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(12) **United States Patent**
**Beyerl**

(10) **Patent No.: US 9,787,159 B2**
(45) **Date of Patent: Oct. 10, 2017**

(54) **BRUSHLESS DC MOTOR CONFIGURATION FOR A POWER TOOL**

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(73) Assignee: **Milwaukee Electric Tool Corporation**, Brookfield, WI (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 430 days.

(21) Appl. No.: **14/295,703**

(22) Filed: **Jun. 4, 2014**

(65) **Prior Publication Data**

US 2014/0361645 A1 Dec. 11, 2014

**Related U.S. Application Data**

(60) Provisional application No. 61/832,012, filed on Jun. 6, 2013.

(51) **Int. Cl.**
***H02K 7/14*** (2006.01)
***B23B 45/02*** (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ..... ***H02K 7/145*** (2013.01); ***B23B 45/02*** (2013.01); ***B25B 21/00*** (2013.01); ***B25F 5/008*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC ..... H02K 7/145; H02K 2211/03; H02K 11/0073; H02K 9/04; H02K 9/06;
(Continued)

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Image of MAX-PJ-ID143 Brushless Impact Driver admitted prior art publicly available as early as Aug. 17, 2012.
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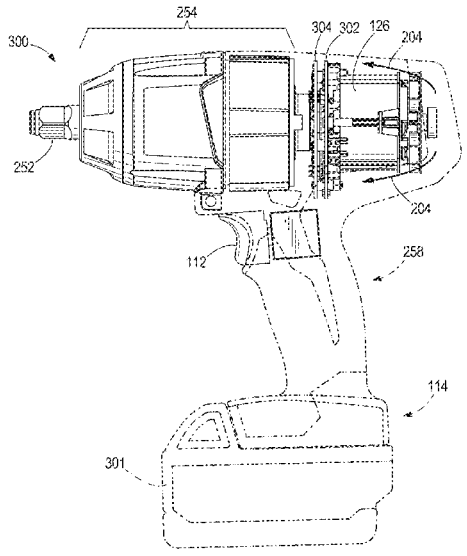
*Assistant Examiner* — Leda Pham
(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

A power tool with a combined printed circuit board (PCB) having a doughnut shape and located coaxially with a motor shaft. The combined PCB is secured to a heat sink on one end of the motor and a metal end piece is positioned on an opposite end of the motor. The metal end cap and heat sink are secured to one another via fasteners to provide a rigid coupling. A tabbed end piece is provided between the heat sink and the motor stator and is also secured into place via the fasteners. The tabbed end piece includes wire support tabs that provide strain relief to motor coil leads. The wire support tabs extend axially from circumferential locations of the tabbed end piece and include channels to guide the motor coil leads to solder contact points on the combined PCB.

**18 Claims, 26 Drawing Sheets**



(51) **Int. Cl.**

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|---|---|
| ***B25B 21/00*** | (2006.01) |
| ***H02K 29/08*** | (2006.01) |
| ***H02K 3/52*** | (2006.01) |
| ***B25F 5/00*** | (2006.01) |
| ***H02K 11/33*** | (2016.01) |

(52) **U.S. Cl.**
CPC ..... ***H02K 3/522*** (2013.01); ***H02K 11/33*** (2016.01); ***H02K 29/08*** (2013.01); *H02K 2203/06* (2013.01)

(58) **Field of Classification Search**
CPC ... H02K 9/22; B25F 5/00; B25F 5/008; B25B 21/02
USPC ..... 310/50
See application file for complete search history.

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Image of Makita BFH040 Impact Driver, admitted prior art publicly available at least as early as Aug. 17, 2012.

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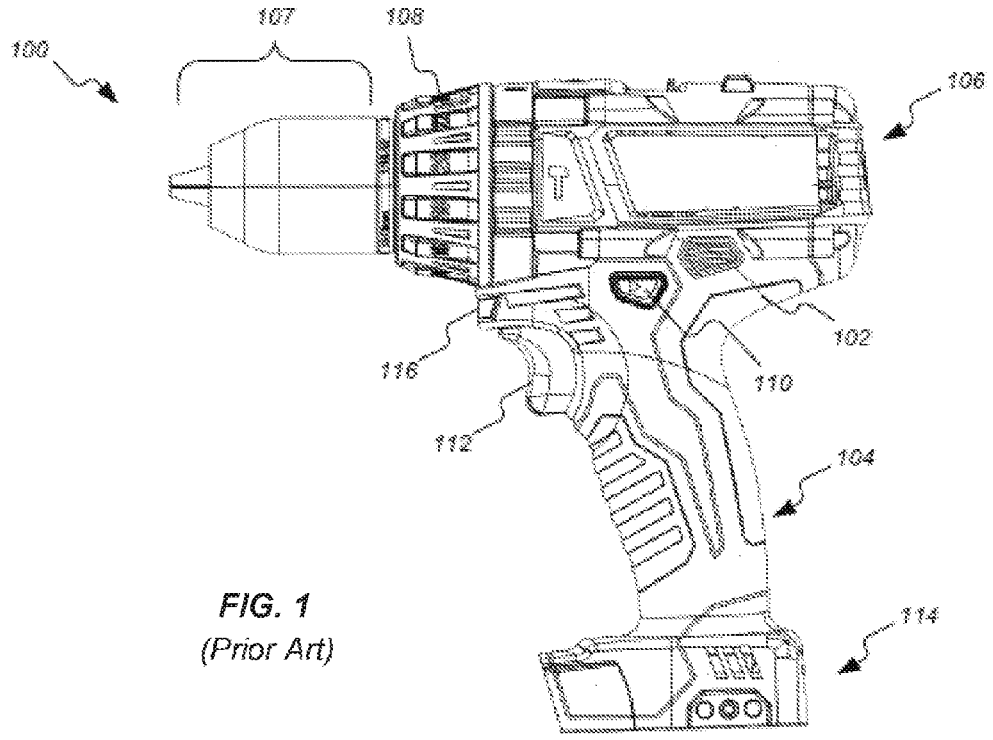


FIG. 1
(Prior Art)

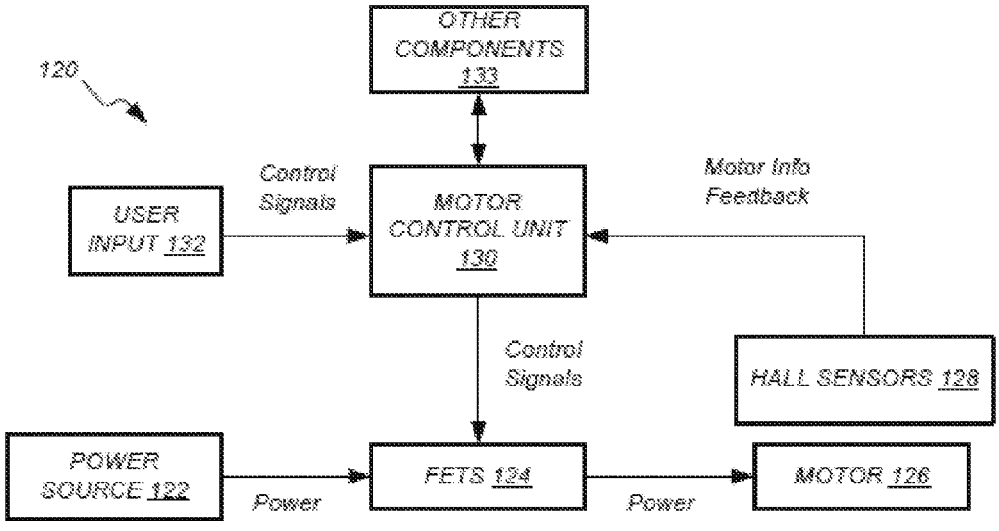


FIG. 2
(Prior Art)

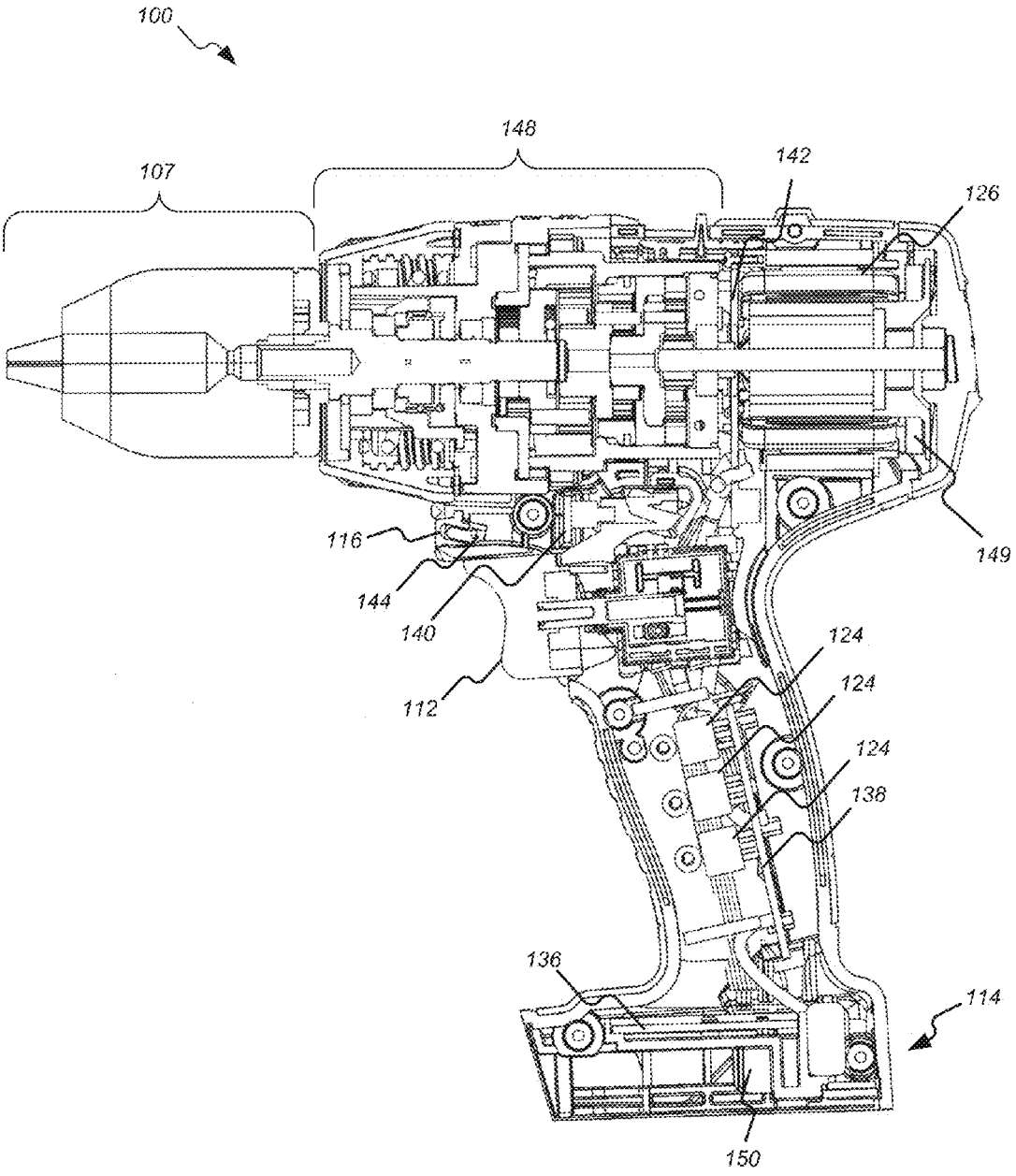
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FIG. 3A

