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(54) Title: APPARATUS FOR AUTOMATED POSITIONING OF EDDY CURRENT TEST PROBE

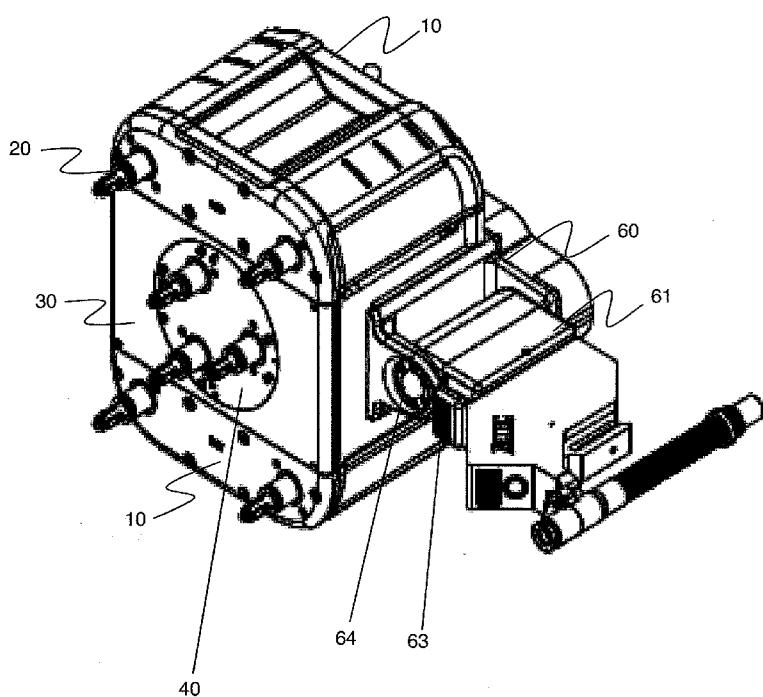


Figure 1

(57) Abstract: An apparatus for automated inspection and repair of a tube sheet. The apparatus has a rotating gripper pod, comprising at least one tube gripper, a sliding body portion containing the gripper pod; a housing portion comprising at least one tube gripper and a tool head coupling. The tool head coupling swappably attaches to an eddy current test probe and at least one kind of tube repair tool. Novel, auto-locking tube grippers are also disclosed. A serial bus connects electronic modules within the apparatus and also connects the apparatus to an external controller.



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## APPARATUS FOR AUTOMATED POSITIONING OF EDDY CURRENT TEST PROBE

### CROSS-REFERENCE TO RELATED APPLICATIONS

This PCT application claims priority to and the benefit under U.S.C. §119(e) of U.S. Provisional Application No. 61/145,629, filed January 19, 2009, for all matter common to both applications. The disclosure of said provisional application is hereby incorporated by reference in its entirety.

### SPECIFICATION

#### BACKGROUND OF THE INVENTION

Regular inspection and testing of steam generator tube sheets is critical to the operation of a steam generator plant. Tube sheets are arrays of parallel tubes that can be accessed at at least one end wherein the tube ends are arranged in a single plane. Testing of each tube is delicate and time consuming. In the past, this has been done by manually placing testing probes in the tubes. Described herein is an improved automated apparatus for positioning test and repair equipment in a tube sheet for steam generators.

Desirable attributes of such an automated apparatus include: single person fast installation; integrated grab features for handling; protection bumpers ; independent of tube sheet and steam generator features; simplified cable systems and single point cable connection; simplified calibration; ease of decontamination; complete integration with data acquisition systems; fast, accurate performance; and support for repair tooling.

#### FIELD OF INVENTION

The present invention relates to automatic inspection and repair systems and more particularly to a robotic apparatus for positioning an eddy current test probe in an array of steam generator tubes.

#### BRIEF SUMMARY OF THE INVENTION

A robotic tool positioner especially adapted for positioning tooling and testing equipment in a tube array, such as in a steam generator. The tool positioner has several novel features, described herein.

In an embodiment, the tool positioner is adapted to move across the face of a tube sheet of open tubes. The positioner includes: a sliding body portion containing a rotating gripper pod with the rotating gripper pod having at least one tube gripper; left and right outer housing portions having at least one tube gripper each; and a tool head coupler to support various

attachments, including an eddy current test probe, repair and maintenance tools. The sliding body portion moves laterally across the tube sheet with respect to the housing portion. The rotating gripper pod allows the positioner to rotate in an axis perpendicular to the plane of the tube sheet.

