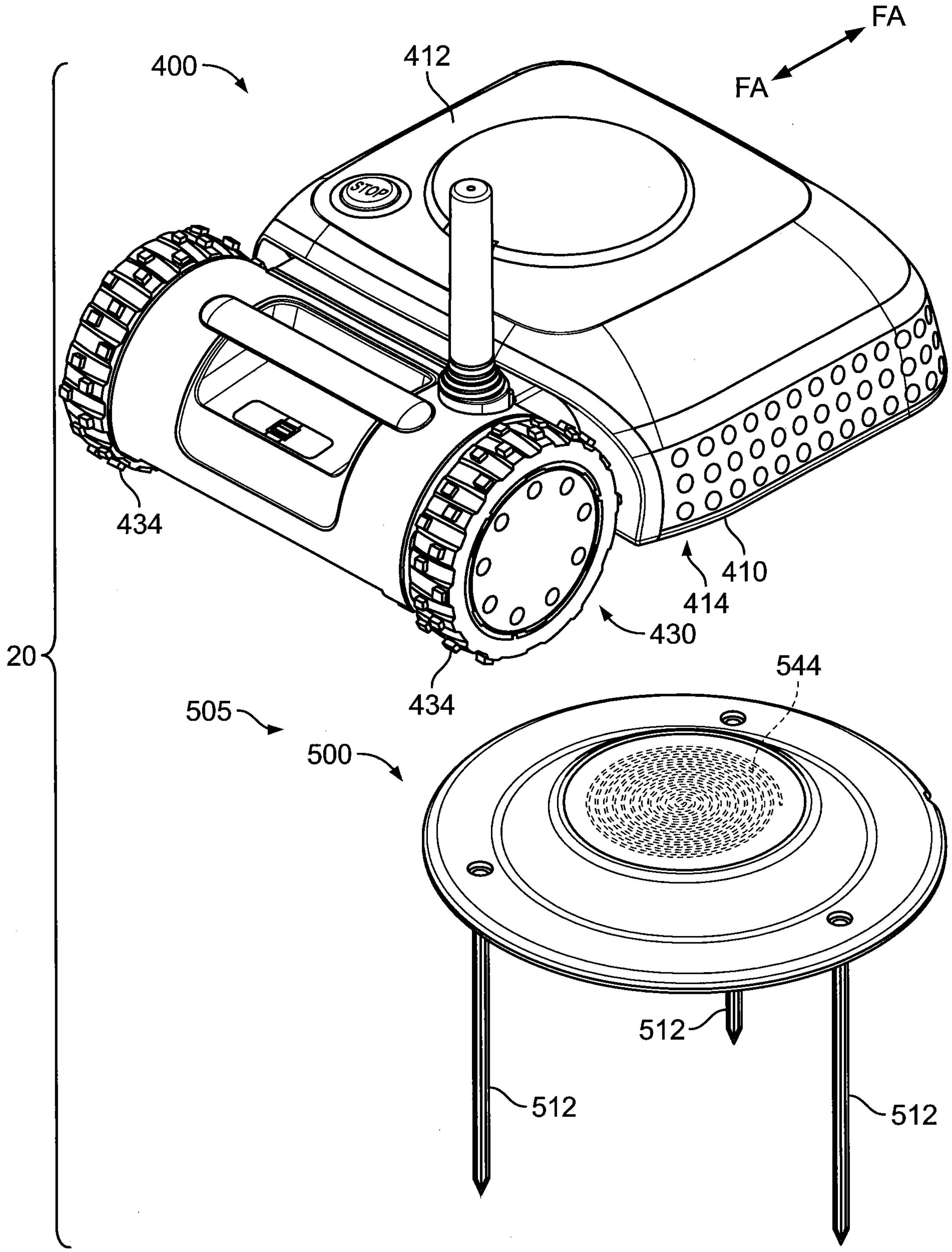


FIG. 15