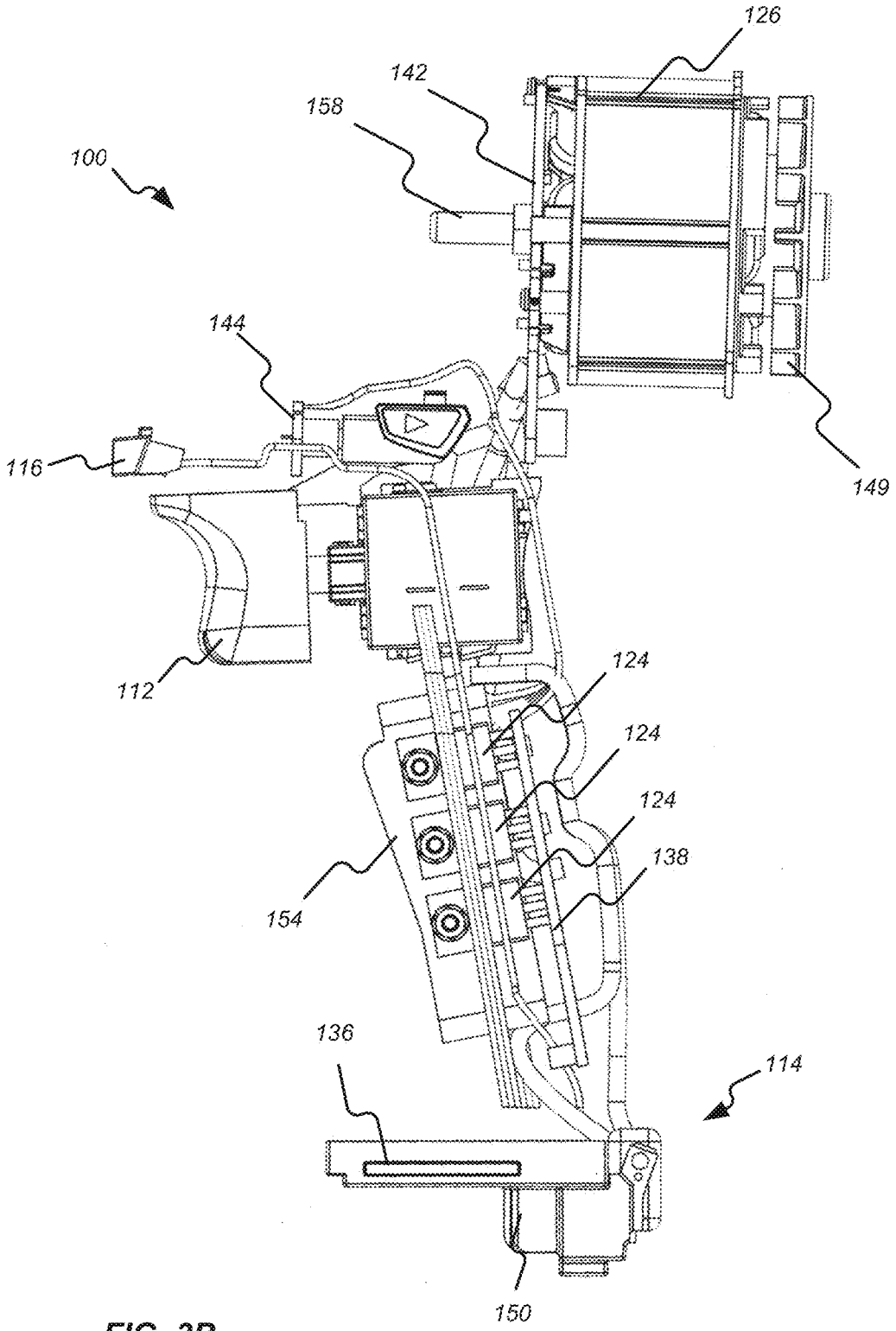



FIG. 3B

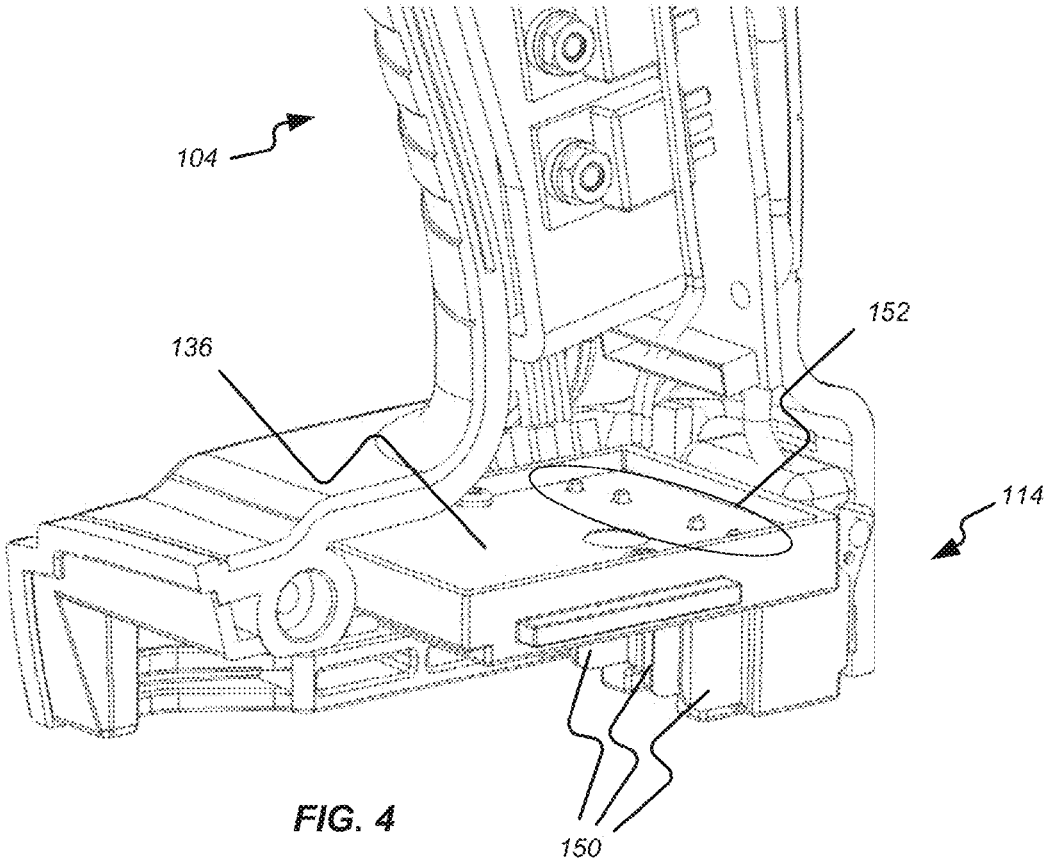



FIG. 4

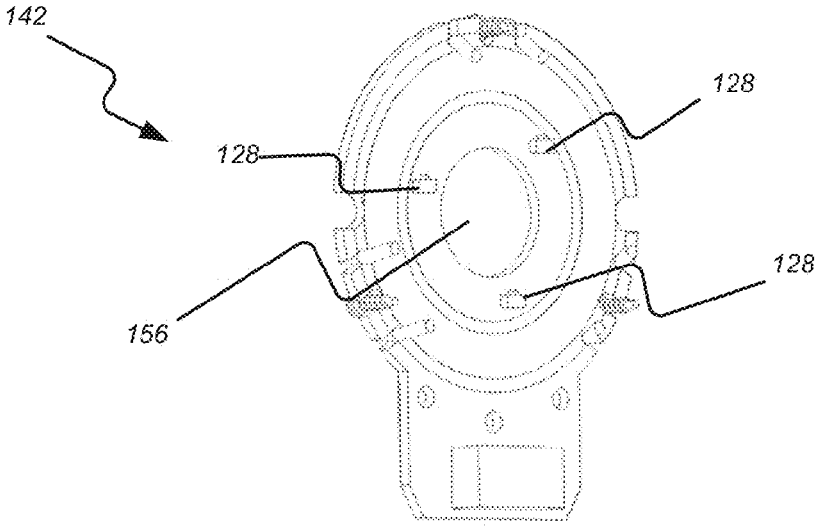



FIG. 5

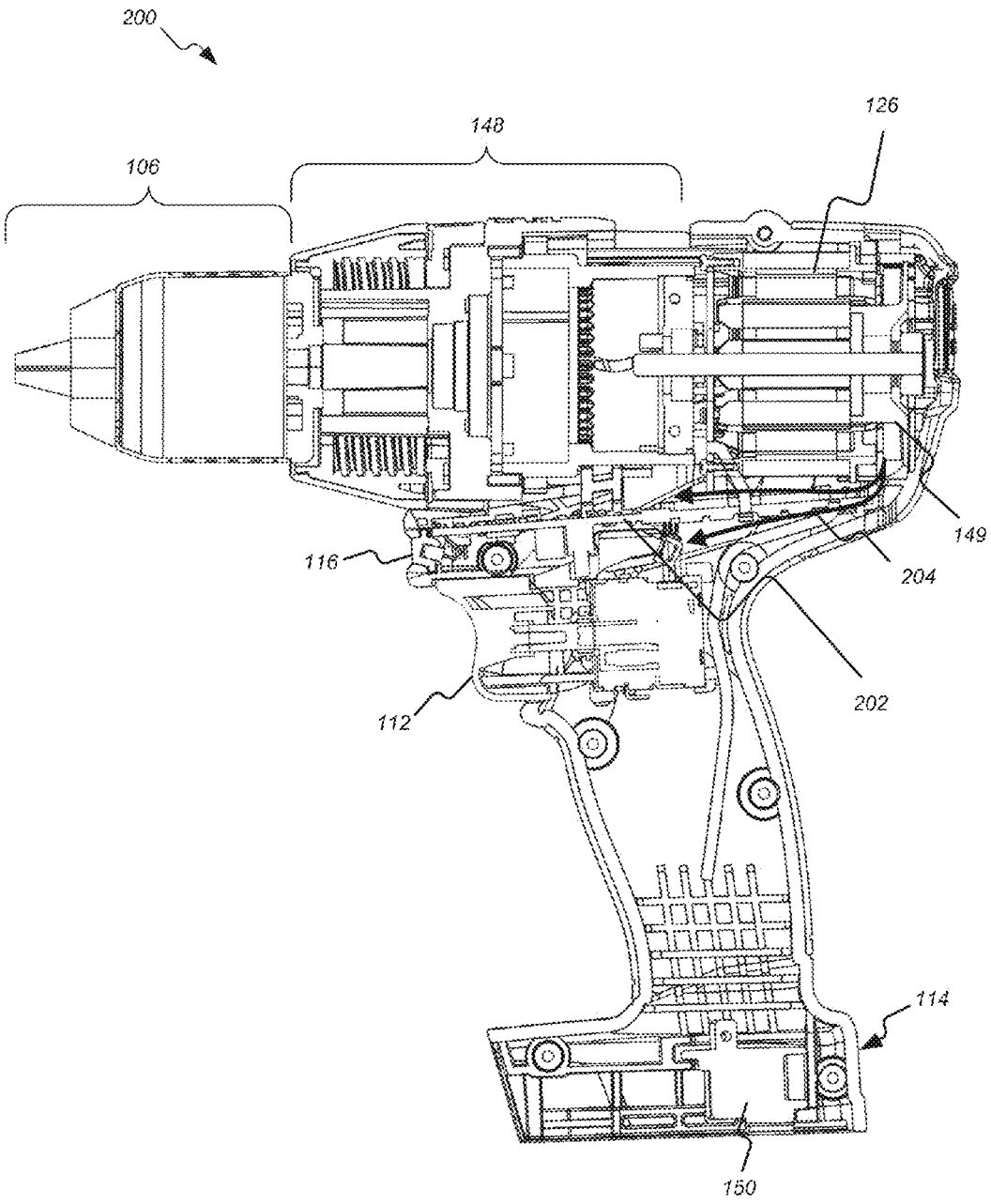



FIG. 6

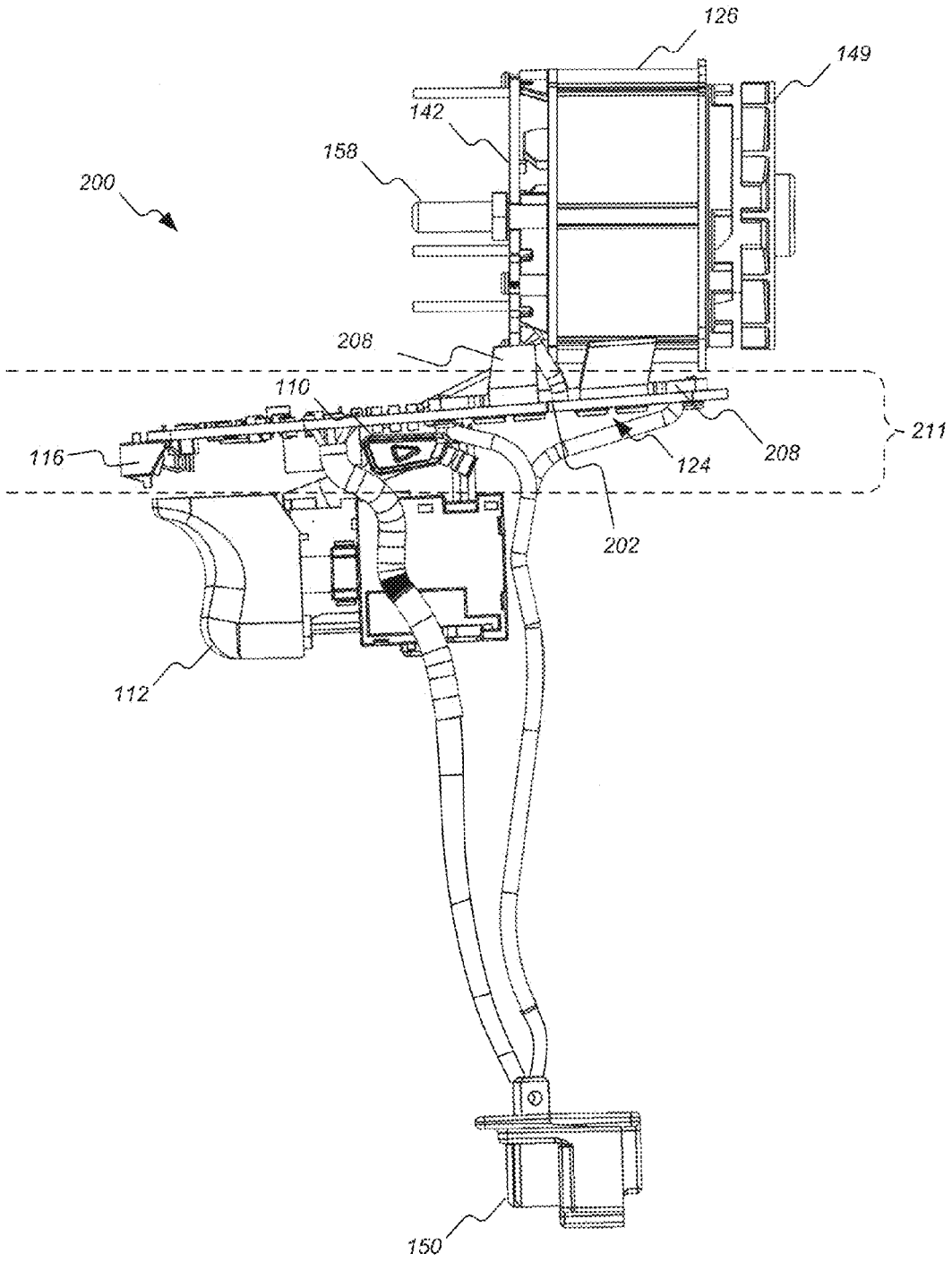



FIG. 7

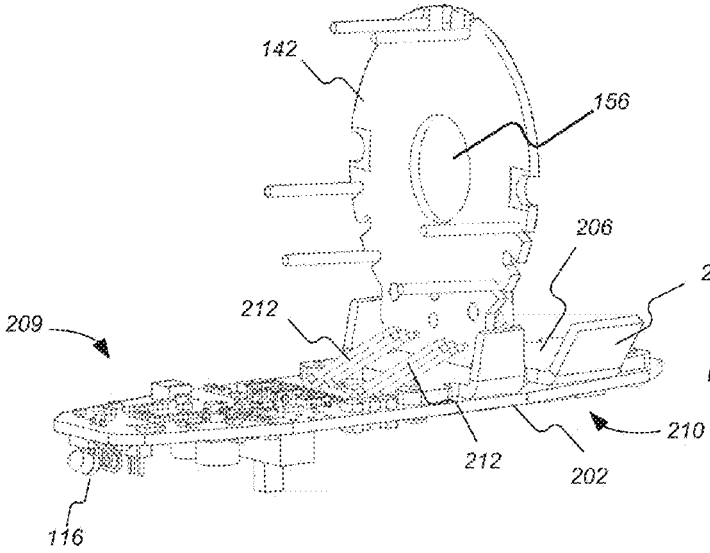



FIG. 8A

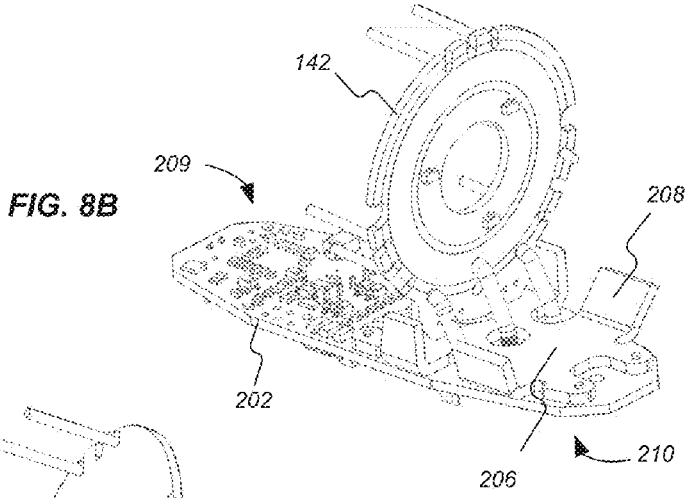



FIG. 8B

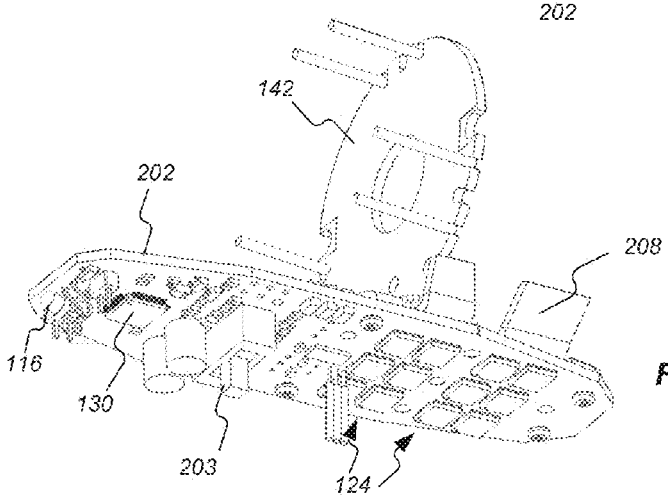
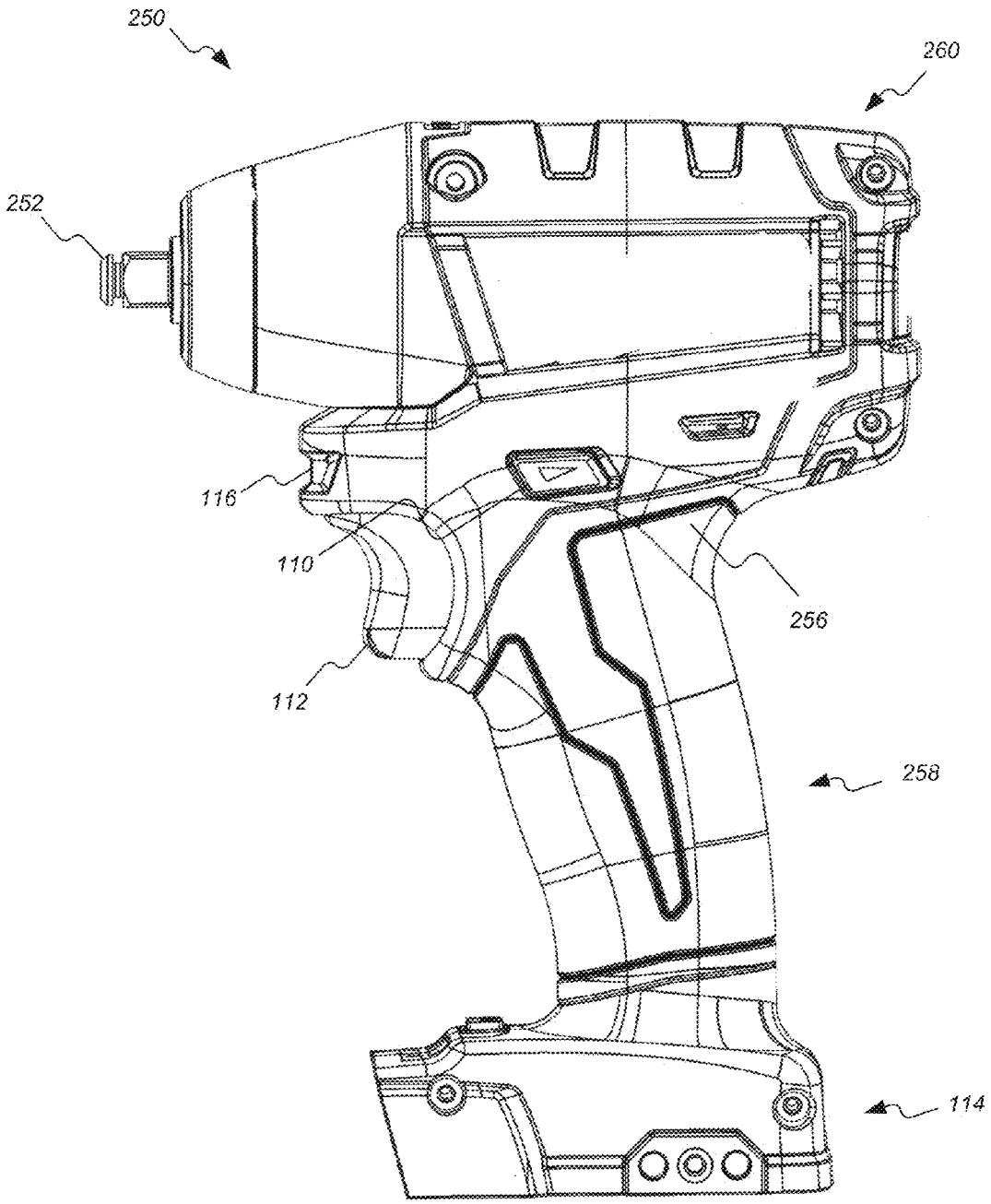