The tool head coupler provides for the attachment of test probes and repair and maintenance tools to the sliding body portion. The robot also includes machine vision and machine vision lighting.

In an embodiment, the tube grippers have a pneumatic actuator, at least one gripper shoes and integrated sensors adapted to detect deployment and retraction position. In an embodiment, the sensors are Hall effect sensors. The tube grippers are adapted so that the reactionary force of the tool positioner pulling away from the tube sheet forces the tube gripper shoes against the tube wall. To retract a tube gripper, the gripper head is pushed up into the tube slightly to release pressure on the gripper shoes, which are then retracted by spring-loaded retractors. In an embodiment, the robot electronics, including an on-board microprocessor, are interconnected by a simplified serial network that minimizes interconnection wires between electronic modules within the robot and allows for installation of new modules and interchangeability and updates to existing modules without costly wiring harness changes. The robot is controlled by an external controller that communicates with the robot over the simplified serial network. In an embodiment, the simplified serial network is the industry standard Controller Area Network or “CAN” bus.

#### BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

The invention will be described in conjunction with the following drawings in which like reference numerals designate like elements and wherein:

Figure 1 is an isometric drawing of an exemplary design of an automated positioner;

Figure 2 is an isometric view of a tube gripper head;

Figure 3 is a cross-sectional drawing of an exemplary tube gripper inserted in a tube;

and

Figure 4 is an exploded view of an exemplary tube gripper.

#### DETAILED DESCRIPTION OF THE INVENTION

An inspection and repair robot is disclosed. The design provides a very efficient footprint for moving and repositioning eddy current test probes within a steam generator. The unique motion and small size provide high flexibility in reaching all tubes within the

tube sheet without complex repositioning motions. This provides quick and efficient motion in positioning the robot to a target zone or specific tube. All of this is accomplished at state of the art speed. In an exemplary embodiment, the robot can transverse across the tube sheet at speeds of up to 5 feet per minute for large moves and can achieve tube-to-tube speeds during test or repair operations of up to 4 inches/second. The robot utilizes built-in machine vision for secondary tube verification for all attached tooling.

### **Robot body**

With reference to Figure 1, an exemplary repair and inspection robot has an outer housing 10 comprising four housing grippers 20; a sliding body center 30, comprising a rotating gripper pod 40, which has three grippers 50. The sliding body center 30 also has a tool head interface 60 comprising a tool head lock 61 with a hot shoe (not shown), machine vision lighting 63 and integrated machine vision camera 64. The tool head lock is rotatably attached to the tool head bracket 60. The robot moves across a tube sheet by alternately inserting and locking grippers into the tubes from either the outer housing 10 or the rotating gripper pod 40. It can be seen that when the three central grippers are inserted into tubes, the outer housing can rotate to any angle and translate a limited distance away from the rotating gripper pod via the sliding relationship between the center body and the outer housing. Once the outer housing 10 has repositioned itself with respect to the center body, the tube grippers 20 in the outer housing 10 are inserted into tubes and locked and the tube grippers 50 in the rotating pod 40 are released and withdrawn from the tube sheet. The sliding body is then free to move with respect to the outer housing to engage new tubes. This process is repeated until the housing reaches the required location on the tube sheet.

The configuration of the four outer housing grippers 20 and three rotating pod grippers is designed to support a broad range of square and tri-pitch tube sheet configuration, pitches and patterns. The body is designed to fit through the smallest man-way openings in existing equipment. The controller for the robot is also as small as possible to maximize platform space. A small diameter control cable minimizes cable tangle.

### **Robot Positioning**

In an exemplary embodiment, there is a host computer, which is outside the tube sheet environment. There is also an external controller in the tube sheet environment that communicates with the host computer and with the robot.

The host computer and software plans the robot movements and sends commands to the controller. It is typically remote to the radioactive environment where the robot and controller work. It sends commands through Ethernet to the controller which is external to the robot. The controller communicates to the robot via a power/data cable that carries the CAN communication and power for the devices. The robot has multiple CAN devices for the specific functions. It receives and executes commands directly from the controller.

The controller has communication with both robot and host computer/software.

Sequences for robot moves from one position to another are determined by the host computer and transmitted to the robot external controller.

