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(19) **United States**(12) **Patent Application Publication****Pryor et al.**(10) **Pub. No.: US 2023/0294313 A1**(43) **Pub. Date: Sep. 21, 2023**(54) **ROBOTIC SYSTEMS AND METHODS FOR
TANK SEAL INSPECTION****Publication Classification**(71) Applicant: **Board of Regents, The University of
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TX (US); Keith Fritz, Austin, TX (US)**

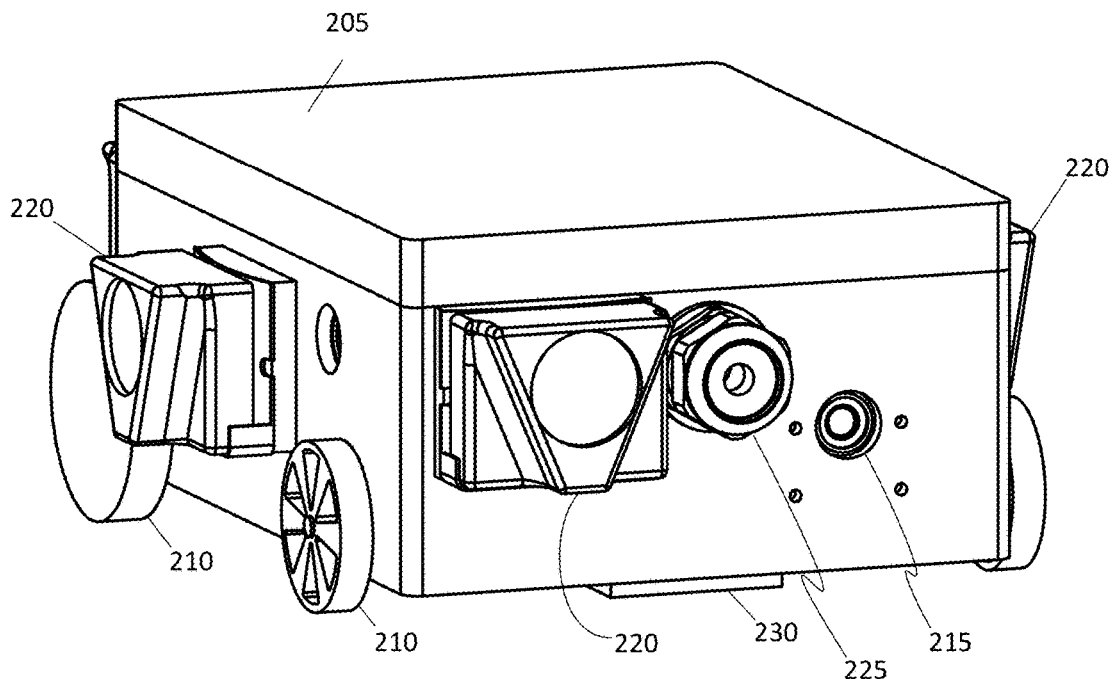
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B25J 5/00 (2006.01)
B25J 19/00 (2006.01)

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B25J 19/0025 (2013.01)

(21) Appl. No.: **18/179,016**(22) Filed: **Mar. 6, 2023****Related U.S. Application Data**(63) Continuation-in-part of application No. 17/431,988,
filed on Aug. 18, 2021, filed as application No.
PCT/US2020/020420 on Feb. 28, 2020.(60) Provisional application No. 62/811,795, filed on Feb.
28, 2019.(57) **ABSTRACT**

Robotic systems and methods for tank seal inspection. A tank inspection robot includes a housing containing a drive assembly, and wheels disposed outside of the housing and operably coupled to the drive assembly. The tank inspection robot also includes at least one sensor coupled to, or disposed in or on a portion of the robot, for collecting data sufficient to evaluate a health, mechanical integrity or effectiveness of one or more circumferential seals between a floating roof, and an interior wall, of a storage tank. The disclosed robot and associated method enable safer and more efficient seal inspection routines as compared to conventional techniques.