FIG. 8C

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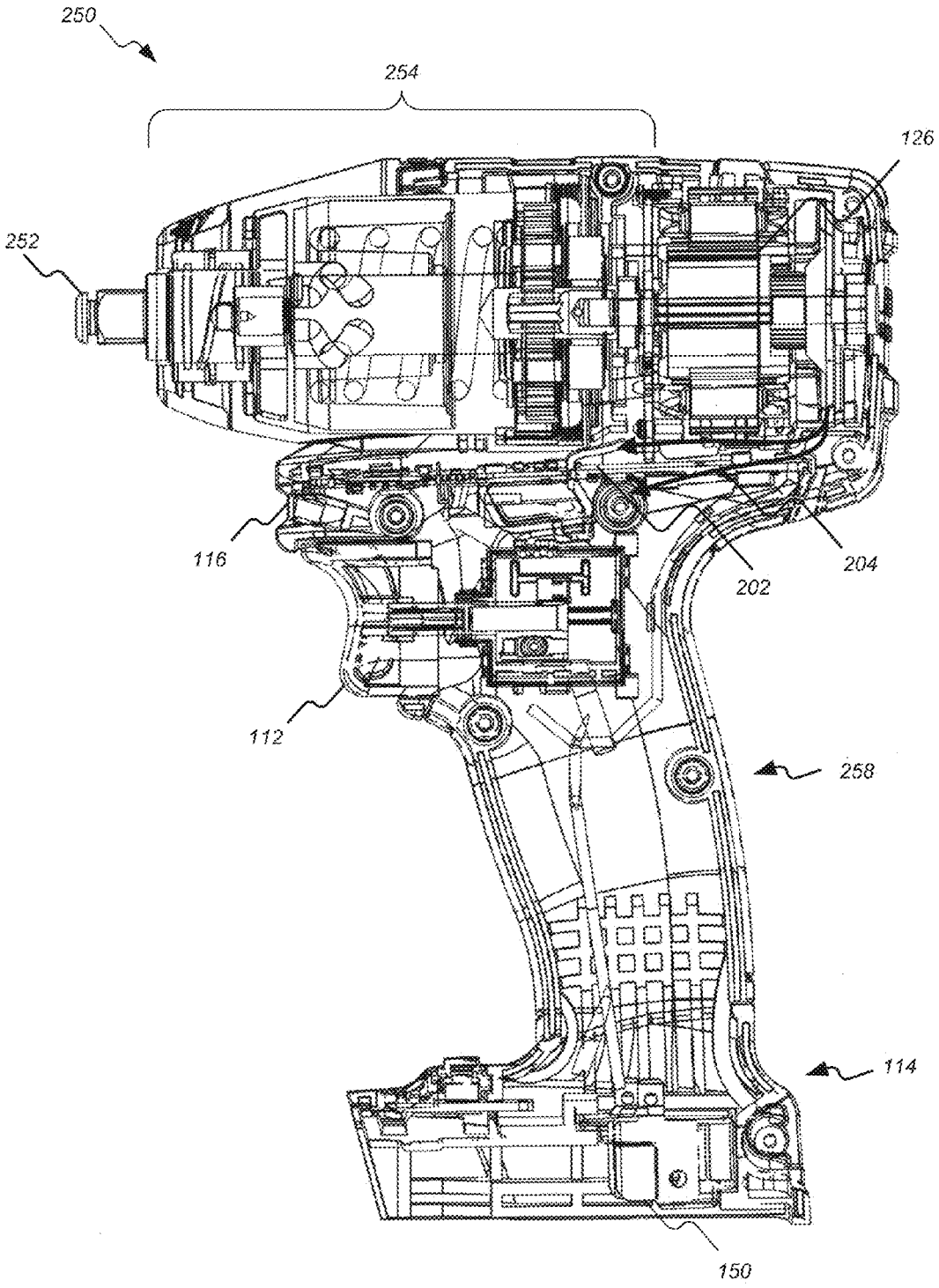


