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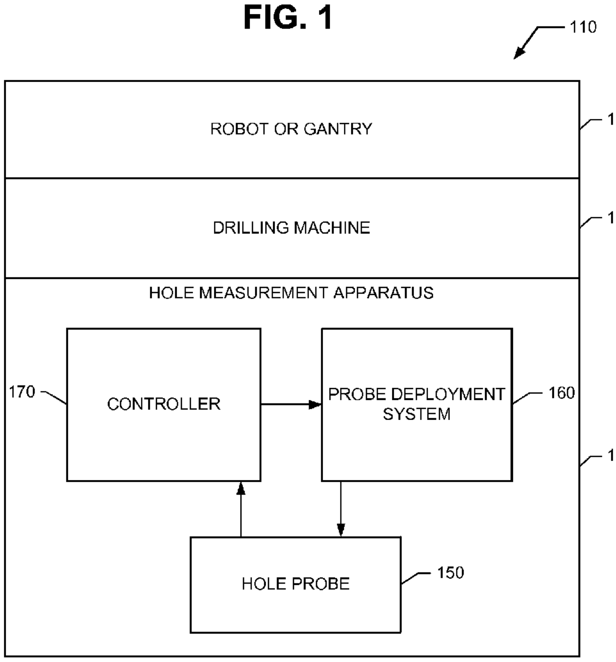
[Continued on next page]

(54) **Title**: DRILLING MACHINE HAVING HOLE MEASUREMENT CAPABILITY

FIG. 1



(57) **Abstract**: A system comprises a drilling machine; a capacitive probe; and a probe deployment system, mounted to the drilling machine, for moving the capacitive probe inside a hole drilled by the machine to measure the drilled hole at different depths.

WO 2012/154319 A2

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— *as to the identity of the inventor (Rule 4.17(i))*

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

DRILLING MACHINE HAVING HOLE MEASUREMENT CAPABILITY

BACKGROUND

During manufacture of a commercial aircraft, hundreds of thousands of precisely located, straight holes may be drilled. These holes are drilled by robotic systems that include drilling end effectors.

After a group of holes has been drilled, the drilled holes are inspected to ensure that they are within tolerance. The inspection does not simply involve checking a single hole diameter. Rather, the inspection involves checking the diameter and circularity of each hole at different depths to ensure that each hole is straight (and not conical or hourglass-shaped). Typically, the inspection is performed by a quality assurance (QA) inspector, who inspects large groups of holes at one time.

Consider a situation where a drill bit becomes chipped while drilling a hole. Due to the chipped bit, the drilled hole is out of tolerance. Subsequent holes drilled by the chipped bit are also out of tolerance. Unfortunately, those subsequent out-of-tolerance holes are not identified until QA inspection.

It would be desirable to minimize the number of holes drilled by a damaged bit. More generally, it would be desirable to minimize the number of out-of-tolerance holes.

SUMMARY

According to an aspect herein, a system comprises a drilling machine; a capacitive probe; and a probe deployment system, mounted to the machine, for moving the capacitive probe inside a hole drilled by the machine to measure the drilled hole at different depths.

According to another aspect herein, a system comprises a drilling end effector; a capacitive probe including a rod and a plurality of capacitive sensors about the rod; and a probe deployment system, mounted to the end effector, for moving the capacitive probe inside a hole drilled by the end effector to measure the drilled hole at different depths. The probe deployment system includes an actuator for moving the probe over the drilled hole, and a piezoelectric motor for incrementally moving the probe to different depths in the drilled hole. The system further comprises a control box, mounted to the drilling end effector, for controlling the actuator and the motor and for processing probe data to determine whether the drilled hole is within tolerance.

According to another aspect herein, a hole measurement apparatus comprising a capacitive probe including a rod and a plurality of capacitive sensors about the rod; and a piezoelectric motor for moving the sensors within a hole to measure hole profile.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustration of a system including a drilling machine and a hole measurement apparatus.

FIG. **2** is an illustration of a capacitive probe.

FIGS. **3A** and **3B** are illustrations of a drilling end effector and a hole measurement apparatus.

FIGS. **4A** and **4B** are illustrations of an embodiment of a probe deployment system.

FIG. **5** is an illustration of an embodiment of a control box.

FIGS. **6A–6D** are illustrations of a method of using a drilling end effector and hole measurement apparatus.

DESCRIPTION

Reference is made to FIG. **1**, which shows a system **110** including a drilling machine **120** for making precise holes in a work piece. The system **110** also includes a robot or gantry **130** for moving the drilling machine **120**.

The system **110** further includes hole measurement apparatus **140** including a probe, **150**, probe deployment system **160** and controller **170**. Under control of the controller **170**, the probe deployment system **160** moves the hole probe **150** over a drilled hole and then into the drilled hole. Once the probe **150** is inside the drilled hole, the deployment system **160** may move the probe **150** to different depths of the drilled hole. At each depth, the probe **150** may measure diameter and circularity of the drilled hole. By taking these measurements at the different depths of the drilled hole, a profile of the drilled hole is obtained.

In addition to controlling the deployment system **160**, the controller **170** also processes data from the probe **150**. The processing includes converting the probe data to meaningful dimensional data. The processing may also include determining whether the drilled hole is within tolerance. In some embodiments, the controller **170** may send a report to the robot or gantry **130**, the report indicating whether the drilled hole is within tolerance. In other embodiments, the controller **170** may report the hole measurements (e.g., diameter and circularity at each depth) to the robot or gantry **130**. Reporting the hole measurements offers certain benefits, which will be discussed below in connection with FIG. **5**.

Additional reference is made to FIG. **2**, which shows an embodiment of a hole probe **150**. The embodiment of FIG. **2** is a capacitive probe **210** having capacitor sensors **220** mounted radially on a non-conducting cylinder **230**. Although four capacitor sensors **220** are illustrated, other numbers of capacitor sensors **220** may be used.

In some embodiments, the probe deployment system **160** may include a piezoelectric motor (not shown) for incrementally moving the probe **210** to different depths within a drilled hole. The piezoelectric motor may be accurate to within 0.1 microns. The probe deployment system **160** may further include a miniature actuator (e.g., an air cylinder, linear motor, hydraulic cylinder) for moving the probe **210** over a drilled hole.

The combination of the capacitive probe **210** and the piezoelectric motor results in a hole measurement apparatus **140** that is very small in size. In some embodiments, the capacitive probe **210** has a height of approximately one inch and a diameter of approximately one inch. The piezoelectric motor may have a height of less than two inches.