125 →



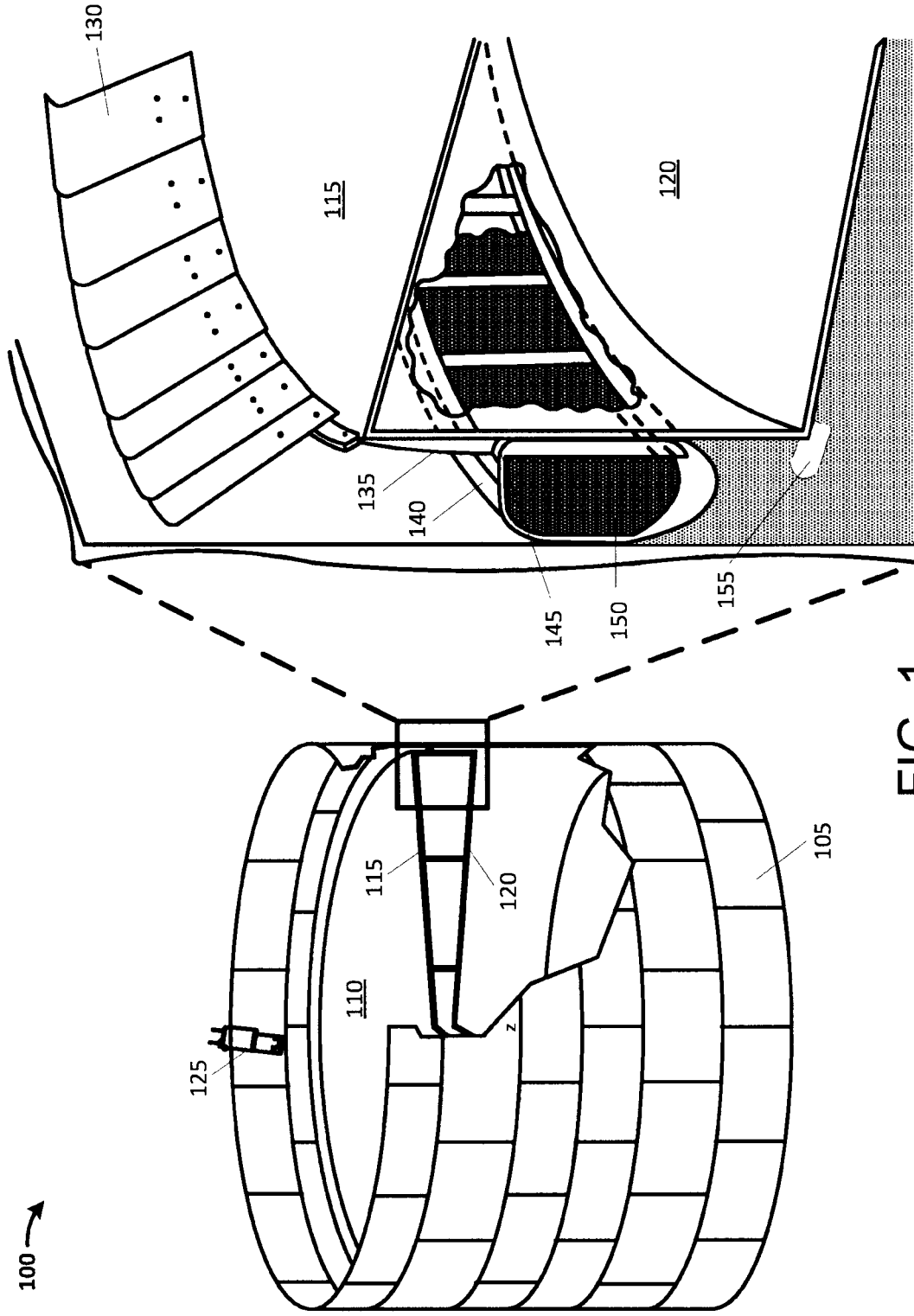


FIG. 1

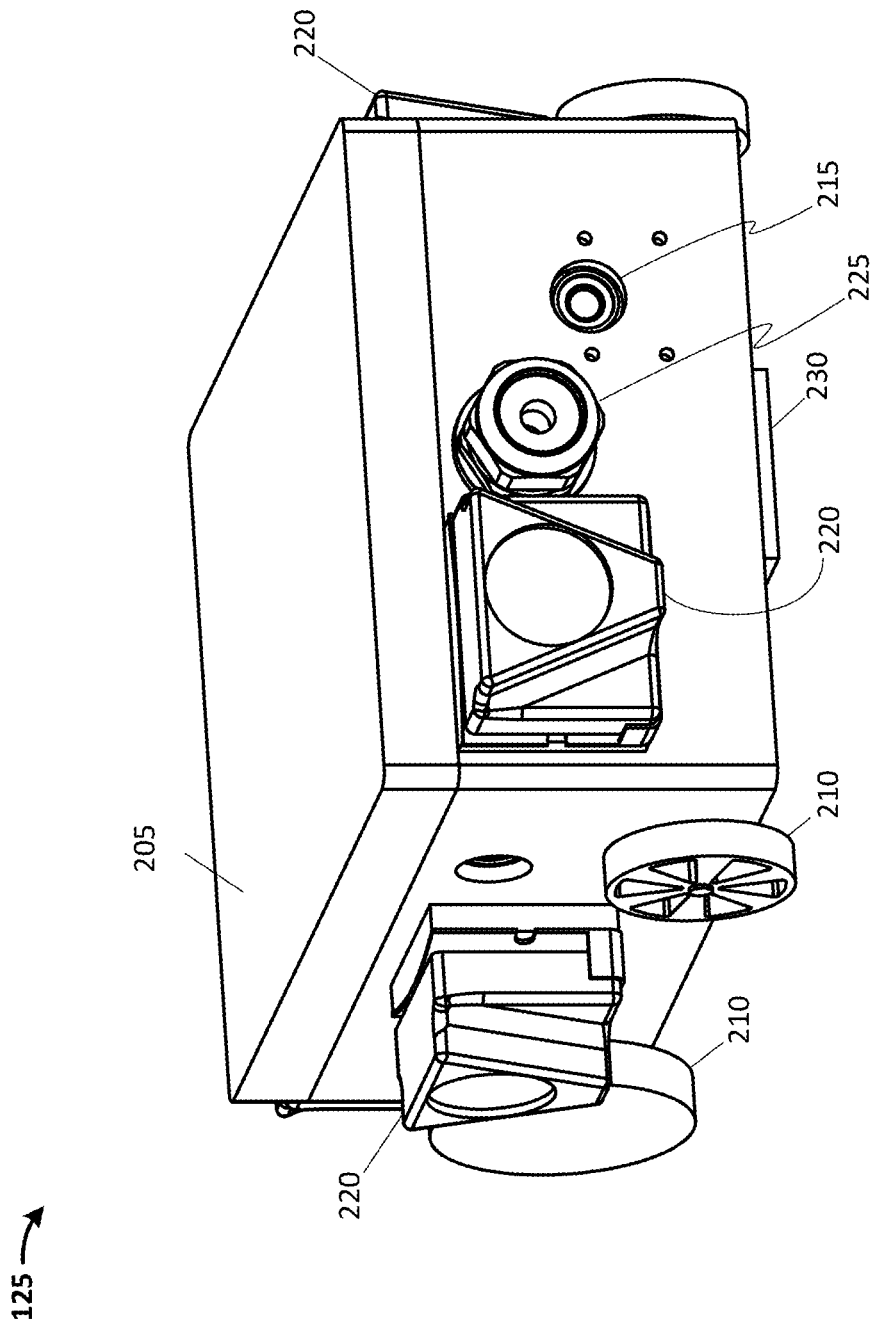


FIG. 2

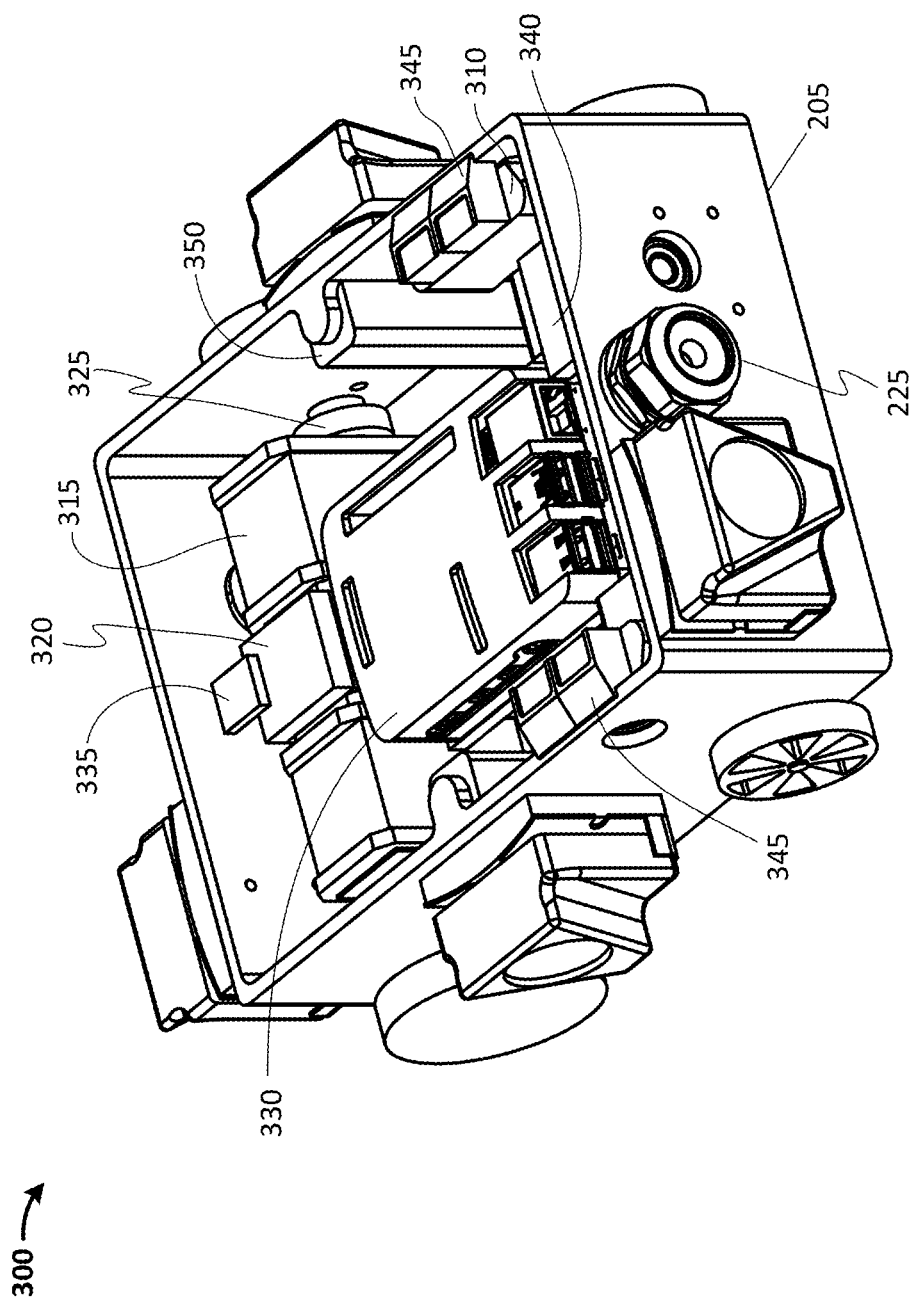


FIG. 3

400 →

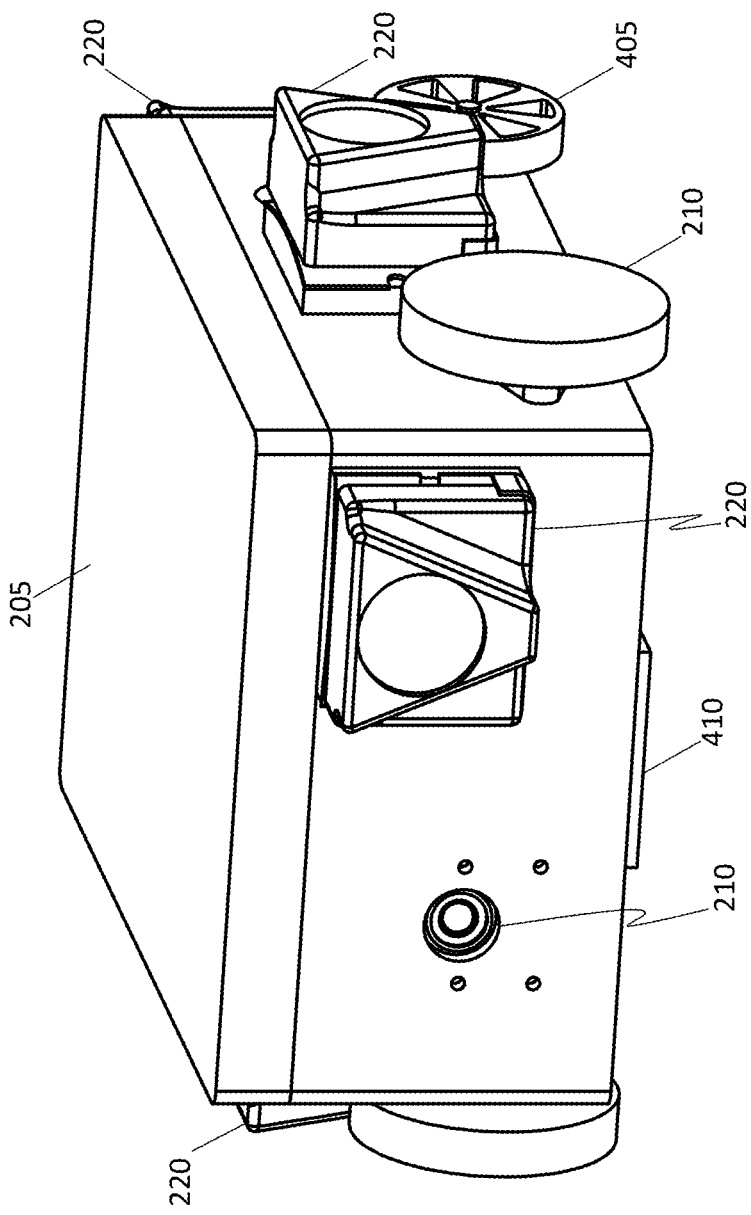


FIG. 4

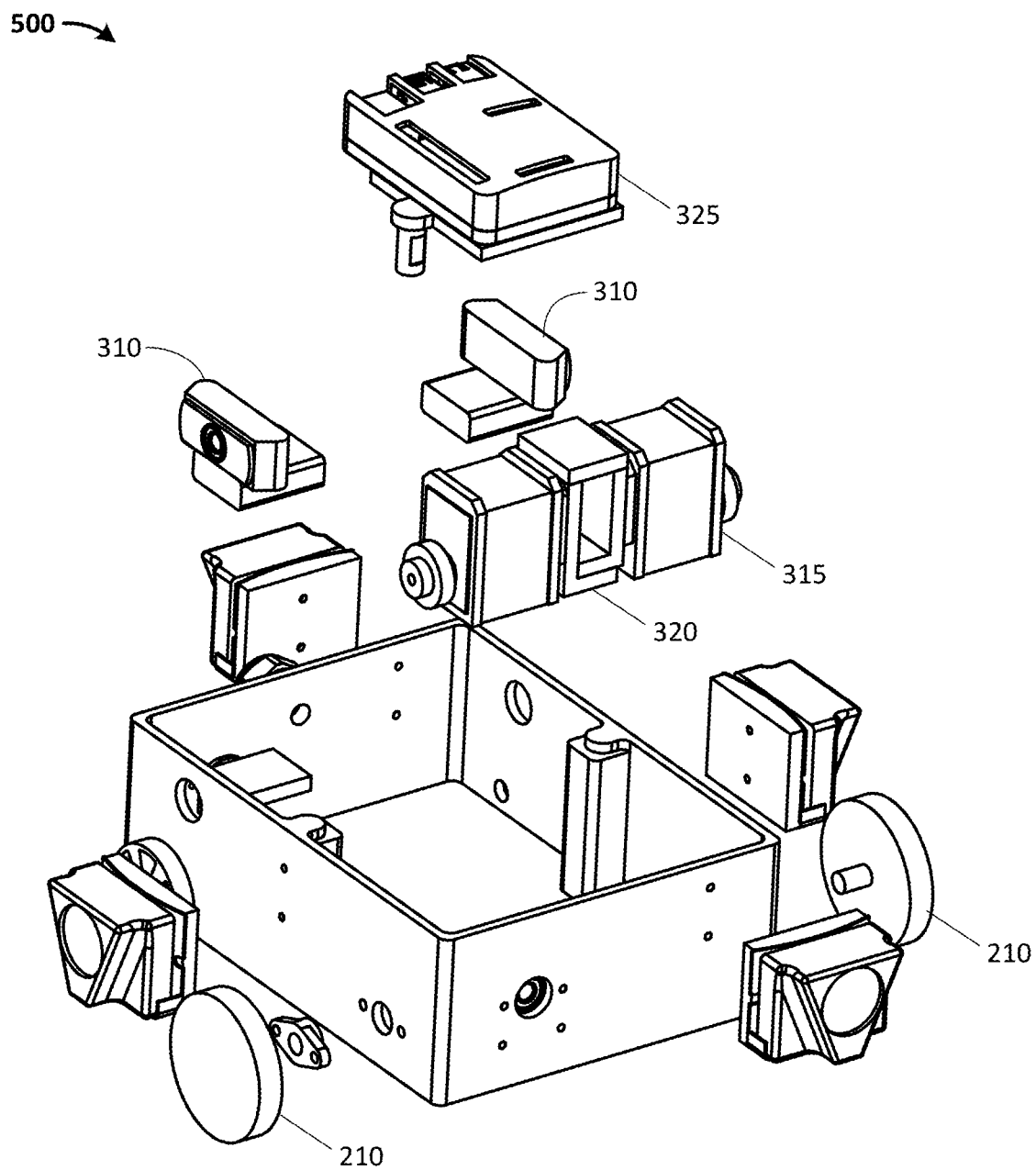


FIG. 5

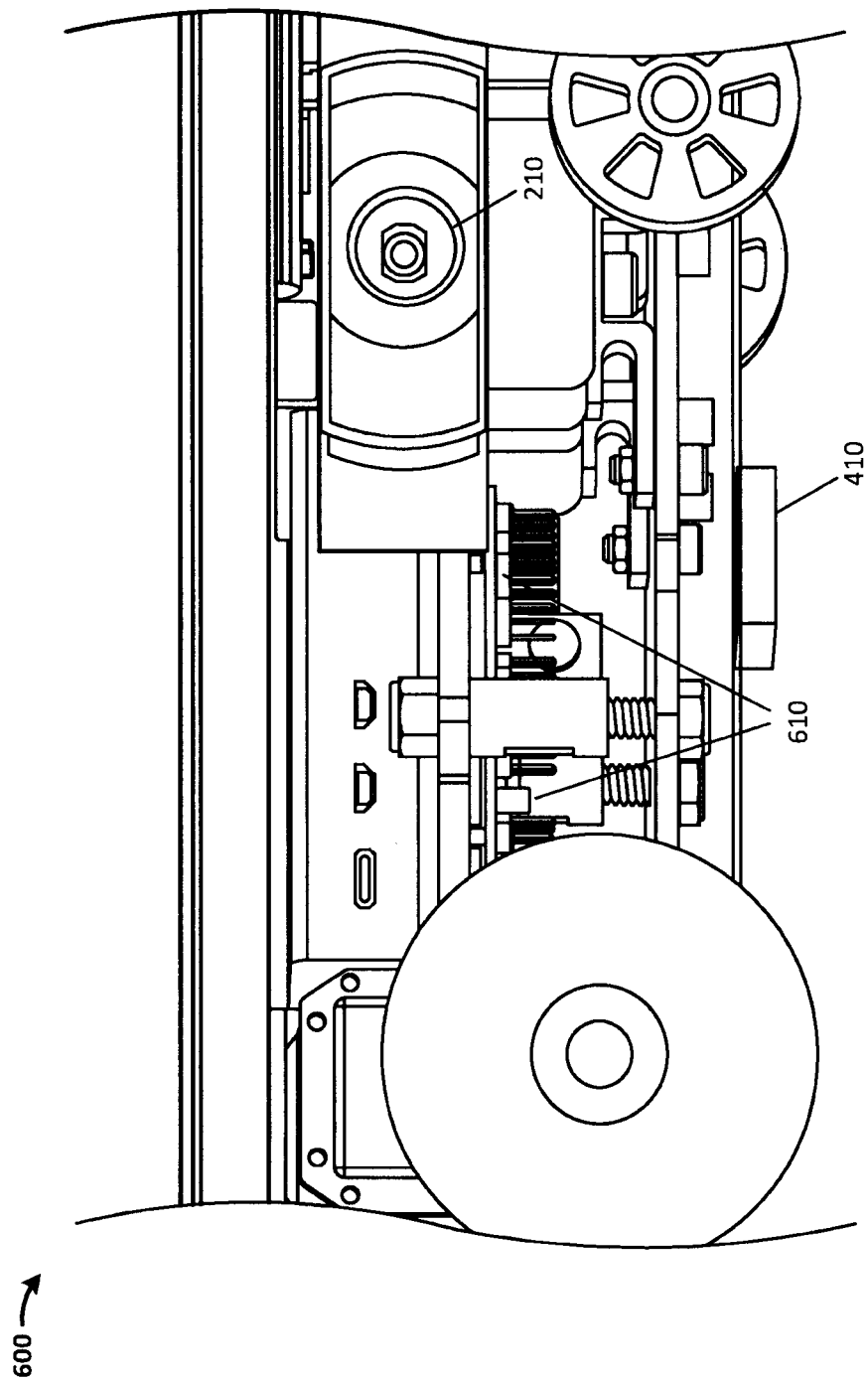


FIG. 6

700 →

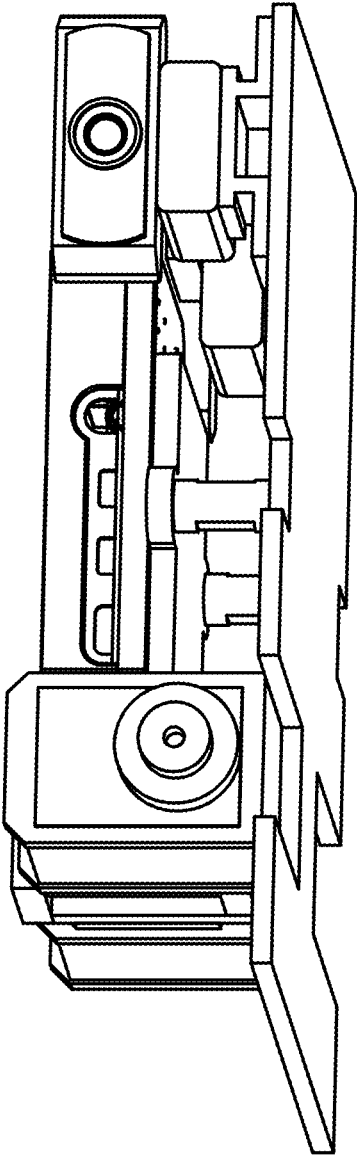


FIG. 7

FIG. 8

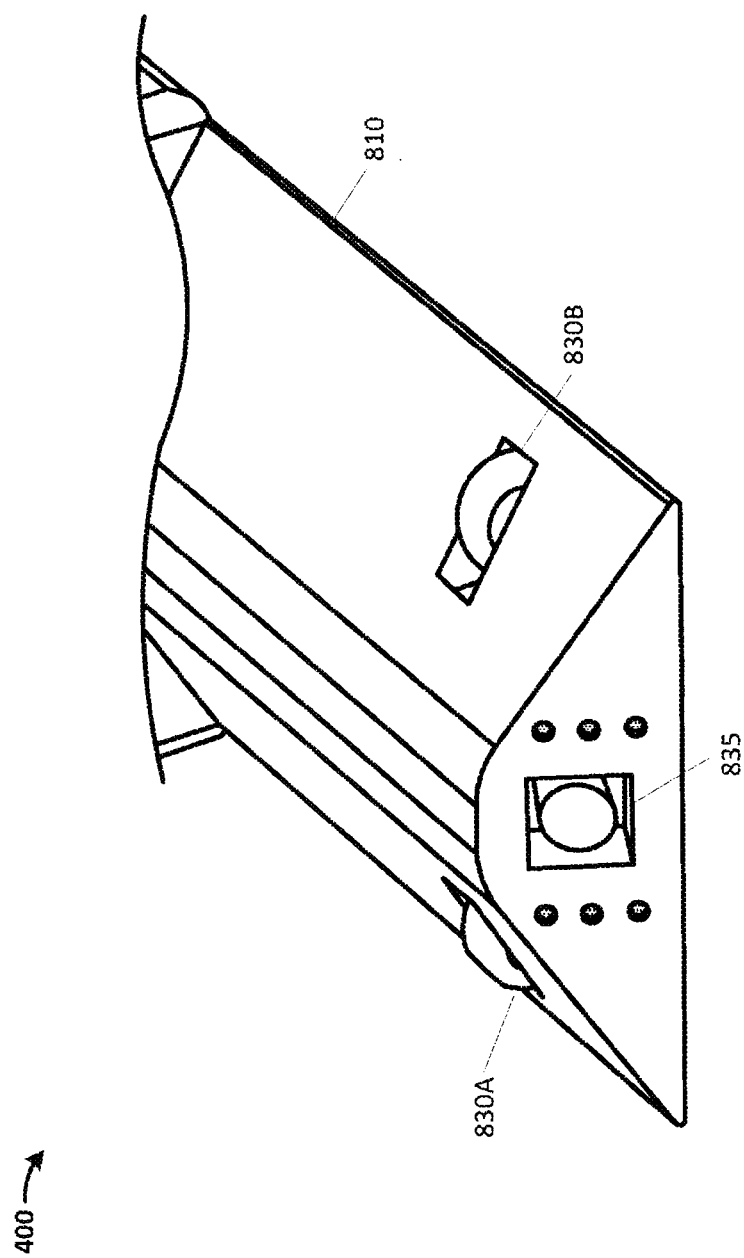


FIG. 9

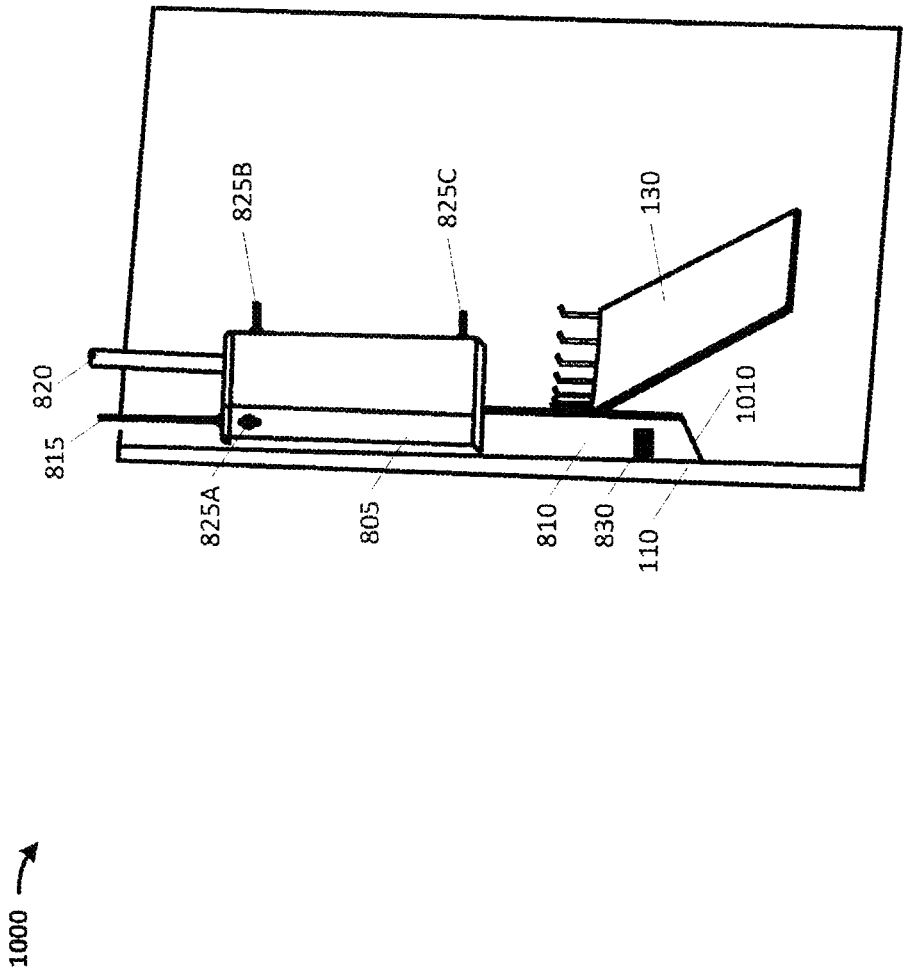


FIG. 10

1100 ↗

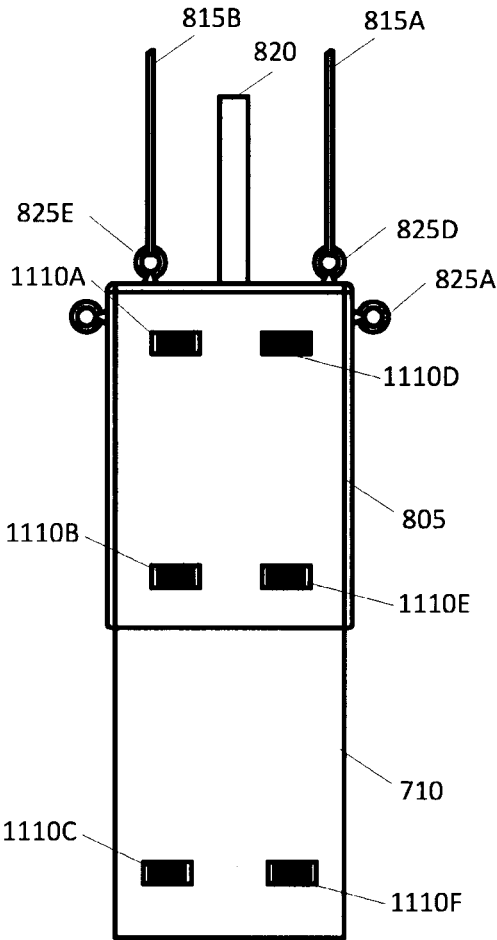


FIG. 11

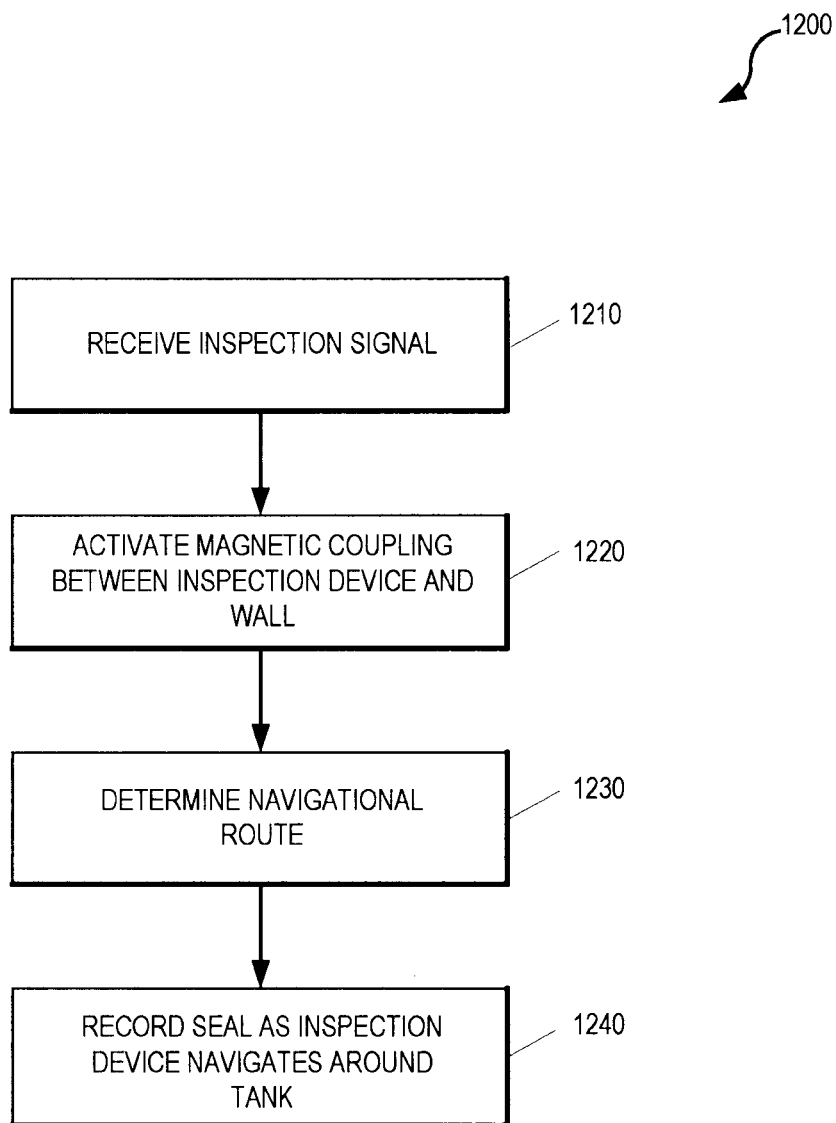