FIG. 10

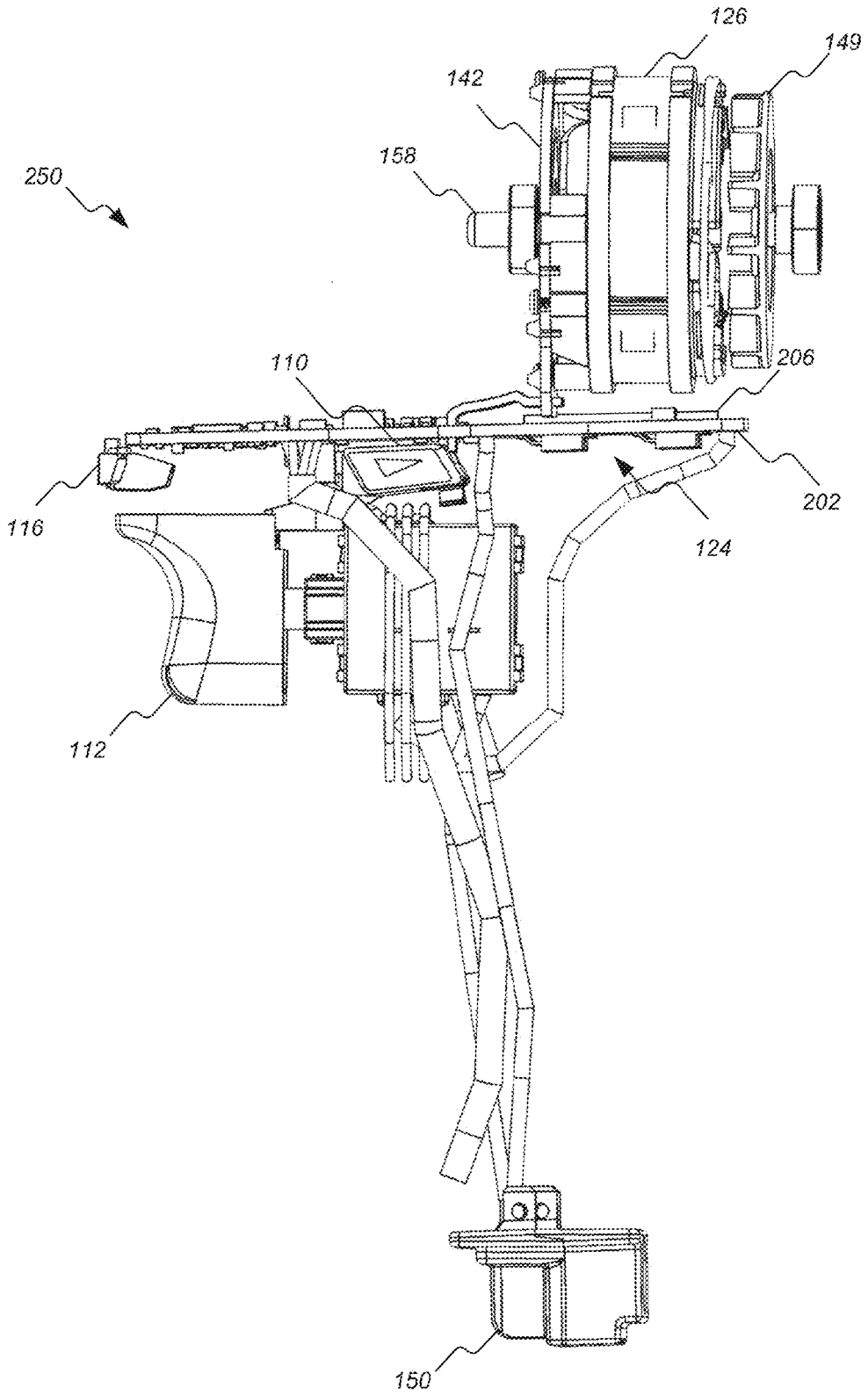


FIG. 11

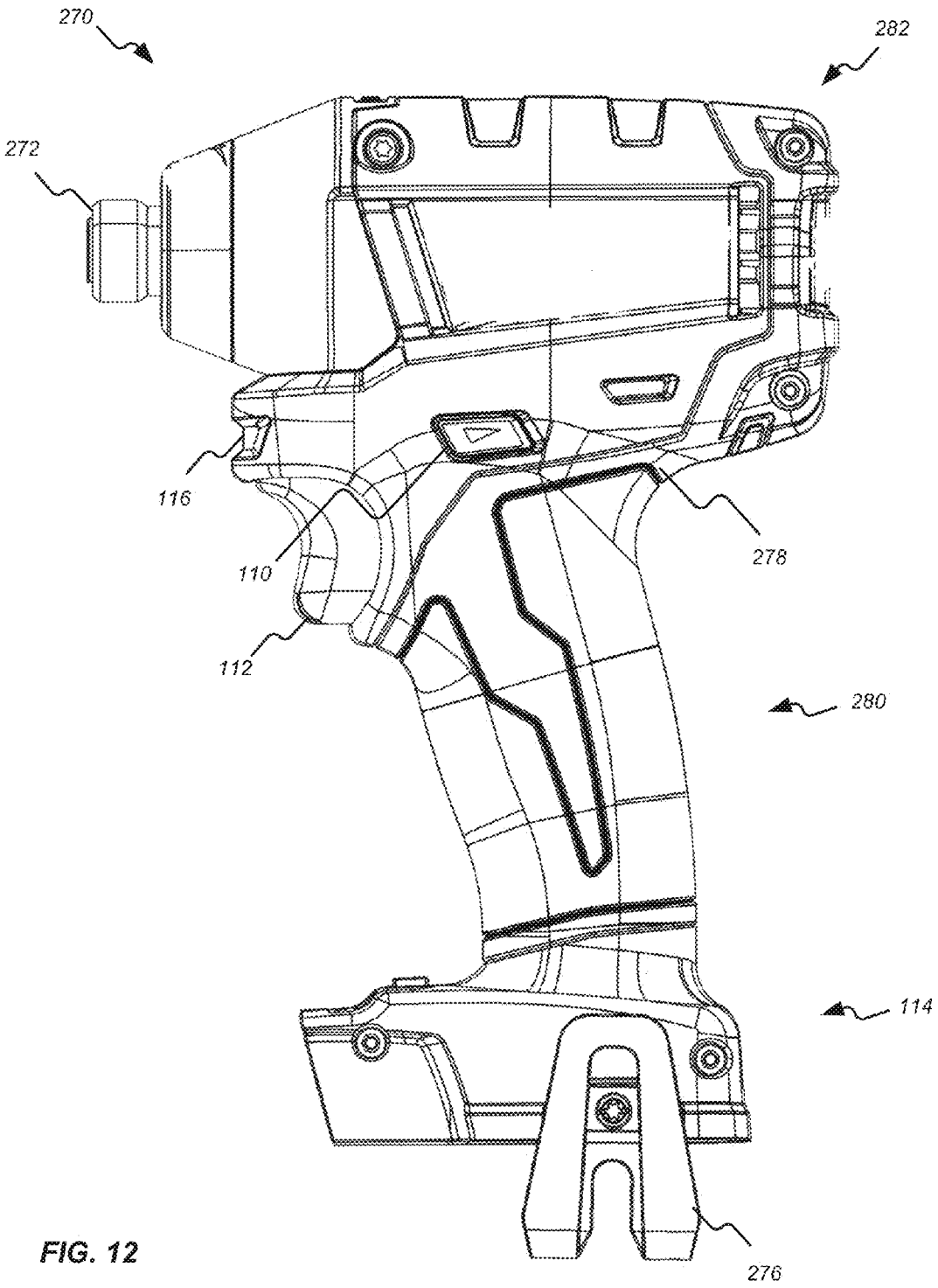


FIG. 12

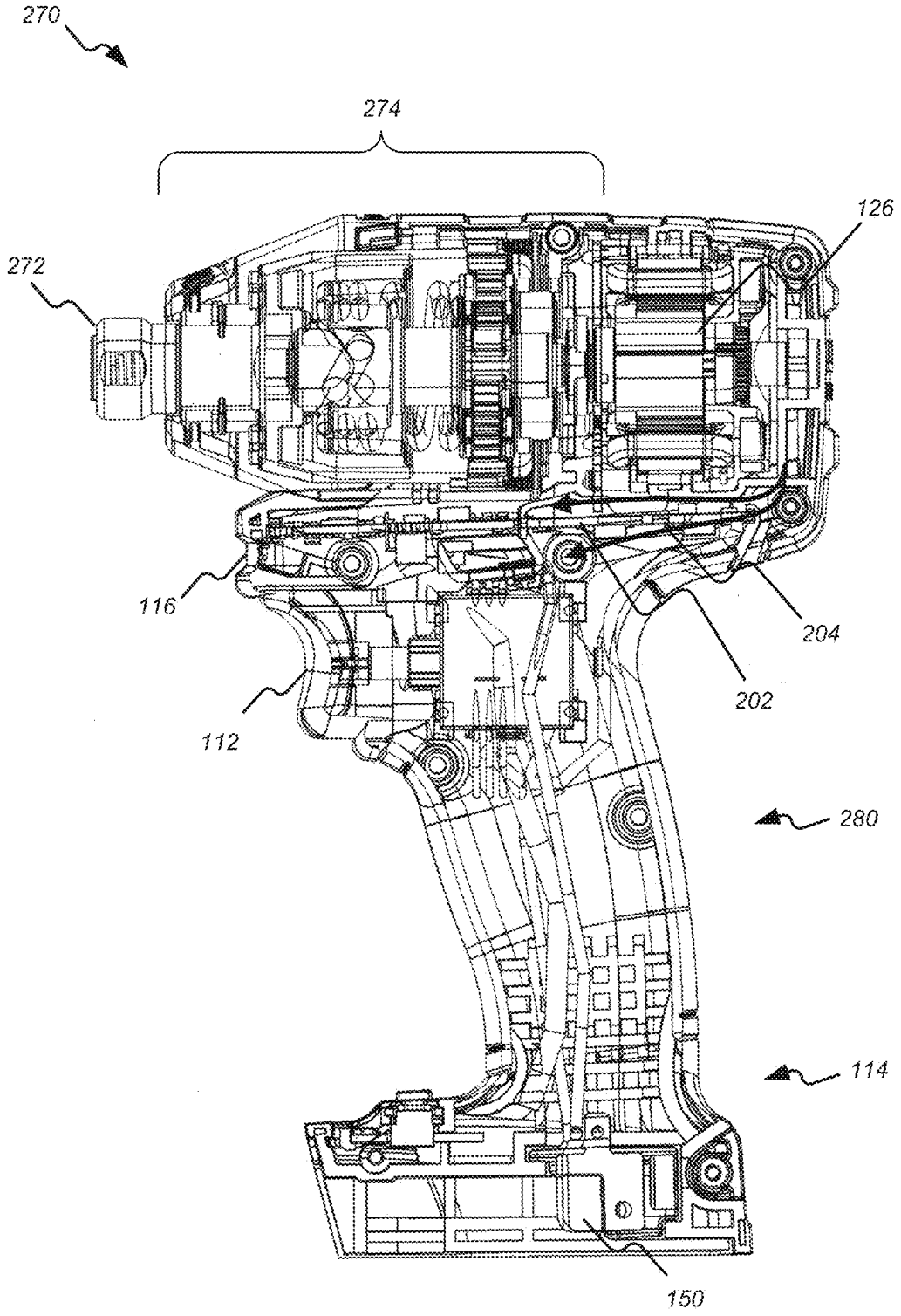


FIG. 13

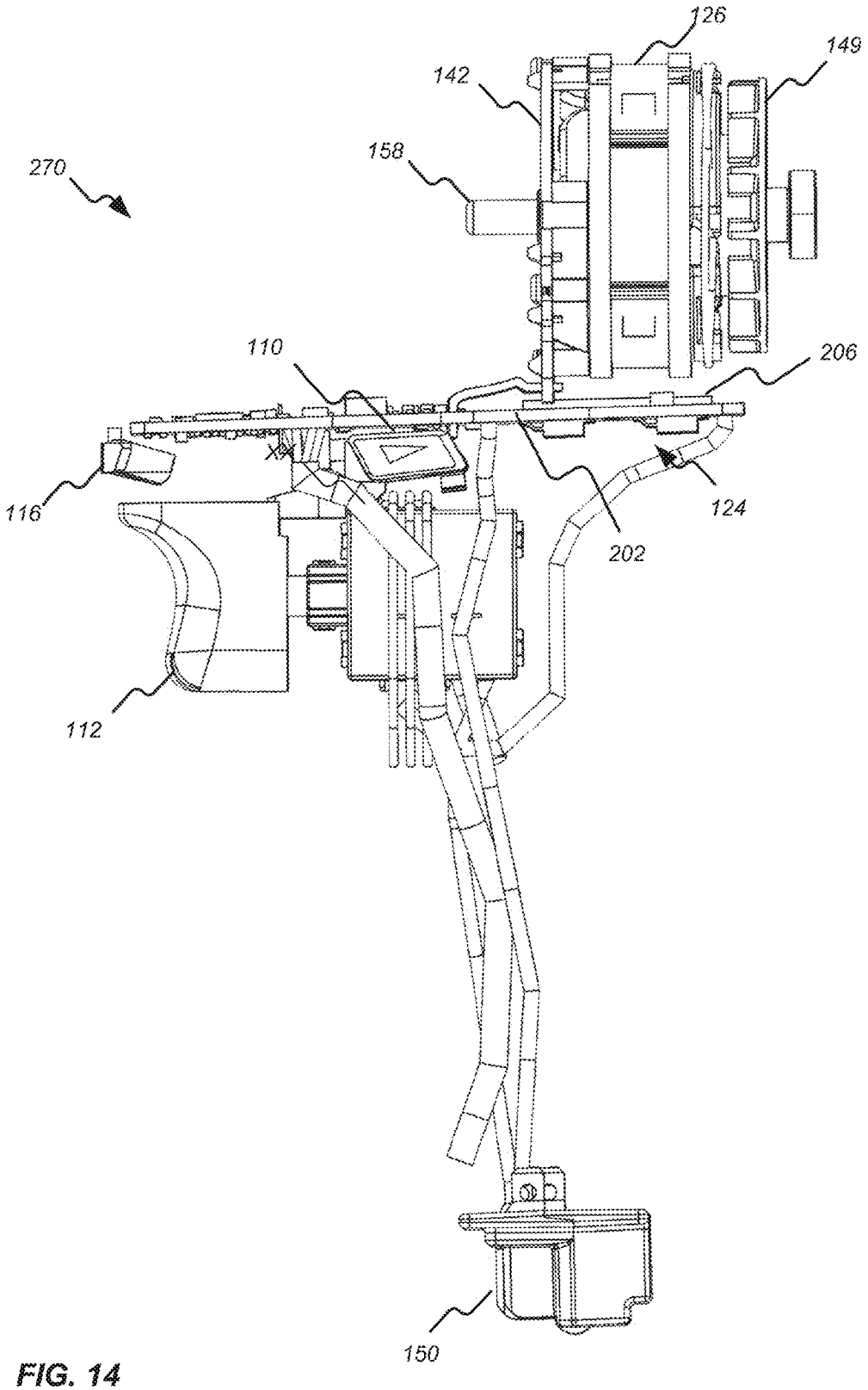


FIG. 14

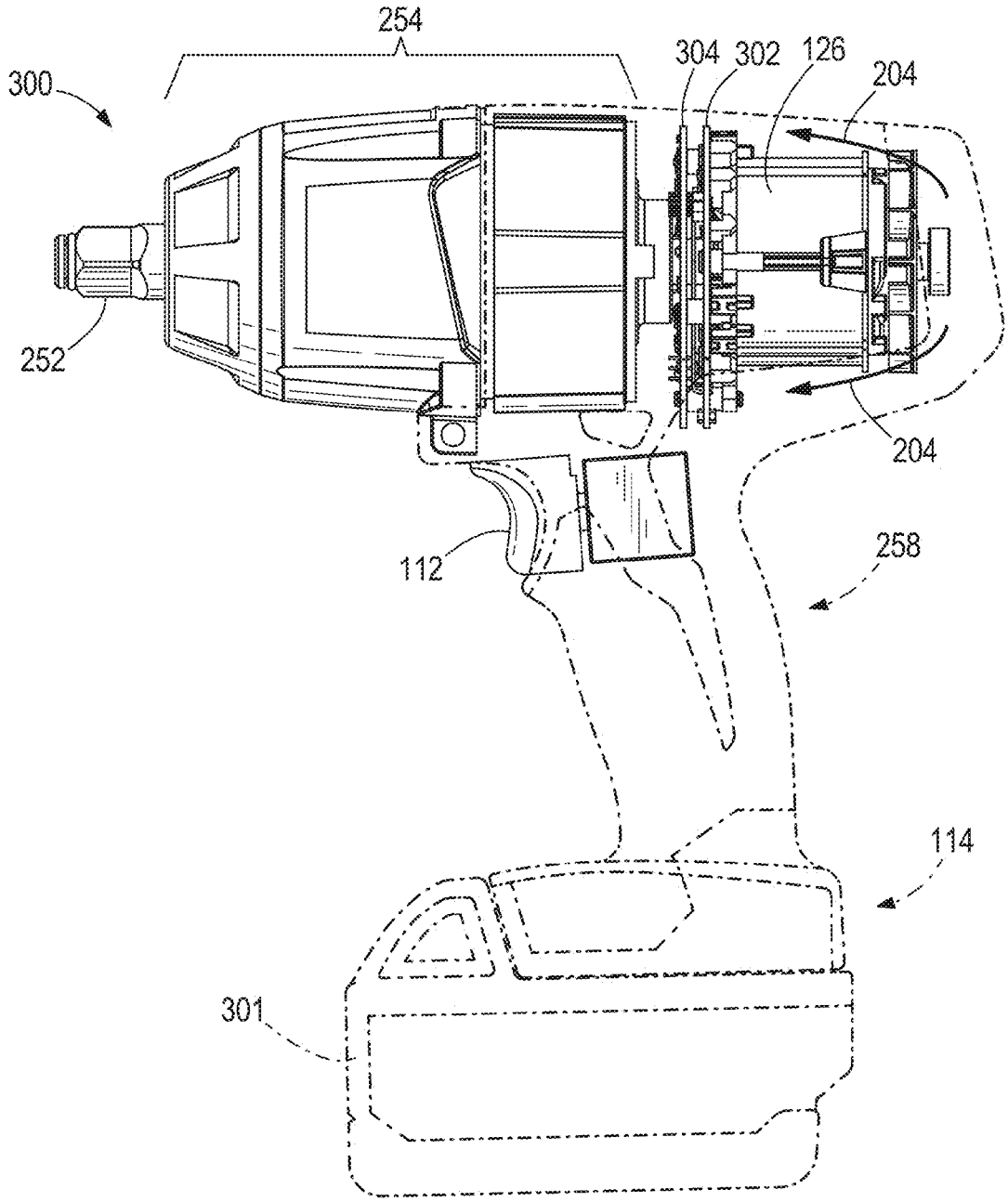


FIG. 15

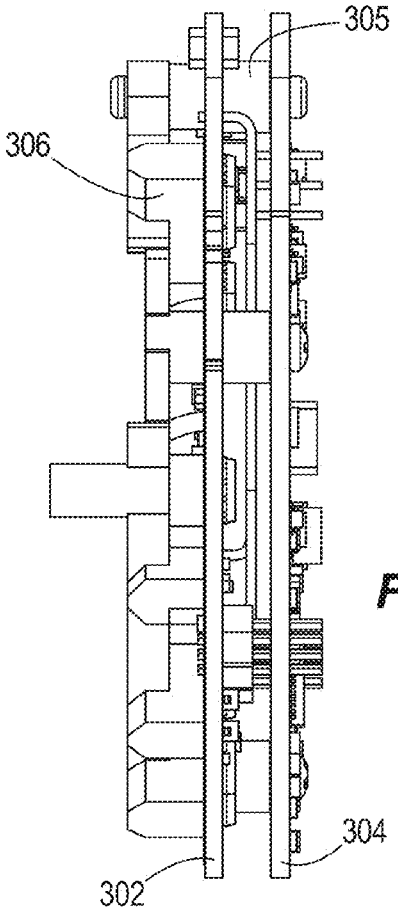


FIG. 16A

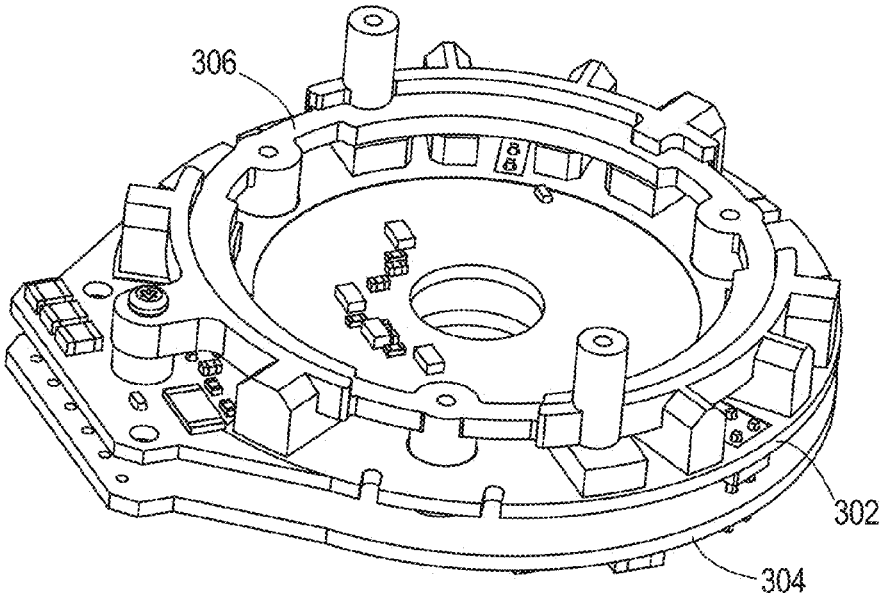


FIG. 16B

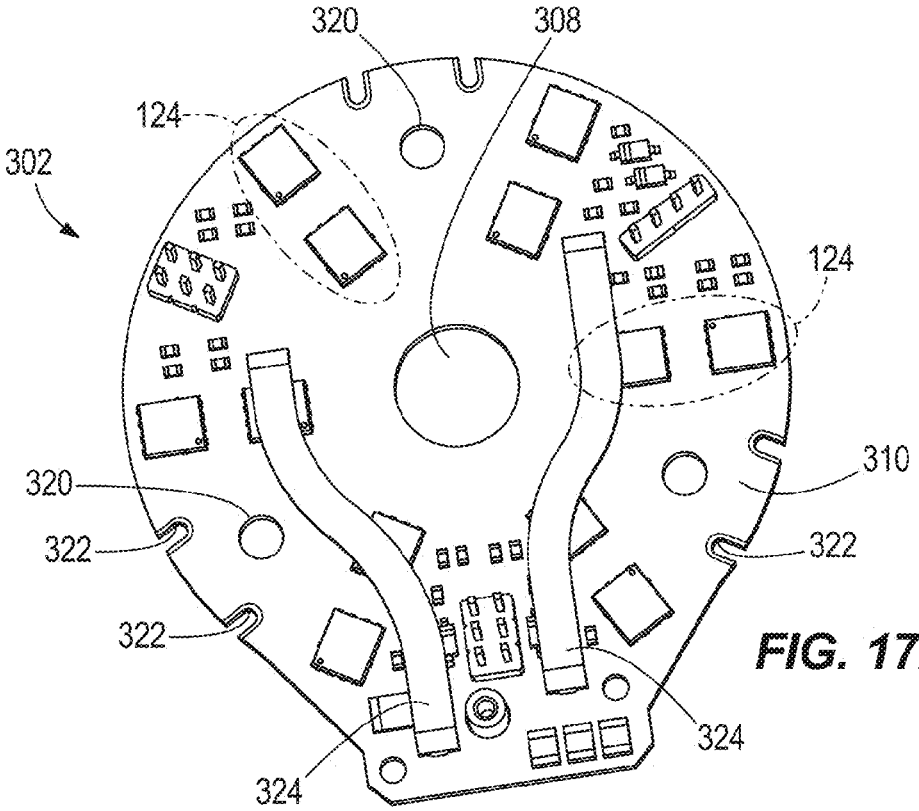


FIG. 17A

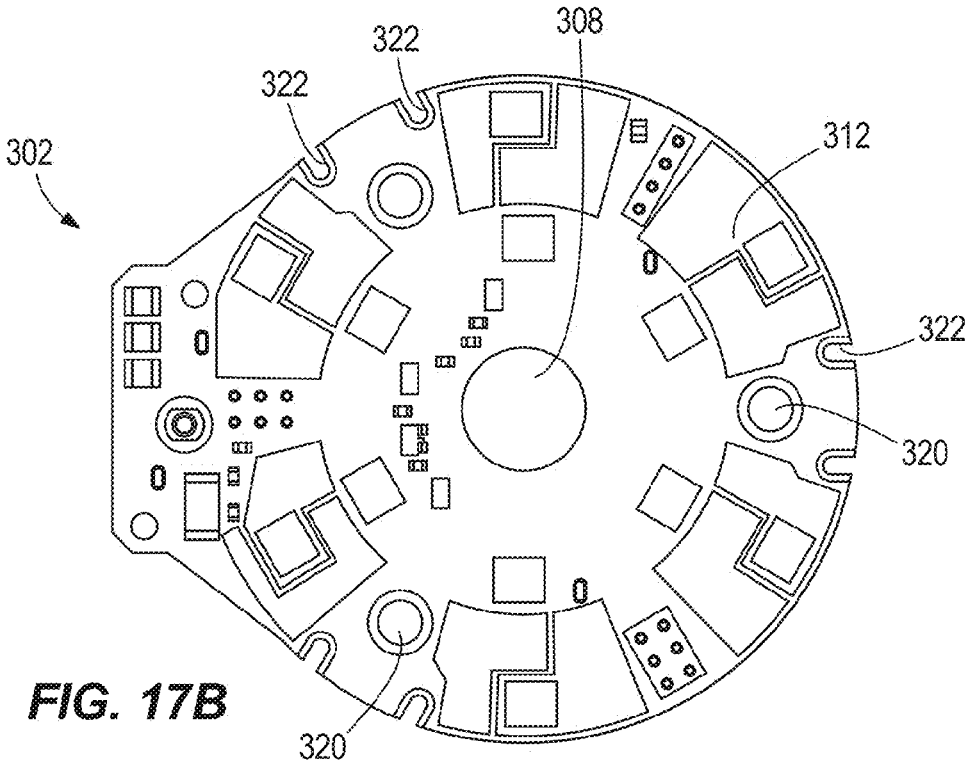


FIG. 17B

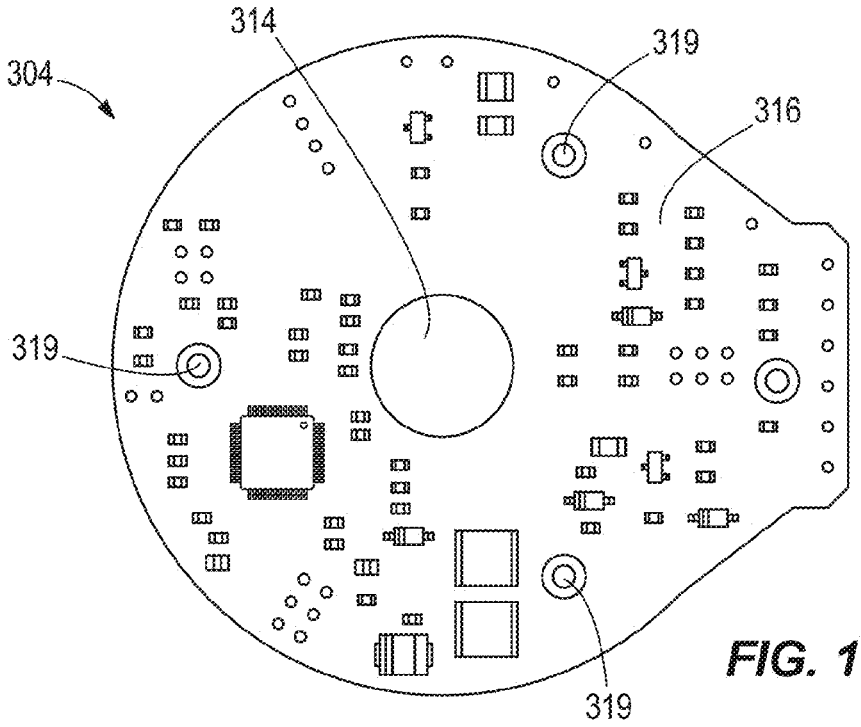


FIG. 18A

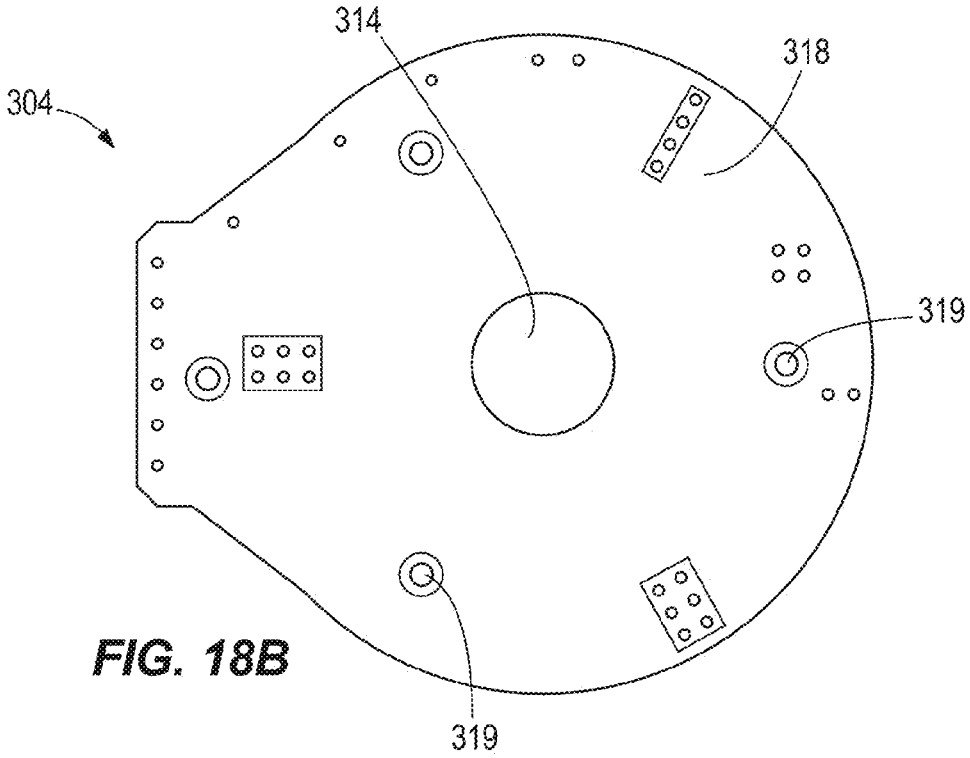


FIG. 18B

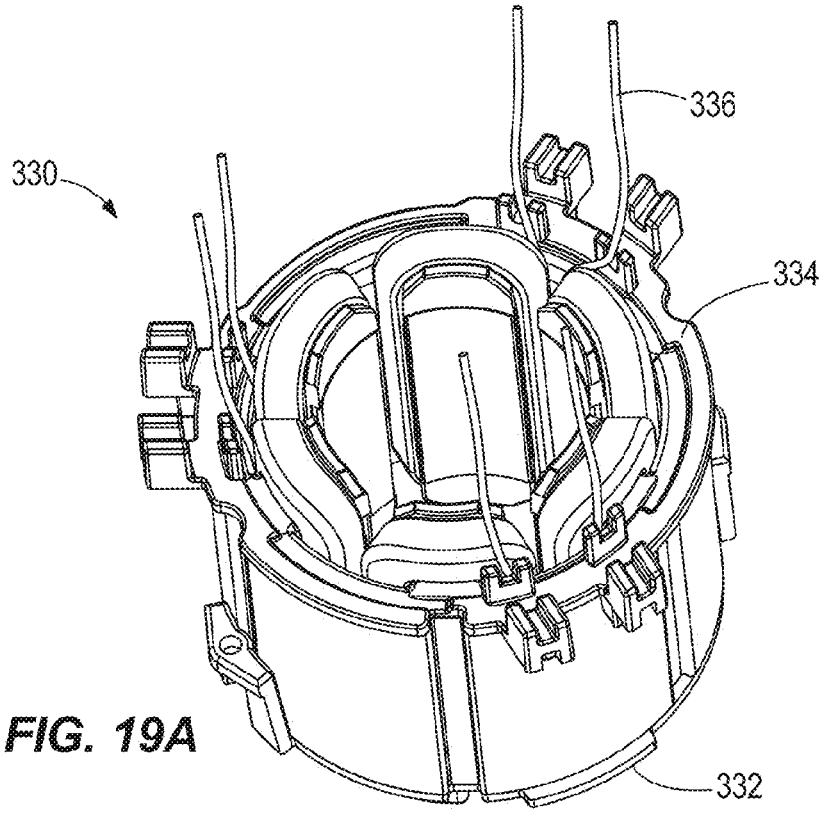


FIG. 19A

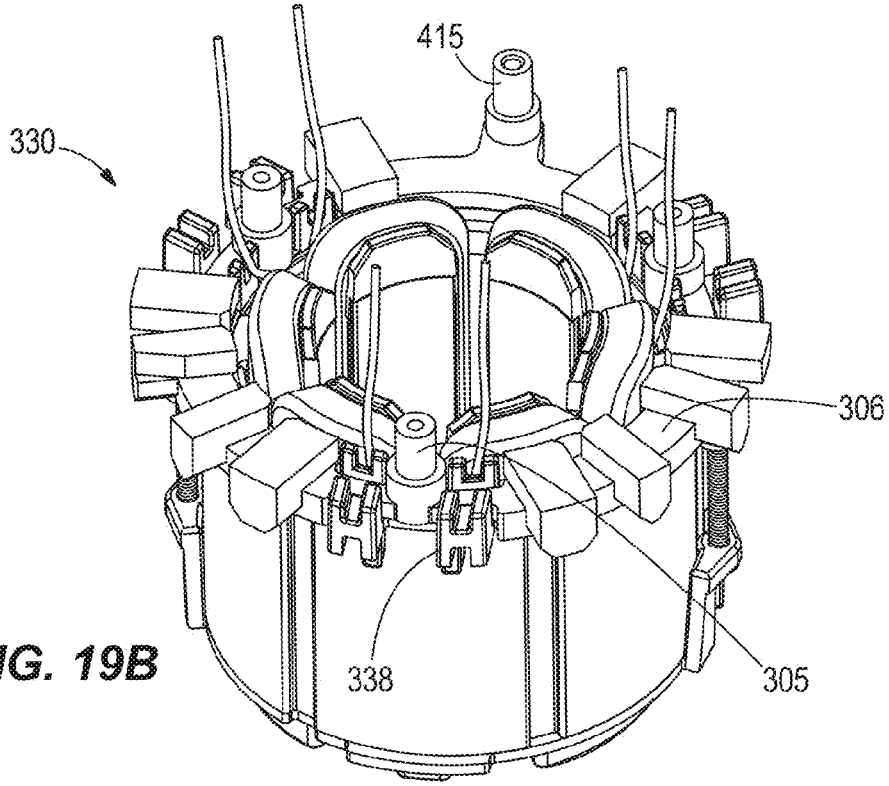


FIG. 19B

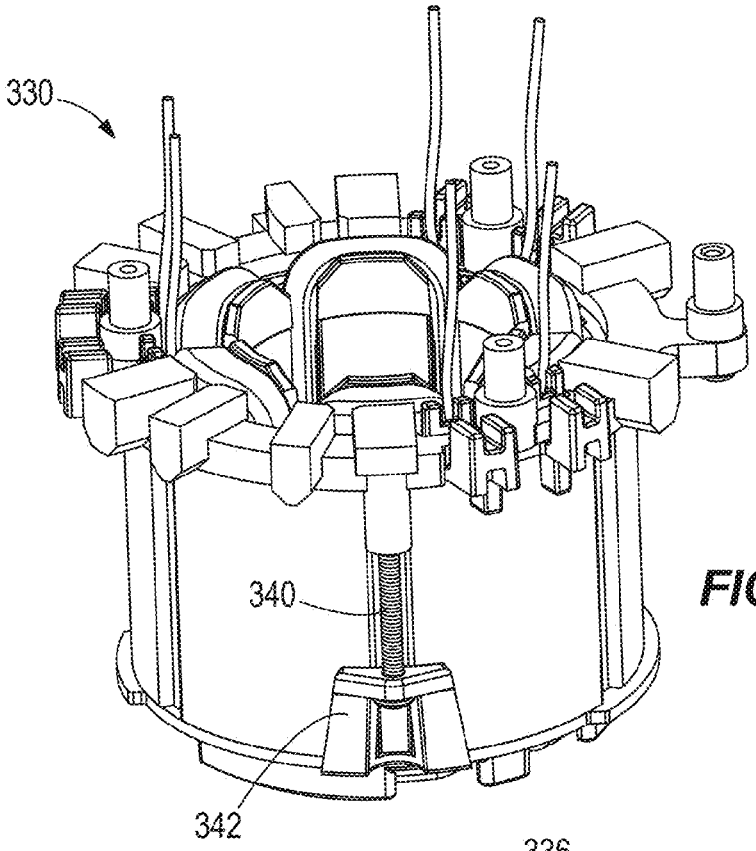


FIG. 19C

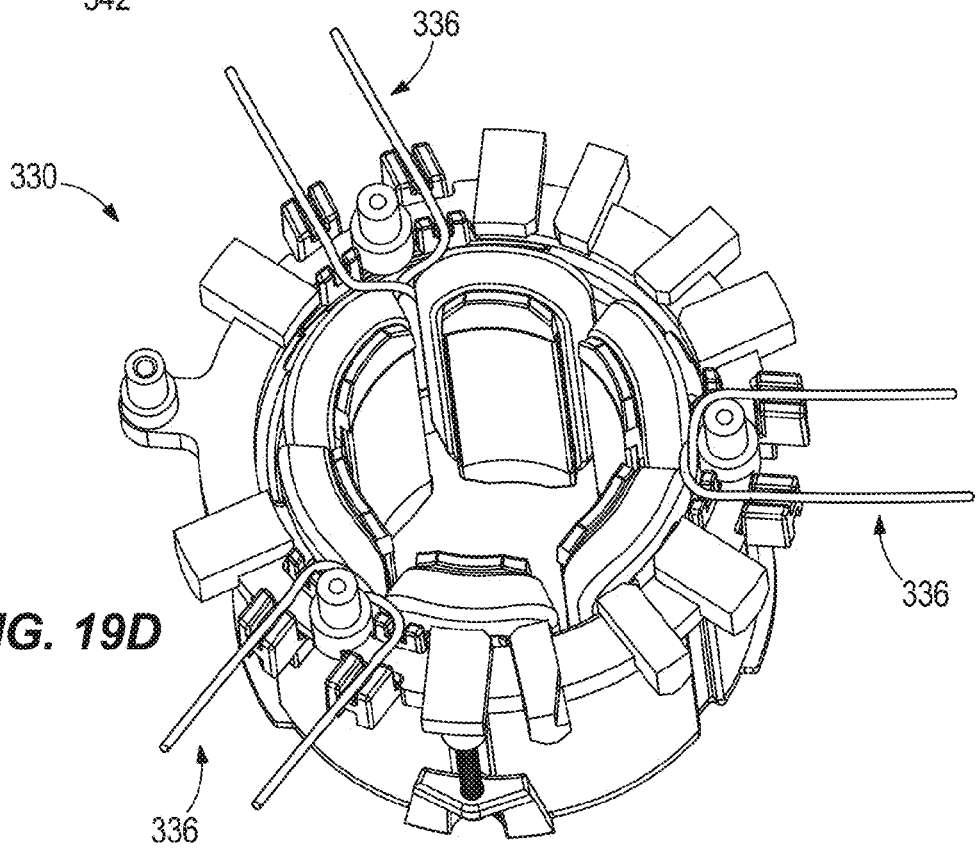


FIG. 19D

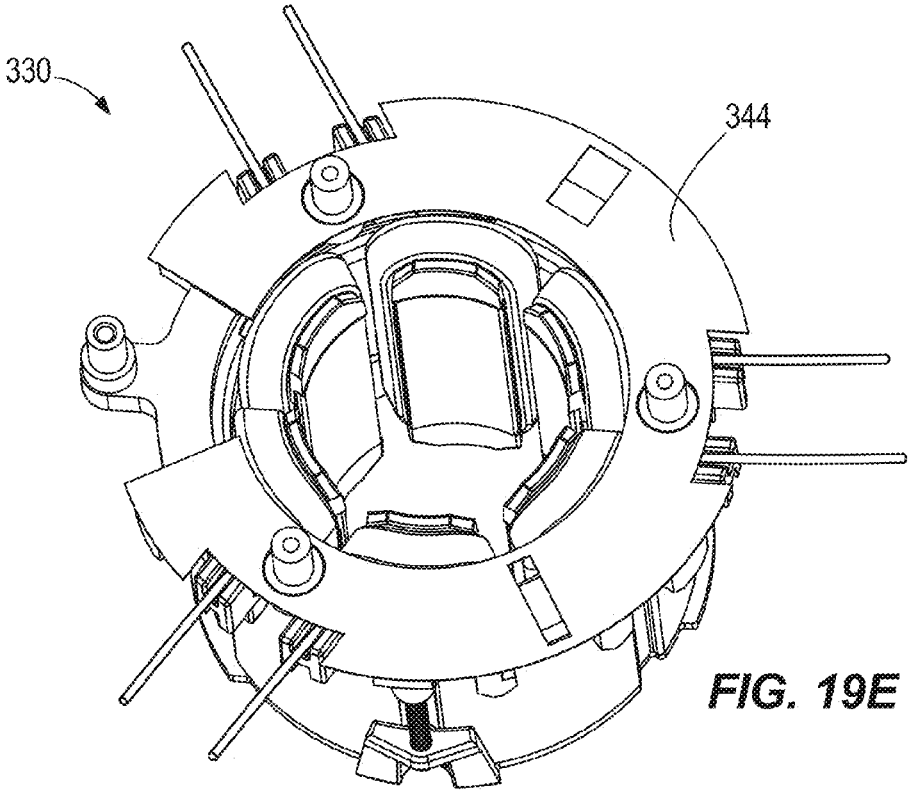


FIG. 19E

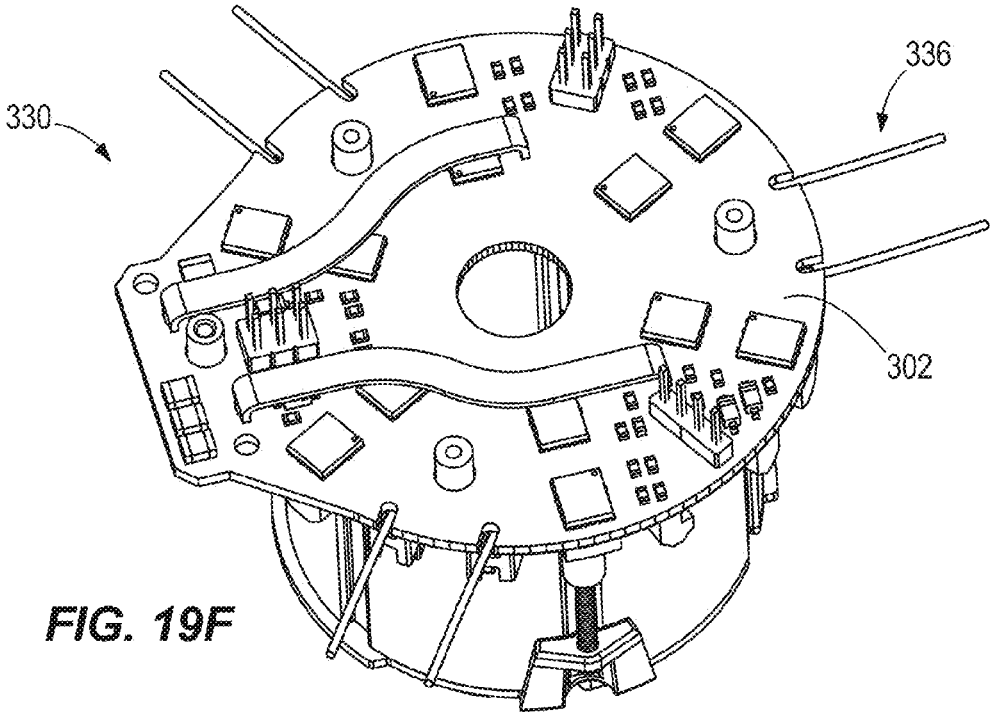


FIG. 19F

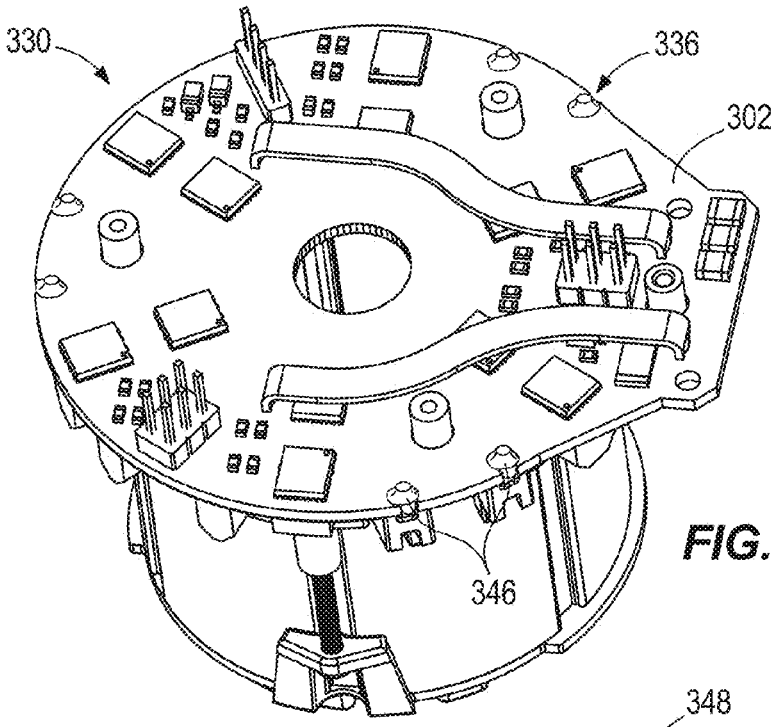


FIG. 19G

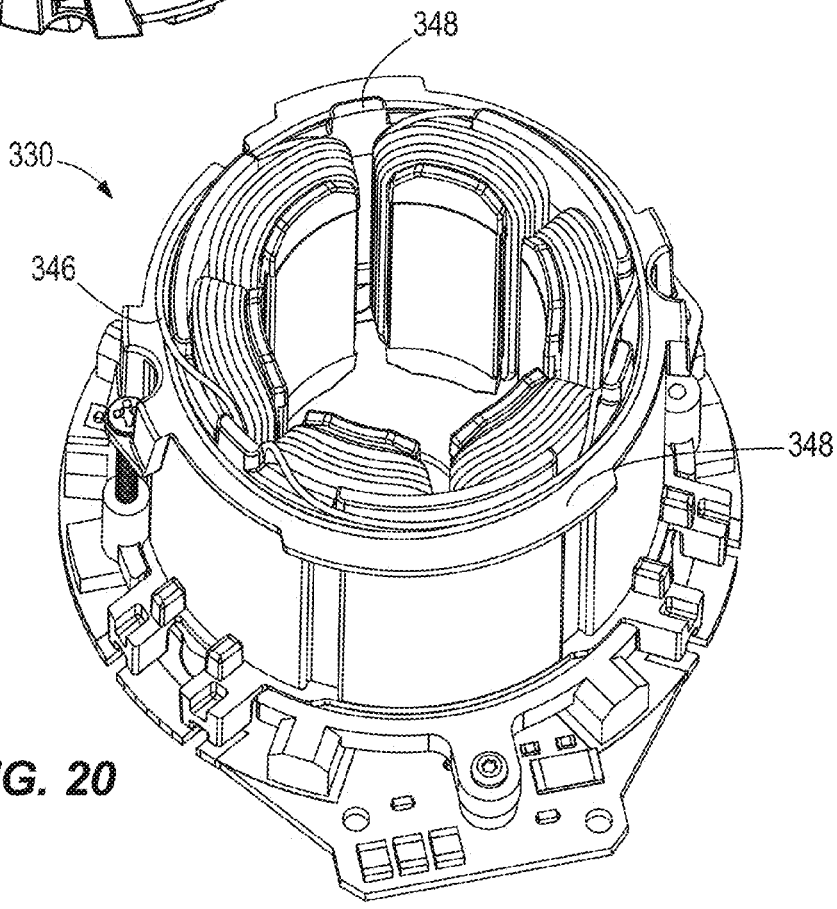


FIG. 20

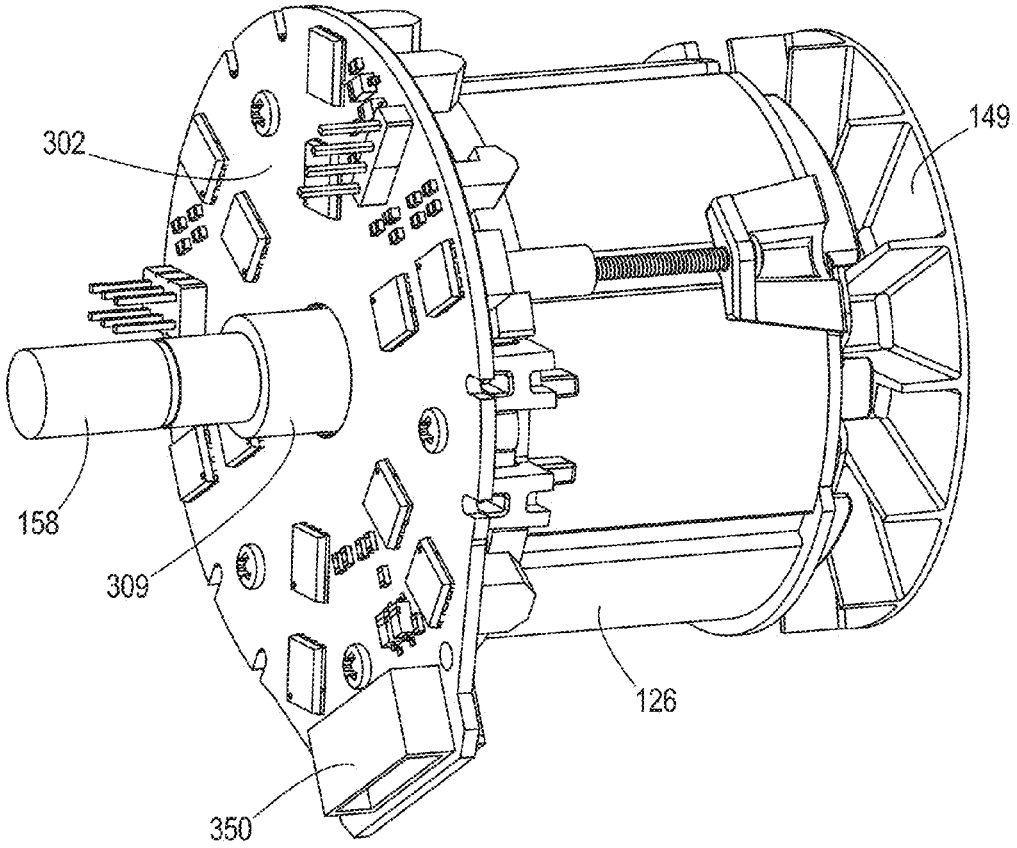


FIG. 21

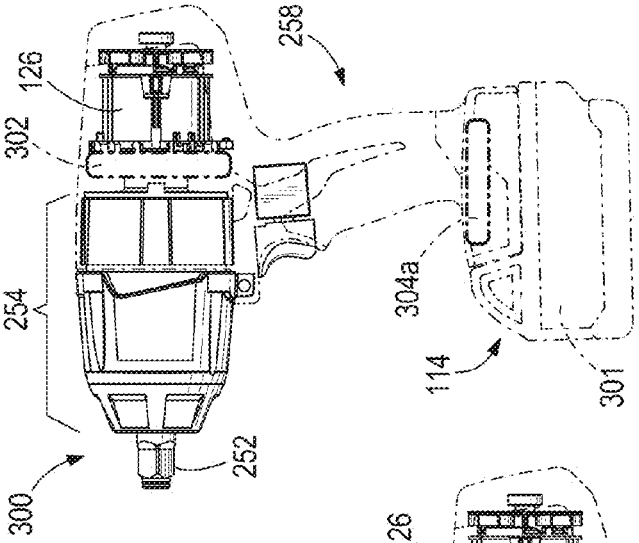


FIG. 22C

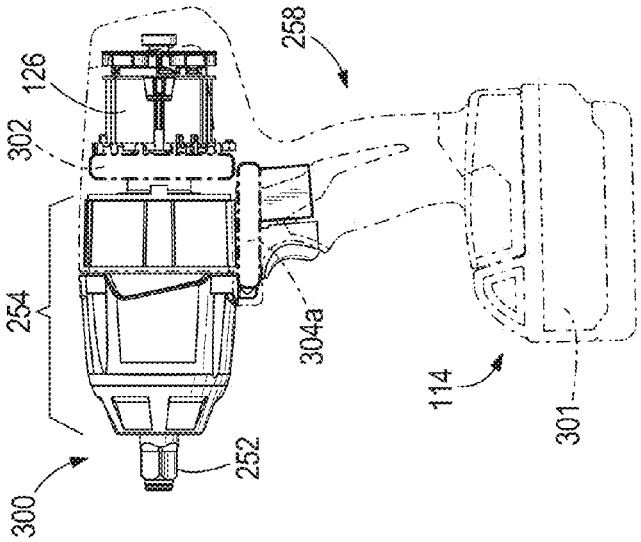


FIG. 22B

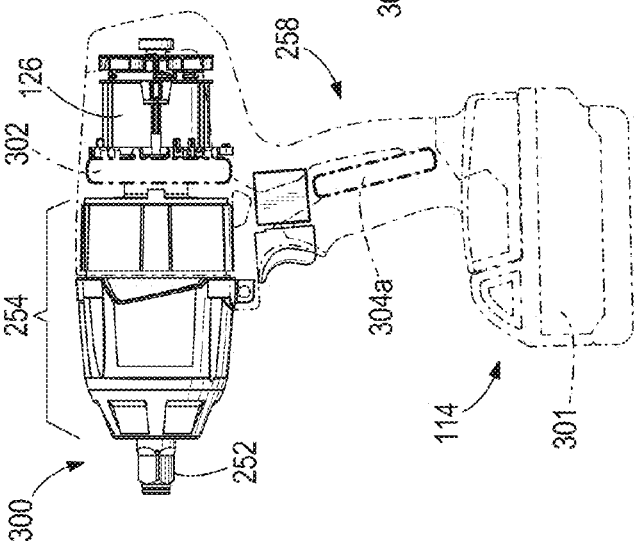


FIG. 22A

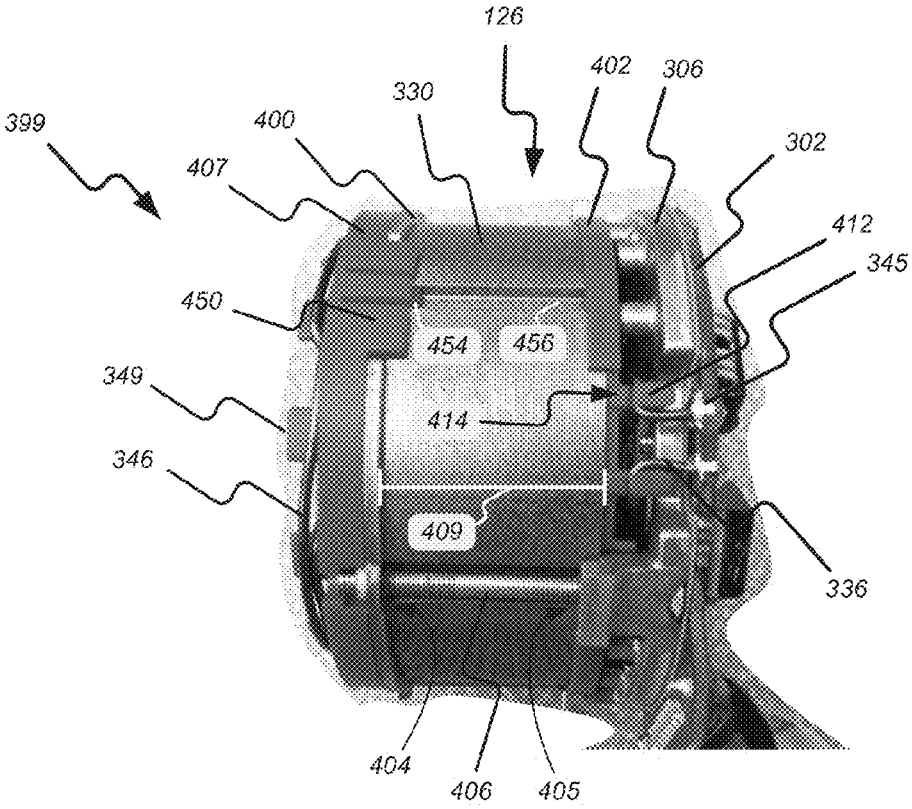


FIG. 23A

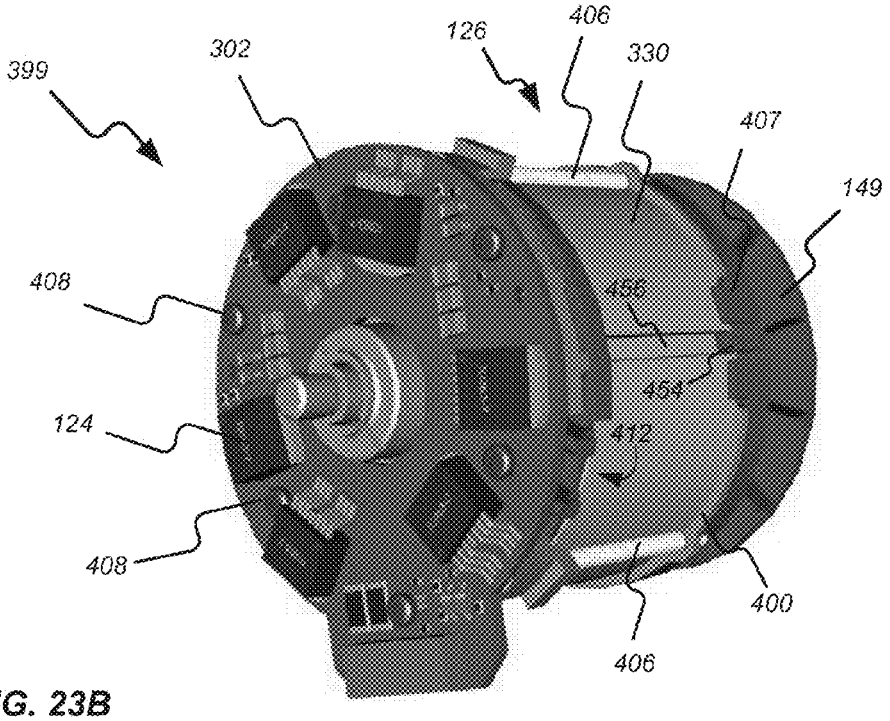


FIG. 23B

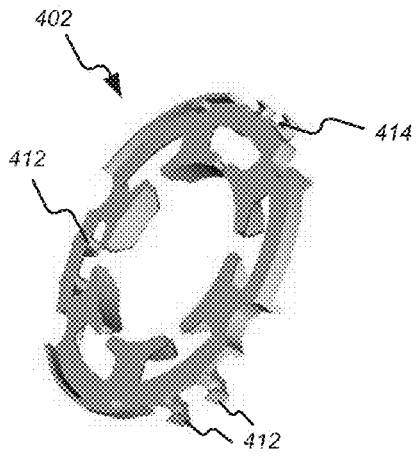


FIG. 24A

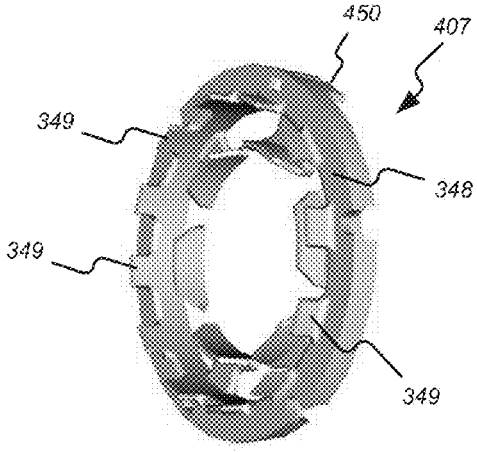


FIG. 24B

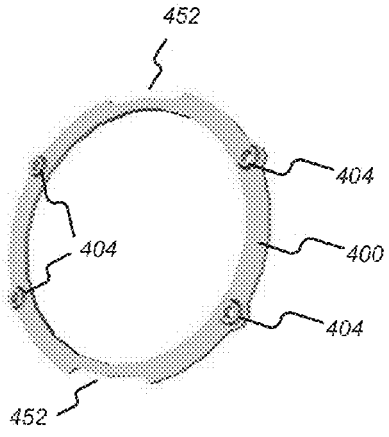


FIG. 24C

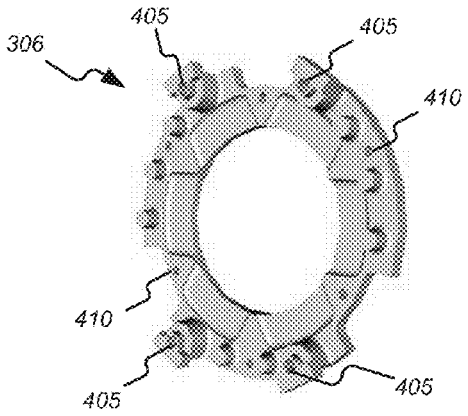


FIG. 24D

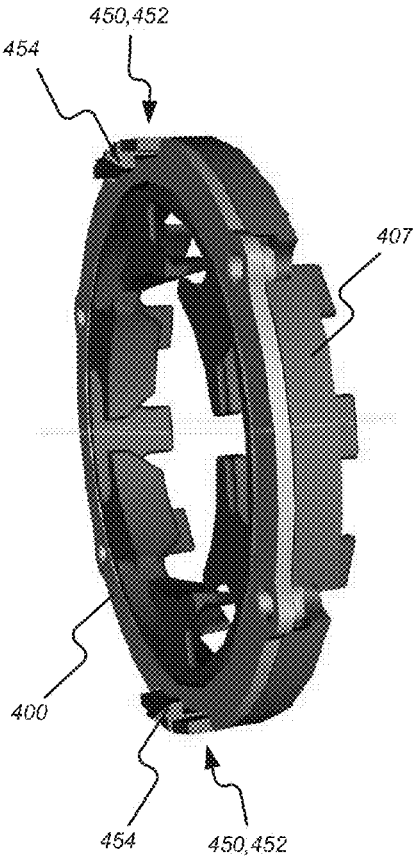


FIG. 25A

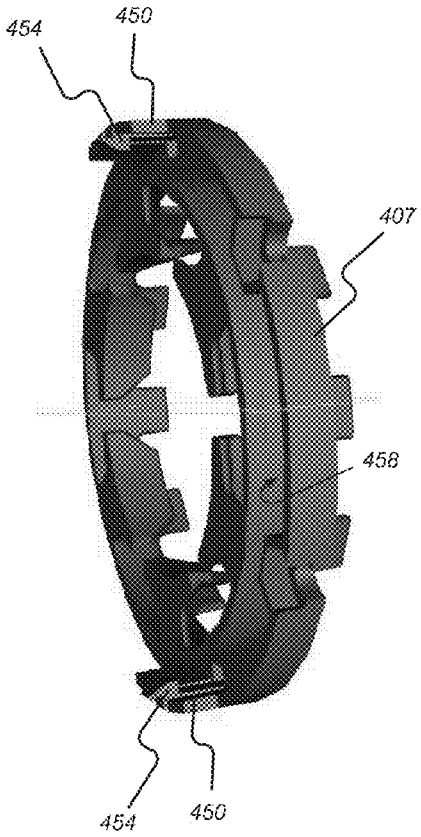


FIG. 25B

# BRUSHLESS DC MOTOR CONFIGURATION FOR A POWER TOOL

## RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Patent Application No. 61/832,012, filed on Jun. 6, 2013, the entire contents of which are hereby incorporated by reference.

## FIELD OF THE INVENTION

The present invention relates to brushless motor power tools.

## BACKGROUND

Power tool motors can generally be grouped into two categories: brushed motors and brushless motors. In a brushed motor, motor brushes make and break electrical connection to the motor due to rotation of the rotor. In a brushless motor power tool, such as power tool **100** of FIG. **1**, switching elements are selectively enabled and disabled by control signals from a controller to selectively apply power from a power source to drive the brushless motor. The power tool **100** is a brushless hammer drill having a housing **102** with a handle portion **104** and motor housing portion **106**. The power tool **100** further includes an output unit **107**, torque setting dial **108**, forward/reverse selector **110**, trigger **112**, battery interface **114**, and light **116**.