The small size allows the hole measurement apparatus **140** to be mounted to the drilling machine **120** in a location that allows each hole to be measured immediately after drilling. Inspecting each hole after drilling is highly advantageous. It allows problems such as worn and chipped drill bits to be identified immediately, and prevents subsequent holes from being drilled with such drill bits.

Reference is made to FIGS. **3A** and **3B**, which illustrate one type of drilling machine: a drilling end effector **310**. The drilling end effector **310** includes a pressure foot **312** for holding a work piece or clamping together two or more work pieces. The drilling end effector **310** further includes a drill bit **314** for drilling a hole in the work pieces(s). During drilling, the drill bit **314** is moved through a passageway in the pressure foot **312** and bears down on the work piece(s).

FIGS. **3A** and **3B** also illustrate a hole measurement apparatus including a capacitive probe **320** and a probe deployment system **330**. In one particular embodiment, the drill bit **314** drills a hole between 0.190 to 0.192 inches. The probe **320** has a diameter of 0.175 inches. If the probe **320** touches the inside of the hole, there will be a minimum of about 0.015 inches of clearance.

FIGS. **4A** and **4B** show a close up view of the probe deployment system **330**. In particular, FIGS. **4A** and **4B** show how the probe **320** is moved from a home position outside of the pressure foot **312**, to a deployed position inside the pressure foot **312** and over a drilled hole.

FIG. **4A** shows the probe in the home position. The probe **320** is attached to a probe arm **412** by a flexible mount **410**. A calibration ring mount **414** holds a calibrated ring gage **416**. The calibration ring gauge **416** has an opening with a precise diameter, which is used to calibrate the probe **320**. A first limit switch **418** indicates when the arm **412** is positioned such that the probe **320** is completely out of the pressure foot **312** and under the calibration ring gauge **416**.

The probe **320** is deployed by turning on a solenoid valve (not shown) to actuate an air cylinder **420**, causing the probe arm **412** to swing and move the probe **320** through an access door **422** and it into the pressure foot **312**. Shock absorbers **424** reduce the abrupt shock of stopping the probe arm **412** over a short distance. The shock absorbers **424** also function as stops for accurately positioning the probe **320**. A second limit switch **426** indicates an arm position where the probe **320** is inside the pressure foot **312**.

FIG. **4A** also shows a piezoelectric linear motor **428**, which moves the probe **320** over different depths of a drilled hole. The piezoelectric linear motor **428** may be operated using high frequency pulses. These high frequency pulses are tuned to the piezoelectric crystal frequency, which results in maximum linear displacement.

FIG. **4B** shows the probe **320** in the deployed position. Once in the deployed position, the controller **170** controls the piezoelectric linear motor **428** and its platform **450** to position the probe **320** in the drilled hole. A probe stop collar **452** may be used to adjust the depth that the probe **320** goes into the drilled hole.

The flexibility of the mount **412** is beneficial in situations where the probe **320** contacts the inside wall of a hole. If contact occurs, the probe **320** will move toward the center of the hole, but will still be in contact with the hole wall. In this situation, accurate hole diameter information can still be obtained.

Reference is once again to FIG. **3A**. The hole measurement apparatus further includes a control box **340**. The control box **340** includes the controller **170**.

Additional reference is made to FIG. **5**, which illustrates an embodiment of the control box **340**. The control box **340** includes a first circuit board **510** that can condition the capacitive probe, and convert capacitance signals obtained by the capacitor sensors **220** to a voltage signal (where the voltage is proportional to the distance between the hole probe radius and the hole radius). The first circuit board **510** also computes the diameter and circularity of the hole at different depths, and determines whether the hole is within the tolerance.

The first circuit board **510** monitors all limit switches **418** and **426** to assure the probe **320** is in a known position. The first circuit board **510** also controls the probe deployment system by generating signals that actuate the air cylinder solenoid, and also by supplying signals to a piezoelectric motor driver (not shown), which is on a second circuit board **520**. The piezoelectric motor driver generates the high frequency pulses that drive the piezoelectric linear motor **428**.

The control box **340** also continuously monitors gap dimensions for the purpose of adjusting probe concentricity with the drilled hole and the ring gage hole.

The control box **340** has input and output ports for communicating with the robot or gantry **130**. The control box **340** may have a data port (e.g., a serial port) for accepting user inputs as well as outputting diagnostics and other information. For instance, the control box **340** can output hole measurement data for post processing.

The post processing may be used to perform drill life estimates. Typically, drills are automatically replaced according to a fixed schedule (e.g., after drilling a set number of holes). By monitoring the hole diameter and instead replacing drills at the end of their lives (e.g., when wear or damage is apparent), fewer drills are replaced. Consequently, time and money are saved.

As shown in FIG. **3A**, the control box **340** and other hole measurement apparatus are mounted to the drilling end effector **310**. This makes for a standalone unit. All functionality is contained and controlled within the unit. All that is needed is power and a signal to perform a drill hole measurement. A robot technician does not have to know how to operate the unit. The unit is little more than a "black box."

Moreover, if the unit is moved from one robot to another, all functionality goes with it. Deployment control and probe signal processing do not have to be changed each time the unit is moved.

FIGS. **6A**–**6D** illustrate the operation of a drilling end effector **310** and hole measurement apparatus. Referring first to FIG. **6A**, the drilling end effector **310** is commanded to drill a hole in a work piece (block **610**). After the hole has been drilled and the drill bit **314** has been withdrawn from both the hole and the pressure foot, the hole measurement apparatus is commanded to determine whether the drilled hole is within tolerance (block **612**).

Referring to FIG. **6B**, the control box **340** commands the air cylinder to move the probe **320** over the drilled hole (block **620**), and it then commands the piezoelectric motor **428** to deploy the probe **320** into the drilled hole (block **622**). The probe **320** is positioned at the bottom of the hole, by pushing the probe **320** until the probe stop **452** contacts the top surface of the work piece. Here a first diameter measurement is made. Gaps between the probe **320** and the wall of the drilled hole are measured by each of the capacitor sensors **220** (block **624**). The control box **340** then commands the piezoelectric motor to withdraw the probe **320** from the hole (block **626**).

Adjustments are made to equalize all of the gaps (block **628**). Two concentric adjustments and two angle adjustments may be made to the probe **320** so that the probe **320** is concentric with the hole and is aligned with the hole.