To make a move the external controller issues a command with arguments for the specific type of the device and an address for the device. For a motion axis, this may include commands for the motor on the axis in the form of rotation in degrees, rotation direction and rotation speed for an axis along with the address on the serial bus for the device.

The host computer software manages the logic of how to move and issues commands to the controller which in turns formats them in to the instructions for the devices described above.

### **Tube Inside Diameter Grippers**

Figure 2 shows an exemplary tube gripper head 100. The gripper head has three gripping shoes 110 that slide along three channels equally spaced around the outside wall of the gripper head. Each channel has an inclined surface 115 that is in contact with the gripper shoe. The inclined surface 115 forces the gripper shoe 110 away from the center of the gripper head when the shoes are pushed up into a tube, in a direction away from the robot body 10. As such, the grippers are self-locking. Once the shoes are forced up into a tube, a force created by air pressure is exerted forcing the gripper bodies away from the tube sheet, thus forcing the shoes against the tube wall. When the robot is below a tube sheet, the weight of the robot pulling down on the gripper head keeps the shoes locked against the tube wall, even if power is removed. When the tube sheet is not horizontal, reactionary force away from the tubes keeps the grippers locked. Any force tending to pull the robot away from the tubes will keep the grippers locked in place. The gripper shoes are withdrawn only by forcibly retracting the shoes while extending the gripper body slightly into the tube wall to aid in pushing the shoes 110 back down the inclined surface 115 and away from the tube wall.

In an embodiment, the friction between the shoe 110 face and the inclined surface 115 is reduced by a friction reduction element (not shown). It is critical to the operation of the gripper

shoes that the friction between the shoe and the inclined surface be controlled so that less force is required to move the shoe across the inclined plane than is required to move the shoe across the tube wall. In an embodiment, a plastic insert is inserted between the shoe 110 and the inclined surface 115.

Figure 3 is a cross section view showing a gripper head inserted in a tube wall 200. A gripper shoe 110 is shown pressed against the wall, being forced into the wall by the inclined surface 115 of the slot in the gripper head. In an exemplary design, each gripper shoe 110 is in contact with a pushrod 120. To lock the shoe against the tube wall 200, the pushrod 120 is urged upward by a plate 150. When the plate 150 is retracted, spring 130 loaded return pins 140 urge the pushrods 120 back down, thus releasing outward pressure on the gripper shoes 110. As stated earlier, to aid in releasing the gripper shoes 110 from the tube wall 200, the entire gripper head assembly is urged upward into the tube slightly, moving the inclined surface 115 up and releasing the outward pressure on the gripper shoes 110.

The embodiment shown is an advanced high performance gripper design that will not cause tube damage, yet provides high load capacity (of up to 300 lbs per gripper) and automatically provides grip force to match the load applied to the robot. All of this is accomplished while remaining fail-safe during power service interruptions.

In an exemplary design, the robot tube grippers (Figures 2-4) have the following features: self locking tube ID gripper concept where the load of the robot helps lock and hold the lock; simultaneous deployment of gripper 110 and toe 116 along with the locking retract step; multi-stage custom air cylinder deployment / release mechanism, telescoping cylinders; simultaneously deploying, but individually retracting gripper shoes 110; individually replaceable gripper shoes; coatings or other friction reduction elements to provide slip plane surface between the gripper mandrel and shoe surface; hall effect, optical other type of sensor in the gripper head senses deployment status and senses plugs in the tube; multistage pneumatic locking gripper; robot load increases lock to tube surface; smooth gripper shoes do not impose stress points on tube wall, will not damage steam generator tubing; integrated hall sensors detect deployment and retraction position; failsafe grip during power interruptions; gripper heads are designed for quick change; and distributed I/O and on-board servo and control. Automatically and individually adjusting each gripper for optimum positioning of gripper within the tube inside diameter for accommodation of variances in tubing diameters for gripping and un-gripping operations.