FIG. **2** illustrates a simplified block diagram **120** of the brushless power tool **100**, which includes a power source **122** (e.g., a battery pack), Field Effect Transistors (FETs) **124**, a motor **126**, hall sensors **128**, a motor control unit **130**, user input **132**, and other components **133** (battery pack fuel gauge, work lights (LEDs), current/voltage sensors, etc.). The Hall sensors **128** provide motor information feedback, such as motor rotational position information, which can be used by the motor control unit **130** to determine motor position, velocity, and/or acceleration. The motor control unit **130** receives user controls from user input **132**, such as by depressing the trigger **112** or shifting the forward/reverse selector **110**. In response to the motor information feedback and user controls, the motor control unit **130** transmits control signals to accurately control the FETs **124** to drive the motor **126**. By selectively enabling and disabling the FETs **124**, power from the power source **122** is selectively applied to the motor **126** to cause rotation of a rotor. Although not shown, the motor control unit **130** and other components of the power tool **100** are electrically coupled to the power source **122** such that the power source **122** provides power thereto.

## SUMMARY

In one embodiment, the invention provides a power tool including a housing and a brushless direct current (DC) motor within the housing. The brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output. The power tool further includes an annular metal end piece, a heat sink, and a printed circuit board (PCB). The annular metal end piece is positioned at a first end of the brushless DC motor, while the heat sink is positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece. The heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor. The PCB is positioned at the second end of the brushless DC motor and is secured to the heat sink.

In another embodiment, the invention provides a power tool comprising: housing and a brushless direct current (DC) motor within the housing. The brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output. The power tool further includes an annular metal end piece, a heat sink, threaded fastening elements, and a printed circuit board (PCB). The annular metal end piece is positioned at