Referring now to FIG. **6C**, the probe **320** measures the hole. The piezoelectric motor **428** is commanded to move the probe **320** to the bottom of the drilled hole (block **630**). The control box **340** uses the hole probe data to compute the hole diameter and circularity at that level (block **632**). For example, the control box **340** stores a table of calibration factors that relate voltage to gap distance. When a gap voltage is measured, the calibration table is searched to locate the two voltages that bracket the measured voltage. The associated gap distance is determined by interpolating between the two voltages. All four gaps are computed in this manner. Then, taking into account each sensor (arc length and width) and the eccentricity of the inserted probe and inside wall of the hole, the diameter is computed.

The probe is incrementally moved to another depth, where the diameter and circularity are again computed (block **632**). After the probe has been moved to the last depth, and after hole diameter and circularity are computed for that last depth, the hole measurements may be repeated (block **634**). After all measurements have been made, the control box **340** determines whether the drilled hole is within specification (block **636**). A report may be sent to the robot (block **638**).

At various times, the probe **320** may be calibrated. The probe **320** may be calibrated before a drilled hole is measured, and it may be calibrated during a hole measurement. For instance, after every three sets of measurements have been made, the probe **320** may be calibrated.

Reference is made to FIG. **6D**, which illustrates a method for calibrating the probe **320**. The probe deployment mechanism is commanded to move the probe **320** to the home position and deploy the probe into the ring gauge **416** (block **640**). The diameter and circularity of the ring gauge **416** are measured (block **642**). If the measured diameter is not within tolerance, the calibration factor is either incremented or decremented (block **644**). The functions at blocks **642** and **644** are repeated until the measured diameter of the calibration gauge falls within tolerance.

In some embodiments, a measurement at only a single depth of a countersunk hole may be performed. For example, a probe may be designed with a cone-shaped base. When the cone-shaped base is inserted into a countersunk hole, the countersunk diameter is measured.

CLAIMS

1. A system comprising:

a drilling machine;

a capacitive probe; and

a probe deployment system, mounted to the machine, for moving the capacitive probe inside a hole drilled by the machine to measure the drilled hole at different depths.

2. The system of claim 1 wherein the probe deployment system includes a piezoelectric motor for incrementally moving the probe within drilled hole.

3. The system of any preceding claim wherein the probe deployment system further includes an actuator for moving the probe from a home position to a deployed position over the drilled hole.

4. The system of any preceding claim wherein the drilling machine includes a pressure foot having a drill passageway; and wherein the probe deployment system includes an arm for swinging the probe from a home position outside of the pressure foot to a deployed position within the pressure foot.

5. The system of claim 4 wherein the probe is attached to the arm by a flexible mount.

6. The system of any preceding claim wherein the probe deployment system further includes shock absorbers and limit switches, the shock absorbers reducing abrupt shock of stopping the arm, the shock absorbers and the limit switches accurately positioning the probe.

7. The system of any preceding claim wherein the drilling machine includes a drilling end effector; and wherein the system further comprises a robot or gantry for moving the end effector; and a control box, mounted on the drilling end effector, for controlling the probe deployment system, processing probe data, and communicating the processed data with the robot or gantry.

8. The system of any preceding claim further comprising a ring gauge mounted to the drilling machine, the ring gauge having a calibration opening for calibrating the probe.

9. A method comprising using the system of any preceding claim to drill a hole in a work piece and measure the drilled hole immediately after drilling.

10. The method of claim 9 further comprising reporting hole measurement data for post-processing, wherein the post-processing includes performing drill life estimates.

11. The method of claim 9 or 10 wherein measuring the drilled hole includes using gap dimensions between the probe and a wall of the drilled hole for adjusting probe concentricity with both the drilled hole.

12. Apparatus comprising:

a drilling end effector;

a capacitive probe including a rod and a plurality of capacitive sensors about the rod;

a probe deployment system, mounted to the end effector, for moving the capacitive probe inside a hole drilled by the end effector to measure the drilled hole at different depths, the probe deployment system including an actuator for moving the probe over the drilled hole, and a piezoelectric motor for incrementally moving the probe to different depths in the drilled hole; and

a control box, mounted to the drilling end effector, for controlling the actuator and the motor and for processing a probe output to determine whether the drilled hole is within tolerance.

13. The apparatus of claim 12 further comprising a calibration ring gauge mounted to the drilling end effector, the ring gauge having a calibration opening for calibrating the probe.

14. The apparatus of claim 12 or 13 wherein the drilling end effector includes a pressure foot having a drill passageway; and wherein the probe deployment system includes an arm for swinging the probe from a home position outside of the pressure foot to a deployed position within the drill passageway, the arm moved by the actuator.

15. The apparatus of claim 14 wherein the probe is attached to the arm by a flexible mount.

16. The apparatus of any claim 12–15 wherein the probe deployment system further includes shock absorbers for reducing abrupt shock of stopping the arm and also accurately positioning the probe.

17. A hole measurement apparatus comprising:

a capacitive probe including a rod and a plurality of capacitive sensors about the rod; and

a piezoelectric motor for moving the sensors within a hole to measure hole profile.

18. The apparatus of claim 17 further comprising a ring gauge having a calibration opening for calibrating the probe.

19. The apparatus of claim 17 or 18 further comprising an arm, mounted to an end effector having a pressure foot, for swinging the probe from a home position outside of the pressure foot to a deployed position within the pressure foot.