In an embodiment, the position of the gripper within the tube is adaptively adjusted to account for variations in tube diameter and opening tolerances. There is an optimal depth range at which the gripper should be inserted into the tube. If the gripper is inserted too far into the tube, it is difficult to extract, since extraction requires extending the gripper slightly farther into the tube than the position where it is anchored. Anchoring the gripper to close to the open end of the tube can possibly damage the tube in some situations. Thus, it is useful to be able to locate the gripper in a limited insertion range in the tube. One way to do this is to include a position sensor on the gripper. The position sensor can be a Hall effect sensor or optical sensor. The gripper is inserted in the tube and locked and its position is determined. If the gripper is not in the desired area, the gripper is released and re-inserted. Positioning the gripper is a function of two timing parameters: there is a gripper insertion duration and a time at which the gripper shoes are forced outward to grip the tube wall. The combination of these two times is adjusted to place the gripper at differing depths within the tube. Because of variations in tube diameter and shape, the timing parameters are not universal. For this reason, an adaptive approach as described here is used to place the gripper in the desired location by adjusting the insertion time and shoe actuation time each time the gripper is repositioned until the gripper is anchored at the desired location in the tube.

### **Serial Network**

In an exemplary embodiment, a serial network connects internal electronic modules of the robot. The serial network also connects any electronics attached to the tool head, the external controller and an installation robot. The serial network eliminates the need for custom wiring between these devices and reduces wire count, thus increasing reliability and reducing cost. The use of the serial network allows for expansion and improvements to existing hardware since additional modules can be added that communicate with the existing modules by simply tapping into the serial network. In an embodiment, the serial network is an electrical network and is implemented with the industry standard CAN bus. In an alternate embodiment, the serial network is a fiber optic network. The serial network also allows a single external controller to control multiple system elements within the robot system on the same bus. An additional serial network is provided in the form of a “1-Wire” memory chip to communicate and manage information stored in system components for use in controlling system level inventory, storing of data and configuration of software operations. The “1-Wire” network provides for insuring proper system operation parameters are respected to avoid undesirable operation.

## **Robot Tool Head**

In an exemplary design, the robot tool head interface has the following features: quick make/break air coupling combined with electrical (power and signal) connection and proximity / Hall effect auto-lock feature.

## **Control Software**

Software for an exemplary design includes: kinematics, multiple robot coordination, and collision detection / avoidance; software inspection planning & simulation; motion path planning algorithms to validate operation in bowl; trajectory planning algorithms to provide optimal path to target location; movement optimization algorithms to control movement around plugs and stays; and efficient inspection planning algorithms to optimize eddy current testing inspection and delivery of repair tooling.

## **Features and Benefits**

Some features and benefits of the present invention include:

Small footprint of the robot provides ultimate maneuverability for efficient repositioning in all regions of the tube sheet while occupying less area thereby allowing the use of multiple robots per head.

Light Weight. At less than 40lbs the robot is easily transportable and installable. In conjunction with the small footprint it requires less energy to grip into the tube sheet.

Fail-safe revolutionary gripper design ensures that the robot will remain attached to the tube sheet through loss of all power, yet remains easily removable during emergency situations.

Fast and strong with a tube-to-tube speed of up to 4 inches/sec and up to 300lbs load capacity per gripper. The robot is capable of performing both high speed inspections and supporting the load demands of repair tooling.

A simplified system uses CAN-bus (Controller-area Network) control system architecture. The robot provides the smallest robot cable bundle in the industry with a diameter of less than 1 inch.

Intelligent software control manages the telemetry of all robots within a steam generator to avoid robot to robot collisions as well as probe collisions with robots operating in the opposite channel head.

Seamless Interface with Zetec's MIZ®-80iD intelligent system capabilities for exchange information between hardware components and tooling.

While the invention has been described in detail and with reference to specific examples thereof, it will be apparent to one skilled in the art that various changes and modifications can be made therein without departing from the spirit and scope thereof.