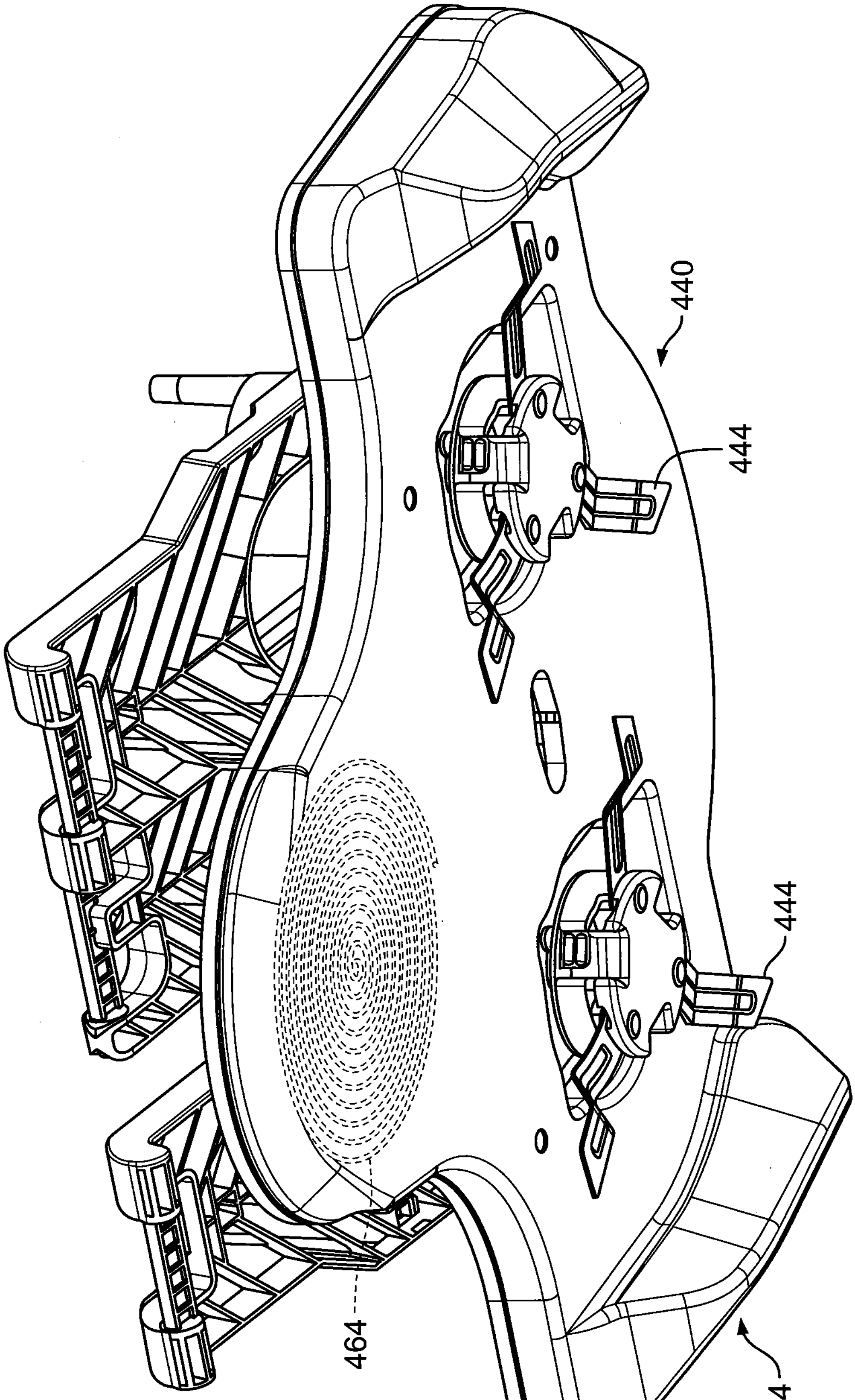
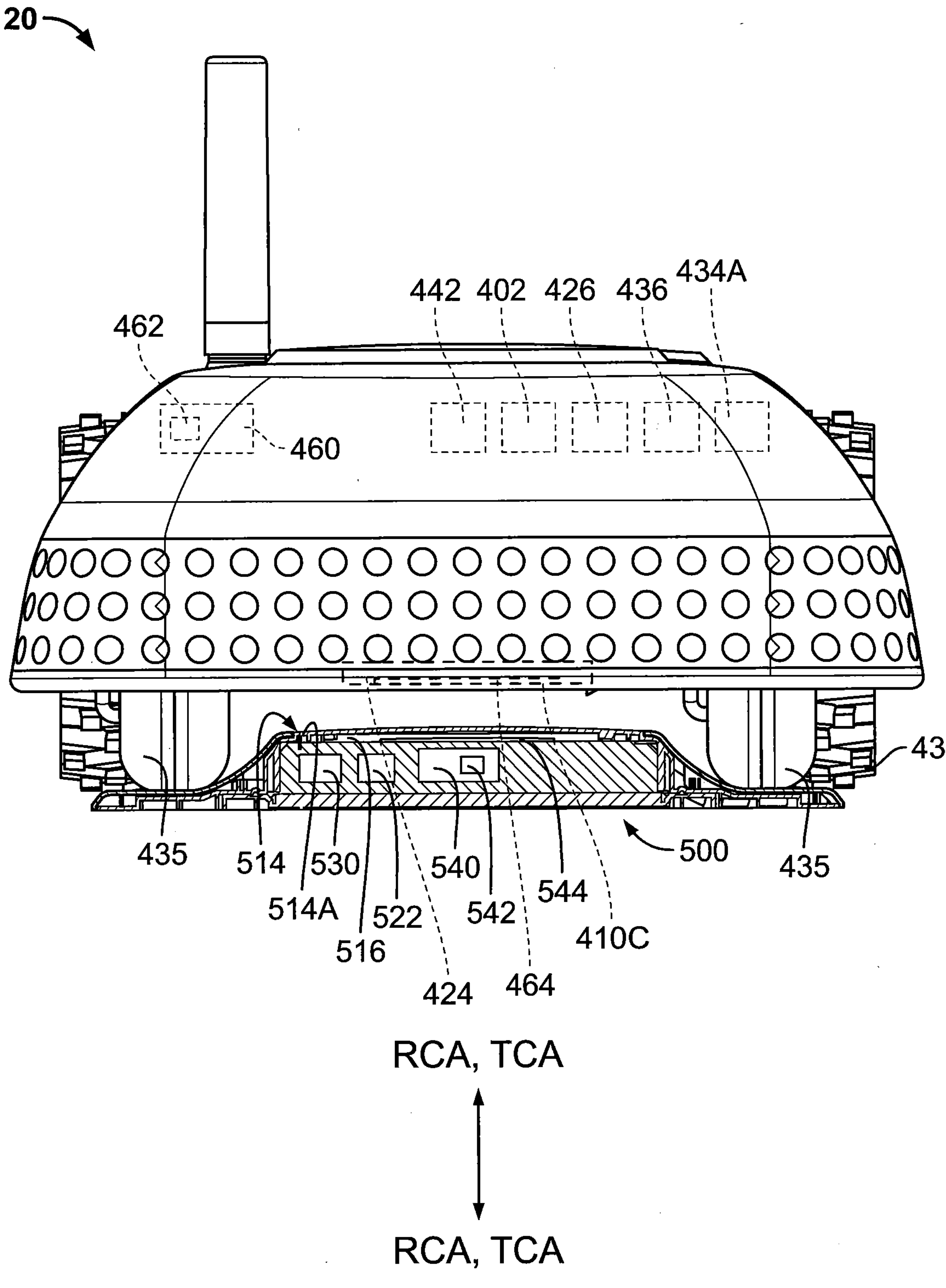