20. The apparatus of claim19 wherein the probe is attached to the arm by a flexible mount.

FIG. 1

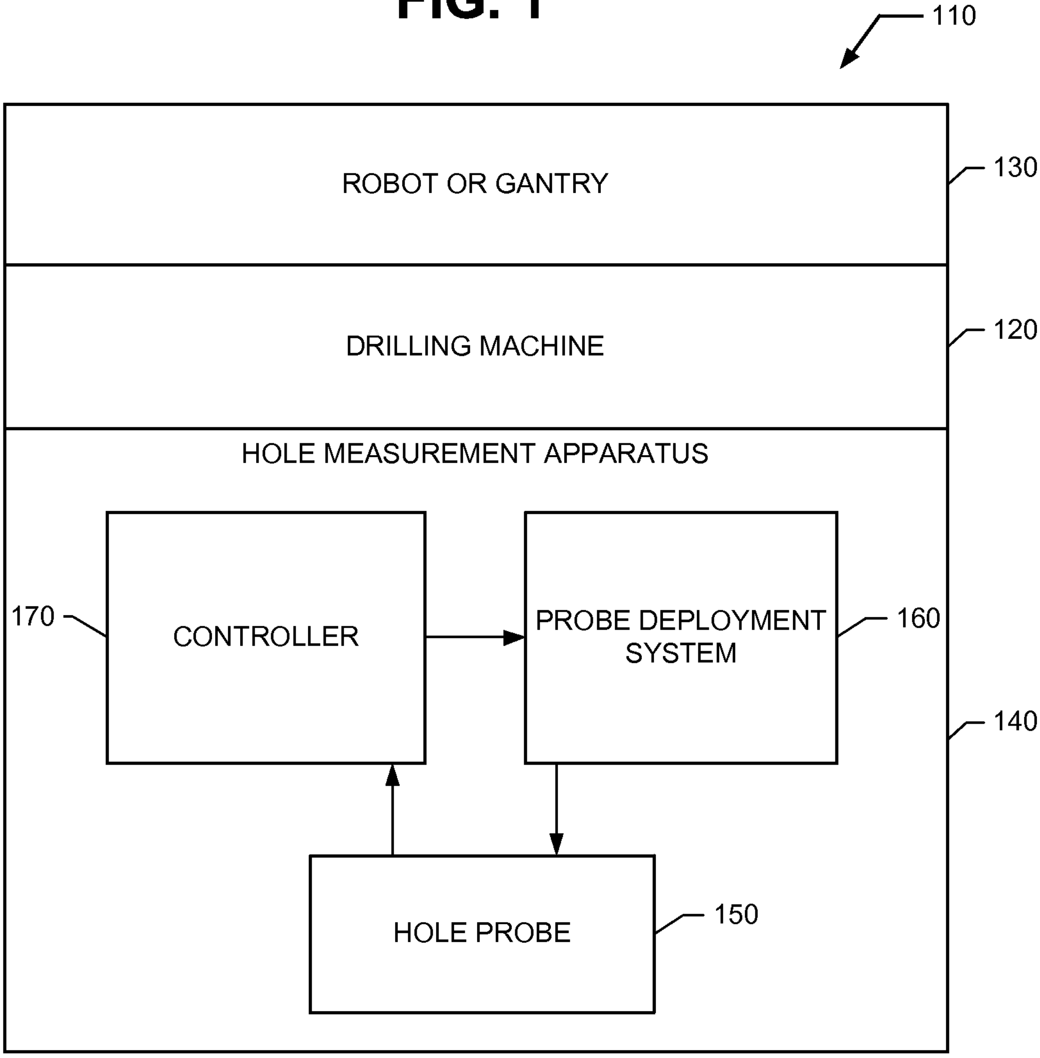

110
ROBOT OR GANTRY
130
DRILLING MACHINE
120
HOLE MEASUREMENT APPARATUS
170
CONTROLLER
PROBE DEPLOYMENT SYSTEM
160
140
HOLE PROBE
150

FIG. 2

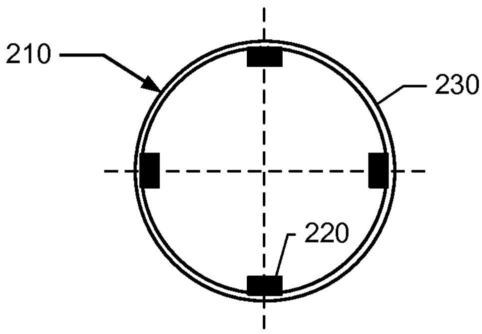
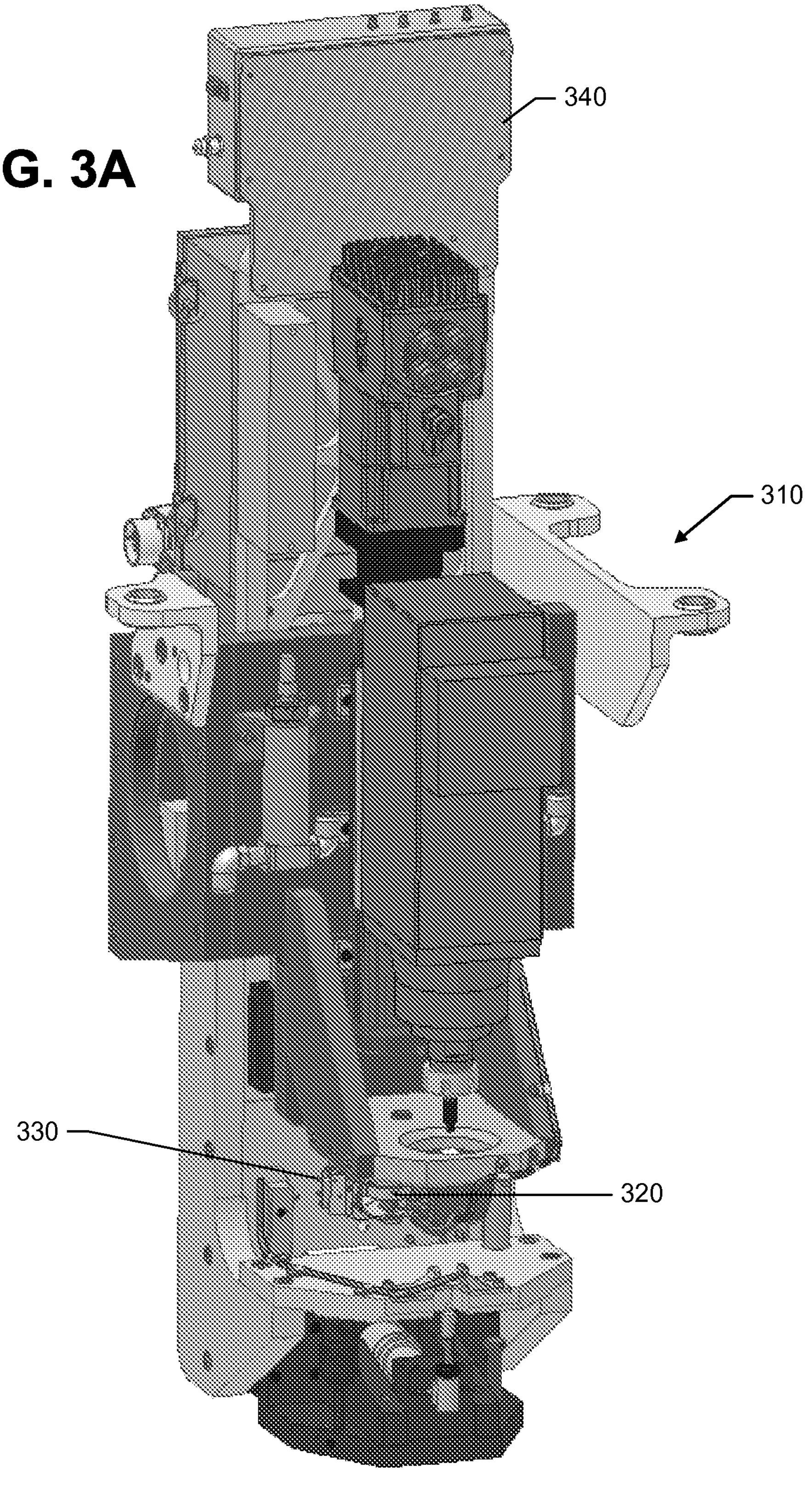