FIG. 12

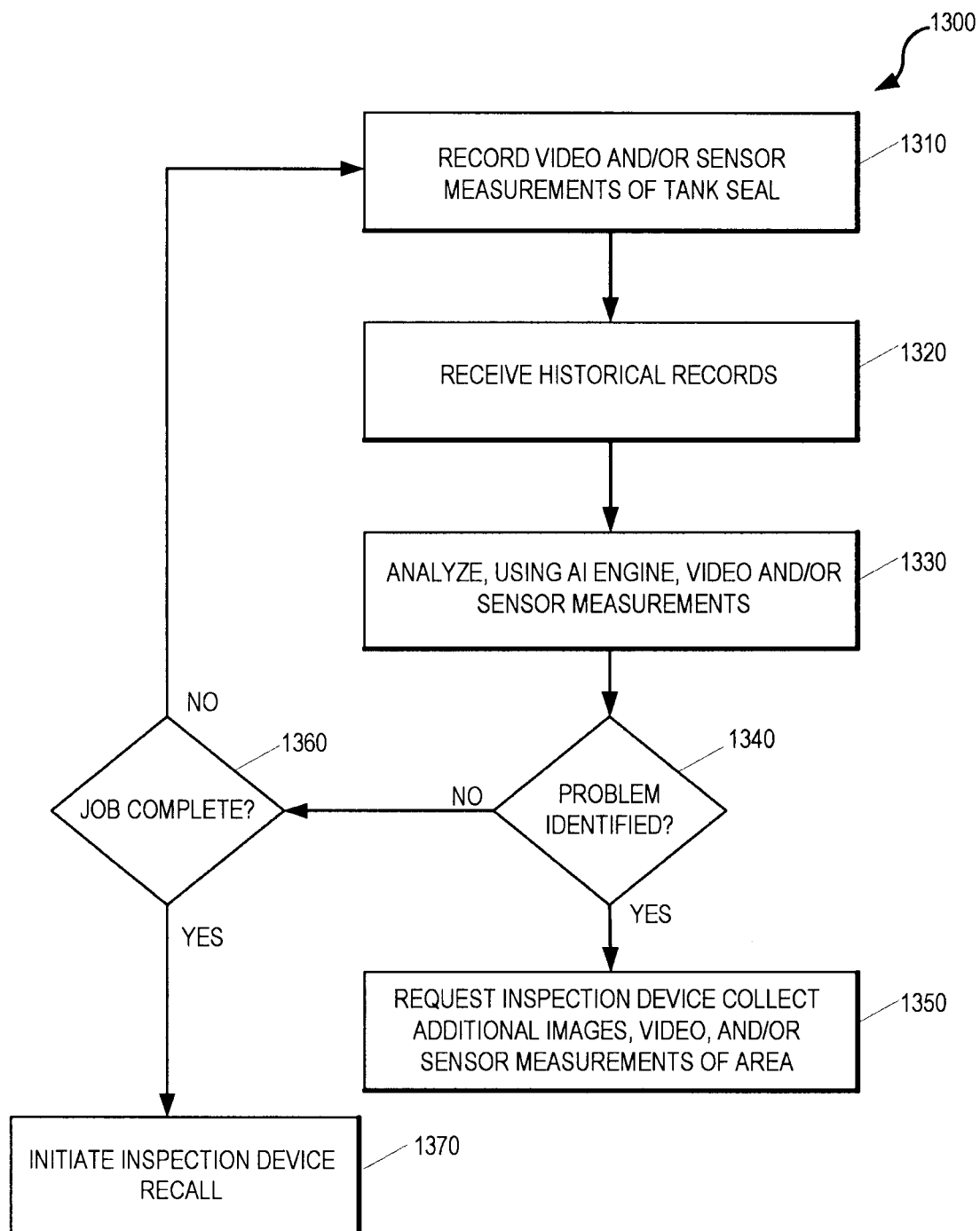


FIG. 13

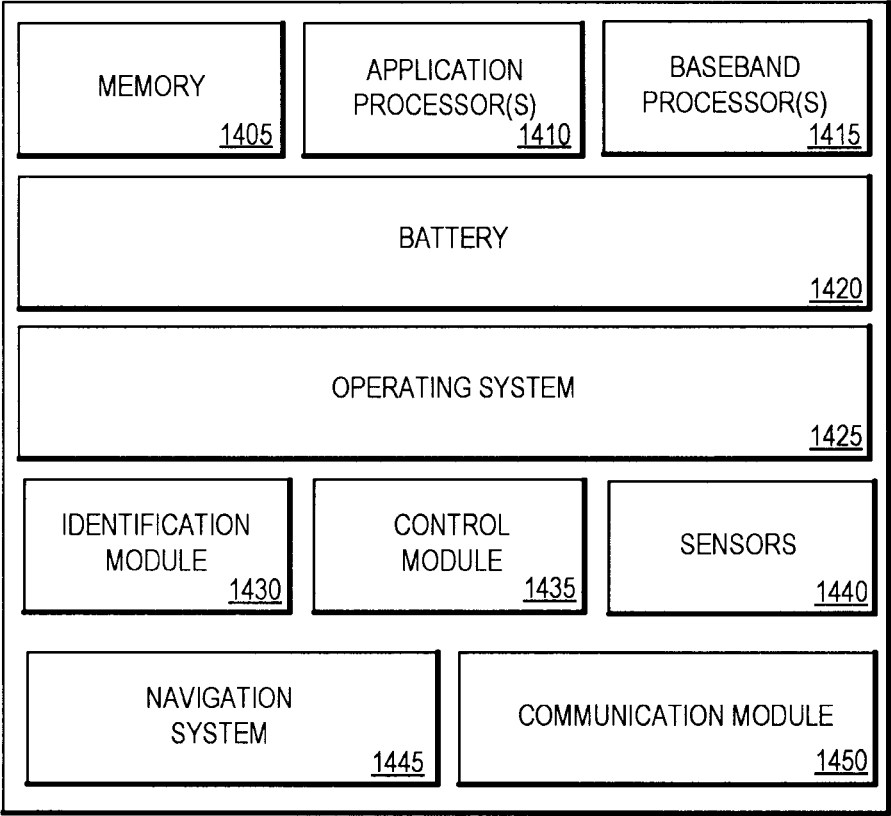


FIG. 14

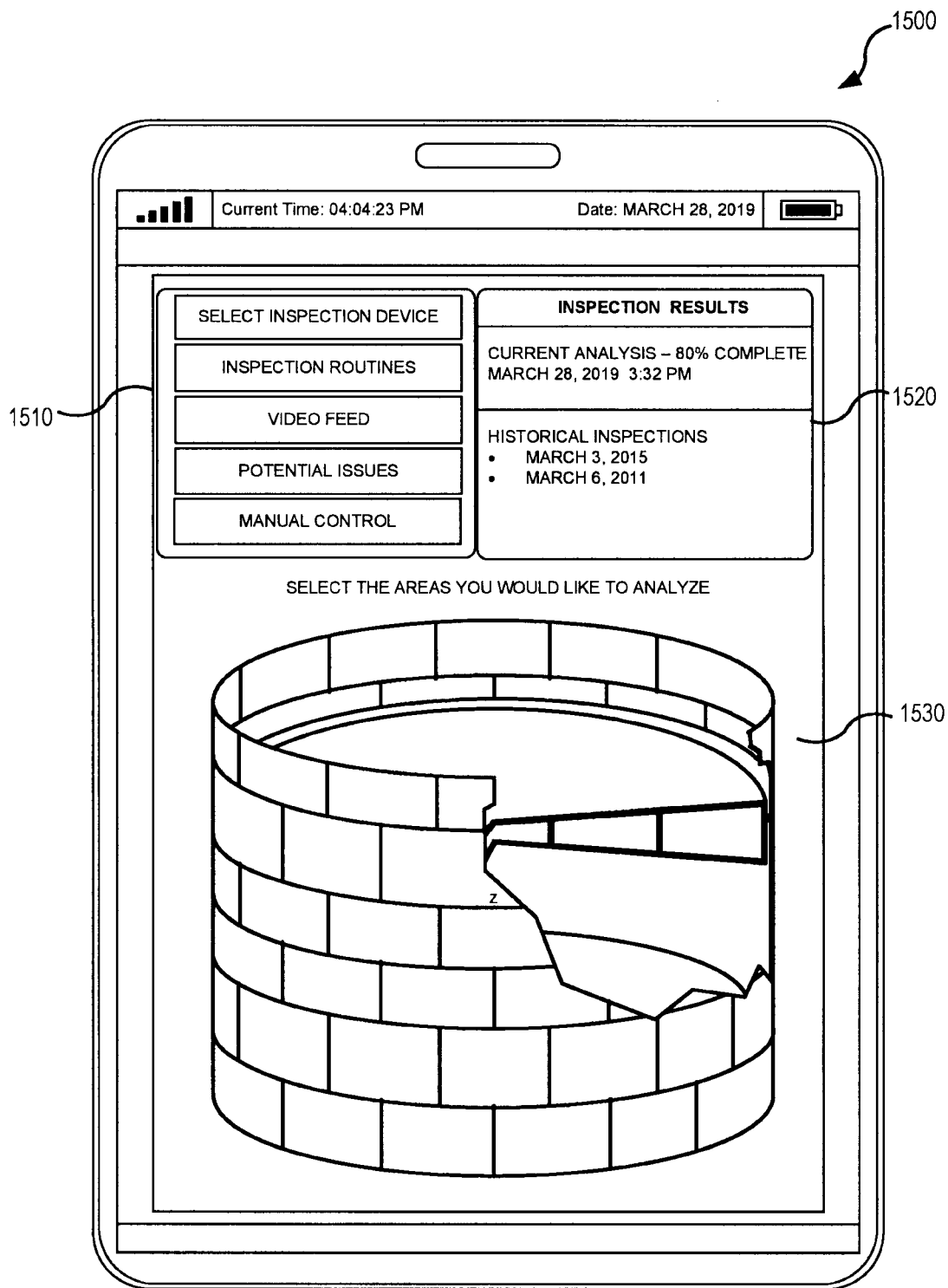


FIG. 15

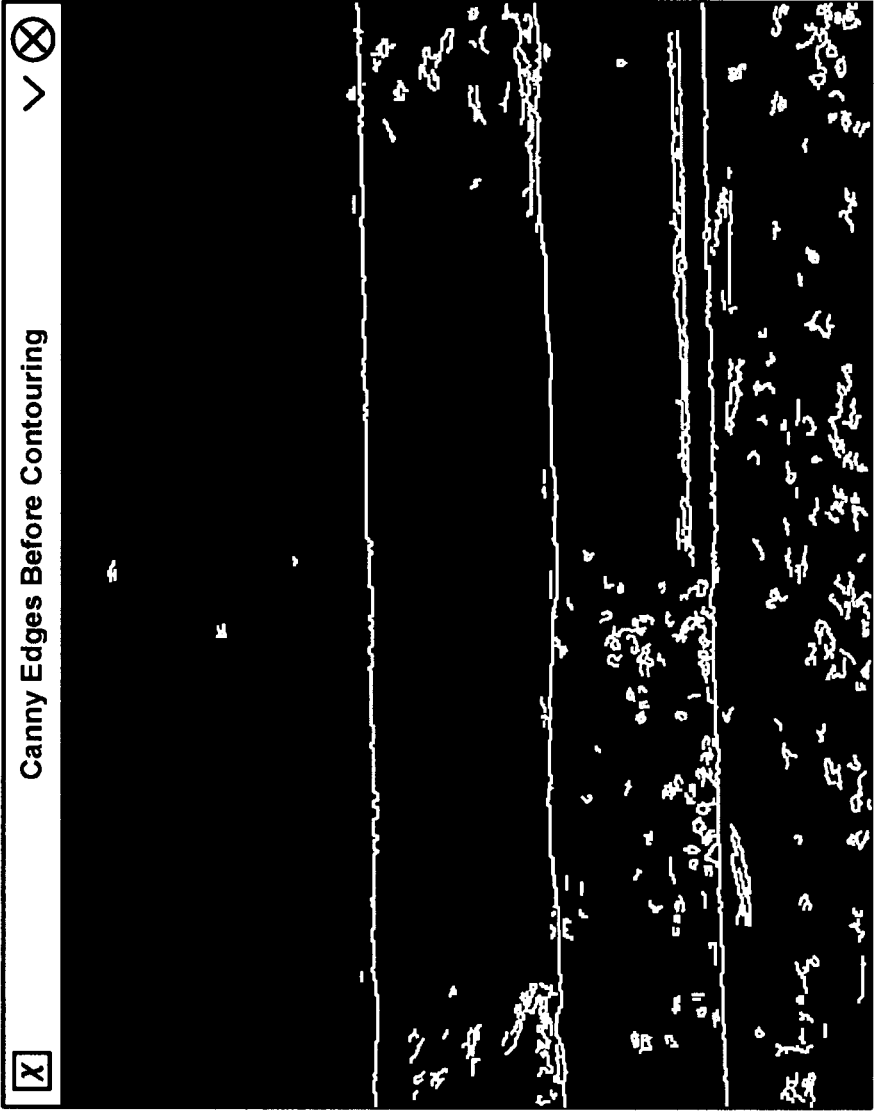


FIG. 16A

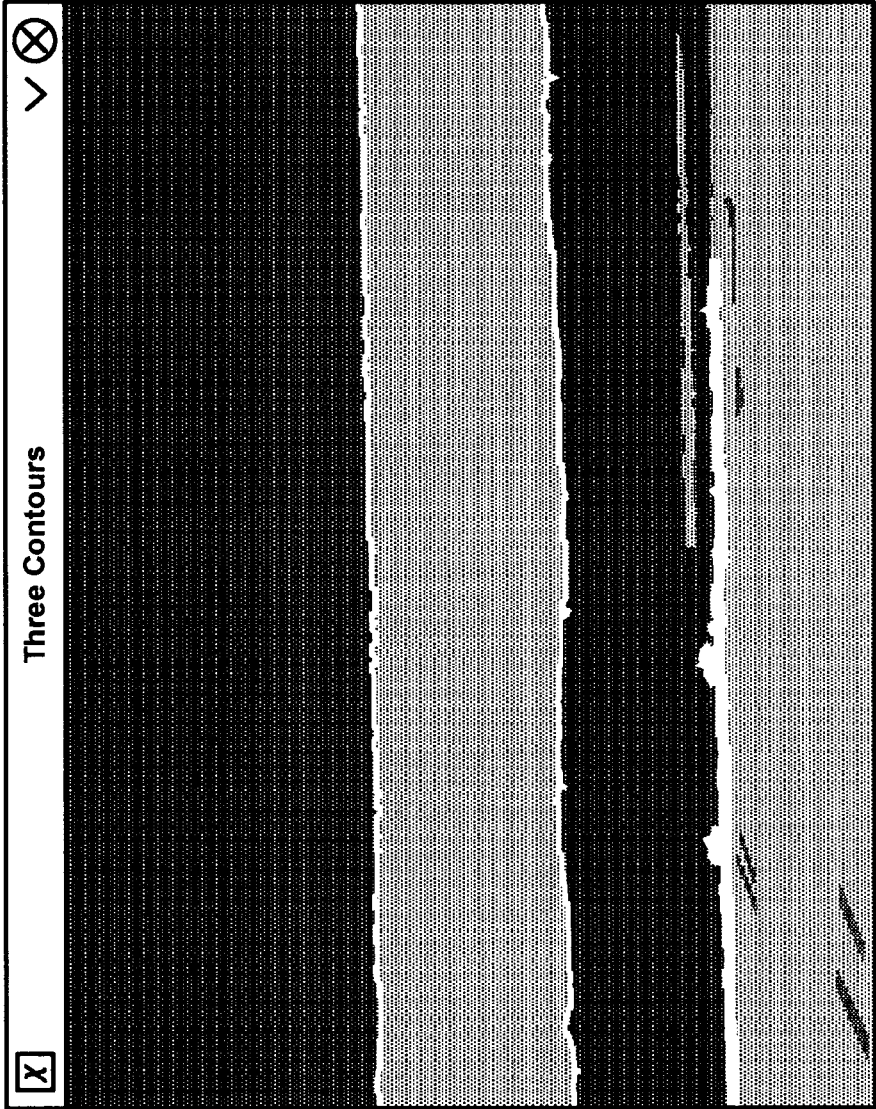


FIG. 16B

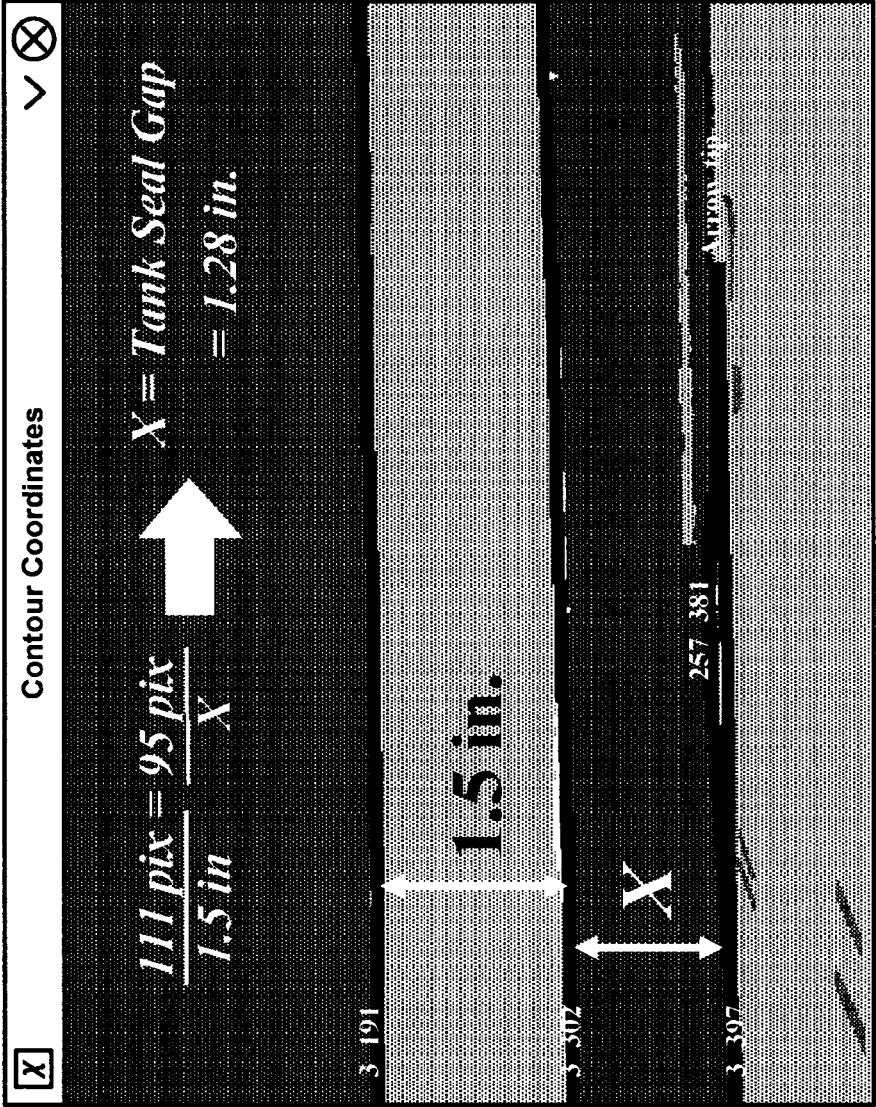
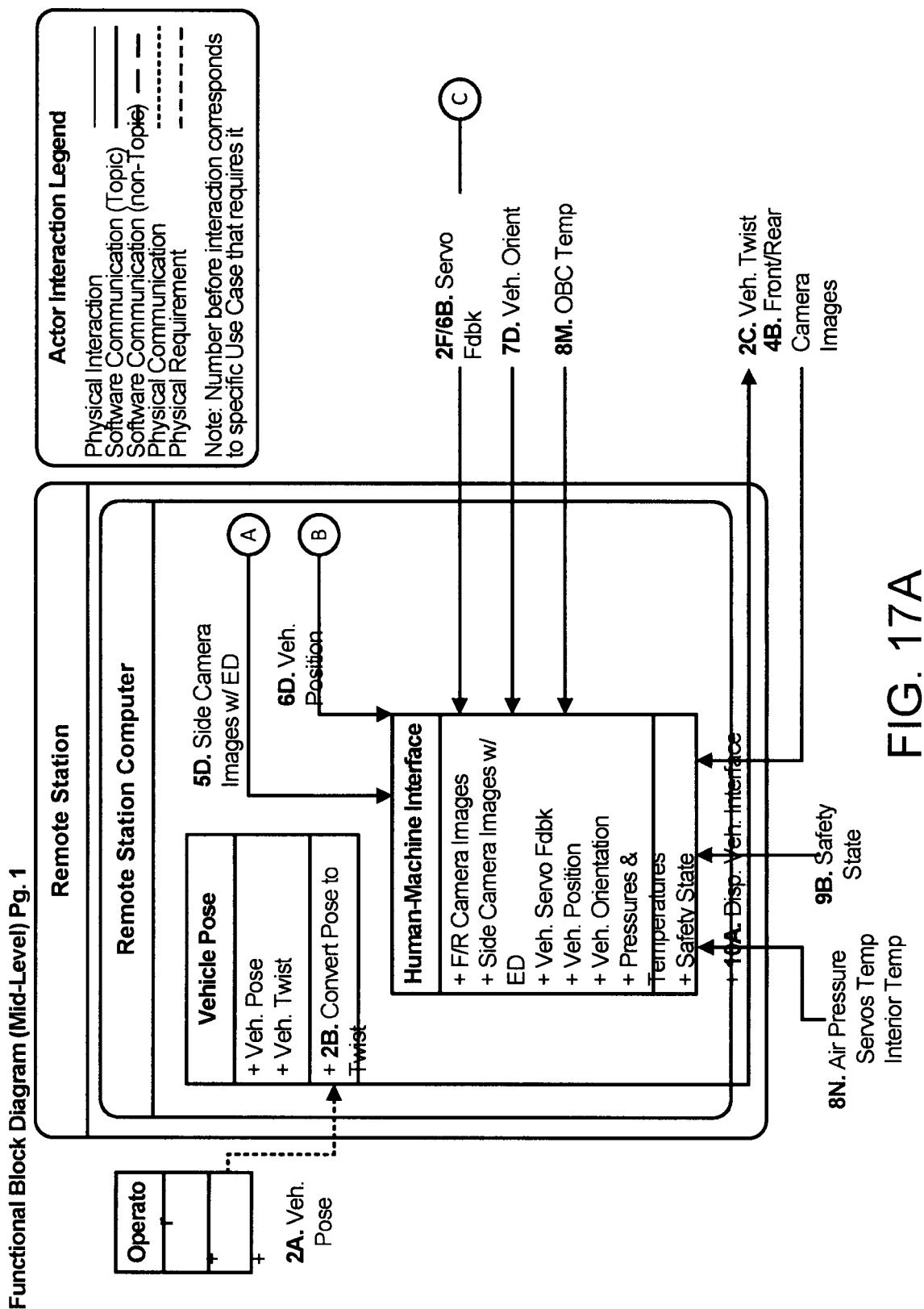


FIG. 16C



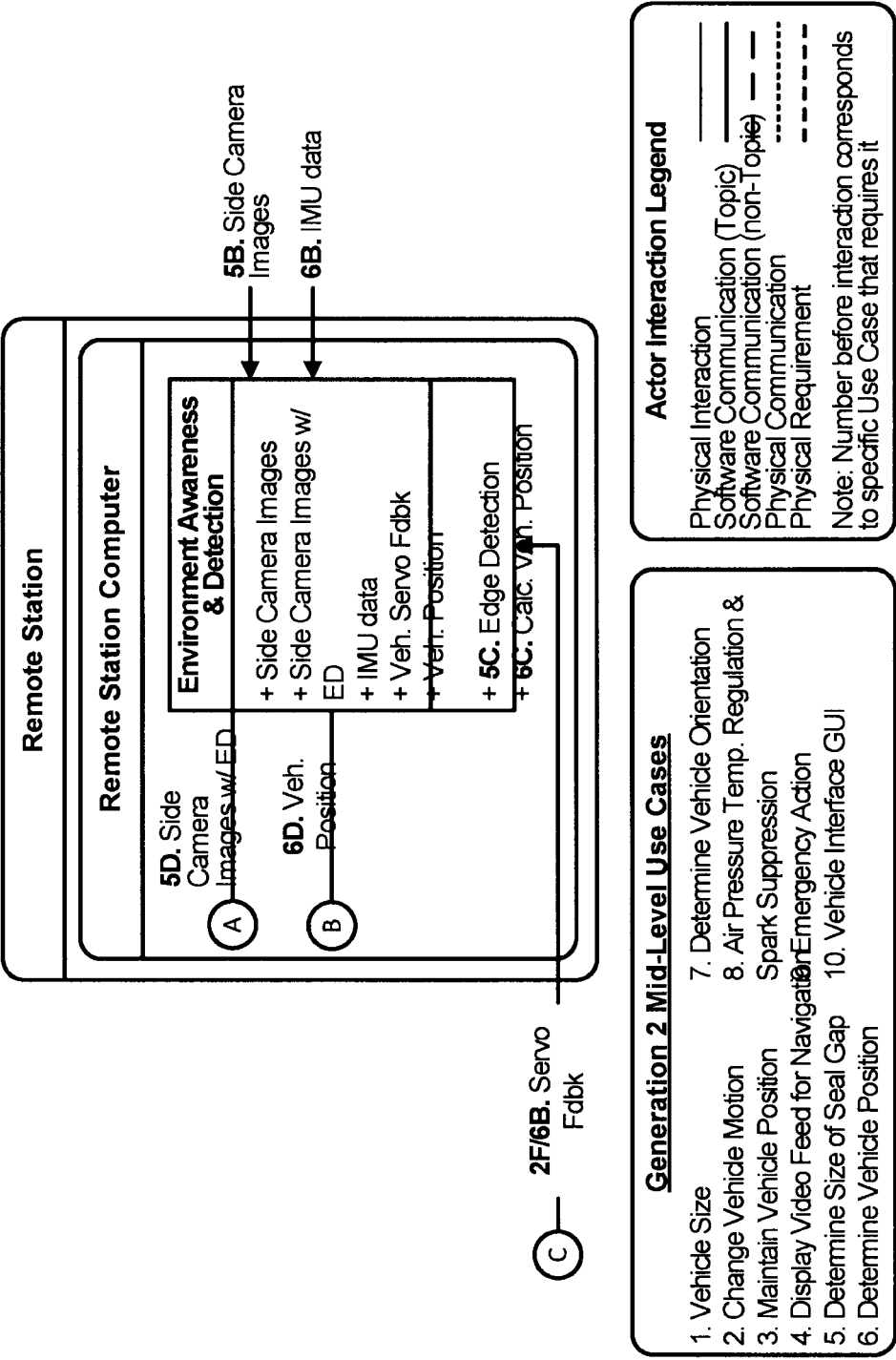


FIG. 17A (Continued)

Functional Block Diagram (Mid-Level) Pg. 2

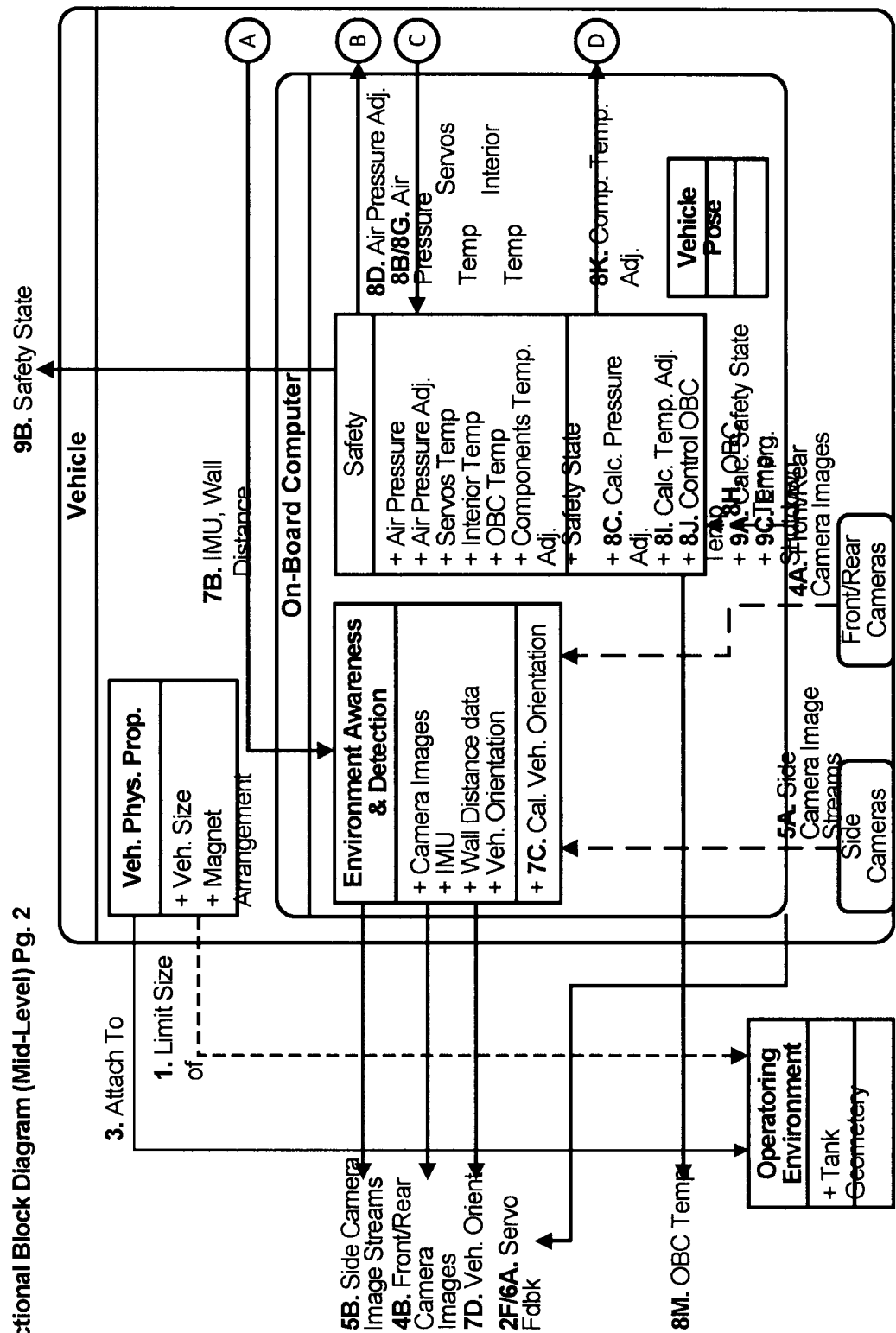


FIG. 17B

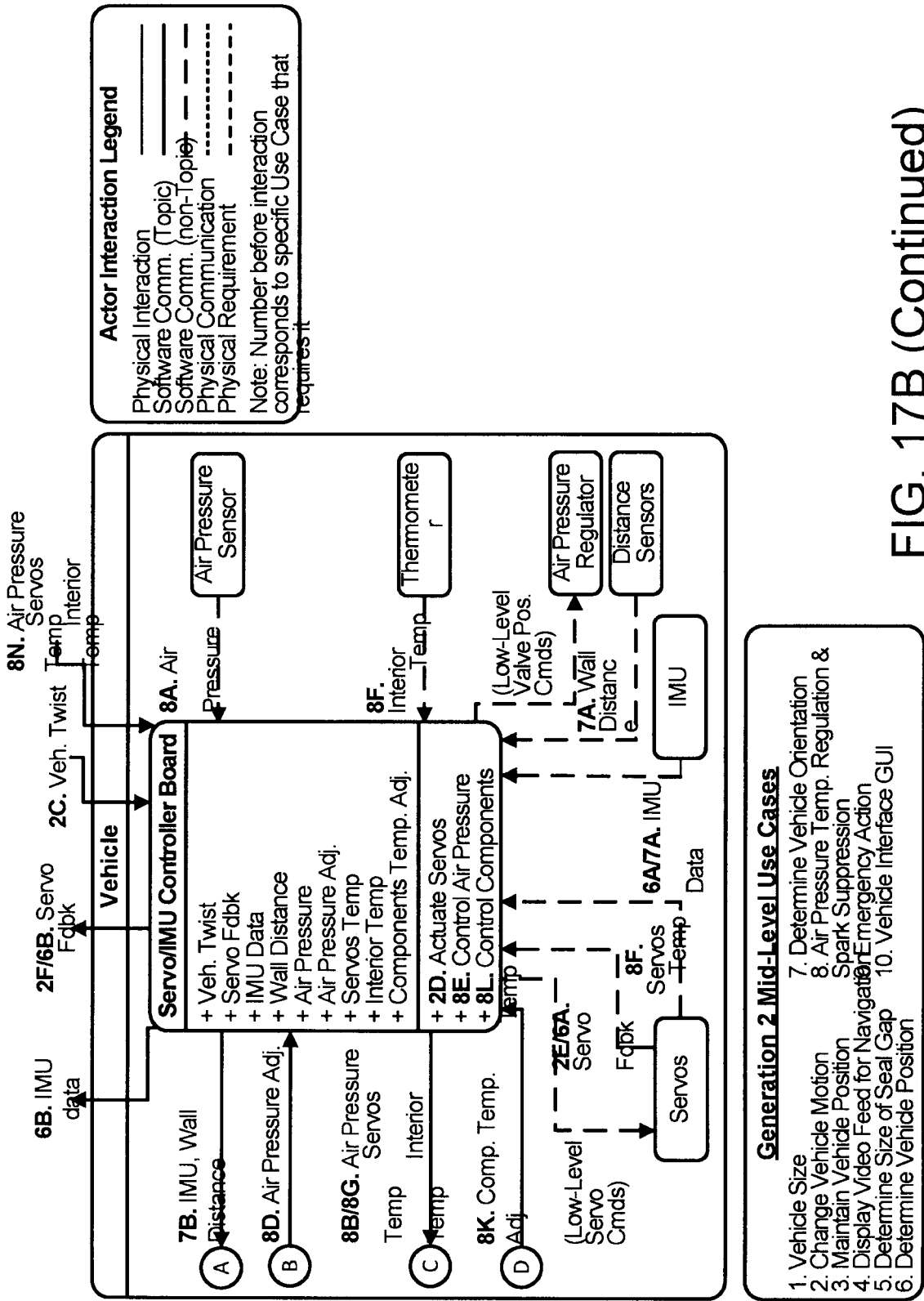


FIG. 17B (Continued)