## CLAIMS

## WHAT IS CLAIMED IS:

1. An apparatus for automated inspection and delivery of repair tooling to a tube sheet comprising open ended tubes having access to an inner tube diameter, said apparatus comprising:
  - a sliding body portion containing a rotating gripper pod;
  - said rotating gripper pod, comprising at least one tube gripper;
  - a housing portion comprising at least one tube gripper; and
  - a tool head coupler, wherein said sliding body portion moves with respect to said housing portion.
2. The apparatus of Claim 1, wherein said tool head coupler is a part of one of said sliding body portion or said sliding housing portion.
3. The apparatus of Claim 1, further comprising machine vision.
4. The apparatus of Claim 1, wherein said tool head coupler supports a tool head comprising an eddy current test probe for insertion into a tube in the tube sheet
5. The apparatus of Claim 1, wherein said tool head coupler supports a tool head comprising tube repair equipment.
6. The apparatus of Claim 1, comprising four tube grippers on said housing portion and three tube grippers on said rotating gripper pod.
7. The apparatus of Claim 1, wherein said tube gripper comprises
  - a pneumatic actuator;
  - gripper shoes; and
  - sensors for detecting deployment and retraction position.
8. The apparatus of Claim 7, wherein the tube gripper shoes are locked against the tube inner wall by reactionary force directed away from the tube.
9. The apparatus of Claim 7, wherein said tube gripper comprises spring-loaded retractors in communication with said gripper shoes.
10. The apparatus of Claim 7, wherein said gripper shoes have a tube contacting surface and an inner surface and said tube gripper further comprises a gripper shoe mating surface, and a gripper shoe friction reducer wherein said gripper shoe friction reducer reduces the friction between said gripper shoe inner surface and said gripper shoe mating surface such that less force is required to slide said gripper shoe along said gripper shoe

mating surface than is required to slide said gripper shoe tube contacting surface against said tube wall.

11. The apparatus of Claim 1, further comprising a plurality of electronic modules interconnected by a serial network.

12. The apparatus of Claim 11, wherein said serial network also connects said apparatus to an external controller.

13. An apparatus for automated inspection and testing of a tube sheet wherein the tube sheet has a plurality of tube openings arranged on a tube sheet plane, the apparatus comprising:

a core assembly comprising:

a rotating module with three tube grippers;

a tool head coupling hingedly mounted to said core assembly; and

outer housing actuators; and

left and right outer housings;

each outer housing comprising one or more tube grippers;

wherein said core assembly is arranged between said left and right outer housing portions, and wherein said core assembly, including said rotating module, and said left and right outer housing portions have top surfaces aligned on a common plane which, when the apparatus is in use, is parallel to said tube sheet plane, and wherein said tube grippers emerge from said rotating module and left and right outer housings, respectively, perpendicular to said common plane and

wherein said core assembly actuators move said left and right outer housings with respect to said core assembly such that said top surfaces remain in said common plane.

14. The apparatus of Claim 13, wherein said tool head coupling supports alternately an eddy current test probe and a tube repair device.

15. The apparatus of Claim 13, wherein each of said tube grippers comprises an actuator; and  
gripper shoes;

wherein said gripper shoes have a tube contacting surface and an inner surface and said tube gripper further comprises a gripper shoe mating surface, and a gripper shoe friction reducer wherein said gripper shoe friction reducer reduces the friction between

said gripper shoe inner surface and said gripper shoe mating surface such that less force is required to slide said gripper shoe along said gripper shoe mating surface than is required to slide said gripper shoe tube contacting surface against said tube wall.

16. The apparatus of Claim 13, wherein when at least two of said rotating module tube grippers are locked into tubes and none of said outer housing tube grippers are inserted into tubes, the rotating module can be actuated to rotate the apparatus about an axis that is perpendicular to said tube sheet plane.

17. The apparatus of Claim 13, wherein when at least two of said rotating module tube grippers are locked into tubes and none of said outer housing tube grippers are inserted into tubes, said outer housing actuators can be actuated to move said outer housings across the tube sheet parallel to said tube sheet plane.

18. The apparatus of Claim 13, wherein when at least two of said outer housing tube grippers are locked into tubes and none of said rotating module tube grippers are inserted into tubes, said outer housing actuators can be actuated to move said core assembly across said tube sheet parallel to said tube sheet plane.

19. The apparatus of Claim 13, further comprising a plurality of electronic modules interconnected by a serial network, wherein said serial network also connects said apparatus to an external controller.

20. The apparatus of claim 19, wherein said serial network also connects an installer device to said external controller.

21. A method for controlling an apparatus for gripping a device to the inside wall of a tube, the apparatus having

an insertion actuator,  
gripper shoes,  
a gripper shoe actuator and  
a position sensor,

the method comprising:

activating said insertion actuator for a first time period during which the device is inserted into the tube;

activating said gripper shoe actuator for a second time period;  
sensing the location of the apparatus within the tube;

adjusting the position of the actuator within in the tube by retracting the apparatus and reinserting the apparatus with different values for at least one of said first and second time periods.