a first end of the brushless DC motor, while the heat sink is positioned at a second end of the brushless DC motor opposite the first end. The brushless DC motor is positioned between the heat sink and the annular metal end piece and has an axial length. The threaded fastening elements extend the axial length of the brushless DC motor and secure the heat sink to the annular metal end piece. The PCB is positioned at the second end of the brushless DC motor and is secured to the heat sink. The PCB includes a Hall sensor, power switching elements (e.g., field effect transistors), and a through-hole through which the motor shaft extends.

In another embodiment, the invention provides a power tool including a housing and a brushless direct current (DC) motor within the housing. The brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output. The power tool further includes an annular metal end piece, an end cap, a heat sink, threaded fastening elements, and a printed circuit board (PCB). The annular metal end piece is positioned at a first end of the brushless DC motor. The end cap is positioned over and secured to the annular metal end piece at the first end of the brushless DC motor. The heat sink is positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece. The heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor. The brushless DC motor has an axial length, and the threaded fastening elements extend the axial length and secure the heat sink to the annular metal end piece. The PCB is positioned at the second end of the brushless DC motor and is secured to the heat sink. The PCB includes a Hall sensor, power switching elements, and a through-hole through which the motor shaft extends.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a brushless power tool.

FIG. **2** illustrates a block diagram of a brushless power tool.

FIGS. **3**A, **3**B, and **4** provide additional view of the brushless power tool of FIG. **1**.

FIG. **5** illustrates a Hall sensor board.

FIGS. **6-7** illustrate a brushless power tool having a combined surfboard PCB.

FIGS. **8**A-C provide additional views of the combined surfboard PCB.

FIGS. **9-11** illustrate another brushless power tool having a combined surfboard PCB.

FIGS. **12-14** illustrate another brushless power tool having a combined surfboard PCB.

FIG. **15** illustrates a brushless power tool having a combined doughnut PCB.

FIGS. **16**A-B show the combined doughnut PCB of the power tool of FIG. **15**.

FIGS. **17**A-B show a combined Hall and FET PCB of the power tool of FIG. **15**.