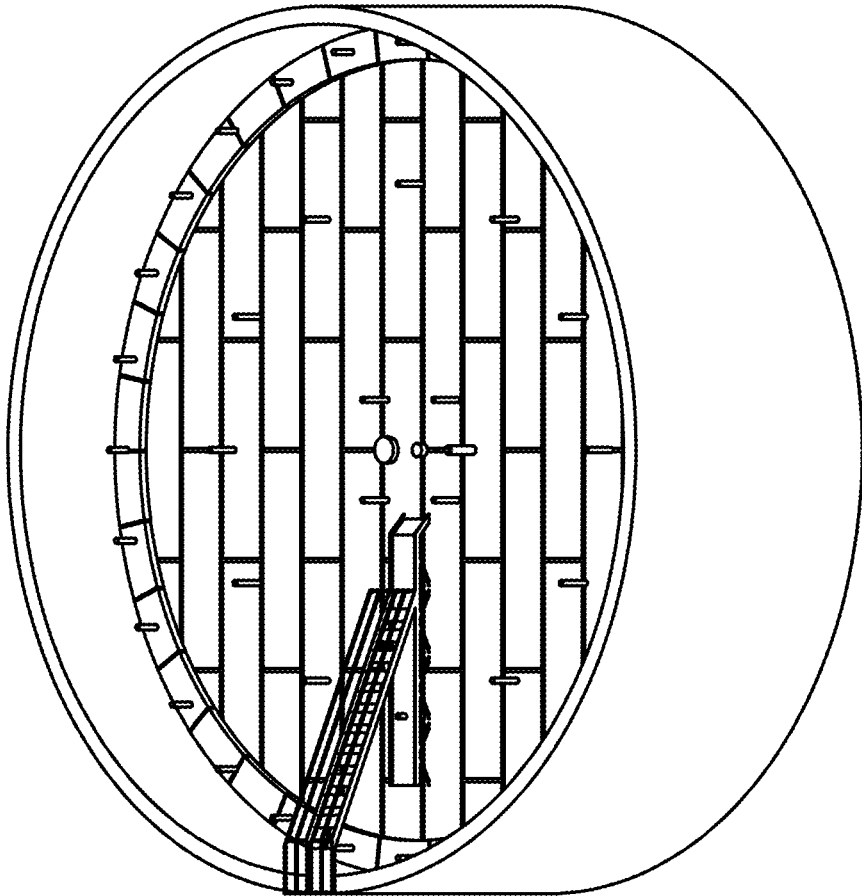


FIG. 18

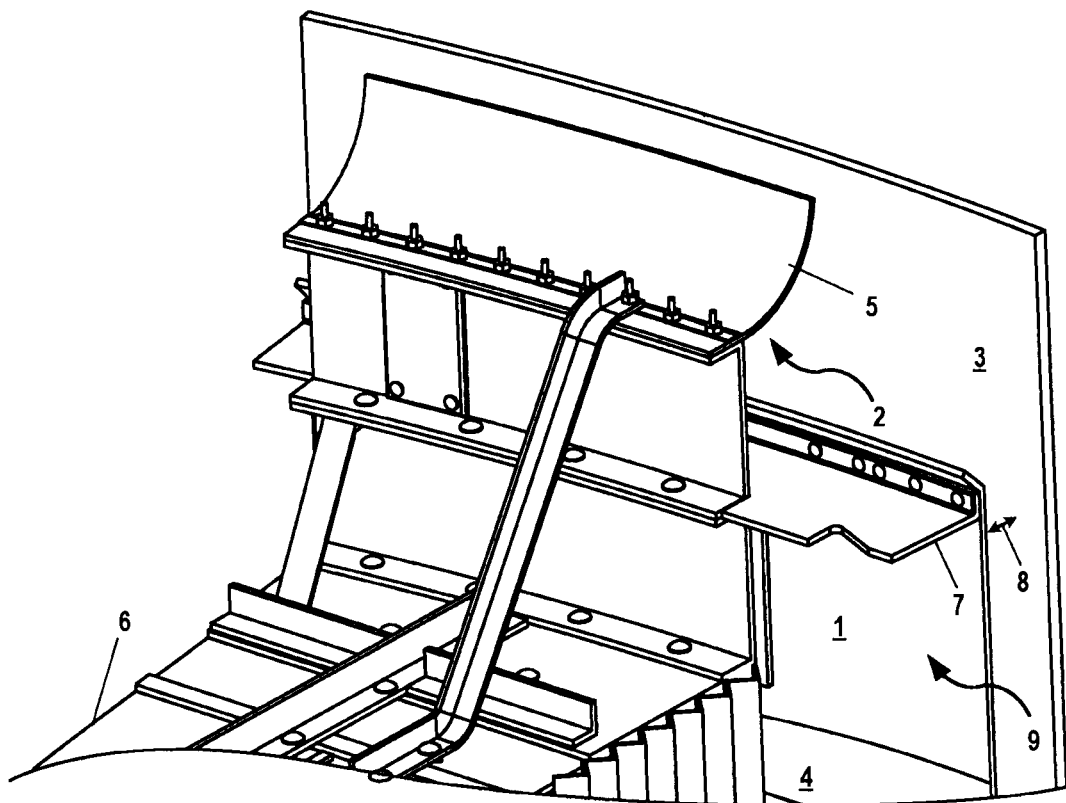


FIG. 19

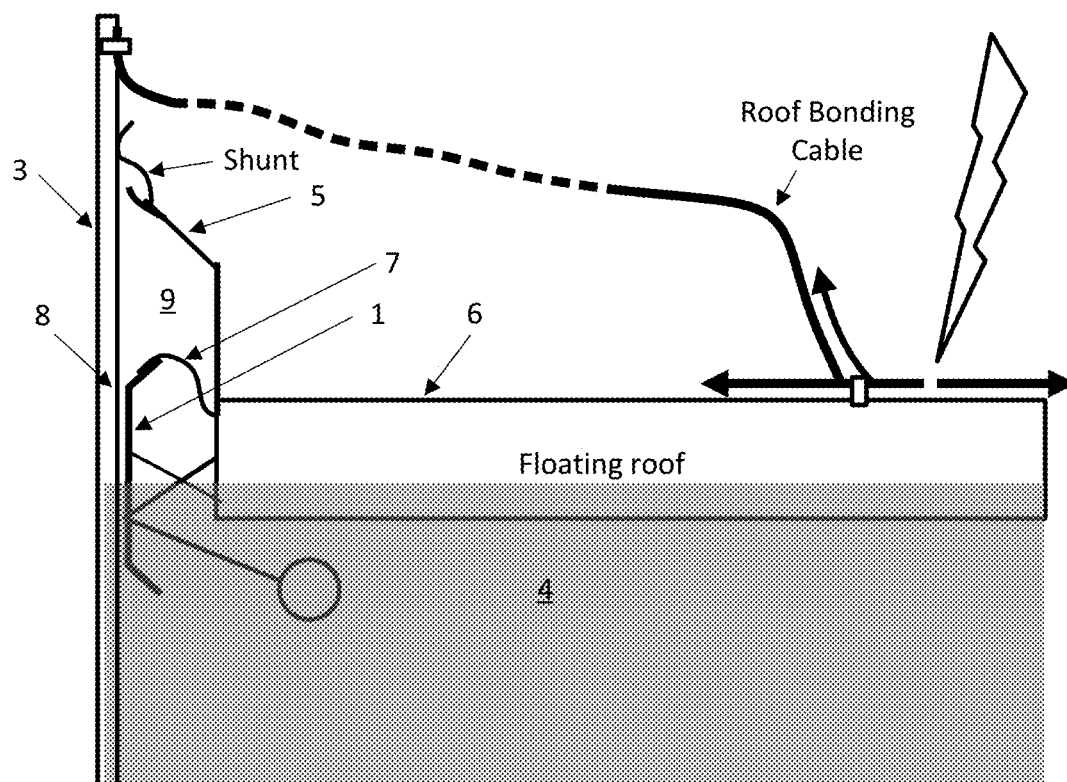


FIG. 20

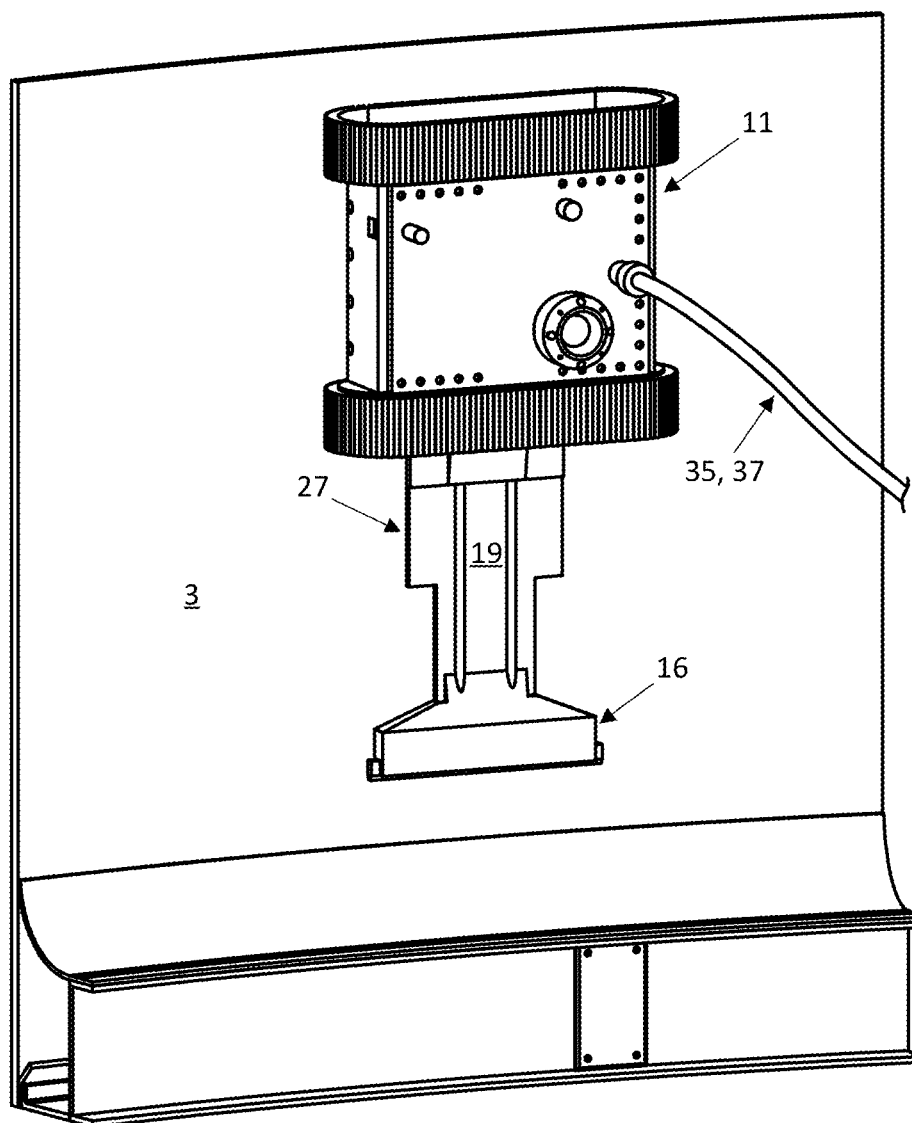


FIG. 21

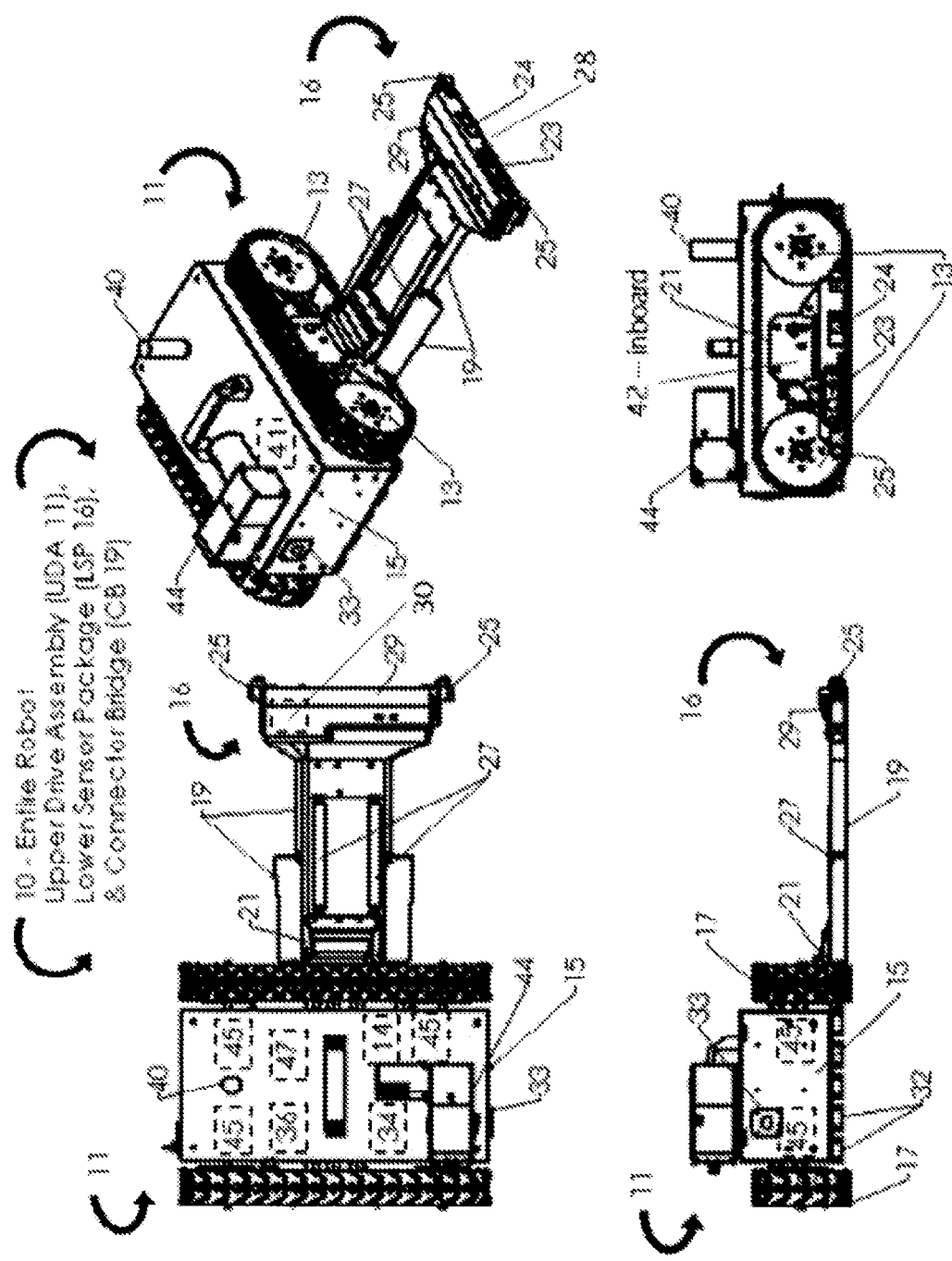


FIG. 22

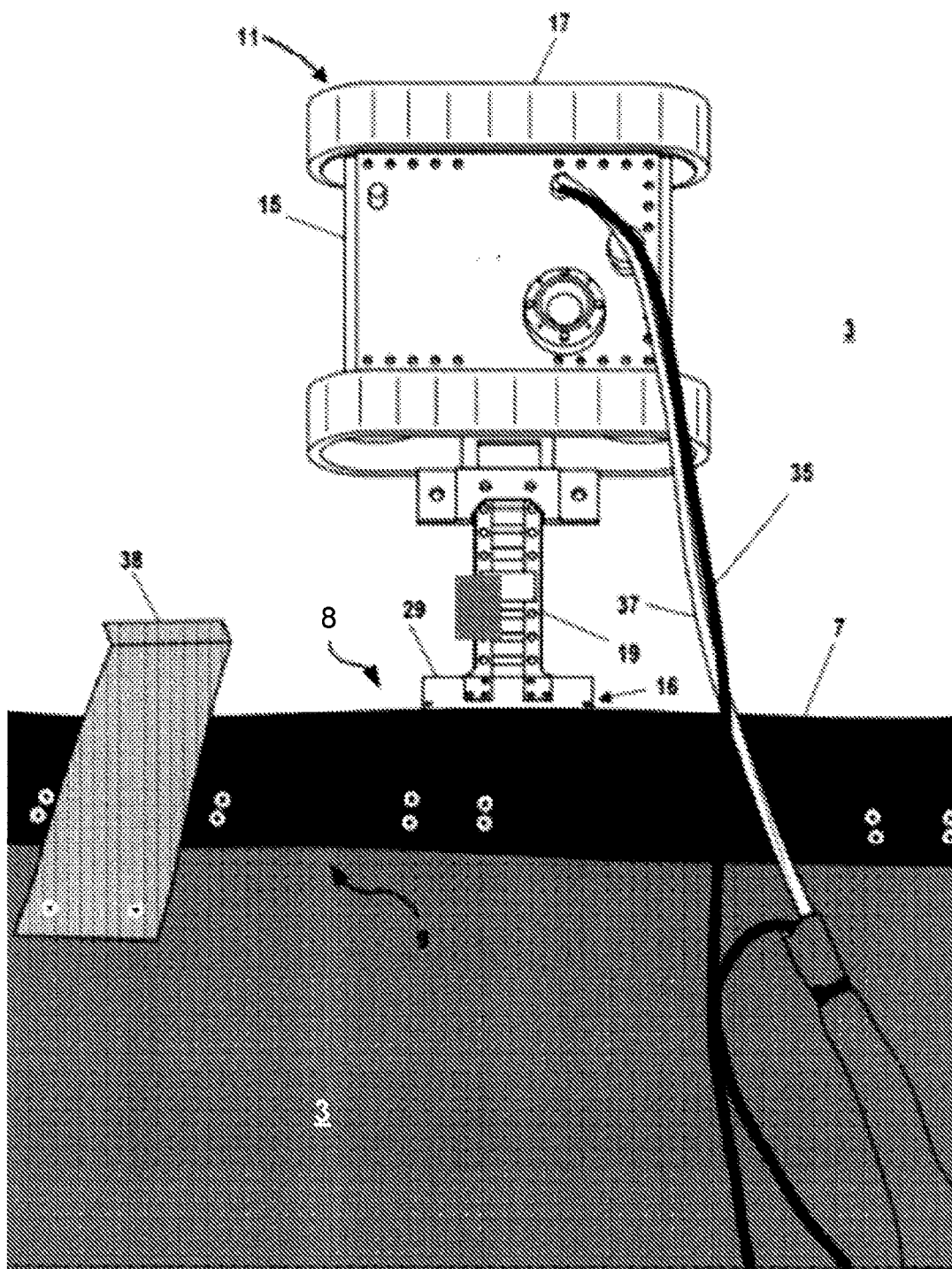


FIG. 23

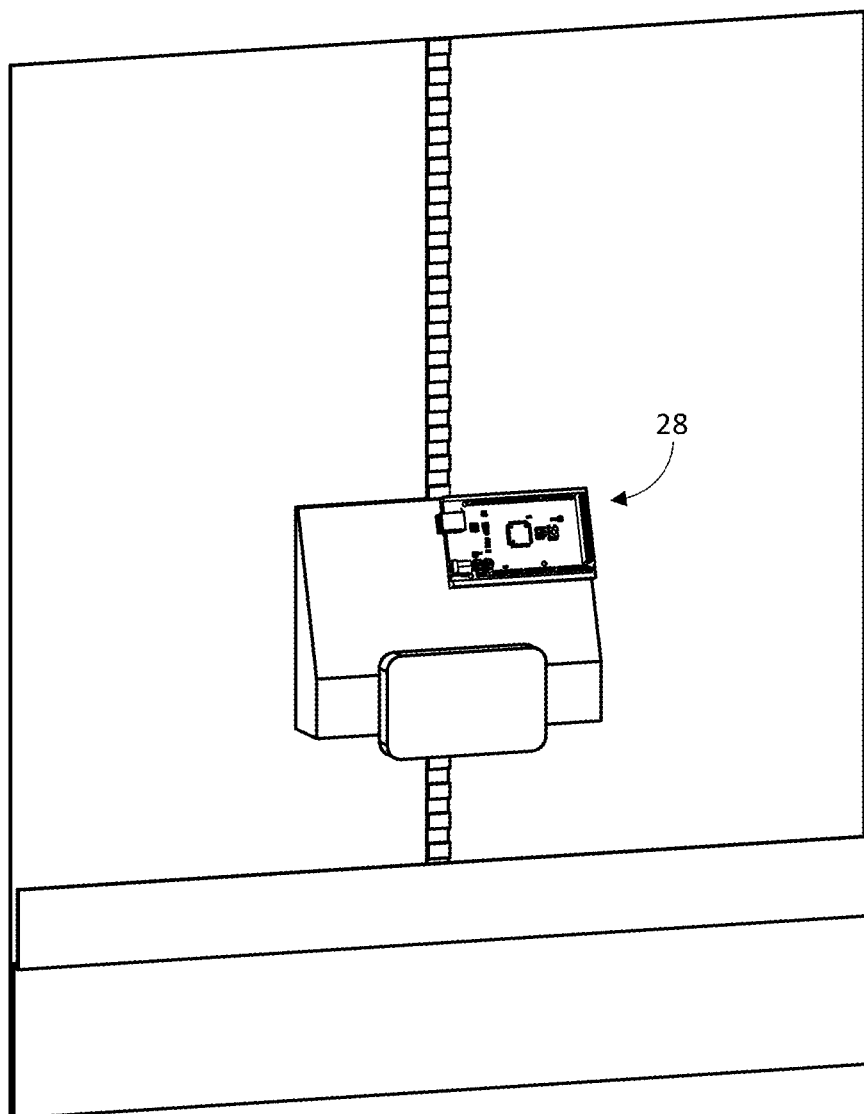


FIG. 24

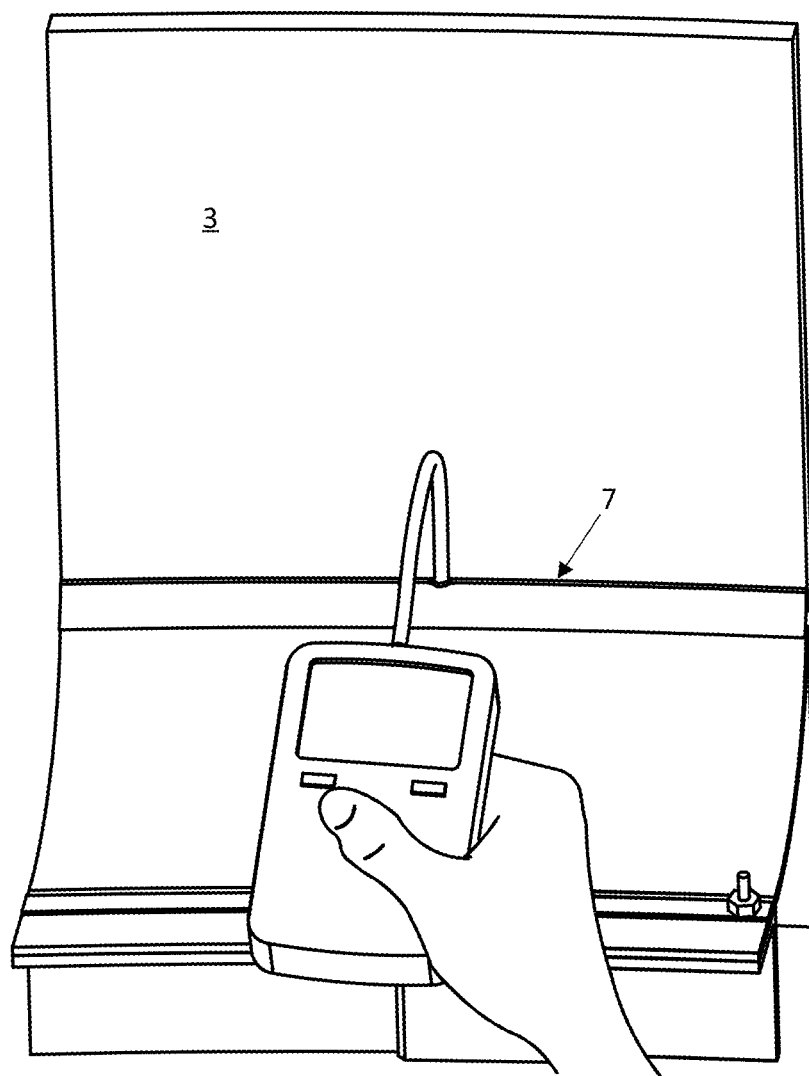


FIG. 25
(PRIOR ART)