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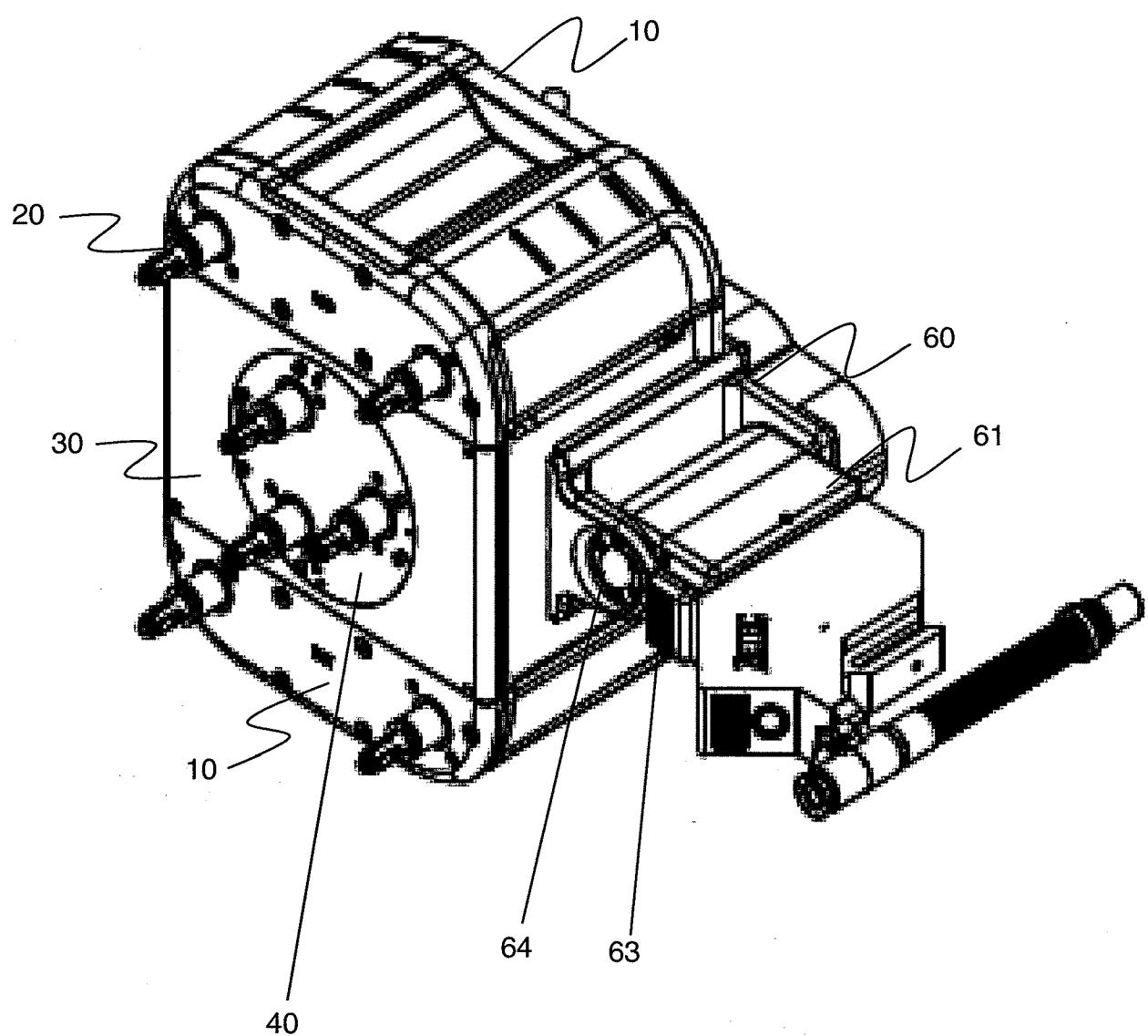


Figure 1

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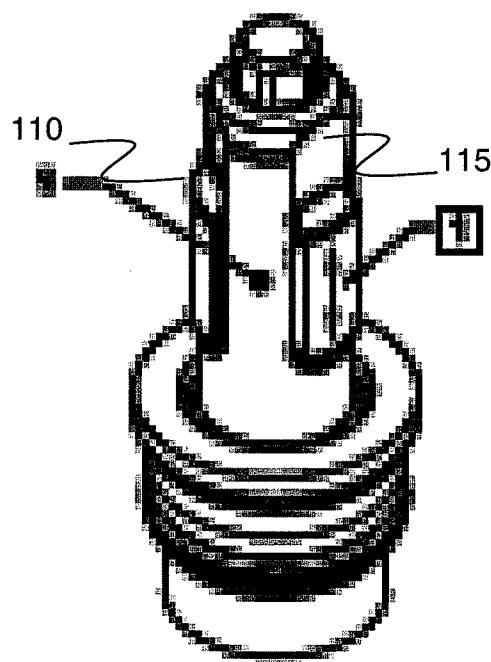
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Figure 2