FIGS. **18**A-B show a combined control PCB of the PCB stack.

FIGS. **19**A-G illustrate a process for attaching a Hall and FET PCB and heat sink to a brushless motor.

FIG. **20** illustrates a wire wrap technique for a brushless motor.

FIG. **21** illustrates another combined Hall sensor and FET PCB for use with a brushless power tool.

FIGS. **22**A-C illustrate alternative locations for a control PCB on the brushless power tool of FIG. **15**.

FIGS. **23**A-B illustrate an alternate brushless motor configuration.

FIGS. **24**A-D illustrate components of the alternate brushless motor configuration of FIGS. **23**A-B.

FIGS. **25**A-B further illustrate components of the alternate brushless motor configuration of FIGS. **23**A-B.

## DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

FIG. **3**A illustrates a cross section of the brushless power tool **100** of FIG. **1**, and FIG. **3**B illustrates select components of the power tool **100**. The power tool **100** includes separate printed circuit boards (PCBs) for various components of the power tool **100**. More particularly, the power tool **100** includes a control printed circuit board (PCB) **136**, a power PCB **138**, a forward/reverse PCB **140**, a Hall sensor PCB **142**, and a light-emitting diode (LED) PCB **144**. Also illustrated in FIG. **3**A is a drive mechanism **148** for transmitting the rotational output of the motor **126** to the output unit **107**, and a cooling fan **149** rotated by the motor **126** and used to provide a cooling air flow over components of the power tool **100**.

As shown in FIG. **4**, the control PCB **136** is positioned at the base of the tool **100** between the handle portion **104** and the battery interface **114**, which may also be referred to as a terminal block portion. The control PCB **136** includes the motor control unit **130**, which is operable to receive user input, to receive motor information feedback, and to control the FETs **124** to drive the motor **126**. The control PCB **136** is electrically and physically coupled to terminal blades **150**. When a battery pack (i.e., the power source **122**) is coupled to the battery interface **114**, terminals of the battery pack are received by and electrically coupled to the terminal blades **150**. The number of terminal blades can vary based on the type of hand-held power tool. However, as an illustrative example, terminal blades **150** can include a battery positive ("B+") terminal, a battery negative ("B−") terminal, a sense or communication terminal, and an identification terminal. As shown in FIG. **4**, the terminal blades **150** have tabs **152** that extend upward through the control PCB **136**. The tabs **152** may be directly soldered to the control PCB **136**, eliminating the need for additional power wires. The motor control unit may use the communication terminal to communicate with a battery pack, allowing the battery pack to communicate whether it is capable of discharging to the power tool **100** and other information.

The power PCB **138** includes the FETs **124**, which are connected to and controlled by the motor control unit **130** of the control PCB **136**. As discussed above, the FETs **124** are also electrically coupled to the power source **122** and the motor **126**. In some embodiments, the FETs **124** are directly coupled (i.e., directly physically and/or thermally coupled) to the heat sink **154** (e.g., directly on the heat sink, via copper tracings on the power PCB **138**, etc.). In other embodiments, the FETs **124** are not directly coupled to the heat sink **154**, but are in a heat transfer relationship with the heat sink **154**.

The forward/reverse PCB **140** includes a forward/reverse switch that is operated by the forward/reverse selector **110**, which has three positions: forward, reverse, and neutral. The positions may be shifted between by moving the forward/reverse selector/shuttle **110** in a direction normal to the plane of the drawing of FIG. **1** (i.e., in/out of the page). When the forward/reverse selector **110** is shifted between these three positions, the selector **110** switches the forward/reverse switch of the forward/reverse PCB **140**, which provides a signal to the motor control unit **130**. When the trigger **112** is depressed, the motor control unit **130** causes the motor **126** to rotate clockwise, rotate counterclockwise, or not rotate (e.g., in neutral) based on the position of the selector **110**.

The Hall sensor PCB **142** includes hall sensors **128** to detect one or more of the rotational position, velocity, and acceleration of the motor **126**. The Hall sensor PCB **142** is electrically coupled to the control PCB **136** to provide the outputs of the Hall sensors **128**. As shown in FIGS. **3**B and **5**, the Hall sensor PCB **142** includes a through-hole **156** through which a motor shaft/spindle **158** passes. Each Hall sensor **128** outputs a pulse when magnet of the rotor rotates across the face of that Hall sensor **128**. Based on the timing of the pulses from the Hall sensors **128**, the motor control unit **130** can determine the position, velocity, and acceleration of the rotor. The motor control unit **130**, in turn, uses the motor feedback information to control the FETs **124**.

The light-emitting element (LED) PCB **144** includes the light **116**, which may be a light emitting diode (LED). The LED PCB **144** is electrically coupled to the control PCB **136** such that the motor control unit **130** is operable to selectively enable and disable the light **116**. The motor control unit **130** may enable the light **116** when the trigger **112** is depressed and/or when a separate light switch on the housing **102** is activated by the user to selectively enable/disable the light **116** independent of the trigger **112**. The motor control unit **130** may further include a delay timer such that the light **116** remains illuminated for a period of time after the trigger **112** or light switch is depressed or released.

The motor control unit **130** is implemented by the control PCB **136**, which includes motor control unit **130** includes combinations of hardware and software that control operation of the power tool **100**. For example, the control PCB **136** includes, among other things, a processing unit (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory, input units, and output units. The processing unit includes, among other things, a control unit, an arithmetic logic unit ("ALU"), and a plurality of registers, and is implemented using a known computer architecture, such as a modified Harvard architecture, a von Neumann architecture, etc. The processing unit, the memory, the input units, and the output units, as well as the various modules connected to or part of the control PCB **136** are connected by one or more control and/or data buses. In some embodiments, the control PCB **136** is implemented

partially or entirely on a semiconductor (e.g., a field-programmable gate array ["FPGA"] semiconductor) chip, such as a chip developed through a register transfer level ("RTL") design process.

The memory of the control PCB **136** includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as read-only memory ("ROM"), random access memory ("RAM") (e.g., dynamic RAM ["DRAM"], synchronous DRAM ["SDRAM"], etc.), electrically erasable programmable read-only memory ("EEPROM"), flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit is connected to the memory and executes software instructions that are capable of being stored in a RAM of the memory (e.g., during execution), a ROM of the memory (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the battery pack can be stored in the memory of the controller. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The processing unit is configured to retrieve from memory and execute, among other things, instructions related to the control of the battery pack described herein. The processing unit can also store various battery pack parameters and characteristics (including battery pack nominal voltage, chemistry, battery cell characteristics, maximum allowed discharge current, maximum allowed temperature, etc.). In other constructions, the control PCB **136** includes additional, fewer, or different components.

The motor control unit **130** may further be in communication with one or more sensors to monitor temperature, voltage, current, etc., of the power tool **100** and an attached battery pack. The motor control unit **130** may also include protection capabilities based on a variety of preset or calculated fault condition values related to temperatures, currents, voltages, etc., associated with the operation of the hand-held power tool.

The various interconnections of the power tool **100** between the control PCB **136**, the power PCB **138**, the forward/reverse PCB **140**, the Hall sensor PCB **142**, and the light-emitting element (LED) PCB **144** can lead to a complex and space-consuming wiring layout within the housing **102**.

FIGS. **6-7** illustrate a brushless power tool **200**, which has similarities to power tool **100**, but has a different electronics layout. The layout of power tool **200** has reduced wiring and assembly complexity relative to the power tool **100**. Additionally, the more compact and efficient layout of the power tool **200** enables additional flexibility in design, such as by allowing different handle and body dimensions and shapes. Elements of the power tool **200** similar to those of the power tool **100** are similarly numbered to simplify the description thereof.

Rather than a separate control PCB **136**, power PCB **138**, forward/reverse PCB **140**, and LED PCB **144**, the power tool **200** includes a combined surfboard PCB **202** incorporating the functionality of each. The combined surfboard PCB **202** includes the FETs **124** of the power PCB **138**, the light **116** of the LED PCB **144**, the motor control unit **130** of the control PCB **136**, and a forward/reverse switch **203** of the forward/reverse PCB **140** (see FIG. **8**C). Accordingly, in place of wires running through the housing **102** to interconnect the various PCBs, the connections are made via conductors on the combined surfboard PCB **202**.

As illustrated, the combined surfboard PCB **202** has an elongated shape, with a length more than twice its width. The combined surfboard PCB **202** has a rear portion adjacent to the motor **126** and a front portion adjacent to a trigger **112**. The Hall sensor PCB **142** is positioned above and generally perpendicularly (i.e., within 15 degrees of a perpendicular) to the combined surfboard PCB **202**).

Moreover, the combined surfboard PCB **202** is positioned near the fan **149**, such that cooling air flow **204** passes over the FETs **124** and other components of the combined surfboard PCB **202**. The fan **149** operates to draw the cooling air flow **204** from the combined surfboard PCB **202** towards the fan **149**, or, as illustrated, to push the cooling air flow **204** from the fan **149** over the combined surfboard PCB **202**. Furthermore, air inlets and outlets are formed on the housing **102** to provide an inlet and outlet path for the cooling air flow **204**.

The components of the combined surfboard PCB **202** are exposed. In other words, the combined surfboard PCB **202** is not encapsulated or potted within the housing **102** and is not protected against fluid within the housing **102** from reaching the FETs **124** or motor control unit **130**. Exposing the combined surfboard PCB **202** improves the thermal management of the components thereon. For example, the cooling air flow **204** is operable to reach and cool the FETs **124**, enabling the FETs **124** to operate at higher current levels and the motor **126** to operate at higher power levels and generate higher torque for longer periods of time.

As shown in FIGS. **8**A-C, the FETs **124** are mounted in a generally flat orientation on the combined surfboard PCB **202**. In contrast, the FETs **124** of the power tool **100** are mounted on the power PCB **138** in a perpendicular orientation. The combined surfboard PCB **202** also has mounted thereon a heat sink **206** on a side opposite of the FETs **124** to provide cooling of the FETs **124**. The heat sink **206** is thermally coupled to the FETs **124** and includes heat sink fins **208** to improve the heat sinking capabilities of the heat sink **206**. In some instances, one or more additional heat sinks are positioned on the same side as the FETs **124**, such that the FETs **124** and the combined surfboard PCB **202** are located between the heat sink **206** and the one or more additional heat sinks The one or more additional heat sinks are thermally coupled to the FETs **124** to provide additional thermal management. A front portion **209** of the bottom surface of the combined surfboard PCB **202** includes the light **116** and the forward/reverse switch **203** mounted thereon. The FETs **124** are mounted on a rear portion **210** of the bottom surface of the combined surfboard PCB **202**. The heat sink **206** is mounted on the rear portion **210** of the top surface of the combined surfboard PCB **202**. The Hall sensor PCB **142** is above the surfboard PCB **202** and, taken together, generally form an upside-down "T" shape.

Additionally, the combined surfboard PCB **202** is centrally located within the power tool **200** above the trigger **112**, but below the motor **126** and drive mechanism **148**. FIG. **7** illustrates a region **211** considered above the trigger **112** and below the motor **126**. "Below the motor" does not require that the combined surfboard PCB **202** be directly below the motor **126**, but, rather, below a line extending parallel to the bottom surface of the motor **126**. Accordingly, a shortened combined surfboard PCB **202** that does not extend rearward in the tool **200** such that it is, in part, directly under the motor **126** as shown in FIG. **7** can still be considered "below the motor." Similarly, "above the trigger"

does not require that the combined surfboard PCB **202** be directly above the trigger, but, rather, within the region **211**.

The central location allows relatively short wire connections between several components of the power tool **200**. Furthermore, the exposed, unencapsulated nature of the combined surfboard PCB **202** further enables more flexibility in connection points to components thereon. That is, wires can reach components of the combined surfboard PCB **202** generally directly, rather than through limited ingress/egress ports of an encapsulation housing, allowing shorter and more direct wire connections. More particularly, the combined surfboard PCB **202** is near the Hall sensor PCB **142**, the light **116**, the trigger **112**, the forward/reverse switch **203**, and terminals of the motor **126**. For instance, FIG. **8**A illustrates the short wires **212** connecting the Hall sensor PCB **142** and the combined surfboard PCB **202**. The wires **212** may be flexible or rigid and are connected generally at a middle portion of the combined surfboard PCB **202**. Additionally, as shown, the wires **212** have a length less than a diameter of the motor **126**, less than one-fourth of the length of the combined surfboard PCB **202**, and less than a diameter of the Hall sensor PCB **142**. Although a top surface of the combined surfboard PCB **202** is substantially parallel to the longitudinal axis of the motor shaft **158**, the combined surfboard PCB **202** is angled slightly downward with respect to the motor shaft **158** from the motor side to the output side of the power tool **200**. As illustrated in FIG. **6-7**, the combined surfboard PCB **202** has a slight downward angle of less than 5 degrees with respect to the motor shaft **158**.

In some embodiments, the forward/reverse selector **110** includes a magnet mounted therein and the combined surfboard PCB **202** includes a forward/reverse Hall sensor (not shown) in place of the forward/reverse switch **203**. The forward/reverse Hall sensor detects movement of the embedded magnet when the forward/reverse selector **110** is moved, and a signal indicating the position or movement of the forward/reverse selector **110** is provided to the motor control unit **130**.

The combined surfboard PCB **202** includes an exemplary component layout. In some embodiments, various components, such as one or more of the FETs **124**, are mounted on a different portion of the combined surfboard PCB **202** (e.g., top instead of bottom surface, front instead of rear portion, etc.).

In some embodiments, the power tool **200** is a (non-hammer) drill/driver power tool that includes a similar electronics layout, housing, motor, etc., but includes a different drive mechanism **148** having no hammer mechanism.

FIGS. **9-11** illustrate a brushless impact wrench power tool **250** including an impact output unit **252**. The impact wrench is another type of hand-held power tool used for generating rotational output, but includes an impact mechanism **254** that differs from the hammer-style drive mechanism **148** of the power tools **100** and **200**.

The power tool **250** includes a similar layout as the power tool **200**. More particularly, the power tool **250** includes a housing **256** with a handle portion **258** and motor housing portion **260**. The motor housing portion **260** houses a motor **126** and is positioned above the handle portion **258**. The handle portion **258** includes the battery interface **114** for coupling to a battery pack. Additionally, the power tool **250** includes the combined surfboard PCB **202** and Hall sensor PCB **142**. The layout of power tool **250** has reduced wiring and assembly complexity relative to the power tool **100**. Additionally, the more compact and efficient layout of the power tool **250** enables additional flexibility in design, such as by allowing different handle and body dimensions and shapes. Elements of the power tool **250** similar to those of the power tools **100** and **250** are similarly numbered to simplify the description thereof.

FIGS. **12-14** illustrate a brushless impact driver power tool **270** including an impact output unit **272**. The impact driver power tool **270** is another type of hand-held power tool used for generating rotational output that includes an impact mechanism **274** similar to the impact mechanism **254**. Additionally, the power tool **270** includes a clip **276** for hanging the power tool **270** on various items, such as on a hook or tool belt.

The power tool **270** includes a similar layout as the power tools **200** and **250**. More particularly, the power tool **270** includes a housing **278** with a handle portion **280** and motor housing portion **282**. The motor portion **282** houses a motor **126** and is positioned above the handle portion **280**. The handle portion **280** includes the battery interface **114** for coupling to a battery pack. Additionally, the power tool **270** includes the combined surfboard PCB **202** and Hall sensor PCB **142**. The layout of power tool **270** has reduced wiring and assembly complexity relative to the power tool **100**. Additionally, the more compact and efficient layout of the power tool **270** enables additional flexibility in design, such as by allowing different handle and body dimensions and shapes. Elements of the power tool **270** similar to those of the power tools **100** and **270** are similarly numbered to simplify the description thereof.

Although the physical layout of the combined surfboard PCB **202** may be generally similar for each of the power tools **200**, **250**, and **270**, the particular software and hardware of the motor control unit **130** and ratings of electrical components and FETs **124** may vary and be optimized for each tool.

FIG. **15** illustrates another brushless impact wrench power tool **300** including the impact output unit **252** and impact mechanism **254**, and having a battery pack **301** attached to the battery interface **114**. Elements of the power tool **300** similar to the previously described power tools are similarly numbered to simplify the description thereof.

The layout of power tool **300**, like that of the power tools **200**, **250**, and **270**, has reduced wiring complexity and reduced costs relative to the power tool **100**. However, the power tool **300** has a different PCB layout in that the combined surfboard PCB **202** is not included. Rather, the components of the combined surfboard PCB **202** are positioned on (generally) doughnut-shaped PCBs near the motor. Separate PCBs similar to the LED PCB **144** and forward/reverse PCB **140** may be provided in the power tool **300** for inclusion and support of the light **116** and switch **203**, respectively.

More specifically, as shown in FIGS. **16**A-B, the power tool **300** includes a Hall and FET PCB **302** and a control PCB **304** stacked on the motor **126** and having a hole through which the motor shaft **158** passes. The Hall and FET PCB **302** is kept separated from the control PCB **304** by spacers **305** (also referred to as standoffs). The Hall and FET PCB **302** includes the Hall sensors **128** and the FETs **124**, while the control PCB **304** includes the motor control unit **130**. Additionally, a heat sink **306**, also with a generally doughnut or ring shape, is secured between the Hall and FET PCB **302** and the motor **126**. The heat sink **306** is generally used to transfer heat away from the FETs **124**.