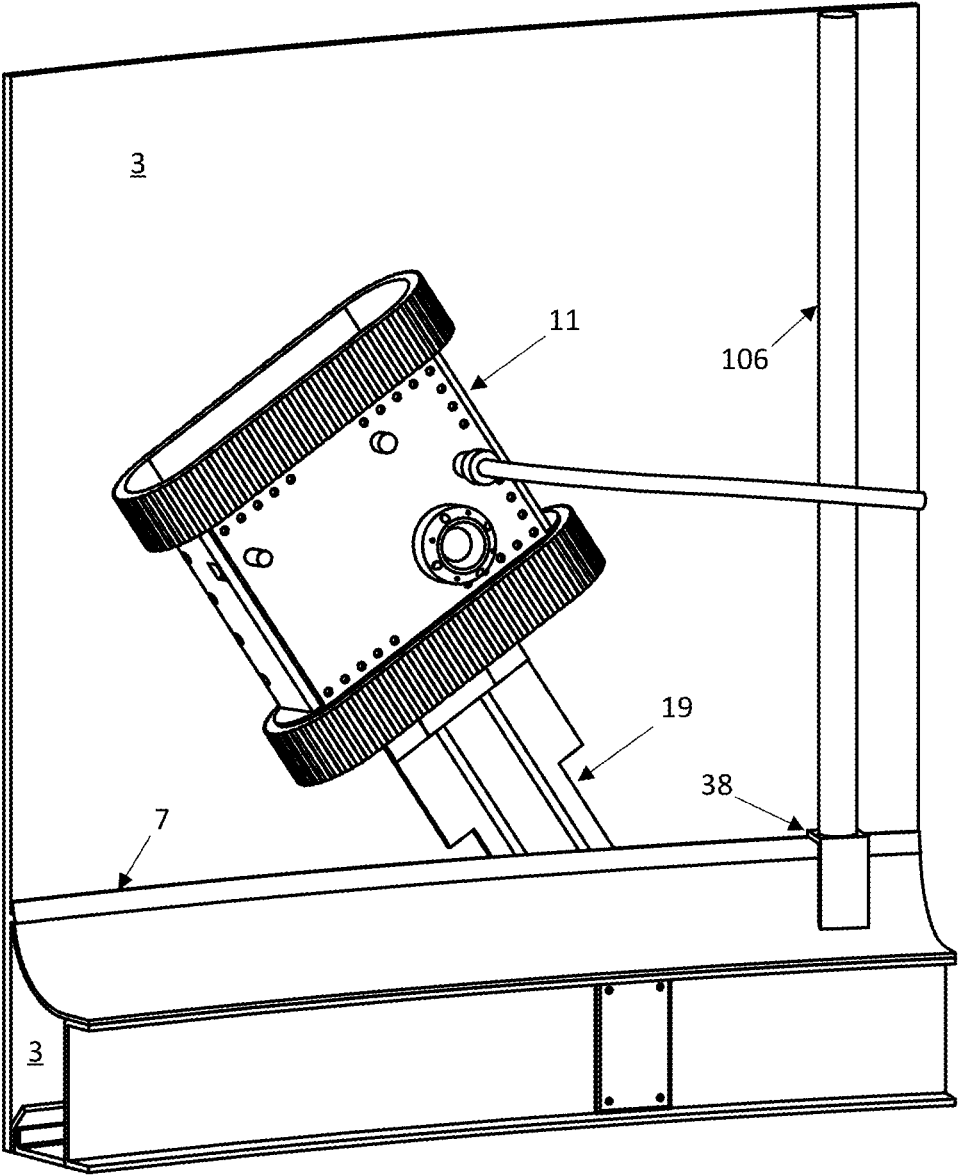


FIG. 26

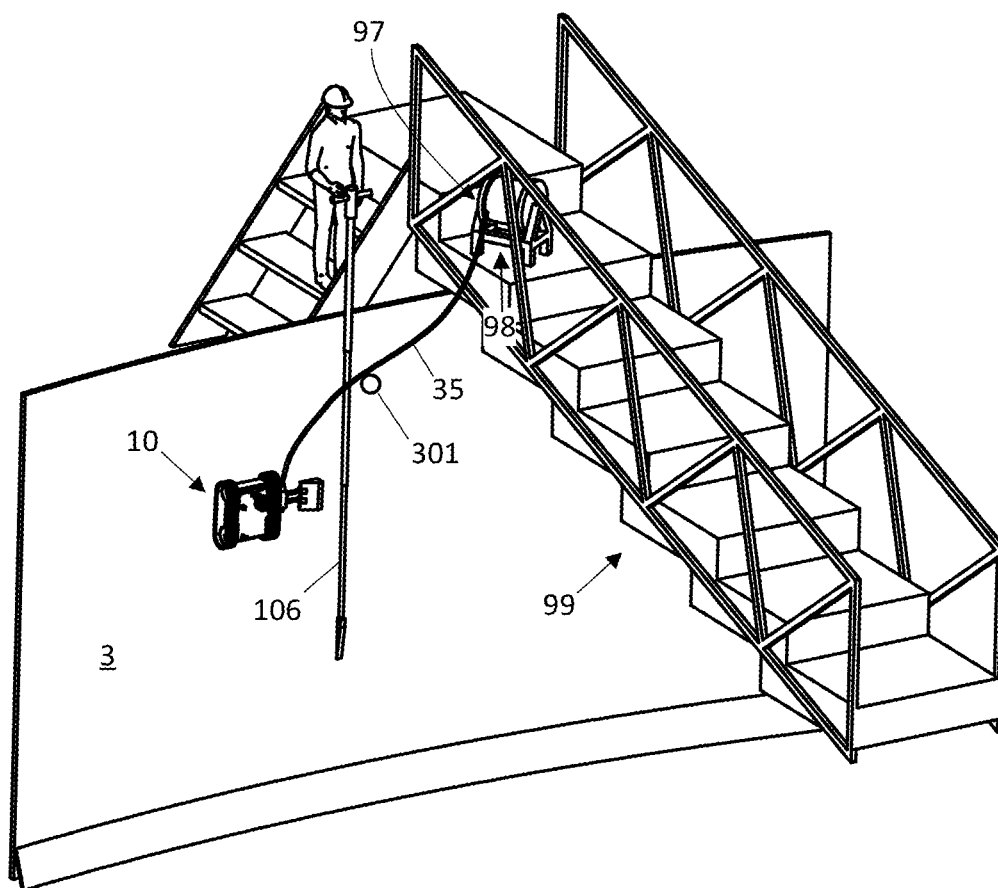


FIG. 27

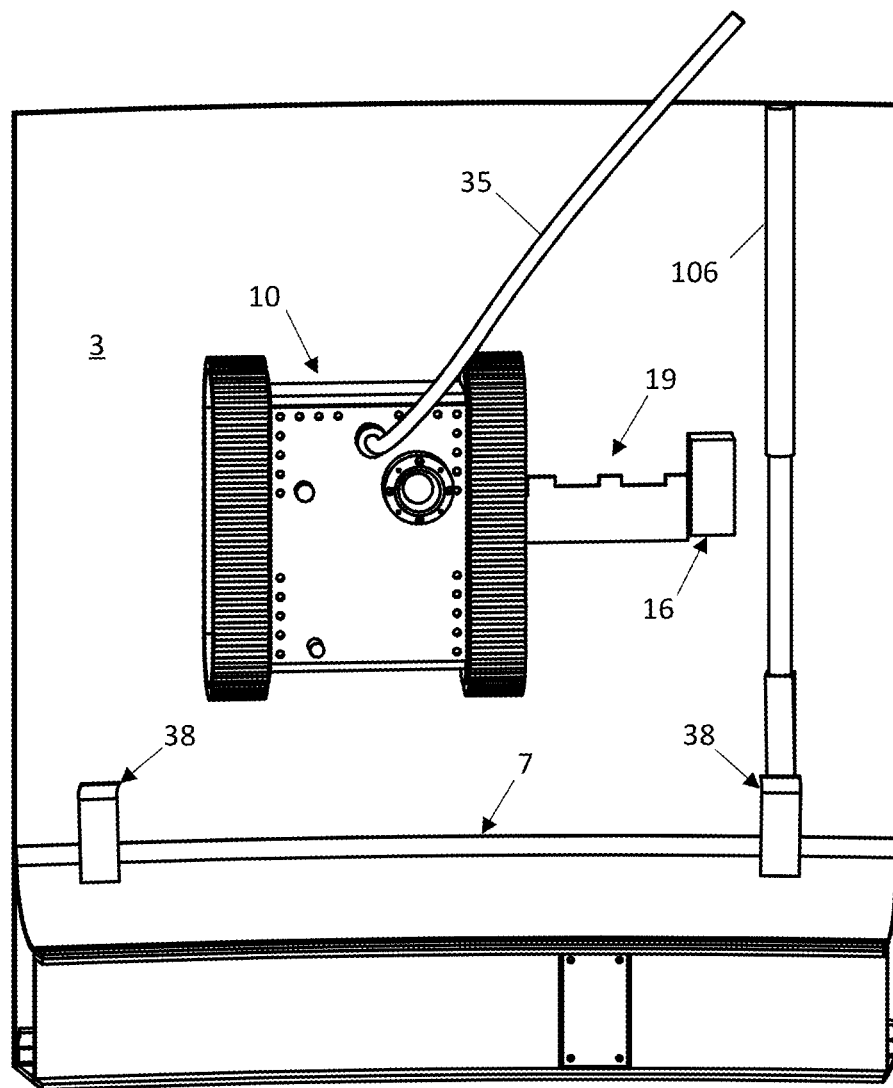


FIG. 28

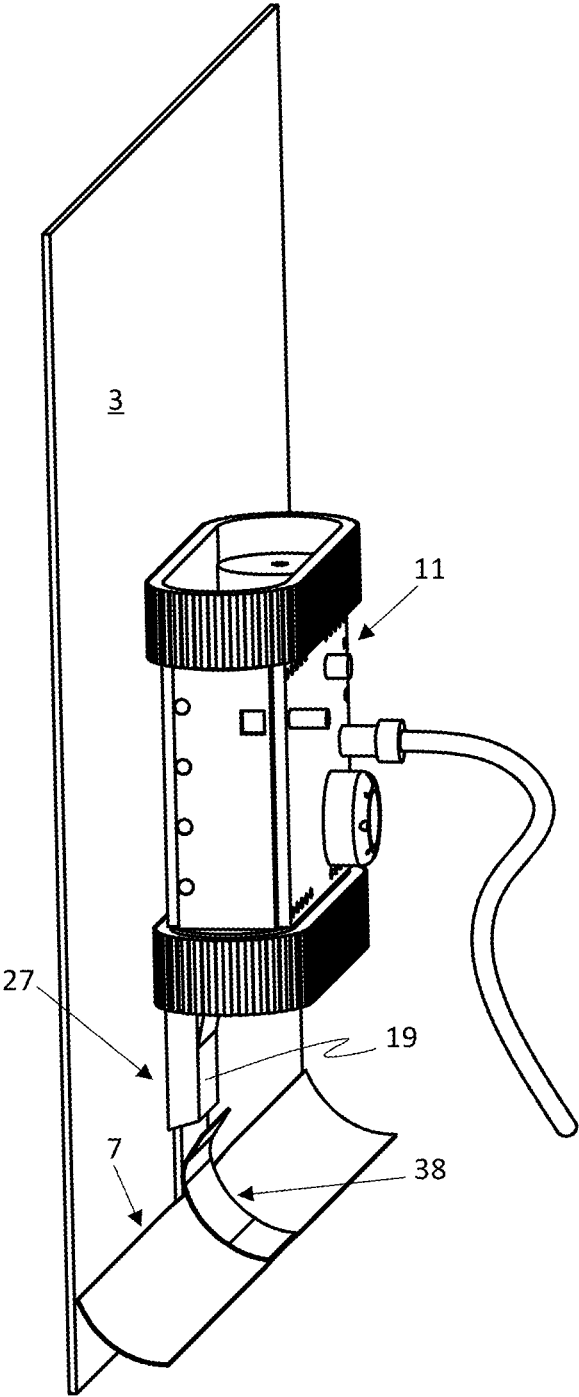


FIG. 29

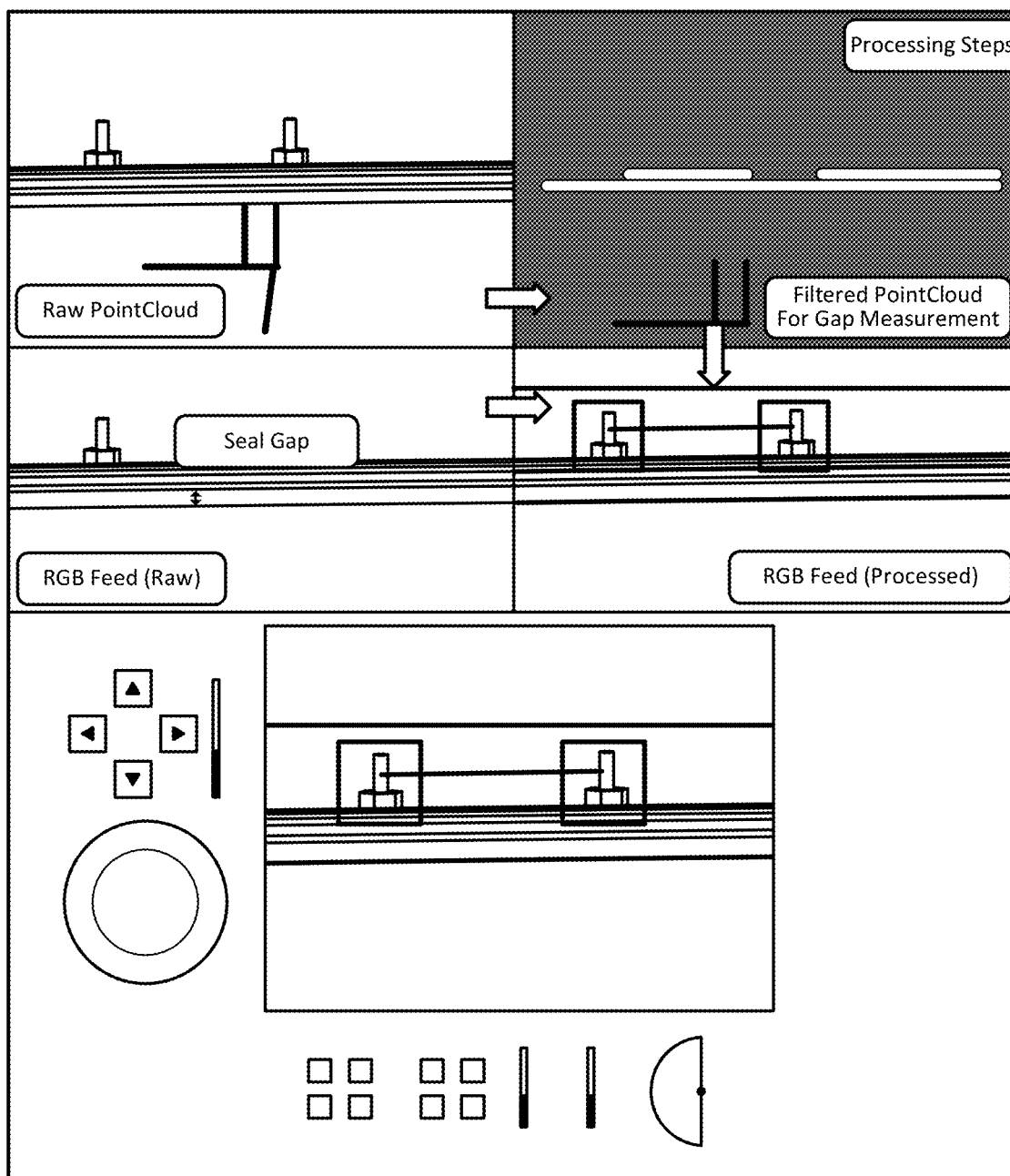
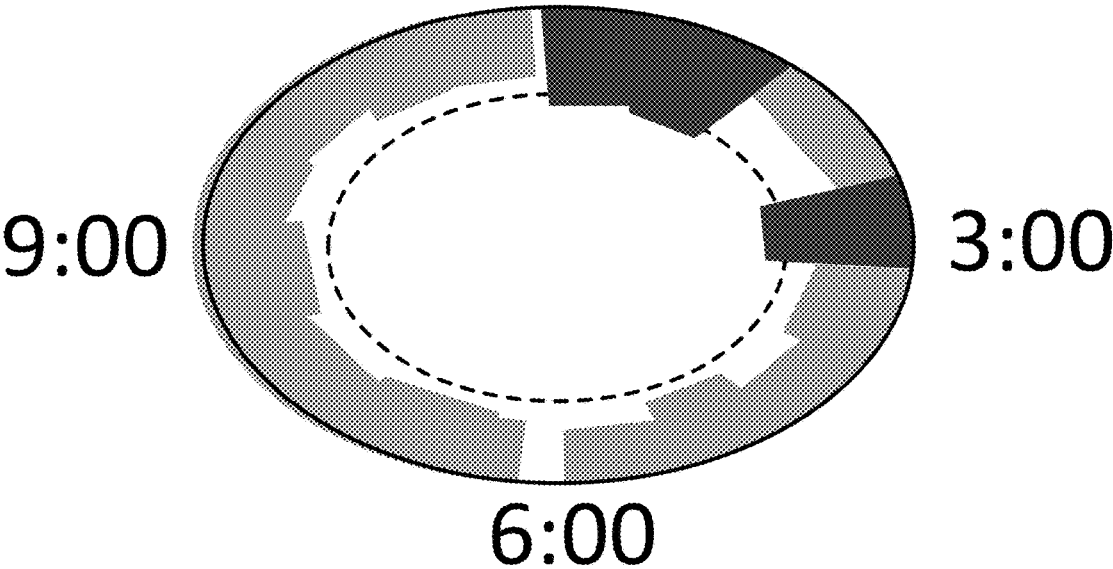


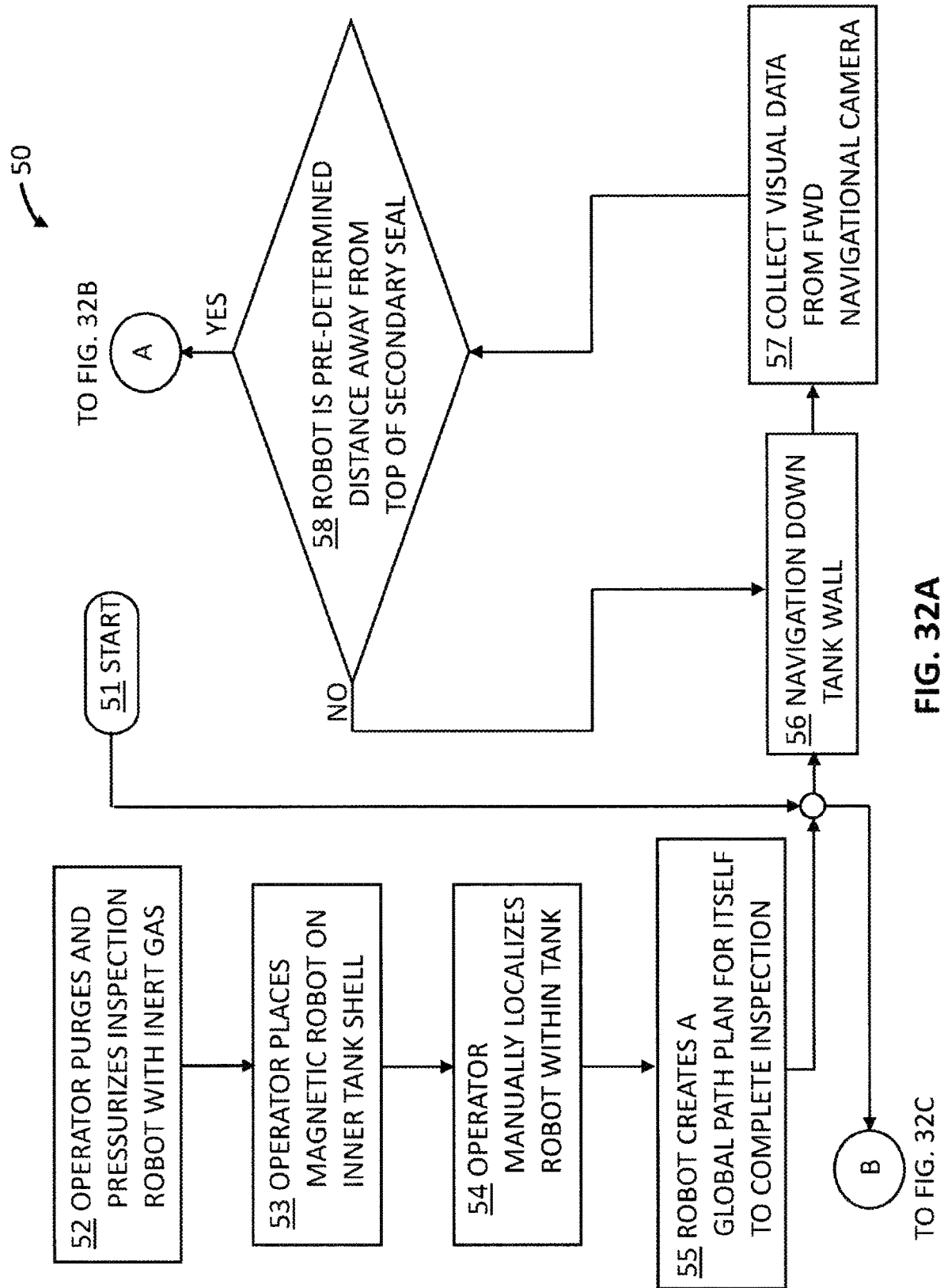
FIG. 30

Inspection Report



Tank Location	Primary, Liquid Seal			Secondary, Vapor Seal Gap		
	Length (in)	Width (in)	Fabric Tears	Length (in)	Width (in)	Rubber Tears
12 to 1	30	0.52				
1 to 2						
2 to 3	15	1.05				
3 to 4						
4 to 5						
5 to 6						
6 to 7						
7 to 8						
8 to 9						
9 to 10						
10 to 11						
11 to 12						

FIG. 31



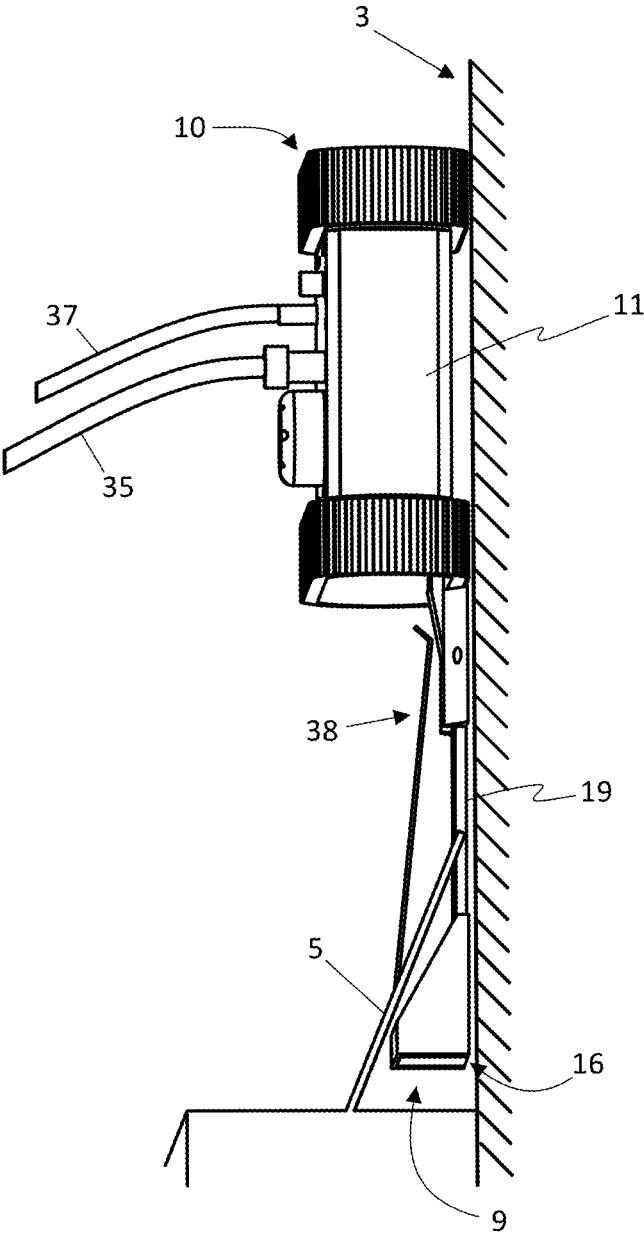


FIG. 33

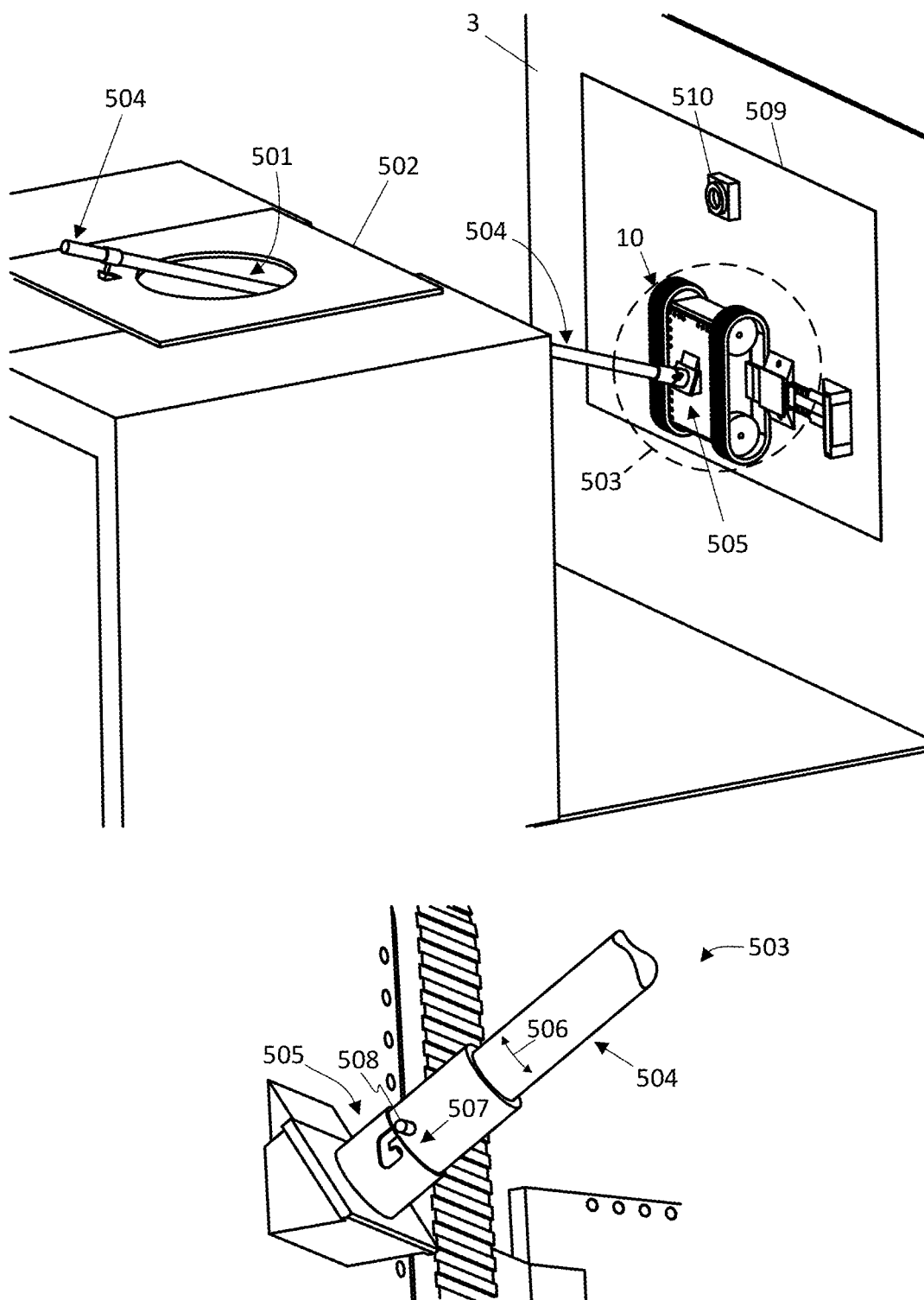


FIG. 34

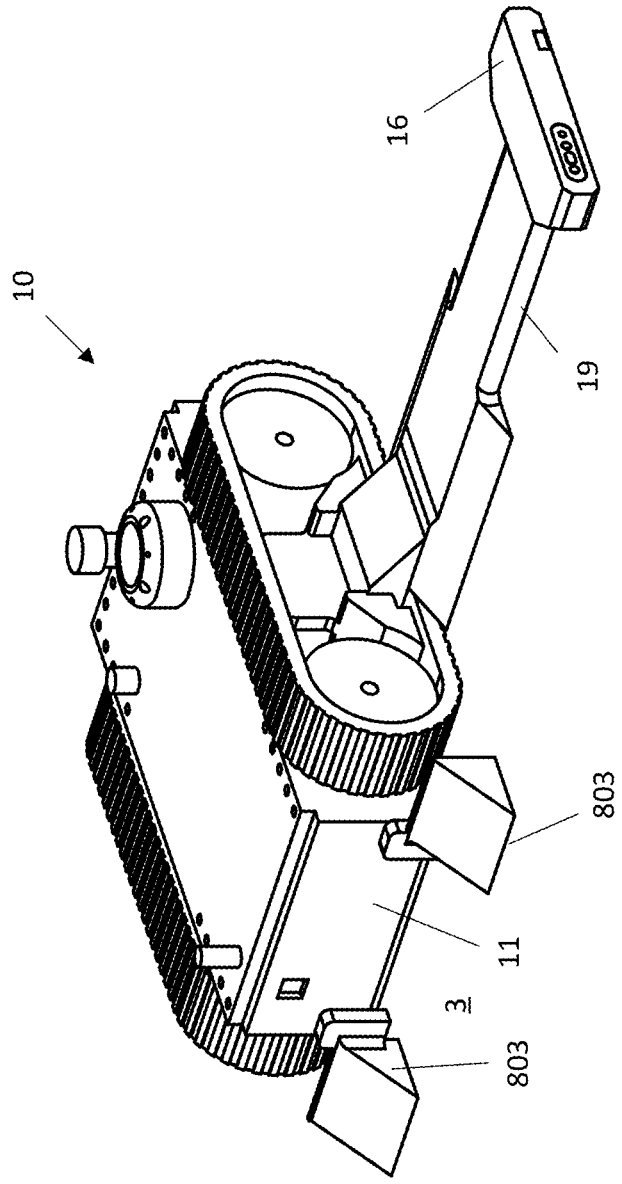


FIG. 36

ROBOTIC SYSTEMS AND METHODS FOR TANK SEAL INSPECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application Ser. No. 17/431,988 filed on Aug. 18, 2021; which claims priority to U.S. Provisional Application Ser. No. 62/811,795 filed Feb. 28, 2019, each of which is incorporated herein by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of the present technology generally relate to robotics. More specifically, some embodiments of the present technology relate to a tank inspection robot and associated methods for performing tank inspections.