210
230
220

FIG. 3A



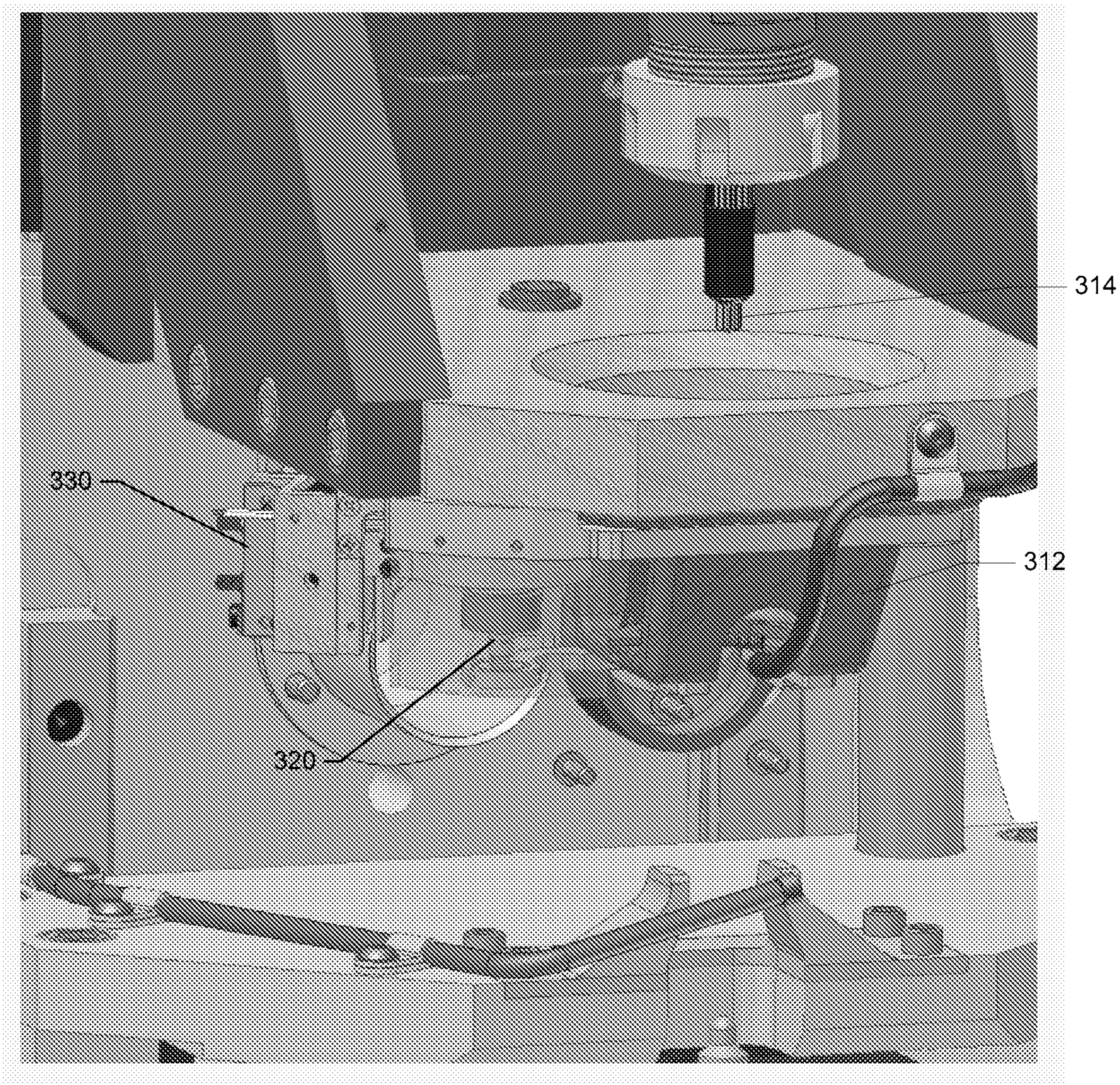


FIG. 3B

FIG. 4A

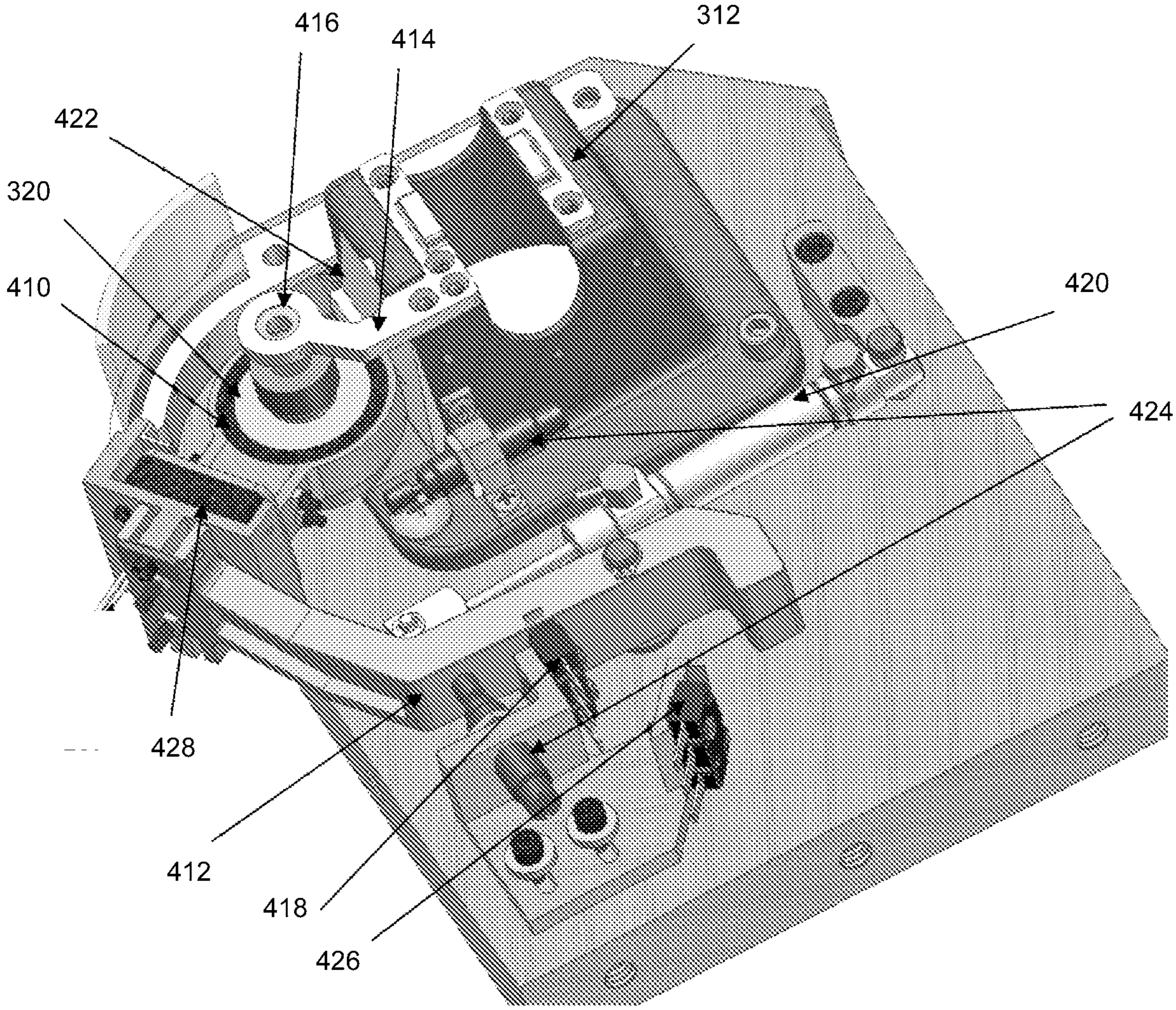


FIG. 4B

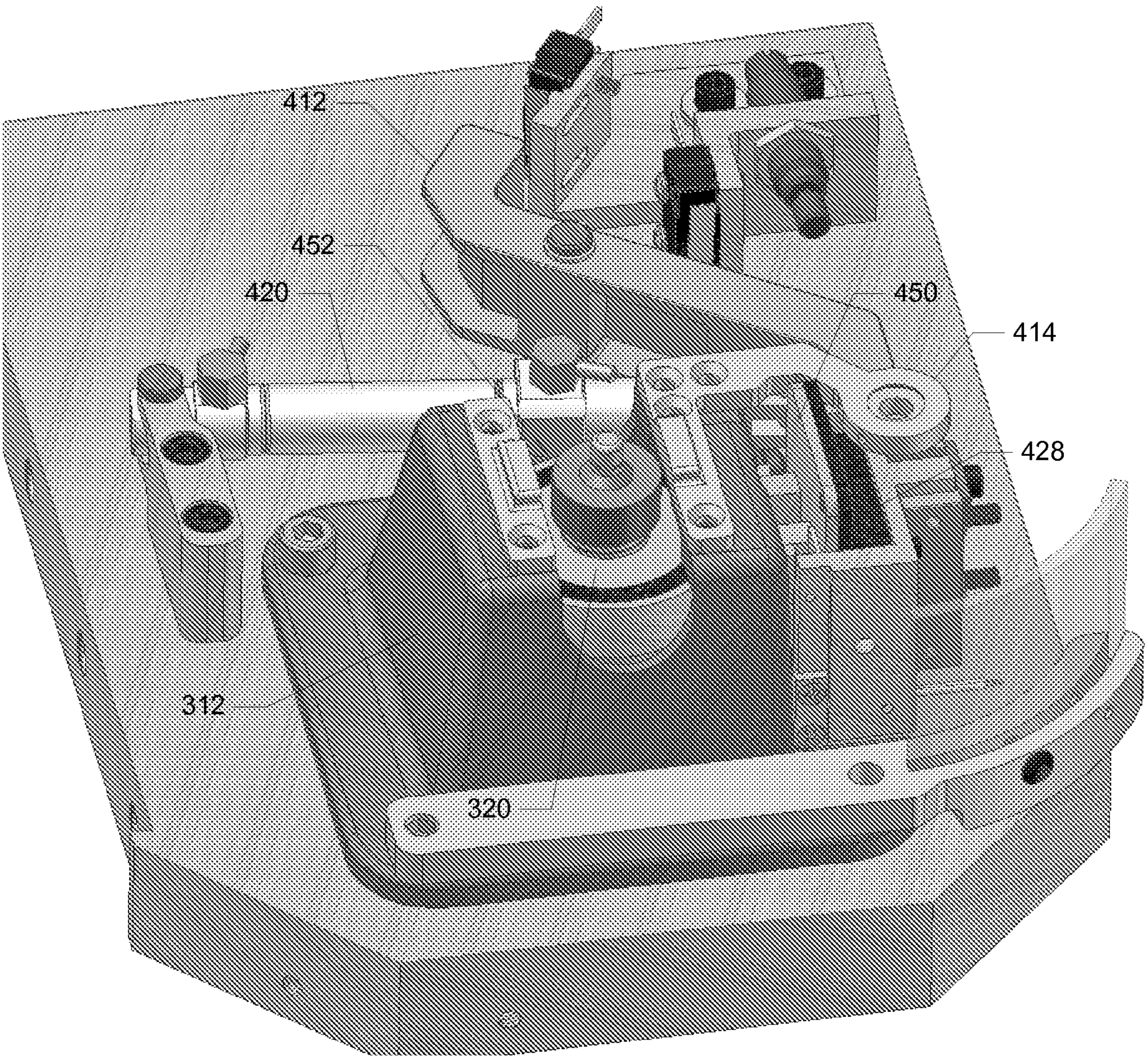


FIG. 5

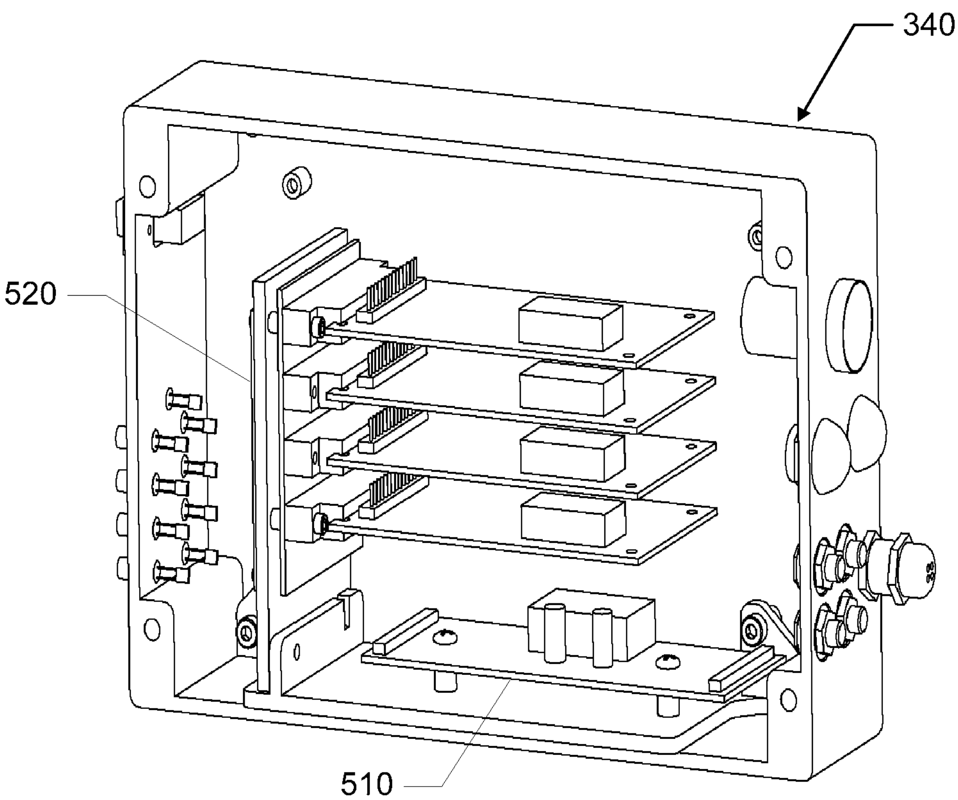


FIG. 6A

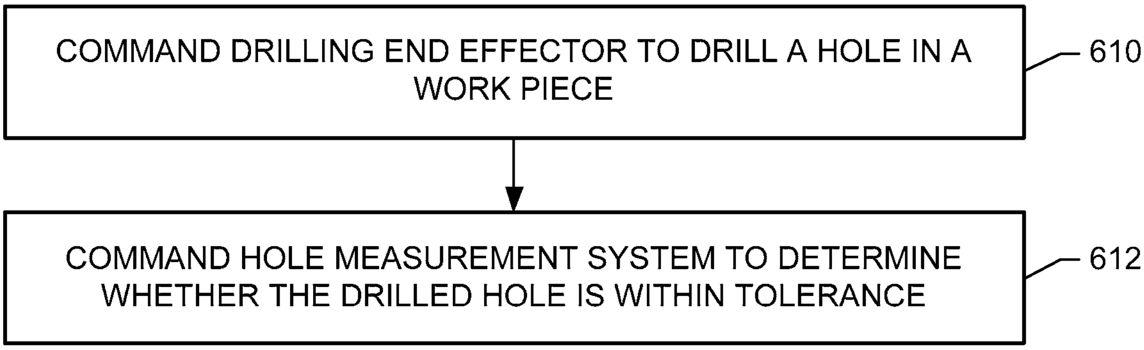