FIG. 16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410C
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464
RCA, TCA
RCA, TCA

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/041840

A. CLASSIFICATION OF SUBJECT MATTER

B25J 9/16(2006.01)i, B25J 19/02(2006.01)i, B25J 19/00(2006.01)i, B25J 11/00(2006.01)i, A47L 9/28(2006.01)i, H02J 50/00(2016.01)i, H02J 5/00(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J 9/16; G06F 19/00; B08B 1/00; B25J 13/00; H02J 7/00; A47L 3/00; H02J 7/02; B25J 19/02; B25J 19/00; B25J 11/00; A47L 9/28; H02J 50/00; H02J 5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: docking, autonomous, robot, clean, receiver, transmitter, coil

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2004-0158357 A1 (LEE et al.) 12 August 2004 See paragraphs [0002], [0025]-[0086]; and figures 1, 3A-3B, 4, 7-12.	1-25
Y	US 2013-0093390 A1 (MOJO MOBILITY, INC.) 18 April 2013 See paragraphs [0061]-[0091], [0100]-[0178], [0224]-[0263]; and figures 1, 20-24, 42.	1-25
A	US 2003-0094922 A1 (PETERSSON et al.) 22 May 2003 See paragraphs [0014]-[0021]; and figures 1-4.	1-25
A	US 2005-0150074 A1 (DIEHL et al.) 14 July 2005 See paragraphs [0036]-[0053]; and figures 1-5.	1-25
A	WO 2008-051027 A1 (LG ELECTRONICS INC. et al.) 02 May 2008 See paragraphs [0022]-[0037]; and figures 1-5.	1-25

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

* Special categories of cited documents:
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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
24 October 2017 (24.10.2017)

Date of mailing of the international search report
24 October 2017 (24.10.2017)

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea
Facsimile No. +82-42-481-8578

Authorized officer
LEE, Dal Kyong
Telephone No. +82-42-481-8440

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