BACKGROUND

[0003] Storage tanks can be used to store large quantities of substances. For example, refineries often have large storage tanks of petroleum products on site. The petroleum products can include crude oil, processed gasoline, kerosene, diesel, and the like. Depending on the flashpoint of the product and other factors, the large storage tanks can be fixed roof tanks or floating roof tanks. Fixed roof tanks (e.g., with cone roofs, dome roofs, etc.) are typically used to store liquids with very high flash points. Floating roof tanks are used for liquids with low flash points (e.g., gasoline, ethanol, etc.) and they are usually cheaper to build than fixed roof tanks. The floating roof may be internal or external.

[0004] External floating roof tanks, for example, typically include a cylindrical shell (e.g., made of steel) with an open top. A lid or roof sits within the cylindrical shell and floats directly on the surface of the stored liquid. This design keeps the air out of these storage tanks and prevents vapors from escaping. The lids float on the stored substance. As a result, the lid rises and falls with the liquid level, and there is no vapor space (ullage) in the floating roof tank except possibly in very low liquid level situations.

[0005] There is a seal between the lid and the wall of the tank which can degrade over time allowing for evaporation and product loss. As a result, these tanks must be inspected at regular intervals (e.g., annually, every five years, when tanks are empty, in accordance with internal policy, etc.) to ensure the seal is intact. Unfortunately, the inspection process is time consuming. For example, the inspection personnel are required to manually inspect the seals with full oxygen equipment. Moreover, the process usually requires various safety permits and multiple people onsite during the inspection which can last for several hours depending on the size of the tank.

[0006] Floating roofs used on Above-Ground Storage Tanks sit atop liquid fuel to prevent the formation of flammable vapors. A lower liquid seal and an upper weather seal are in place to contain the vapors. As the level of the product fluctuates, the floating roof moves up and down with it, maintaining a sliding contact with the tank wall. The seal assembly can fail over time due to this motion, which allows vapors to escape, producing an unsafe environment in and around the tank. To know when this has occurred, a manual inspection is required. The weather seal is pulled back and

a judgement is made on the condition of the liquid seal. This inspection may be visual or physical using a dowel rod or other item to determine the spacing between the seal and tank wall. Current manual inspection is dangerous, costly to perform, and imprecise. The inspection typically requires a team of up to 5 humans with oxygen supplies and personal protective equipment (PPE), as well as a rescue team on standby. The safety paperwork to approve a technician on the floating roof is also very onerous.

[0007] Energy producers need a place to store their product once they get it out of the ground. Most of the time they will use an above-ground floating roof storage tank to do the job. These are used in large part due to their ability to reduce evaporative emissions by 98% relative to a fixed-roof style tank. While they do their job exceedingly well, the seals will fail over time and lose their competitive advantage over fixed roof tanks. Vapors will begin to collect in the space between the vapor seal, producing a combustible mixture. The presence of these Volatile Organic Compounds (VOCs) above a certain level dictates that a tank must be taken out of service and repaired. In order to prevent an untimely and costly repair, facility managers will inspect their assets at regular intervals (usually on an annual and quinquennial basis) in order to catch a mechanical defect while it is still simple to repair. The current methodology consists of a visual and physical inspection of the seal assembly around the entirety of the tank circumference. The asset is shut down for influx of product, and a team of 5 persons is sent in to pull back the vapor seal and measure or otherwise evaluate gapping at the liquid seal. If the cumulative gap area around the tank exceeds the allowable threshold, a repair team is sent in.

[0008] The current method of inspecting these seals needs improvement. On the safety and environmental side, there is a risk of injury to the human team by sending them into a confined space. Tank entry is widely recognized as being one of the most hazardous operations in the tank cleaning business and every year results in injuries and deaths. Additionally, poor inspection practices can miss a problem spot on a floating roof seal, allowing an excess emission of volatile organic compounds. This results in contamination of the surrounding facility, as well as the surrounding soil, water, and atmosphere.

[0009] On the cost side, the main issue is the tank downtime associated with inspections. While it may only be a day of down-time with external floating roof inspections, it can be as much as a few weeks to a month for internal floating roofs. This can cost the asset owner \$150,000 a day or \$4,500,000 a month in lost tank productivity. Unnecessary labor and equipment expenses are also concerns for these energy companies, though not to the extent that down-time is. Related to the complexity of the inspection task, the biggest pain point for tank owners is the lost efficiency and headache associated with obtaining hot-work permits (often-times required to send personnel into confined space areas). The actual evaluation or measurement of the seal gap is also prone to human error and requires a large amount of time to complete around the entire circumference of the tank.

[0010] As such, a need exists for improved techniques for inspecting the storage tank seals.

SUMMARY

[0011] Various embodiments of the present technology generally relate to robotics. More specifically, some embodiments of the present technology relate to an integrated

system design for tank seal inspections. Some embodiments provide for a robotic inspection device comprising a power supply, a body, a drive system, one or more cameras, a navigational system, and/or one or more sensors. In some embodiments, the housing may be a rectangle or box-shaped design. In some embodiments, the device is composed of multiple sections with different shapes and sizes. For example, the body of the robotic inspection device can have an upper portion and a lower portion. The lower portion may be smaller than the upper portion allowing for insertion into smaller spaces within the tank (e.g., between a floating lid and side of the wall of the tank). The drive system may include one or more surface engaging drivers (e.g., magnetic wheels, endless tracks, etc.) to propel the robotic inspection device along a surface of a tank. The one or more surface engaging drivers may be positioned, in accordance with one or more embodiments, on a back side and/or on a front side of the robotic inspection device.

[0012] The camera can be housed within the body to capture images and/or video of a seal within the tank. The navigational system can compute a route and send commands to the drive system to navigate the robotic inspection device along the surface of the tank allowing the camera to capture the images or video of the seal. Navigation commands may or may not include a human operator in the control loop. Some embodiments may use an artificial intelligence, machine learning, or other analysis software engine(s) to review the images or video of the seal within the tank and identify problems with the seal. The software engine may be located within the robotic inspection device and/or on a remote computing platform. In some embodiments, the software engine can review the images or video of the seal and schedule additional passes over areas of the seal with identified issues. The issues may include poor image or video quality, fading, cracks, breaks, gaps, discolorations, or the like.

[0013] In some embodiments, the body may include an interchangeable nose section allowing an operator to select the interchangeable nose section with a size and a shape to fit between a weather shield affixed to the tank. The body or interchangeable nose section may include an opening allowing the lens of the camera to view the seal. In addition to the camera, these components of the robotic inspection device may also include one or more light sources (e.g., light emitting diodes) to illuminate an area of the tank (e.g., seal) for inspection. The light source, in some embodiments, may include two rows of multiple light emitting diodes (LED) positioned on opposite sides of the camera.

[0014] Some embodiments may include a manipulator arm having a proximal end coupled to the body of the robotic inspection device and a distal end connected to gripper to engage. The manipulator arm can be used to retract a weather shield on the tank to allow at least a portion of the robotic inspection device be inserted between the weather shield and a wall of the tank. Some embodiments of the robotic inspection device may also include a failsafe system with an independent power source and one or more direct current electromagnets. Upon failure of a primary power source the one or more direct current electromagnets can be automatically engaged to anchor the robotic inspection device to the surface of the tank.

[0015] In some embodiments, a method of operating a robotic inspection device is provided. The robotic inspection device can be lowered into an initial position (e.g., using a

hydraulic lift with cables attached to hooks located on the body of the robotic inspection device). An inspection signal directing the robotic inspection device to inspect a seal of a tank can be received (e.g., from an external computing device or control platform). Then, a magnetic coupling between the robotic inspection device and a wall of the tank can be activated. The robotic inspection device can be navigated so that a camera within the robotic inspection device can view a seal between a floating lid and the wall of the tank. Using the camera, images or video of the seal can be recorded as the robotic inspection device traverses the wall of the tank. In some embodiments, the images or video can be presented to a human operator for analysis. In other embodiments, an artificial intelligence, machine learning, or other analysis engine analyzes the images or video of the seal recorded by the camera. The images or video of the seal can be transmitted to an external computing device that creates a two or three-dimensional model of the seal.

[0016] In accordance with various embodiments, the robotic inspection device operates in a set of states including a setup state, an inspection state, and a failsafe state. The setup state can be used to receive commands from an operator or external computing platform. The inspection state can cause the robotic inspection device to capture sensor data and/or images/video of the seal. The robotic inspection device can monitor for a failure in a primary power supply providing power to the robotic inspection device and transition, upon detection of the failure in the primary power supply, from a current state of operation of the robotic inspection devices to a failsafe state that activates a magnetic coupling between the robotic inspection device and the wall of the tank. Some embodiments may use magnets for the magnetic coupling as the primary holding force in an inspection state which may also then transition to a second set of magnets and/or a secondary power supply if a fault is detected.

[0017] In some embodiments, the robotic inspection device features a system for determining, tracking, and reporting the position and orientation of the vehicle on the tank wall. Such a system may include odometers, gyroscopes, accelerometers, magnetic compasses, and/or GPS components. In embodiments that include a magnetic compass, the system is equipped with a method of calibrating and/or isolating the compass to account for the magnetic fields of the magnets on the vehicle.

[0018] To address the issues with the conventional manual methods of floating roof tank seal inspection, automated robotic systems and methods are provided by the present technology. In this regard, the present technology may be composed of three sub-systems: an inspection robot, an insertion-extraction mechanism, and a tether management system. In some examples of the present technology, the inspection robot may have a bifurcated design, which keeps the bulk of the tethered robot above the weather seal in a configuration akin to an inverted periscope.

[0019] In accordance with various embodiments, a tank inspection robot is provided. The tank inspection robot includes a housing containing a drive assembly. The tank inspection robot also includes wheels disposed inside or outside of the housing and operably coupled to the drive assembly. The tank inspection robot further includes at least one sensor coupled to and/or disposed in or on a portion of the housing. The at least one sensor functions to collect data sufficient to evaluate a gap between one or more

circumferential seals, and a wall, of a storage tank. In some embodiments, the evaluation of the gap according to the present technology may include automated measurement of one or more dimensions of the gap using, e.g., the sensor(s).

[0020] In some embodiments of the present technology, a tank inspection method is provided. The tank inspection method includes the step of actuating, by a drive assembly of a tank inspection robot, wheels of the robot to navigate the robot to one or more circumferential seals positioned proximal an interior wall of a storage tank. The tank inspection method also includes the step of collecting, by at least one sensor on the robot, data sufficient to evaluate a gap between the one or more seals and the wall of the storage tank. In some embodiments, the evaluation of the gap according to the present technology may include automatically measuring of one or more dimensions of the gap using, e.g., the sensor(s).

[0021] Embodiments of the present invention also include computer-readable storage media containing sets of instructions to cause one or more processors to perform the methods, variations of the methods, and other operations described herein.

[0022] In some embodiments of the present technology, one or more non-transitory computer readable media are provided. The one or more non-transitory computer readable media have program instructions stored thereon. When executed by at least one processor of or associated with a tank inspection robot, the program instructions cause the tank inspection robot to direct a drive assembly of the tank inspection robot to actuate wheels of the robot to navigate the robot to one or more circumferential seals positioned proximal an interior wall of a storage tank. When executed by at least one processor, the program instructions also cause the tank inspection robot to direct at least one sensor of the robot to data sufficient to evaluate a gap between the one or more seals and the wall of the storage tank.

[0023] While multiple embodiments are disclosed, still other embodiments of the present invention will become apparent to those skilled in the art from the following detailed description, which shows and describes illustrative embodiments of the invention. As will be realized, the invention is capable of modifications in various aspects, all without departing from the scope of the present invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0025] Embodiments of the present technology will be described and explained through the use of the accompanying drawings.

[0026] FIG. 1 illustrates an example of a tank with a seal that can be inspected by a robotic inspection device in accordance with one or more embodiments of the present technology.

[0027] FIG. 2 illustrates an example of a robotic inspection device according to various embodiments of the present technology.

[0028] FIG. 3 is an illustration that allows various internal components to be seen of a portion of the robotic inspection device illustrated in FIG. 2.

[0029] FIG. 4 is a front view of the robotic inspection device of FIGS. 2-3.

[0030] FIG. 5 is an exploded view showing various components of the robotic inspection device of FIGS. 2-4.

[0031] FIG. 6 is a side view showing various components of the robotic inspection device of FIGS. 2-5.

[0032] FIG. 7 is a perspective view of an electronic assembly that may be used within various embodiments of the present technology.

[0033] FIG. 8 is a view of an example robotic inspection device, illustrating various embodiments of the present technology.

[0034] FIG. 9 illustrates a design of a lower portion of the robotic inspection device shown in FIG. 8.

[0035] FIG. 10 illustrates a view of the robotic inspection device with a lower portion inserted beyond a weather shield on a tank for inspection of a seal in accordance with some embodiments of the present technology.

[0036] FIG. 11 is a view of the back the robotic inspection device that may be used in various embodiments of the present technology.

[0037] FIG. 12 is a flowchart illustrating an example of a set of operations for using the robotic inspection device in one or more embodiments of the present technology.

[0038] FIG. 13 is a flowchart illustrating an example of a set of operations for generating inspection data via the robotic inspection device in some embodiments of the present technology.

[0039] FIG. 14 illustrates a set of components of the robotic inspection device that may be used in various embodiments of the present technology.

[0040] FIG. 15 illustrates an example of a graphical user interface that may be used in one or more embodiments of the present technology.

[0041] FIG. 16A-16C illustrates example of images collected and processed to identify degradation of a seal according to some embodiments of the present technology.

[0042] FIGS. 17A and 17B illustrate examples of functional block diagrams illustrating logical interconnections that may be created between various components of the robotic inspection device according to various embodiments of the present technology.

[0043] FIG. 18 presents a typical open-roof or external floating roof storage tank (FRT).

[0044] FIG. 19 illustrates a specific part of that storage tank known as the floating roof seal assembly.

[0045] FIG. 20 provides a cross-section view of a typical seal used on open-topped floating roof tanks.

[0046] FIG. 21 depicts a tank inspection robot deployed on an interior wall of an FRT in accordance with some embodiments of the present technology.

[0047] FIG. 22 illustrates top, side, front and perspective views of the robotic inspection device in accordance with some embodiments of the present technology.

[0048] FIG. 23 illustrates an in-situ view of a tank inspection robot in accordance with some embodiments of the present technology.

[0049] FIG. 24 depicts deployable resistance probe (DRP) of a tank inspection robot in accordance with some embodiments of the present technology.

[0050] FIG. 25 depicts gas concentration measurement in an FRT according to a known manual inspection technique.

[0051] FIG. 26 depicts manipulation of an FRT upper vapor seal by an insertion and extraction tool.

[0052] FIG. 27 illustrates deployment of a tank inspection robot with a tether management system according to some embodiments of the present technology.

[0053] FIG. 28 depicts deployment of a tank inspection robot with an attached tether and an insertion and extraction tool according to some embodiments of the present technology.

[0054] FIG. 29 depicts a tank inspection robot navigating around obstacles present on an interior wall of an FRT in accordance with some embodiments of the present technology.

[0055] FIG. 30 illustrates aspects of a seal integrity detection process with a computer vision algorithm utilizing data collected by a tank inspection robot in accordance with some embodiments of the present technology.

[0056] FIG. 31 is a tank inspection report originating with a tank inspection robot in accordance with some embodiments of the present technology.

[0057] FIGS. 32A-32F illustrate a flow charts of a tank inspection method in accordance with some embodiments of the present technology.

[0058] FIG. 33 illustrates a side view of the robotic inspection device with its lower sensor package inserted in a space under an upper vapor seal (UVS) and with its connect bridge in contact with the UVS in accordance with some embodiments of the present technology.

[0059] FIG. 34 illustrates deployment of the robotic inspection device into an enclosed space of a storage tank having a roof and a manway in accordance with some embodiments of the present technology.

[0060] FIG. 35 illustrates an example of a computer architecture that may be used in some embodiments of the present technology.

[0061] FIG. 36 illustrates a tank inspection robot having a plow mechanism according to some embodiments of the present technology.

[0062] The drawings have not necessarily been drawn to scale. Similarly, some components and/or operations may be separated into different blocks or combined into a single block for the purposes of discussion of some of the embodiments of the present technology. Moreover, while the technology is amenable to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and are described in detail below. The intention, however, is not to limit the technology to the particular embodiments described. On the contrary, the technology is intended to cover all modifications, equivalents, and alternatives falling within the scope of the technology as defined by the appended claims.

DETAILED DESCRIPTION

[0063] Various embodiments of the present technology generally relate to robotics. More specifically, some embodiments of the present technology relate to an integrated system design for tank seal inspections. Oil and gas producers (among other types of companies) own many large tanks which have a “floating” roof. This roof moves up and down as the volume of material in the tank ebbs and flows. The seal between the roof and the wall of the tank must be inspected periodically, and inspection typically requires a

human technician with an oxygen supply and a medical team on standby. The seals are often referred to as a “foam log” or a “wiper.” The seal is often protected by a weather shield which must be lifted by the inspection technician. Historically, the technician manually inspects the seal and judges whether the condition of the tank seal is acceptable. The safety paperwork to approve a technician on the floating roof is onerous.

[0064] To avoid the expense associated with an oxygen supply and a medical team on standby, various embodiments of the present technology provide for a robotic inspection device which includes a camera and/or other sensors. The camera could be any combination of a traditional color camera, a stereo camera, a depth camera, or several other types of data collection systems. The robot can be lowered from the rim of the tank and inserted under the weather shield (if it exists). Then, the robotic inspection device would propel itself around the circumference of the tank, collecting data on the condition of the seal. An electromagnet (or magnet, or suction) might be used to hold the robot against the tank wall in some embodiments. As the robot traverses the tank, camera data can be saved. In some embodiments, a digital model of the tank seal can be recreated.

[0065] Various embodiments of the present technology provide for a wide range of technical effects, advantages, and/or improvements to tank inspections. For example, various embodiments include one or more of the following technical effects, advantages, and/or improvements: 1) use of an automated (or semi-automated) robotic inspection device to reduce or eliminate the lengthy approval process, oxygen supply, and a backup medical team that have historically made it very expensive to perform tank seal inspections with human technicians; 2) unconventional operations for the recreation of a high-fidelity 3D model of the tank seal; 3) integrated use of machine learning and/or artificial intelligence to automatically identify potential issues with the seal; 4) use of non-routine operations for reduction or removal of human judgment in seal inspections; 5) creation of detailed documentation; 6) the use of real-time feedback of video and sensor data to focus inspection on potential problem areas; and/or 7) use of interchangeable segments to allow for proper fitting of multiple different tank designs and configurations.

[0066] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present technology. It will be apparent, however, to one skilled in the art that embodiments of the present technology may be practiced without some of these specific details. The robot can include various special-purpose hardware, programmable circuitry appropriately programmed with software and/or firmware, and the like.

[0067] The phrases “in some embodiments,” “according to some embodiments,” “in the embodiments shown,” “in other embodiments,” and the like generally mean the particular feature, structure, or characteristic following the phrase is included in at least one implementation of the present technology, and may be included in more than one implementation. In addition, such phrases do not necessarily refer to the same embodiments or different embodiments.

[0068] There are an estimated 150,000 above-ground floating roof storage tanks in the U.S., which have a perimeter seal that reduces harmful evaporative emissions. These

roof seals float up and down with the level of product and will fail over time. As such, regular inspection is required to ensure they are functioning properly. Known methods consist of a 5 person human crew sent down into the tank to physically inspect the liquid-vapor seal. There are significant safety concerns associated with this process, a financial operating loss due to down-time of the tank, and issues with the accuracy and speed of the inspection. Robotic inspection techniques present opportunities to improve upon conventional methods on a variety of levels.

[0069] FIG. 1 illustrates an example of a tank **100** with a seal that can be inspected by a robotic inspection device in accordance with one or more embodiments of the present technology. More specifically, FIG. 1 illustrates a typical external floating roof tank that can be used by various refineries or storage facilities. While FIG. 1 shows an external floating roof tank **100**, the robotic inspection device may be used within other tank designs such as but not limited to internal floating roof tanks.

[0070] External floating roof tanks typically include a cylindrical shell **105** which can be made of steel or other metal depending on the stored liquid. The cylindrical shell **105** is open at the top and includes a floating lid **110**. In the embodiments illustrated in FIG. 1, the floating lid **110** is a double decker lid that includes a top deck **115** and a bottom deck **120**. The floating lid **110** is slightly smaller in diameter than the diameter of the cylindrical shell **105**. The floating lid **110** sits atop the liquid within the tank and will rise or fall with the liquid level. In some designs, floating lid **110** may sit on pontoons floating on the liquid. As a result, there is little or no space between the bottom of lid **110** and the top of the liquid internal to the tank **100**.

[0071] While not illustrated in FIG. 1, the floating lid **110** may include vents and/or access ports to allow inspection personnel to view or gain access to the inside of the tank **100**. Around the floating lid **110** sits a seal to provide an airtight connection between the floating lid **110** and the cylindrical housing **105**. Robotic inspection device **125** can be lowered down the inner wall of the cylindrical housing **105**. The right side of FIG. 1 provides a cross section of an enlarged portion of the seal between the floating lid **110** and the cylindrical housing **105**.

[0072] Attached to the upper deck **115** is a weather shield **130**. A seal assembly can be positioned underneath the weather shield **130** and between the cylindrical wall **105** and floating lid **110**. In the embodiments shown in FIG. 1, the seal assembly can include a hanging bar **135** attached to the floating lid **110** to secure seal envelope **140** with seal support ring **145** and resilient urethane foam **150**.

[0073] FIG. 2 illustrates an example of a robotic inspection device **125** according to various embodiments of the present technology. As shown in FIG. 2, robot inspection device **125** is a smaller robot that passes entirely underneath the weather shield (see, e.g., weather shield **130** in FIG. 1). A typical weather shield will restrict the robot height to less than six inches and the robot width to less than eighteen inches. Some embodiments may have a height equal to or greater than six inches and/or a width equal to or greater than eighteen inches. Length is a less critical dimension and can be minimized to maximize the robot mobility.

[0074] As illustrated in FIG. 2, the robot inspection device may include a housing **205** (e.g., having a rectangular shape). The housing can be made from a variety of materials including, but not limited to, plastics, metals, composite

materials, or the like. In accordance with various embodiments, the material may be suitable for deployment in explosive vapor environments and be compliant with regulations pertaining to those environments. For example, the material must not produce sparks due to contact with other objects and be rugged enough to survive outdoor environments. Housing **205** can enclose a variety of components such as, but not limited to power sources (e.g., a battery), processors, controller, drive assemblies, magnetic coupling assemblies, sensors, lights, drive motors, and/or other components.

[0075] In the embodiments shown in FIG. 2, the drive motors are connected to wheels **210** (e.g., larger drive wheels and smaller idler wheels) allowing the robotic inspection device to drive around the tank in the space between the weather shield and seal. Camera **215** can be mounted on or within housing **205** (e.g., on each side) to capture images of the seal. The embodiments of robotic inspection device **125** shown in FIG. 2 are designed to pass underneath the weather shield. As such, a worker can pull the weather shield back during initial deployment. Since robotic inspection device **125** cannot be seen by the operator (since the robotic inspection device is concealed by the weather shield) a navigation system can be used to track the robot position under the weather shield. Flashlights **220** can illuminate an area underneath the weather shield.

[0076] In some embodiments, robotic inspection device **125** can be teleoperated and/or equipped with object manipulation and detection capabilities provide a safe option for executing dangerous tasks in hazardous environments without putting humans at direct risk. In the embodiments shown in FIG. 2, tether attachment point **225** can be used to attach a tether allowing commands from an operator to be processed. In some embodiments, robotic inspection device **125** may also include wireless components to receive commands without attachment of the tether. In addition, various embodiments may include a variety of components (e.g. housed within housing **205** or on an ground-station computer) to provide environmental awareness. Examples include, but are limited to displays for video feed navigation and use of assisted or automated video analysis tools to determine size of fixture gaps. Static magnet **230** can be activated to secure robotic inspection device to a magnetic wall of the tank or portion of the weather shield.

[0077] FIG. 3 is an illustration **300** that allows various internal components to be seen of a portion of the robotic inspection device **125** illustrated in FIG. 2. In the embodiments illustrated in FIG. 3, robotic inspection device **125** can include one or more apertures allowing for camera assemblies **310** within housing **205** to capture video, images, or data. Apertures may also allow light (e.g., from an LED within the housing) to illuminate the area under the weather shield.

[0078] Drive motors (e.g., servos) **315** may be mounted on chassis mount **320** and be part of a differential drive system allowing the drive wheels **210** to independently move. Servo-axle couplings As such, by changing the relative rate of rotation of drive wheels, robotic inspection device **125** can navigate obstacles or reach desired destinations without additional steering components. While various embodiments may include load-bearing wheels and/or drive wheels, alternative surface-engaging drivers such as endless tread (e.g., tracks) may be used in some embodiments. Note that the drive system will have to be sufficient to overcome the

friction between the vehicle and the weather shield. Otherwise, the robotic inspection device **125** could get stuck.

[0079] Computational device **330** can be configured to take instructions from a remote operator and translate those commands into a tasks to be completed by the robotic inspection device. In accordance with various embodiments, computational device **330** can provide control and integration of various sub-systems (e.g., vehicle motion, environmental awareness and detection, navigation, etc.). In some embodiments, the vehicle motion can be computed and set to change vehicle motion, servo speed/torque, estimate or determine vehicle velocity and drift. The computational device may decide to maintain vehicle position, engage or disengage magnetic couplings (e.g., block and/or wheel magnets, determine orientation of the vehicle, or the like. In some embodiments, computational device **330** can determine the size of a gap using depth camera, initialize and calibrate various cameras to improve 3D images, or the like. In the embodiments illustrated in FIG. 3, computational device **330** can be communicably coupled to inertial measurement unit (IMU) board **335**.