COMMAND DRILLING END EFFECTOR TO DRILL A HOLE IN A WORK PIECE
610
COMMAND HOLE MEASUREMENT SYSTEM TO DETERMINE WHETHER THE DRILLED HOLE IS WITHIN TOLERANCE
612

FIG. 6B

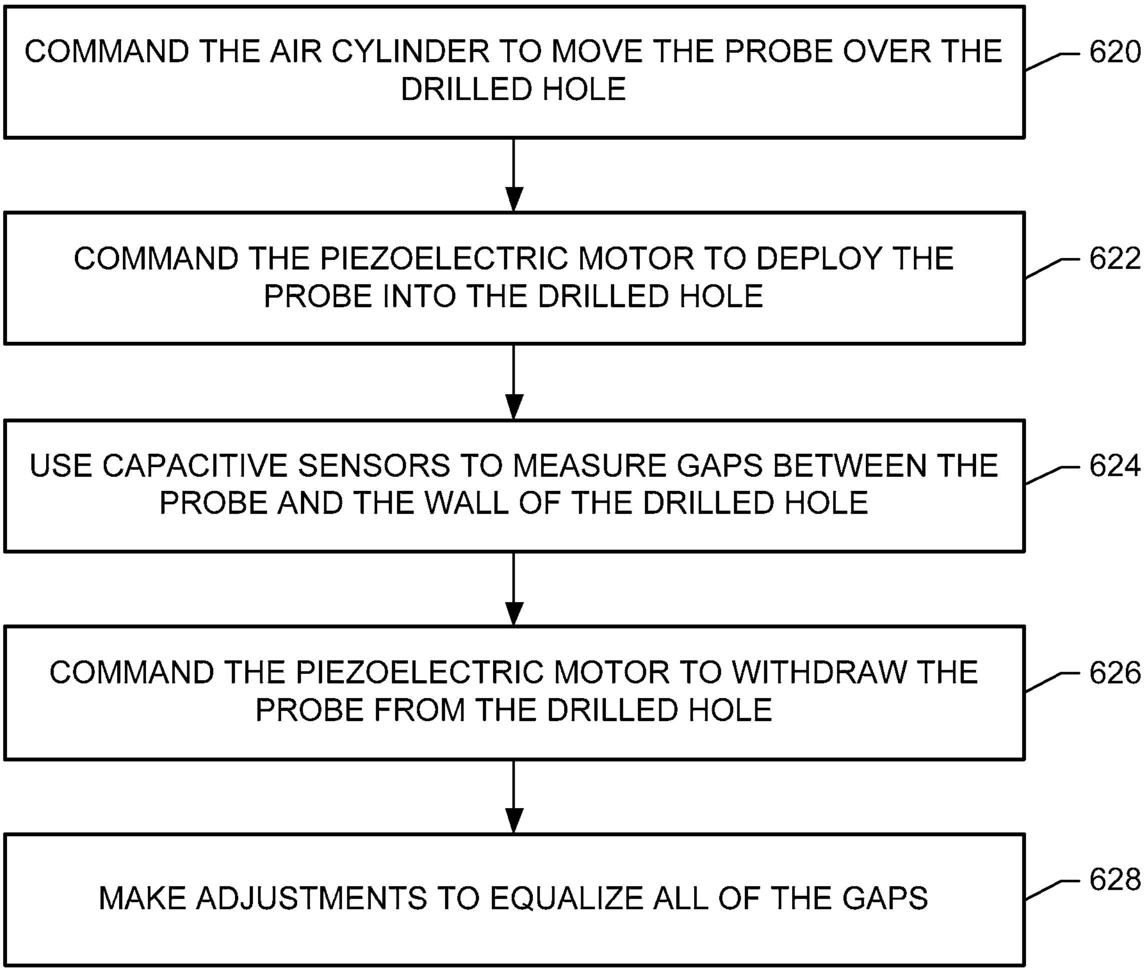

COMMAND THE AIR CYLINDER TO MOVE THE PROBE OVER THE DRILLED HOLE
620
COMMAND THE PIEZOELECTRIC MOTOR TO DEPLOY THE PROBE INTO THE DRILLED HOLE
622
USE CAPACITIVE SENSORS TO MEASURE GAPS BETWEEN THE PROBE AND THE WALL OF THE DRILLED HOLE
624
COMMAND THE PIEZOELECTRIC MOTOR TO WITHDRAW THE PROBE FROM THE DRILLED HOLE
626
MAKE ADJUSTMENTS TO EQUALIZE ALL OF THE GAPS
628