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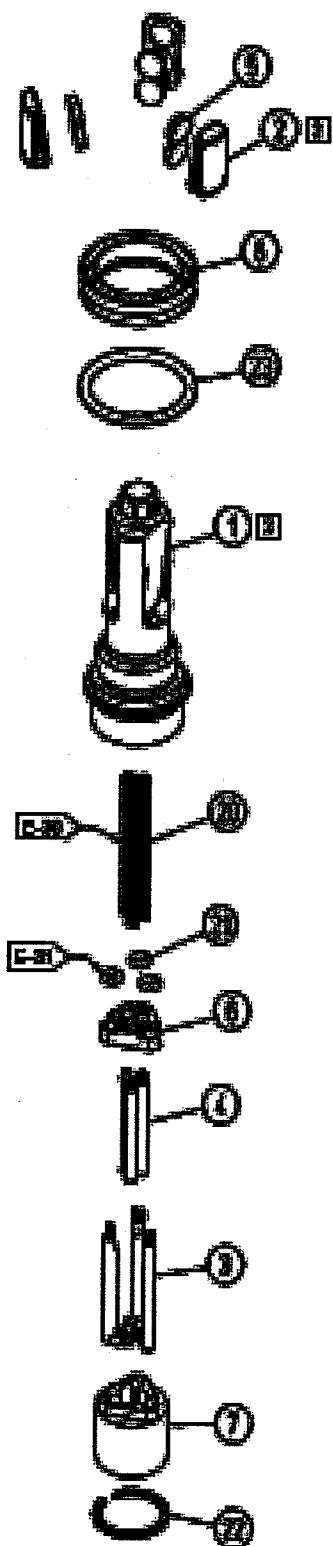


Figure 3

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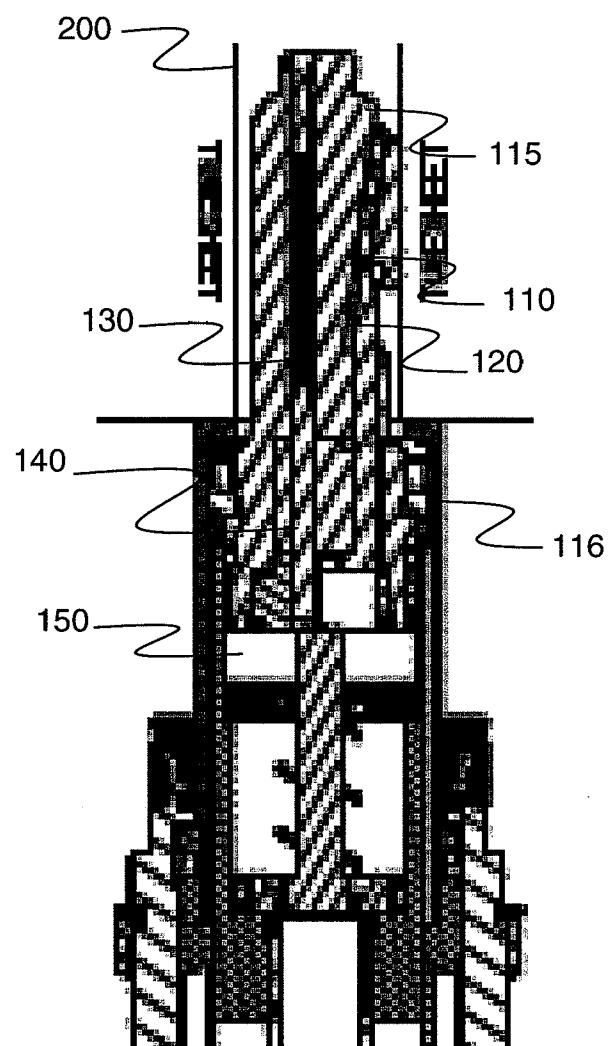


Figure 4