[0080] The robotic inspection device may also include voltage converters **340** to change the voltage levels received through tether attachment point **225** (or from one or more internal power supplies) from one voltage to another (e.g., from 12 volts to 5 volts or 3.3 volts). Power distribution units **345** can then provide appropriate power to the various components (e.g., computational device **330**, drive motors **315**, IMU board **335**, flashlights **350**, etc.).

[0081] FIG. 4 is a front perspective view **400** of the robotic inspection device of FIGS. 2-3. As illustrated in the embodiments shown in FIG. 4, component **405** is an example of a location of a support wheel or caster on the bottom of the vehicle towards the rear. One, two, or more such support wheels or casters may be used. Component **410** illustrates possible locations for the adhesion magnets. The number, shape, strength, and locations of the magnets may vary. Magnets may be located closer to the edges of the vehicle bottom. Magnets may be installed on the wheels instead of, or in addition to, the vehicle bottom.

[0082] FIG. 5 is an exploded view **500** showing various components of the robotic inspection device of FIGS. 2-4. Component **315** is the motors for the drive wheels **210**. Component **310** is the side-vision cameras. The specific make and model of the cameras may vary. Component **320** is the mounting subassembly for the drive motors. Component **325** is the onboard computer. FIG. 6 is a side view **600** showing various components of the robotic inspection device of FIGS. 2-5. In addition to side camera **215** and static magnet **410**, the embodiments shown in FIG. 6 also include serial controller and sensor board **610** which provides an interface to the various components and sensors within the robotic inspection device. FIG. 7 is a perspective view **700** of an electronic assembly that may be used within various embodiments of the present technology.

[0083] While robotic inspection device **125** illustrated in FIG. 2 is designed to fit entirely underneath the weather shield. Other embodiments may include housing designs that only partially fit underneath the weather shield. One advantage of these embodiments is that it allows the operator to visually see the location of the robotic inspection device. FIG. 8 is a view of a robotic inspection device **125** in accordance with various embodiments of the present technology. As shown in FIG. 8, robotic inspection device

125 inspection device can have a body with an upper portion **805** and a lower portion **810**. Within the upper portion **805** and/or the lower portion **810**, the robotic inspection device **125** can include various power sources (e.g., a battery), processors, controller, drive assemblies, magnetic coupling assemblies, sensors, lights, drive motors, and/or other components. The lower portion **810** may be smaller than upper portion **805** to allow the lower portion **810** to pass the weather shield and visually access the seal between the floating lid and the cylindrical shell of the tank. The upper portion **805** may be attached to cables **815A** and **815B** for lowering and raising the robotic inspection device into place. In addition, some embodiments may use tether **820** for providing additional power and/or communication between external computing devices and the robotic inspection device. Tether **820** may include a Kevlar covering to protect the internal cables providing the power and communications.

[0084] The cables **815A** and **815B** may be connected to any of eyebolts **825A-825E**. Once the device is set into place, a magnetic or suction based engagement system may be used to secure the robotic inspection device **125** to the wall. The cables **815A** and **815B** can be unclipped and removed from the robotic inspection device **125**. A pair of load-bearing wheels **830A-830B** may be located outside of lower portion **810**. Additional wheels may be located on the opposite side of the robotic inspection device (see, e.g., FIG. 11). Each of these wheels may be powered by a drive assembly (not shown) or rotate freely.

[0085] In addition, to load-bearing wheels **830A-830B**, various embodiments may also include drive wheels (see, e.g., FIG. 11, wheels **1110A-1110B** and **1110D-1110E**) which may be part of a differential drive system allowing the drive wheels to independently move. As such, by changing the relative rate of rotation of drive wheels **1110A-1110B** and **1110D-1110E**, robotic inspection device **125** can navigate obstacles or reach desired destinations without additional steering components. While various embodiments may include load-bearing wheels **830A-830B** and/or drive wheels **1110A-1110B** and **1110D-1110E** (in FIG. 11), alternative surface-engaging drivers such as endless tread (e.g., tracks) may be used in some embodiments.

[0086] While not illustrated in FIG. 8, some embodiments of the robotic inspection device **125** may include a manipulator arm. The manipulator arm can be connected to a portion of the body (e.g., upper portion **805** or lower portion **810**) of the robotic inspection device **125**. For example, a proximal end of the manipulator arm can be coupled to the body and a distal end connected to one or more tools (e.g., a gripper for lifting the weather shield or grabbing the seal, a rod for prodding the seal, additional cameras, and the like) for inspecting and/or gaining access to the seal. The manipulator arm can include multiple segments connected by actuated joints to allow the manipulator arm flexibility in performing desired tasks.

[0087] The design of tank seals varies and there is no guarantee that one robot design will work for all tank types. As such, various embodiments allow for interchangeable segments and/or portions with different sizes, shapes, curvatures, and the like. For example, in some embodiments, the robotic inspection device may include an interchangeable nose piece, an interchangeable lower portion, or a back with different curvatures. Moreover, some tanks have irregular structural additions on the rim of the tank, such as

antennas or irregular flanges. As such, it will be difficult for the power/communications tether **820** to pass over these obstructions. Various embodiments may use an onboard battery and Wi-Fi module to operate the robotic inspection device wirelessly. In other embodiments, the cable may be fed over these obstructions with a long pole or a hydraulic lift.

[0088] While not illustrated in FIG. 8, some embodiments may include a second assembly that follows the robotic inspection device along the top of the tank. The follower assembly allows the tether to be threaded to the vehicle and supports recovery of the vehicle from the tank.

[0089] FIG. 9 illustrates a design of a lower portion **810** of the robotic inspection device shown in FIG. 8. At the bottom of the lower portion **810** can be one or more integrated sensors **835** and/or lights for inspecting the seal. In accordance with various embodiments, the integrated sensors may include video cameras, thermal sensors, chemical sensors, and the like. The recordings and measurements from the integrated sensors **835** may be stored locally within the robotic storage device and retrieved once the inspection is complete. In other embodiments, the recording and measurements may be streamed back to a remote computing device where the results can be analyzed in real-time. This real-time analysis can allow for additional data to be collected in suspect areas or areas of interest.

[0090] FIG. 10 illustrates a view **1000** of the robotic inspection device **125** with the lower portion **810** inserted beyond the weather shield **130** on the tank **100** for inspection of a seal in accordance with some embodiments of the present technology. The weather shield **130** may be manually retracted by an operator using a pole-mounted tool. In other embodiments, the lower portion **810** of robotic inspection device **125** may include a manipulator arm (not shown) with an access tool to create space between the top edge of the weather shield **130**. In other embodiments, the wedge-shaped leading edge **1010** of the lower portion **810** may allow the robotic inspection device to drive beneath the weather shield. This can allow the robotic inspection device **125** access to the seal. The wheels **830A-830B** on the front of the inspection device may engage the weather shield as the device navigates around the internal perimeter of the shell.

[0091] FIG. 11 is a view **1100** of the back of the robotic inspection device **125** that may be used in various embodiments of the present technology. In the embodiments shown in FIG. 11, upper portion **805** and lower portion **810** may each include sets of wheels **1110A-1110F**. Some of the wheels may be load-bearing wheels similar to wheels **830A-830B**, while other wheels may be drive wheels which are part of a differential drive system allowing drive wheels to independently move. As such, by changing the relative rate of rotation of drive wheels **1110A-1110F**, robotic inspection device **125** can navigate obstacles or reach desired destinations without additional steering components. Other embodiments may use alternative surface-engaging drivers such as endless tread (e.g., tracks). The back side of upper portion **805** and lower portion **810** may be flat. In some embodiments, the back side of upper portion **805** and/or lower portion **810** may be slightly rounded to fit with common curvatures of the cylindrical shells.

[0092] FIG. 12 is a flowchart illustrating an example of a set of operations **1200** for using the robotic inspection device in one or more embodiments of the present technol-

ogy. As illustrated in FIG. 12, receiving operation **1210** receives an inspection signal from a controller. The inspection signal may be sent wirelessly or via a wire routed to the robotic inspection device via a tether. The inspection command may include a variety of parameters such as, but not limited to, tank dimensions (e.g., diameter), inspection routines, identified areas of interest, areas to avoid, and the like. Other examples of parameters may include time limits, communication channel information, location/tank information (e.g., for tagging recorded data), external weather conditions (e.g., temperature), maximum inspection times, waypoints, and the like.

[0093] Activation operation **1220** can activate a magnetic coupling between the robotic inspection device and the wall of the tank once the robotic inspection device is in place. The magnetic coupling can support the weight of the robotic inspection device and allow the drive wheels to be used to navigate the robotic inspection device around the inner perimeter of the tank. Determination operation **1230** then determines (e.g., using the parameters from the inspection command, from selection of a pre-planned path, etc.) a navigational route for the robotic inspection device. The navigational route may avoid known obstacles and may be dynamically updated (e.g., based on sensor measurements) as the robotic inspection device navigates the tank's inner perimeter. Recording operation **1240** can use the sensors to inspect the seal located below the weather shield. If a seal fault is detected, additional measurements (e.g., from different angles or using different sensors) may be taken in some embodiments. As such, the inspection process may dynamically depend on the measurements being recorded, external commands, and the like.

[0094] FIG. 13 is a flowchart illustrating an example of a set of operations **1300** for generating inspection data via the robotic inspection device in some embodiments of the present technology. Recording operation **1310** can record video and/or sensor measurements of the tank seal. In some embodiments, the recording operation may take still images with high resolution, use thermal imaging sensors, measurements using chemical sensors, and the like. In some embodiments, the recordings and measurements from the integrated sensors (e.g., cameras, LIDAR, depth sensors, stereovision, etc.) on the robotic inspection device may be stored locally and retrieved once the inspection is complete. In other embodiments, the recordings and measurements may be streamed back to a remote computing device where the results can be analyzed in real-time. This real-time analysis can allow for additional data to be collected in suspect areas or areas of interest. Recording operation **1310** may also format the data (e.g., video or sensor data) into compliant formats before storing or streaming the data.

[0095] During retrieval operation **1320**, various historical records of the seal can be retrieved. The historical records can include installation dates, part numbers, manufacturing lots, previous inspection reports, video, and/or sensor data, chemicals stored within the tank, geographic location, and the like. Using, for example, a machine learning or artificial intelligence engine, analysis operation **1330** can analyze the current inspection data. The machine learning or artificial intelligence engine can ingest the historical records and the current measurements and identify possible failures within the seal. In some embodiments, the results may include a flag which can trigger additional real-time inspections (e.g., additional imaging or collection of sensor data). In accor-

dance with various embodiments, the machine learning, artificial intelligence, or other decision-making engine can use one or more supervised, semi-supervised, or unsupervised learning techniques.

[0096] Determination operation 1330 takes the output from analysis operation 1330 and determines whether a problem has been identified. When determination operation 1340 determines a problem exists, then determination operation 1340 can branch to request operation 1350 where additional inspection data (e.g., additional images, video, and/or sensor measurements) of a particular area is requested. The robotic inspection device can process the request and collect additional inspection data for review by a human technician or by a machine learning or artificial intelligence engine. When determination operation 1340 determines that the analysis did not identify a problem, then determination operation 1340 can branch to completion decision 1360 where a determination can be made as to whether the job is complete. When completion decision operation 1360 determines that the job is not complete, then completion decision operation 1360 can branch to recording operation 1310 where another area of the seal is inspected. When completion decision operation 1360 determines that the job is complete, then completion decision operation 1360 can branch to recall operation 1370 where an inspection device recall is initiated. The recall may cause the robotic inspection device to return to the starting location to be retrieved by the operators. In some embodiments, the recall may cause the robotic inspection device to search for a beacon and navigate to that location.

[0097] FIG. 14 illustrates a set of components of the robotic inspection device that may be used in various embodiments of the present technology. According to the embodiments shown in FIG. 14, the robotic inspection device can include memory 1405, one or more processors (e.g., application processors 1410 and/or baseband processors 1415), power source 1420 (e.g., battery), operating system 1425, identification module 1430, control module 1435, sensors 1440, navigation system 1445, and communication module 1450. Each of these modules can be embodied as special-purpose hardware (e.g., one or more ASICs, PLDs, FPGAs, or the like), or as programmable circuitry (e.g., one or more microprocessors, microcontrollers, or the like) appropriately programmed with software and/or firmware, or as a combination of special purpose hardware and programmable circuitry. Other embodiments of the present technology may include some, all, or none of these modules and components along with other modules, applications, and/or components. Still yet, some embodiments may incorporate two or more of these modules and components into a single module and/or associate a portion of the functionality of one or more of these modules with a different module.

[0098] Memory 1405 can be any device, mechanism, or populated data structure used for storing information. In accordance with some embodiments of the present technology, memory 1405 can encompass any type of, but is not limited to, volatile memory, nonvolatile memory and dynamic memory. For example, memory 1405 can be random access memory, memory storage devices, optical memory devices, media magnetic media, floppy disks, magnetic tapes, hard drives, SDRAM, RDRAM, DDR RAM, erasable programmable read-only memories (EPROMs), electrically erasable programmable read-only memories (EEPROMs), compact disks, DVDs, and/or the like. In

accordance with some embodiments, memory 1405 may include one or more disk drives, flash drives, one or more databases, one or more tables, one or more files, local cache memories, processor cache memories, relational databases, flat databases, and/or the like. In addition, those of ordinary skill in the art will appreciate many additional devices and techniques for storing information which can be used as memory 1405.

[0099] Memory 1405 may be used to store instructions for running one or more applications or modules on processor(s) 1410. For example, memory 1405 could be used in one or more embodiments to house all or some of the instructions needed to execute the functionality of operating system 1425, identification module 1430, control module 1435, sensors 1440, navigation system 1445, and/or communication module 1450. Operating system 1425 can provide a software package that is capable of managing the hardware resources of the robotic inspection device. Operating system 1425 can also provide common services for software applications running on application processor(s) 1410.

[0100] Identification module 1430 may analyze the sensor data in real-time to identify any faults with the seal. Control module 1435 can control the operations of the robotic inspection device. For example, control module may control magnets for coupling the device to the wall of the tank, sensors 1440, and/or navigation system 1445 which can control the drive wheels. Communication module 1450 can transmit and receive signals between the robotic inspection device and an external computing platform (e.g., laptop, cloud-based inspection platform, etc.).

[0101] FIG. 15 illustrates an example of a graphical user interface 1500 that may be used in one or more embodiments of the present technology. Graphical user interface 1500 may include a control panel 1510 that allows the user to select the inspection device, inspection routines, view of video feed, see identified issues, and/or control the robotic inspection device manually. Inspection panel 1520 can allow the user to see the status of the current inspection results and/or view historical records. Data panel 1530 can display the selections of the user. For example, data panel 1530 can display the historical inspection results, live video feed, sensor data, and the like as selected by the user.

[0102] FIG. 16A-16C illustrates example of images collected and processed to identify degradation of a seal according to some embodiments of the present technology. These are example output of the edge detection method which allows the vehicle to determine the gap width between the seal and the tank wall.

[0103] FIGS. 17A-17B illustrate examples of functional block diagrams illustrating logical interconnections that may be created between various components of the robotic inspection device according to various embodiments of the present technology.

EXAMPLE 1

[0104] Regarding the object of inspection for the present technology, FIG. 18 presents a typical open-roof or external floating roof storage tank (FRT) and FIG. 19 illustrates a specific part of that storage tank known as the floating roof seal assembly. FRTs are commonly used for storing large quantities of crude oil, gasoline, jet fuel, diesel, etc. across both midstream and downstream segments of the global energy industry. FRTs are often large (from 40 to 300 ft in diameter) closed or open-topped cylindrical steel shells with

a roof **6** that floats on the top of the liquid **4**. The roof falls and rises as the level of liquid **4** product in the tank changes, leaving little to no space between the roof **6** and the liquid **4**. A lower liquid seal (LLS) **7** and an upper vapor seal (UVS) **5** are in place on the outer edge of the roof **6** to prevent the evaporation of volatile chemicals. UVS **5** and LLS **7** may together comprise a seal assembly **2**. Both seals **5** and **7** maintain a sliding contact with the tank wall **3** and can fail over time due to this up-and-down motion. Escaped vapors are troublesome for four reasons: 1) pollution of the environment, 2) resulting fines for the tank owner from federal and state agencies, 3) financial loss from loss of product, and 4) the potential for fire (due to the high combustibility of vapors in a space **9** between UVS **5** and LLS **7**). As a result, maintaining the integrity of floating roofs **6** is a vital risk concern for terminals and refineries. Regular inspection is necessary in order to prevent failure and plan repairs. The current manual inspection process employs a team of five humans (two inspectors, one spotter, and two rescue personnel on standby) equipped with PPE who travel down into the tank to inspect both seals **5** and **7**. This inspection employs visual and physical means to assess the integrity or health of the seals **5** and **7**. By looking at a few factors (as described in greater detail, below), the inspection crews make a subjective judgement about the seal and decide if it requires repair. This manual inspection is dangerous, costly to perform, and imprecise. The safety paperwork to approve a technician on the floating roof is also very onerous. The inaccuracy and long intervals between inspections also mean that a percentage of defective seals will not be found and thus continue leaking hazardous vapors into the atmosphere.

[0105] Regarding the condition or state of UVS **5** and LLS **7**, FIG. **20** provides a cross-section view of a typical seal assembly **2** used on open-topped floating roof tanks (e.g., as shown in FIG. **18**). The defectiveness of UVS **5** and/or LLS **7** depends on two categories of potential seal problems: 1) mechanical integrity and 2) emissions. The mechanical integrity is assessed in two ways: a) through identifying the existence and size of a gap **8** between a metallic shoe **1** and inner tank wall **3** and b) identifying the existence of and size of a tear in the fabric or other material of LLS **7**. The size of these features may include measurement of the length, width, and depth of the defect. For the emissions category, a gas monitor can be used to detect concentrations of volatile organic compounds (VOCs) both below (e.g., in space **9**) and above the UVS **5**. However, in practice, gas monitoring is very rarely done and is sometimes turned off entirely during these inspections. This decision severely impacts the comprehensiveness and quality of the inspection.

[0106] To address the issues with the conventional manual methods of floating roof tank seal inspection, automated robotic systems and methods are provided by the present technology. In this regard, the present technology may be composed of three sub-systems: 1) an inspection robot to navigate around the interior of the storage tank and collect data, 2) an insertion-extraction tool to manipulate the UVS **5** for insertion of required sensors below, and 3) a tether management system (TMS) to keep the power, communication, and inert gas lines from becoming entangled with various storage tank features.

[0107] Referring now to FIG. **21**, in some examples of the present technology, the inspection robot **10** is further divided into three subassemblies: 1) an upper drive assembly (UDA)

11 magnetically adhered to the tank shell, for propelling the entire system; 2) a lower sensor package (LSP) **16** offset from the UDA **11**; and 3) a connector bridge (CB) **19** that joins the first two sub-assemblies **11** and **16**. This design configuration keeps the bulk of the tethered robot **10** above the UVS **5** in a configuration akin to an inverted periscope. Additionally, this robot **10** may be explosion-proof or Ex-rated, so as to not cause a rim seal fire during its mission. The robot **10** according to the present technology is made safe in this way through various onboard safety sub-systems, which may be positioned within and across all three of its subassemblies **11**, **16** and **19**. This safety sub-system and overall design of the robot **10** means it can earn a NEC Class 1, Division 1 or ATEX/IECE Zone 0 certification, which would allow it to operate in flammable vapor environments. These sub-systems of the inspection system, as well as sub-assemblies of the robot **10** are described in greater detail below.

[0108] FIG. **22** illustrates top, side, front and perspective views of the inspection robot **10** in accordance with some embodiments of the present technology. FIG. **23** illustrates an in-situ view of the inspection robot **10** in accordance with some embodiments of the present technology. While inspection robot **10** is described herein as a separate and distinct example embodiment from robotic inspection device **125** as described above with reference to FIGS. **2-17B**, inspection robot **10** according to the present technology may include some or all of the features of robotic inspection device **125**.

[0109] The inspection of the floating roof **6** seals **5** and **7** may be carried out through collection and real-time processing of data collected by the LSP **16** as it propelled around the tank wall **3** by the UDA **11**. In some examples of the present technology, the LSP **16** houses and employs at least four sensor types to properly evaluate the state or condition of the entire floating roof seal assembly **2**. Data collected from the sensors contained in the LSP **16** may include color images or video feeds (RGB), pointcloud, echoed sound waves, and gas concentration/flow rate. The individual processing and fusion of these sensor data (see, e.g., FIGS. **30** and **31**) are used for determining the mechanical integrity of the seal assembly **2** and the emissions that result. Notably, the process depicted in FIG. **32A-32F** is an update to that shown and described above with reference to FIGS. **16A-16C**. This data collection is done while the LSP **16** is directly above the LLS **7**, as well as when it is directly above the UVS **5**. The four different sensors are described in greater detail below.

[0110] Referring now to FIGS. **22** and **23**, and with further reference to FIGS. **19-20**, the UDA **11** of the inspection robot **10** includes at least four motor driven wheels **13** positioned on opposing sides of a housing **15**. In the example shown in FIG. **22**, inspection robot **11** includes four wheels **13**, with two wheels **13** on one side of housing **15**, and another two wheels **13** on the opposite side of housing **15**. The housing **15** may be equipped, on the bottom side of the housing, with permanent magnets or electro-magnets **32** to enable the entirety of inspection robot **10** to be suspended on a vertical or near vertical wall **3** of the tank, as shown in FIG. **21**, while also allowing for actuating the drive system. Wheels **13** may be formed at least in part of a material having magnetic properties sufficient to enable the entirety of inspection robot **10** to be suspended on a vertical or near vertical wall **3** of the tank, as shown in FIG. **21**. In an example, UDA **11** of inspection robot **11** with four wheels **13** includes tracks **17**, with one track **17** operably coupled to a

first pair of wheels **13** on one side of housing **15**, and a second track **17** operably coupled to a second pair of wheels **13** on the opposite side of housing **15**. In some embodiments, tracks **17** may be formed at least in part of a magnetic material to facilitate enabling the entire weight of inspection robot **10** to be suspended on the wall **3**, as shown in FIG. **21**. In one example, tracks **17** instead of wheels are formed at least in part of the magnetic material. In another example, both tracks **17** and wheels **13** are formed at least in part of the magnetic material.

[0111] Other capabilities that may exist within the inspection robot **10** include 1) a forward and/or rear navigational camera **33**, 2) computers/memory storage devices **34**, 3) wired and/or wireless communications interface(s) **40**, 4) inertial measurement unit(s) (IMU(s)) **41**, 5) actuators for sensor deployment **42**, and 6) pneumatic connections **37**, each of which being configured in a manner sufficient to facilitate operation of inspection robot according to the present technology.

[0112] Regarding the LSP **16** and the sensors housed within, some embodiments may include visual, sound, physical, and chemical sensors. In the situation where the LSP **16** is inspecting the LLS **7** and also possibly the space **9**, this sub-assembly **16** will be located below the UVS **5**. In the case where the UVS **5** is being inspected, it will be located above LLS **7**. In either situation, the distance that the LSP **16** will be positioned from the object of inspection may be calibrated for each tank and seal. A low-profile design of a housing **29** of LSP **16** may facilitate its insertion and travel around the small space of the seal assembly **2**. These sensors of LSP **16** may be installed or otherwise configured such that they point or are directed down at the object of interest (e.g., UVS **5** or LLS **7**).

[0113] Regarding visual sensors, the LSP **16** may include a depth camera **23** used to collect color (RGB) and point-cloud data. The LSP **16** may also include one or more light(s) **25** (e.g., light emitting diode (LED)) situated proximal to (e.g., to the side of) the depth camera **23** to illuminate an area or interest and facilitate the collection of color and pointcloud data.

[0114] Regarding sound sensors, the LSP **16** may include an ultrasonic transducer **24** that emits a cone-shaped burst of energy, after which it receives the echoed sound waves. An external time of flight recorder can measure the travel time of the sound wave and convert that into a distance measurement (considering the speed of sound in air). When sound waves are so directed toward the seal gap **8**, the distance values vary based on how wide the gap **8** is. This distance measurements obtained from directing the sensor at the seal gap **8** can be calibrated and used to determine or deduce the dimensions of the gap **8**.

[0115] Regarding physical sensors, the LSP **16** may also include a deployable resistance probe **28** (DRP) as one possible measuring apparatus, shown in FIG. **22**. The DRP **28** may be expelled from the LSP **16** when there is a gap **8** detected (e.g., by other means) between the tank wall **3** and the upper portion of the LLS **7**, as shown in FIG. **20**. This DRP **28** may be used to assess how far the gap **8** extends down the height of the LLS **7**. If no resistance torque is measured during deployment, then it can be assumed the gap **8** extends all the way down into the liquid **4** product. This knowledge is important for accurate characterization of seal integrity. The actuator **42** mechanism that deploys the DRP **28** may be contained in the UDA **11** housing **15**. This

actuator **42** may include or be coupled with encoders and/or torque feedback sensors (not shown in FIG. **22**) to facilitate determination of distance traveled and/or resistance experienced.

[0116] Regarding chemical sensors, the LSP **16** may also include a gas monitor **30** to detect high concentrations and mass flow (leakage) rates of dangerous vapors (e.g., VOCs), similar to the device worn and/or used by human crews during manned inspections of the seals, as shown in FIG. **25**. Usage of this type of device for detecting whether the gas (fuel) concentration below the UVS **5** exceeds the lower explosive limit or LEL of the ignitable range can be seen in FIG. **25**, which illustrates this aspect of the conventional manual inspection technique. This manual gas measurement, e.g., during a repair procedure, may validate the identification and sizing of LLS **7** defects found during the assessment of the seal's mechanical integrity using robot **10** according to the present technology. If a gas concentration above an LEL is detected using monitor **30**, then the tank inspection robot **10** according to the present technology can be immediately powered down and removed from the hazardous zone.