FIGS. **17**A-B illustrate the Hall and FET PCB **302** in greater detail. The Hall and FET PCB **302** has a generally circular shape with a through-hole **308** in the center. A motor

shaft **158**, as well as a motor bushing **309** (see, e.g., FIG. **21**), pass through the through-hole **308**. The Hall and FET PCB **302** has two generally flat mounting surfaces: a first face **310** (see FIG. **17**A) and a second face **312** (see FIG. **17**B). The FETs **124** are mounted on the Hall and FET PCB **302** in a flat orientation. Similarly, the control PCB **304** has a through-hole **314** and two generally flat mounting surfaces: a first face **316** (see FIG. **18**A) and a second face **318** (see FIG. **18**B). The FETs **124** are shown mounted on the first face **310**, while the Hall sensors **128** may be mounted on the second face **318**, staggered at approximately 120 degrees, to be closer to the rotor magnets similar to the PCB **142** (see, e.g., FIG. **5**). The control PCB **304** further includes control PCB mounting holes **319**. The control PCB **304** and Hall and FET PCB **302** are located coaxially about the motor shaft **158** and the faces **310**, **312**, **316**, and **318** are generally parallel to each other. The PCBs **302** and **304** are secured to an end of the motor **126**. By locating FETs **124** with Hall sensors **128** on a single Hall and FET PCB **302** secured to the end of the motor **126**, the Hall and FET PCB **302** is able to receive a large amount of air flow **204** for cooling in addition to reducing the internal wiring of the power tool **300**.

The Hall and FET PCB **302** further includes Hall and FET PCB mounting holes **320**, motor lead pads **322**, and copper bus bars **324**. The copper bus bars **324** allow for additional space on the Hall and FET PCB **302** to be used for other features such as high current traces. Accordingly, rather than occupying space on the Hall and FET PCB **302**, the copper bus bars **324** jump above the Hall and FET PCB **302**. In alternative embodiments, traces on the Hall and FET PCB **302** are used instead of the copper bus bars **324**.

The Hall and FET PCB mounting holes **320** allow metal standoffs **305** (see FIG. **16**A-B) of the heat sink **306** to pass through the Hall and FET PCB **302**. The metal standoffs **305** provide spacing between the PCBs **302** and **304** and allow the control PCB **304** to be attached to the heat sink **306**. The metal standoffs **305** receive control PCB mounting screws inserted through mounting holes **319** of the control PCB **304** to secure the control PCB **304** to the heat sink **306**. In some embodiments, the control PCB mounting screws secure both the control PCB **304** and the Hall and FET PCB **302** to the heat sink **306**.

Furthermore, in some embodiments, Hall and FET PCB mounting holes **320** may be used for both allowing metal standoffs **305** of the heat sink **306** to pass through the Hall and FET PCB **302** and for securing the Hall and FET PCB **302** to the heat sink **306**. Tightly securing the Hall and FET PCB **302** to the heat sink **326** allows for heat to dissipate from the Hall and FET PCB **302** to the heat sink **306** more easily and minimizes vibration between the Hall and FET PCB **302** and the motor **126**. In other embodiments of the invention, the number of mounting holes **319** and **320** and their location on the PCBs **302** and **304** are varied. Furthermore, in other embodiments, the general shape of the PCBs **302** and **304** is varied.

FIGS. **19**A-G illustrate a process for attaching the motor **126**, Hall and FET PCB **302**, and heat sink **306** together. FIG. **19**A illustrates a motor stator **330** of the motor **126** with plastic end caps **332** and **334** at each end of the motor stator **330**, respectively, and six motor leads **336** that are stripped down to the plastic end cap **334**. Wire support features **338** are part of the plastic end cap **334** and will be used to properly guide the motor leads **336**, as explained below. FIG. **19**B illustrates the heat sink **306** placed on the plastic end cap **334** of the motor stator **330**. The metal standoffs **305** of the heat sink **306** may be used for mounting the control PCB **304** and/or locating the Hall and FET PCB **302** in some embodiments.

FIG. **19**C illustrates the heat sink **306** fastened to the motor stator **330** using heat sink mounting screws **340**. Heat sink mounting clips **342** are attached to an end of the motor stator **330** opposite the end where the heat sink **306** is attached. The heat sink mounting screws **340** are threadingly engaged with heat sink mounting standoffs of the heat sink **306** and the heat sink mounting clips **342** to secure the heat sink **306** to the motor stator **330**. In some embodiments the number and location of heat sink mounting elements are varied.

After securing the heat sink **306**, the motor leads **336** are then bent downward to fit within the wire support features **338** as shown in FIG. **19**D. Wrapping the motor leads **336** around the wire support features **338** relieves strain on the motor leads **336** before they are soldered to the Hall and FET PCB **302**. In some embodiments, glue can also be applied to the motor leads **336** to secure them to the heat sink **306**.

FIG. **19**E illustrates a heat sink pad **344** placed on top of the heat sink **306**. The heat sink pad **344** is a thin, electrical insulator with high thermal conductivity. These characteristics allow the heat sink pad **306** to electrically isolate the metal heat sink **306** from the Hall and FET PCB **302** while still allowing heat from the Hall and FET PCB **302** to dissipate via the heat sink **306**.

FIG. **19**F illustrates the Hall and FET PCB **302** placed on top of the heat sink pad **344** and heat sink **306**. The motor leads **336** align with the openings of the motor lead pads **322**, and the metal standoffs **305** of the heat sink **306** pass through the Hall and FET PCB mounting holes **320**. To ensure contact between the Hall and FET PCB **302** and the heat sink **306**, downward force is applied to the Hall and FET PCB **302**.

As illustrated in FIG. **19**G, the motor leads **336** are soldered to the motor lead pads **322** to create solder joints **345**, which not only electrically connect the motor leads **336** to the Hall and FET PCB **302**, but also mechanically attach the two components together. After creating the solder joints **345**, the motor leads **336** are cut near the motor lead pads **322**. As described above, in addition to the solder joints **345**, the Hall and FET PCB **302** can be secured to the heat sink **306** (which is secured to the motor **126**) using Hall and FET PCB mounting screws.

After securing the Hall and FET PCB **302** to the motor **126** and heat sink **306** combination, the control PCB **304** is then secured to the heat sink **306** with the Hall and FET PCB **302** positioned between the heat sink **306** and the control PCB **304**. The control PCB **304** is secured to the heat sink **306** using control PCB mounting screws received by the standoffs **305**.

FIG. **20** illustrates the end of the motor stator **330** opposite from the end having the Hall and FET PCB **302**. This view of the motor stator **330** illustrates a wire crossover design, which wraps a wire behind the plastic end cap **332**. Wrapping the wires of the motor stator **330** around the plastic end cap **332** allows them to travel 180 degrees from one pole to the opposite pole of the motor stator **330** in an efficient manner. The wrapped wires **346** are on top of a ledge portion **348**, which wraps around the motor stator **330**, and are radially outside of tab portions **349** that extend up from the ledge portion **348**. As illustrated, at no point are three wires located at the same circumferential position and stacked along the ledge portion **348**. Rather, at most, two wires are stacked, allowing a reduced height of the tab portions **349** and overall length of the motor stator **330**.

In some embodiments, the control PCB **304** is not located adjacent to the Hall and FET PCB **302** about the motor shaft **158**, and the metal standoffs **305** do not pass through the Hall and FET PCB **302**. Rather, the length of the metal standoffs **305** is reduced such that they terminate at the surface of the Hall and FET PCB **302**. The reduced metal standoffs **305**, which no longer provide spacing functionality, then receive Hall and FET PCB mounting screws to secure the Hall and FET PCB **302** to the heat sink **306** and motor **126** combination, as shown in FIG. **21**.

In embodiments in which the control PCB **304** is not located adjacent to the Hall and FET PCB **302**, the control PCB **304** may be referred to as the control PCB **304***a*. The control PCB **304***a* may be located in several locations within the power tool **300**. The Hall and FET PCB **302** is coupled to the control PCB **304***a* via cable connector **350** and a ribbon cable (not shown).

FIGS. **22**A-C illustrate exemplary locations within the power tool **300** that the control PCB **304***a* may be positioned. In FIG. **22**A, similar to the power PCB **138** of the power tool **100**, the control PCB **304***a* is located in the handle portion **258** of the power tool **300**. In FIG. **22**B, similar to the combined surfboard PCB **202**, the control PCB **304***a* is located above the trigger **112** and handle portion **258**, but below the motor **126** and impact mechanism **254**. In FIG. **22**C, similar to the control PCB **136** of the power tool **100**, the control PCB **304***a* is located below the handle portion **258** and above the battery interface **114**.

Although FIGS. **15-22** are described with respect to an impact wrench power tool **300**, the various layout and motor assembly described may be implemented in other types of power tools, such as a non-hammer drill/driver power tool, a hammer drill/driver power tool (see, e.g., FIGS. **1-9**) and an impact driver power tool (see, e.g., FIGS. **12-14**).

The above power tools (e.g., power tools **200**, **250**, **270**, and **300**) are described as cordless, battery-powered tools. The battery packs, such as battery pack **301**, used to power these power tools may be, for instance, 18 volt lithium ion type battery packs, although battery packs with other battery chemistries, shapes, voltage levels, etc. may be used in other embodiments. In some embodiments, these power tools are corded, AC-powered tools. For instance, in place of the battery interface **114** and battery pack, the power tools include an AC power cord coupled to a transformer block to condition and transform the AC power for use by the components of the power tools. These AC-powered tools may also include one of the above-described layouts including one of the combined surfboard PCB layouts and doughnut PCB layouts.

FIGS. **23**A and B illustrate an alternate brushless motor configuration **399** that may be used in place of the configuration shown in, for instance, FIGS. **15** and **22**A-C. The brushless motor configuration **399** includes a metal end piece **400** and a tabbed end piece **402** on opposite ends of the motor **126**. The metal end piece **400** and tabbed end piece **402** are more clearly illustrated in FIGS. **24**C and **24**A, respectively. The metal end piece **400** and tabbed end piece **402** have a generally ring-like shape. In the brushless motor configuration **399**, the metal end piece **400** is used in place of the plastic end cap **332** shown in FIG. **19**A. The plastic material of the plastic end cap **332** may be subject to deformation or movement at elevated temperatures when the motor **126** is in operation. The movement can include relative movement between the PCB **302** and motor coils, which can lead to an increased risk of fracture to leads **336**.

Use of the metal end piece **400** enables a rigid connection of the PCB **302** to the motor **126**. The metal end piece **400** and heat sink **306** include through-holes **404** and **405**, respectively, for receipt of threaded fasteners **406**, which secure the stator **330** and tabbed end piece **402** therebetween. The threaded fasteners **406** may be thread-forming screws. The heat sink **306** is coupled to the metal end piece **400** via the threaded fasteners **406** to clamp the brushless DC motor between the heat sink **306** and the metal end piece **400**, thereby rigidly coupling the heat sink **306** to the motor **126**. The PCB **302** is rigidly coupled to the heat sink **306** via screws **408**; thus, rigidly coupling the heat sink **306** to the brushless DC motor **126** rigidly couples the PCB **302** to the motor **126**.

In some embodiments, the threaded fastener **406** is secured to the metal end piece **400** with a nut or the like. The motor configuration **399** includes four through-holes **404** and fasteners **406** spread apart by approximately 90 degrees along the circumference of the motor **126**. The PCB **302** is coupled to the heat sink **306** via six screws **408** spaced apart by approximately 60 degrees. The heat sink **306** is annular and includes six through-holes **410** for receiving screws **408**, as shown in greater detail in FIG. **24**D. The motor **126** has an axial length **409**, and the threaded fasteners **406** extend the axial length **409** along the outer circumference of the motor **126**.

The brushless motor configuration **399** also includes the wire crossover design as described with reference to FIG. **20**. For instance, the brushless motor configuration **399** includes an end cap **407** having the ledge portion **348**, tab portions **349**, and wrapped wires **346**. At no point are more than two wires stacked at the same circumferential position along the ledge portion **348**. The end cap **407** is more clearly illustrated in FIG. **24**B and FIGS. **25**A-B. The end cap **407** includes two locator tabs **450** that are received in two respective recesses **452** of the metal end piece **400**. The locator tabs **450** each further include a snap tab **454** extending over the outer circumference of the metal end piece **400** in the axial direction of the motor **126**, and then radially inward (i.e., towards the motor shaft). The radially inward portion of the snap tab **454** resides in a channel **456** on the outer circumference of the motor **126** (see FIGS. **23**A-B). The snap tab **454** flexes radially outward to allow axial insertion of the metal end piece **400** into an annular recess **458** of the end cap **407**. Once the metal end piece **400** is axially inserted, the snap tab **454** returns to the radially inward position to securely couple the end cap **407** to the metal end piece **400** (see FIG. **25**A).

As shown in FIG. **24**A, the tabbed end piece **402** (also referred to as a second end cap) includes wire support tabs **412**. The wire support tabs **412** provide strain relief to reduce the stress on the leads **336** and, thereby, reduce the risk of damage or breakage of the leads **336**. The leads **336** are wrapped around the wire support tabs **412** before reaching the soldering contact points (solder joints **345**) on the PCB **302**. The wire support tabs **412** extend axially toward the PCB **302** from outer circumferential points of the tabbed end piece **402**. The wire support tabs **412** include channels **414** for receiving the leads **336**. After passing through one of the channels **414**, the lead **336** is bent at an approximately ninety degree angle toward the soldering contact points on the PCB **302** (see FIG. **23**A). The motor configuration **399** includes three sets of wire support tabs **412**, one tab **412** per lead **336**, spread around the tabbed end piece **402**. The wire support tabs **412** are spaced apart by approximately 120 degrees along the circumference of the tabbed end piece **402**.

Thus, the invention provides, among other things, a layout design and assembly of brushless power tools. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

**1**. A power tool comprising:

a housing;

a brushless direct current (DC) motor within the housing, wherein the brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output;

an annular metal end piece positioned at a first end of the brushless DC motor;

an end cap positioned over the annular metal end piece at the first end of the brushless DC motor;

a heat sink positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece, wherein the heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor; and

a printed circuit board (PCB) positioned at the second end of the brushless DC motor and secured to the heat sink.

**2**. The power tool of claim **1**, wherein the PCB includes a Hall sensor, power switching elements, and a through-hole through which the motor shaft extends.

**3**. The power tool of claim **2**, further comprising a control PCB having a motor control unit communicatively coupled to

the Hall sensor to receive motor positional information from the Hall sensor, and

the power switching elements to send control signals to the power switching elements to drive the brushless DC motor.

**4**. The power tool of claim **1**, wherein the heat sink is annular.

**5**. The power tool of claim **1**, further comprising fastening elements that secure the heat sink to the annular metal end piece, wherein the brushless DC motor has an axial length, and the fastening elements extend the axial length of the brushless DC motor.

**6**. The power tool of claim **1**, further comprising a fastening element that secures the heat sink to the annular metal end piece, wherein the fastening element is received by a through hole of the heat sink and by a through hole of the annular metal end piece.

**7**. The power tool of claim **1**, wherein the metal end piece includes a recess and the end cap includes a locator tab configured to fit in the recess and thereby align the end cap and the metal end piece.

**8**. The power tool of claim **7**, wherein the locator tab further includes a snap tab to secure the end cap to the metal end piece, the snap tab extending axially over the metal end piece and then radially inward.

**9**. A power tool comprising:

a housing;

a brushless direct current (DC) motor within the housing, wherein the brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output;

an annular metal end piece positioned at a first end of the brushless DC motor;

a heat sink positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece, wherein the heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor;

a printed circuit board (PCB) positioned at the second end of the brushless DC motor and secured to the heat sink; and

an end cap having an annular recess facing the brushless DC motor and in which the annular metal end piece is received.

**10**. A power tool comprising:

a housing;

a brushless direct current (DC) motor within the housing, wherein the brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output;

an annular metal end piece positioned at a first end of the brushless DC motor;

a heat sink positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece, wherein the heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor;

a printed circuit board (PCB) positioned at the second end of the brushless DC motor and secured to the heat sink; and

a second end cap positioned between the heat sink and the second end of the brushless DC motor.

**11**. The power tool of claim **10**, the second end cap including wire support tabs, each wire support tab having a channel that guides a portion of a motor lead wire extending to the PCB.

**12**. The power tool of claim **10**, wherein a motor lead wire is received in a channel of a wire support tab of the second end cap, extends along the channel in a first direction, and is bent at an exit of the channel to extend in a second direction toward the PCB.

**13**. A power tool comprising:

a housing;

a brushless direct current (DC) motor within the housing, wherein the brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output;

an annular metal end piece positioned at a first end of the brushless DC motor;

a heat sink positioned at a second end of the brushless DC motor opposite the first end, wherein the brushless DC motor is positioned between the heat sink and the annular metal end piece;

threaded fastening elements securing the heat sink to the annular metal end piece, wherein the brushless DC motor has an axial length, and the threaded fastening elements extend the axial length of the brushless DC motor;

a printed circuit board (PCB) positioned at the second end of the brushless DC motor and secured to the heat sink, wherein the PCB includes a Hall sensor, power switching elements, and a through-hole through which the motor shaft extends; and

a second end cap positioned between the heat sink and the second end of the brushless DC motor.

**14**. The power tool of claim **13**, the second end cap including wire support tabs, each wire support tab having a channel that guides a portion of a motor lead wire extending to the PCB.

15. The power tool of claim 13, wherein the heat sink include a shaft through-hole through which the motor shaft extends.

16. A power tool comprising:

a housing;

a brushless direct current (DC) motor within the housing, wherein the brushless DC motor includes a rotor and a stator, wherein the rotor is coupled to a motor shaft to produce a rotational output;

an annular metal end piece positioned at a first end of the brushless DC motor;

an end cap positioned over and secured to the annular metal end piece at the first end of the brushless DC motor;

a heat sink positioned at a second end of the brushless DC motor opposite the first end such that the brushless DC motor is between the heat sink and the annular metal end piece, wherein the heat sink and the annular metal end piece are secured together to clamp the brushless DC motor, thereby rigidly coupling the heat sink to the brushless DC motor;

threaded fastening elements that secure the heat sink to the annular metal end piece, wherein the brushless DC motor has an axial length, and the fastening elements extend the axial length of the brushless DC motor; and

a printed circuit board (PCB) positioned at the second end of the brushless DC motor and secured to the heat sink, wherein the PCB includes a Hall sensor, power switching elements, and a through-hole through which the motor shaft extends.

17. The power tool of claim 16, further comprising a second end cap positioned between the heat sink and the second end of the brushless DC motor.

18. The power tool of claim 17, the second end cap including wire support tabs, each wire support tab having a channel that guides a portion of a motor lead wire extending to the PCB.

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