FIG. 6C

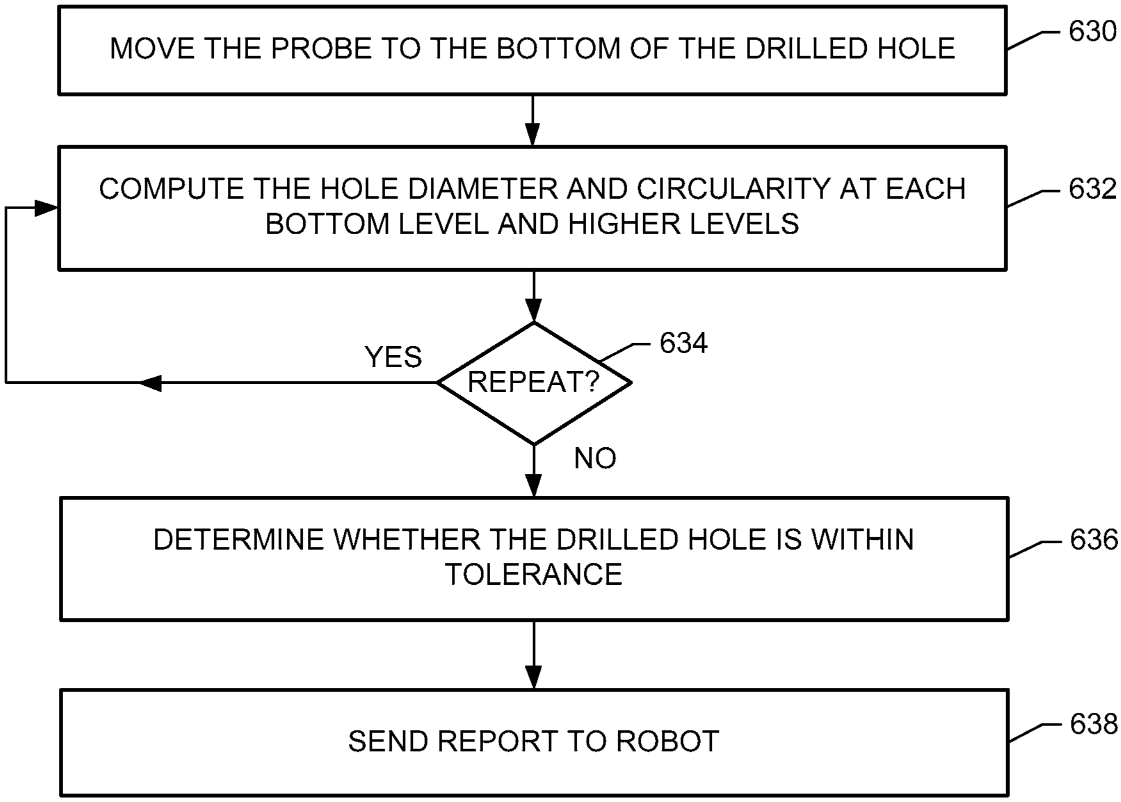
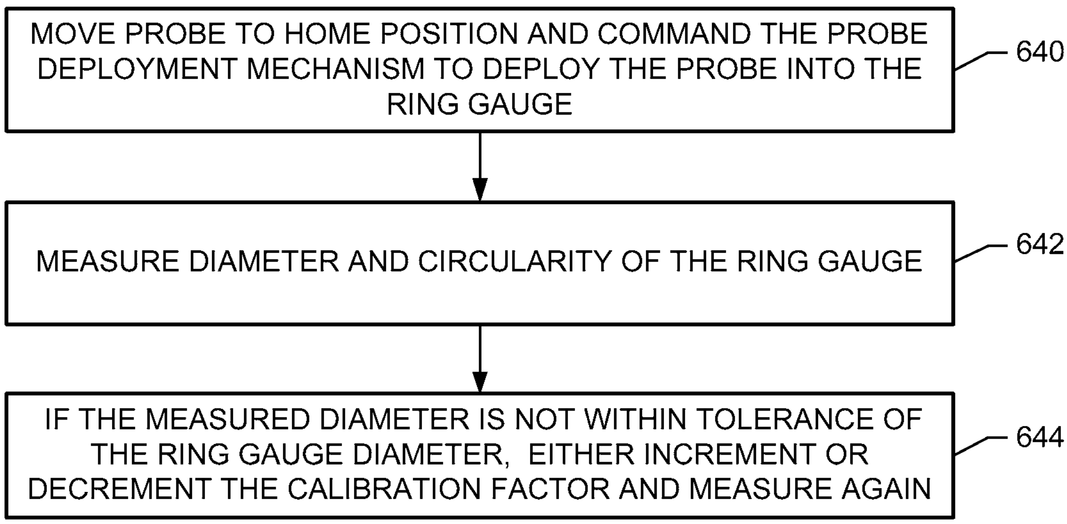

MOVE THE PROBE TO THE BOTTOM OF THE DRILLED HOLE
630
COMPUTE THE HOLE DIAMETER AND CIRCULARITY AT EACH BOTTOM LEVEL AND HIGHER LEVELS
632
YES
REPEAT?
634
NO
DETERMINE WHETHER THE DRILLED HOLE IS WITHIN TOLERANCE
636
SEND REPORT TO ROBOT
638

FIG. 6D


MOVE PROBE TO HOME POSITION AND COMMAND THE PROBE DEPLOYMENT MECHANISM TO DEPLOY THE PROBE INTO THE RING GAUGE
640
MEASURE DIAMETER AND CIRCULARITY OF THE RING GAUGE
642
IF THE MEASURED DIAMETER IS NOT WITHIN TOLERANCE OF THE RING GAUGE DIAMETER, EITHER INCREMENT OR DECREMENT THE CALIBRATION FACTOR AND MEASURE AGAIN
644