[0117] Regarding the connector bridge (CB) **19** that joins the UDA **11** and LSP **16** via a side plate mount **21**, this allows for power and communication between the two sub-assemblies **11** and **16**, in addition to providing the force necessary to propel the LSP **16** alongside the UDA **11** while it is moving, akin to a sidecar. Some embodiments of the CB **19**, as shown in FIGS. **21** and **22**, may include active or passive roller elements **27** designed to minimize friction between the CB **19**, UVS **5**, and tank shell **3** during an inspection of the LLS **7** and/or space **9**. This minimization of friction while the UVS **5** is sliding across the CB **19** facilitates a successful navigation around the inner tank wall **3**. In some embodiments, these roller elements **27** may exist both above and below the CB **19**, as well as proximal to the CB **19**. In some embodiments, the roller elements **27** may be actively driven, as by motor(s). In some cases, the same energy imparted by the drive motors of UDA **11** into the wheels **13** to move tracks **17** may be further directed into the roller elements **27** through a gearing mechanism (not depicted). The CB **19** may also include features designed to help pry open the lightning protection grounding straps **38** that exist at regular intervals around the tank, affixed to the UVS **5**.

[0118] Regarding the safety features of the inspection robot **10** according to the present technology, the following non-limiting examples of methods and components may be employed to satisfy a safe design and operation, as well as achievement of an Ex-rated certification: 1) inert gas purge and pressurization from an external source into the UDA **11**, as well as into the LSP **16**, made possible through at least one air passageway incorporated into the CB **19**; 2) power from a source positioned distally from inspection robot **10**, allowing the robot **10** to not need a battery and be grounded to the earth; 3) diversion or prevention of static electricity buildup; 4) selection/modification of low-power draw, intrinsically safe components and immersion of high-power draw, non-intrinsically safe components into a dense liquid, such as oil (to effectively remove it from the combustible air environment); and 5) use of explosion-proof, air-tight enclosures/housings.

[0119] Inert gas purge and pressurization of the inspection robot **10** may be implemented using commercially available

equipment capable of, or otherwise adapted to suit the needs of the mission, where up to 250' of tether flow connection may be required at times. The inert gas will flow through an air line included as part of the power/comm tether line 35 that the inspection robot 10 may utilize, as described above. This inert gas may then be re-routed, once inside the UDA 11, through the CB 19, and into the LSP 16, as needed or desired. A purge and pressurization system (flow/pressure controller), mainly located external to the tank (and not depicted), may be used to monitor air pressure and regulate the flow of the inert gas when the pressure invariably changes. If the pressure drops below an acceptable level, indicating failure of the external gas supply system or UDA 11 and/or LSP 16 housings 15 and 29, respectively, this may initiate action of an onboard positive pressurization subsystem 36. This is described in greater detail below. If positive pressure within housing 16 and/or 29 still cannot be maintained, an electronic shut down switch may be used to de-energize the robot 10.

[0120] Supplementally, the onboard positive pressurization subsystem 36 may serve as a backup to an external inert gas air supply routed to housings 15 and/or 29 with and as a part of the tether 35. In some embodiments, the onboard positive pressure subsystem 36 may include a pressure sensor, an inert gas canister, and a servo-regulated valve for flow control (which may be actuated based on the feedback from the pressure sensor). The controlled release of the inert gas replaces any air that has leaked out from the various housings (e.g., 15 and/or 29) to the outside (or vice versa), ensuring that the atmosphere inside the UDA 11 and/or LSP 16 is free of VOCs. This significantly mitigates the chance of a fire caused by the sparking of one or more electrical components, held within the two sub-assemblies 11 and 16 of the inspection robot 10, the interiors of which may have concentrations of combustible air mixtures.

[0121] Regarding static electricity, grounding of the robot to an external sink through the wired tether 35 will drain the static charges away from the inspection robot 10 as they are produced.

[0122] Regarding selection/modification of low-power draw, intrinsically-safe components, the at least one sensor may be selected that falls under the max voltage and current that a piece of electrical equipment can have in a hazardous zone. Additionally, the housing 29 of the depth camera(s) 23 and other sensors may be modified to ensure their electrical boards are exposed to the inert gas flowing within the LSP 16. Most all gas monitors 30 commercially available today are already rated for flammable environments, as defined by National Fire Protection Association (NFPA) Publication 70, and so modification of these sensors is not expected to be necessary for fabrication and/or assembly of the tank inspection robot 10 according to the present technology.

[0123] Regarding explosion-proofing of the various housings 15 and 29, in some embodiments, the enclosure may be air-tight. To account for the various holes that are put into the chassis to allow for install of various components, the inert gas purge and pressurization (discussed above) may be used to maintain that positive pressure inside. The assembly of the housing and components therein will make use of various gaskets positioned at mating surfaces of various sub-assemblies. The metal chassis may also be made robust enough to fully contain any potential explosion, not allowing the fire to spread. Some embodiments of the present technology may include long flame paths placed into the

housing(s) (e.g., 15 and/or 29) and mounting holes so as to starve out the fire (from lack of oxygen) before it escapes into the outer environment.

[0124] Regarding the tether 35 previously mentioned, the inspection robot 10 may include at least one communications interface 40 disposed on or in the UDA 11 and LSP 16. Communication and power may first be routed to the UDA 11 via the umbilical power/communication tether 35 that follows behind the robot 10 while it is operating inside the tank under inspection. This umbilical assembly may also include the pneumatic line 37 in order to provide an external supply of inert gas to the inspection robot 10 during operation. In some embodiments, this tether 35 may be a couple hundred feet in length to handle inspections of very large FRTs. A tether management system (TMS) 98 will be used to control the rate at which the umbilical tether is deployed from the top of the tank, in order to match the speed at which the inspection robot 10 is pulling it along. This TMS 98 (located at the top of the tank staircase 99, as shown in FIG. 27) will also prevent entanglement of the tether 35 with various tank features that may become obstacles during the robot's 10 mission around the tank. It will do this by keeping the tether 35 close to the inner tank wall 3 as it is pulled off of the spool or other means 97. A rolling trailer 301 for the tether 35, magnetically adhered to the wall 3, will assist in this effort. The TMS 98 may include means 97 for managing the tether assembly 35 during operation of the tank inspection robot 10. Such means 97 may include a reel, a spool, a spindle, a cylinder, a frame, or like rotary devices that turns on an axis and is used to wind up or paying out the tether 35 line.

[0125] An Insertion/Extraction Tool (IET) 106 may be used to manipulate the UVS 5 to allow for insertion of the LSP 16 into the space 9 between the seals, as demonstrated in FIGS. 26-28. The IET 106 may be a carbon fiber pole with a wedge-type feature at the bottom, and it may be deployed from the top of the tank by the operator or through motor-powered actuation. In some instances, it may also be used as part of the TMS 98, previously discussed. The IET 106 in the form presented here is reserved exclusively for servicing external FRTs.

[0126] Regarding the sequential mission of the tank inspection robot 10 according to the present technology, in some embodiments, the inspection robot 10 is placed at the top of the tank by a single operator, as seen in FIG. 27. It is purged and pressurized before breaking the tank rim barrier, allowing it to enter into the flammable Ex-rated environment/zone of the storage tank. Using its magnetic adhesion ability provide by magnet(s) 32 and drivetrain 45, it travels down the tank wall 3 to a location directly above the UVS 5 and roof 6. The IET 106 may then be lowered down and used to pry open the UVS 5 just enough to allow for the insertion of the LSP 16 into the space 9 between the seals 5 and 7. Using the cable and air-carrying CB 19, which joins the two sub-assemblies 11 and 16 of inspection robot 10, the UDA 11 is commanded to rotate, which positions the LSP 16 directly above the LLS 7 to gain visual and physical access to it. It is now ready to collect useful data about the mechanical integrity of the LLS 7. Once the IET 106 is raised back up by the operator, and with the LSP 16 so inserted, the connector bridge 19 experiences a large force from the UVS 5. The inclusion of roller elements 27 and thickness of joining parts minimizes this adverse friction and allows for ease of motion around the tank shell.

[0127] In some embodiments, the inspection robot 10 may include a motor controller 47 operably coupled to the drive assembly for keeping the robot 10 on a straight circumferential line of travel around the tank, compensating for the large frictional or other disturbances whilst the connector bridge 19 is in contact with the UVS 5, as shown in FIGS. 29 and 33. Additionally, raw video feeds from the navigational camera 33 can be used to detect grounding straps 38 or other obstacles in the path of travel. This information can be used to plan a local path plan deviation to avoid such obstacles before resuming on the main global path plan around the wall 3 of the storage tank.

[0128] As the robot 10 starts to autonomously travel around the tank, data is collected real-time on the mechanical integrity and health of the seals 5 and/or 7 of the seal assembly 2, as well as the hazardous gas concentrations and/or leak rates that can result from a defective seal. The upper portion of the seal gap 8 may be inspected through visual and ultrasonic means, but in order to characterize the lower portion of the seal gap 8, in situations where there is an upper initial gapping, the DRP 28 may be used to prod down into the space between the metallic shoe 1 and the tank wall 3. A mass flow rate sensor may also be present on or inside the LSP 16 in order to measure methane leaks. All of the collected sensor data (e.g., around the entire circumference of the tank wall 3) may be fused together to generate a seal inspection report real-time (e.g., through the use of the onboard computer 34 as well as the remote station computer). The current identified problem areas or spots may be analyzed against previous inspection results to predict time to seal failure and formulate an actionable repair plan. Software and/or firmware executed as program instructions by computer 34 may also be able to pinpoint the mechanical defect source responsible for excess methane emissions.

[0129] After completion of the data collection, the IET 106 is re-deployed to open up a space between the tank shell 3 and UVS 5, allowing the UDA 11 to rotate and extract the LSP 16. The inspection robot 10 then navigates back up to the top of the tank to be picked up by the operator. Alternatively, in some instances, the robot 10 may drive only part way toward the top of the tank, and then an operator may use a pole with, e.g., a hook and similar mechanism, to pry robot 10 off of the interior tank wall and then lift it to the top of the wall. In some instances, to help with management of the tether 35, the robot 10 may only go halfway around the tank and then return to its starting point. The robot 10 can then be sent to inspect the other half of the tank. This will help prevent the tether 35 from becoming entangled with the obstacles situation atop the floating roof.

[0130] Through the collection and processing of at least four different types of sensor data, the results of the inspection are packaged into a human readable form (e.g., digital twin CAD model and/or pdf report). The inspection report, an example of which is shown in FIG. 31, allows a facility manager, for instance, to make an informed decision on whether or not a tank needs to be shut down and a repair scheduled.

[0131] Software and/or firmware stored as program instructions on non-transitory computer 34 readable storage memory (e.g., memory) onboard the inspection robot 10 and/or in subsystems communicably coupled to robot 10 (e.g., via tether 35) may implement, mediate or otherwise facilitate performance of one or more of the functions and operations of inspection robot 10 as discussed herein accord-

ing to the present technology. For example, and without limitation, such program instructions may provide operators of inspection robot 10 access to a number of software and/or firmware packages which accomplish a variety of low-level and high-level tasks, such as handling of navigational control commands, turning power supplies to components off/on, and general sharing of data between the different components of robot 10 to properly manage the functions thereof.

[0132] FIGS. 32A-32F illustrates a flow chart of a tank inspection method 50 in accordance with some embodiments of the present technology. In FIGS. 32A-32F, circles having a letter in them denote process flow transitions between different figures. With reference to FIGS. 32A-32F, as well as the foregoing figures and accompanying description, method 50 may proceed from a start state 51, which begins with the operator purging 52 the interior of the robot of any VOCs and pressurizing the interior of the robot sub-assemblies with an inert gas. This inert gas may flow from a source outside of inspection robot 10 and into the housing 15 of the UDA 11, from which it can be directed to other sub-assemblies of the robot, which are housing electrical components. In some embodiments, for step 52, inert gas may also be flowed into the housing 29 of LSP 16.

[0133] The robot 10 will then be allowed to enter into Ex-rated zones of the interior of the storage tank, while a liquid 4 product such as crude oil or gasoline is present inside the tank. The operator will proceed to place 53 the robot 10 at a top portion of the storage tank wall 3, above its floating roof 6. The robot 10 stays on the tank without falling off or sliding through the use of magnetic adhesion by way of magnet(s) 32 affixed to the bottom of the robot 10 chassis. This magnetic adhesion may be accomplished through permanent magnets or electro-magnets. The robot 10 will still be able to maneuver even while magnetically coupled to the tank shell. The operator will select, on, for example, a computer-generated 3D model of the tank, the location that they placed the robot 10. The above actions thus localize 54 the robot 10 in its operating environment, allowing the onboard software to then create a global path plan for the actuation 55 of drive motor 45 of robot 10 such that the robot 10 will follow the planned path to complete its inspection mission.

[0134] In some embodiments, method 50 may include the step of actuating 56, e.g., by wheels 13 of the UDA 11, to navigate the robot 10 downwards to one or more circumferential seals (e.g., UVS 5) positioned proximal the interior wall 3 of the storage tank. In order to know when to cease downward motion, method 50 may also include the step of collecting 57, via a forward-facing navigational camera 33 (e.g. depth or rgb camera), visual data sufficient to identify an optimal position above the secondary seal (e.g., UVS 5), where the robot 10 could be commanded to stop 59 after a logical branch 58 of method 50 identifies that state of affairs. Such an optimal position may include the robot 10 being positioned a pre-determined distance away from the top of the UVS 5 (also referred to herein as secondary, or weather, seal). Otherwise, method 50 loops through the above described steps 56 and 57 until such time that the optimal position is identified in logical branch 58. This identification of a starting position for the rest of the robot 10 inspection mission may be done by recognizing at least one physical characteristic of the seal assembly 2 or floating roof 6.

[0135] In some embodiments, the at least one sensor may be positioned on, or in, an offset LSP 16. The LSP 16 may be connected to and offset from one side of the UDA 11. This connection or union is made possible by use of a CB 19 and side plate mount 21 between the two sub-assemblies 11 and 19. In order to put this LSP 16 in an optimal location for data collection, method 50 may include the step of inserting 62 the LSP 16 between the one or more seals 5 and/or 7, and the wall 3 of the storage tank. This insertion may be accomplished via a rotation of the inspection robot 10, as in, for example and without limitation, ninety-degrees clockwise. Before this maneuver can be completed successfully, a space just large enough for the height of the LSP 16 and its housing 29 must be created. While this is traditionally done by human hands, in this method, the IET 106 will be used. This tool may be set up 60 by the operator from their position on the tank stairwell landing. A cylindrical guide will be mounted at the top of the tank via permanent magnets. The tool may be deployed 61 downwards, through this guide, by the operator via physical force, aided or not by a tool to provide mechanical advantage, or an electronically driven system (e.g. a telescoping linear actuator that can vertically translate a mass). The IET 106 may have a wedge-like feature on its end that will engage a physical feature of the UVS 5 (e.g. a lightning protection grounding strap 38 or shunt) in order to aid in the prying open of the UVS 5. Once the LSP 16 of robot 10 is in position, the IET 106 will be retracted 63, making it so that now the material (e.g., rubber) of the UVS 5 is in contact with the CB 19, as shown in FIG. 33. The inspection robot 10 is now ready to begin 64 its data collection mission.

[0136] In some embodiments of method 50, the inspection mission begun at step 64 may include Motion Control 65 and Inspection 71. In some embodiments, Motion Control 65 and Inspection 71 may be concurrently performed processes in method 50, as discussed in greater detail below.

[0137] Motion Control 65 of the inspection robot 10 is necessary due to adverse frictional forces imposed on the CB 19 and other obstacles in the path of travel. In some embodiments, as shown in FIG. 32D, Motion Control 65 may be assisted through use of forward-facing navigational depth camera 33, which can recognize 66, locate and determine distance away from obstacles in the path of travel, giving the robot 10 time to plan a local deviation in order to avoid getting stuck or damaging the treads of the drive assembly. In some cases, the CB 19 may be designed long, thin, and smooth enough such that it would not have to navigate around the obstacles, but can instead go under them (e.g., under grounding strap 38, as shown in FIG. 29).

[0138] Still referring to FIG. 32D, in some embodiments, the LSP 16 equipped with a depth camera 23 or ultrasonic transducer 24 can be used to measure 67 distance of the LSP 16 from a physical characteristic of the LLS 7 (also referred to herein as a lower, primary seal). This information can be used to assist in the navigational control the robot 10. In another example, the IMU(s) 41, affixed to the UDA 11, can be used to detect 68 sliding down or dipping of robot 10 during its mission around the tank. All of these sensors and their data as may be utilized in one or more of method 50 steps 66, 67 and 68 may be fused 69 together and processed by computer 34 and/or computing system(s) remote from robot 10 to determine the error of the robot 10 (and its LSP 16) from their desired, pre-planned paths. Through a motion controller (which, in some embodiments, may include soft-

ware and/or firmware), this error will be used to apply 70 a control correction to the actuating 55 of the drive motors 45 to compensate for frictional or other disturbances during such times that the LSP 16 is inserted 62 between seals 5 and/or 7, and the wall 3, of the storage tank. In some embodiments, the above described fusing 69 and correcting 70 steps of method 50 may be performed concurrently with the actuating 55 step.

[0139] In some embodiments, the inspection method 71 will consist of multiple sub-processes and logical branches. Characterization of the integrity of LLS 7 is accomplished by looking at four things: 1) the upper portion of the seal gap 8; 2) the lower portion of the seal gap 8; 3) the presence and size of primary seal fabric tears; and 4) the concentration and leak rate of VOCs.

[0140] Referring now to FIG. 32E, to address the first of the above-listed sub-processes/capabilities—the upper portion of the seal gap 8—in one example, the depth camera 23 pointed at the LLS 7 collects 72 pointcloud data to facilitate a two or three-dimensional model of the one or more seals 5 and/or 7, and possibly also a portion of the wall 3. The color (RGB) image data collected by the depth camera 72 may be used as a base image upon which to overlay the information gleaned from the processed pointcloud data (e.g., as shown in FIG. 30). Additionally, the RGB data may be also processed in order to help size the upper portion of the seal gap 8. Additionally, or instead, the ultrasonic transducer 24 (or similar rangefinder, e.g., laser based) may, in some embodiments, be used to collect 73 distance measurements, which can be used to determine or deduce the size of the seal gap 8. In examples of method 50 that include both of the aforementioned collecting steps 72 and 73, the pointcloud, RGB, and ultrasonic data may then be fused 75 together and processed by computer 34 and/or computing system(s) remote from robot 10 to produce an accurate measurement of the upper portion of the seal gap 8.

[0141] To address the second of the above-listed sub-processes/capabilities—the lower portion of seal gap—in one example, if the upper portion of the seal gap 8 size exceeds a predetermined magnitude at logical branch 76 in method, then the robot will be commanded to stop 77 in order to perform an additional inspection. This additional inspection may include deployment 78 of the DRP 28 having a small enough thickness to enter into the seal gap 8 in order to assess how far the seal gap 8 goes down the height of the LLS 7, which may also be referred to in the art as the primary mechanical shoe seal (as shown, for example, in FIG. 24). If the DRP 28 is deployed all the way to the liquid 4 product below and no resistance is felt, that portion of the LLS 7 will be marked faulty. If resistance is detected by the DRP 28, this portion of the LLS 7 will be deemed fit for continued service. This additional inspection may also include real-time re-calibration of the ultrasonic rangefinder 24 in order to inspect lower down into the seal gap 8. After retraction of the DRP 28 to a safe height, the robot 10 will continue 79 its motion.

[0142] To address the third of the above-listed sub-processes/capabilities—location and dimensions of fabric tears—in one example, the collected 72 RGB data may be processed by the computer 34 and/or computing system(s) remote from the robot 10 using image processing, or other, algorithm(s) to recognize various cuts, tears, holes, or other defects located on the LLS 7 material (e.g., fabric).

[0143] To address the fourth of the above listed sub-processes/capabilities—concentration and leak rate of VOCs—in one example, method 50 may include the step of measuring 74, e.g., by gas monitor 30 contained in or on the LSP 16, a concentration or leak rate of one or more gases (e.g., VOCs) in the space 9 between the UVS 5 and the LLS 5 of the seal assembly 2. This information will be related to the location of other mechanical defects and be used to relate the leak result to its cause. This information, along with the upper and lower portion gap 8 sizes, as well as the location of fabric tears, will be utilized to generate 80 a real-time inspection report of the seal integrity (e.g., as shown in FIG. 31). If the seal health is in an unsafe or failed condition as determined by the above described inspection method 71 and associated method 50 steps, along with inspection standards approved by Steel Tank Institute and American Petroleum Institute, then corrective maintenance can then be planned.

[0144] Referring now to FIG. 32F, in some embodiments of method 50, odometry of the UDA 11 drive motor encoders may be monitored 82. Based on the diameter and circumference of the storage tank, if it is determined at logical branch 83 that the robot 10 has navigated around the entire circumference of the inner tank wall 3, then the mission will be complete an extraction procedure will be initiated. If the robot 10 has not yet navigated around the entire circumference of the inner tank shell, then the method 50 including processes controlling the robot 10 will continue looping 81 through the Motion Control 65 and Inspection Method 71 routines.

[0145] Still referring to FIG. 32F, for the aforementioned extraction procedure, method 50 may include steps 85-87. In some embodiments, these steps may be, or at least resemble, a reversal of the robot 10 insertion-related steps 53 and 60-63 performed earlier in the mission, as described above. The IET 106 may be deployed 84 by the operator until engagement of the end wedge with a physical characteristic of, or proximate to, the UVS 5 (e.g., grounding strap 38) to pry it open. Next, the robot 10 will rotate 85 ninety degrees in order to remove the LSP 16 from below the UVS 5. The robot 10 will proceed to navigate 86 up the tank wall 3 to be picked up by the operator and removed 87 from the wall 3. The IET 106 may also be extracted upwards and the robot 10 thereby removed 87 from the inner tank wall 3 once the robot 10 is evacuated. After the conclusion of all these robot 10 extraction-related steps in method 50, an end state 302 may be reached.

[0146] Referring now to FIG. 32C, in some embodiments, method 50 may also include other safety-related steps 88-96, which may proceed concurrently with the above described motion control 65 and inspection method 71. Continuing from method 50 step 52 with the purging and pressurizing of the interior of the robot 10 housing(s) 15 and/or 29 with an inert gas, this flow is continued 88 into those housing(s) 15 and/or 29. The flow rate of inert gas is monitored 89 and, in a logical branch 90, it is determined, e.g., by a flow meter/regulator or pressure sensor 44, or similar means, disposed in or on housing 15, whether a flow of the inert gas from the external source (not shown) has ceased or dropped below a necessary flow rate to maintain positive pressurization within the various housings 15 and 29. For the continued flowing 88 of inert gas being determined in logical branch 90 to have ceased or dropped below the necessary rate, method 50 may initiate a flow 91 of inert gas from the

onboard backup positive pressurization subsystem 36 to continue or maintain the positive pressure inside of the housing 15 in response to the cessation or unacceptable decrease of the flowing 88 of the inert gas from the external source. Following the flowing 91 step in method 50 (and also in the event that the flow rate did not cease or unacceptably decrease as determined in logical branch 90), real-time monitoring 92 of the internal pressure and air quality within the robot's 10 various housings 15 and/or 29 is performed, as they are a direct result of the functionality of the inert gas flow system. Method 50 proceeds to a logical branch 93, wherein if these readings of pressure and air quality are within acceptable levels, as specified by, for example and without limitation, a NEC, ATEX, or IEC code, then the robot 10 and associated systems will continue operation as normal. In that case, method 50 proceeds to a logical branch 94 that determines if the aforementioned onboard subsystem 36 has already been deployed/initiated. If not, the flowing 88 of inert gas from an outside source will continue. If it has been previously deployed, then the flow 91 of an inert gas from an onboard source (e.g., subsystem 36) will continue.

[0147] In the above described logical branch 93 of method 50, if despite deployment of subsystem 36, the pressure and air quality within housing(s) 15 and/or 29 of robot 10 are not within the applicable acceptable safe level, then method 50 may proceed to cut 95 power to the robot 10 to power it down completely, thereby interrupting the mission. In that case, the robot 10 may be extracted 96 according to the various techniques as described herein according to the present technology.

[0148] In one embodiment of this example, method 50 may further include the step of transmitting, by the communications interface 40, various signals encoding data representative of the integrity of the seal.

[0149] Following completion of some or all of the above described steps, method 50 may proceed to the end state 302. In some embodiments, the end state 302 may represent operations to be completed by inspection robot 10, or the operator and/or subsystem thereof, after performance of an inspection routine for the seal(s) 5 and/or 7 of the storage tank. For example, and without limitation, such operations may include transmission and/or download of results stored in a memory storage device 34 of robot 10, robot 10 using its navigation camera 33 to return to the top of tank wall 3 to facilitate retrieval by the operator, deployment of sensor (s) contained in the LSP 16, and/or powering down of robot 10, among other things.

[0150] The present technology related to inspection robot 10 and supporting equipment/tools is believed to be the first and only robotic system and method intended for this particular floating roof seal inspection task and the only one that can actually perform it successfully. The manner in which the present technology including robot 10 and method 50 collects data about the condition of the roof seal(s) and how it communicates those findings to the facility manager provides uniquely suited techniques to operators in the field. Furthermore, the present technology is believed to be the only one "allowed" to safely operate in the potentially dangerous vapor-space environment where the seal (the object of inspection) resides.

[0151] Tank seal inspection using inspection robot 10 according to the present technology requires (on the most basic level) two capabilities. Placing of the above described

LSP 16 into the space 9 between the UVS 5 and the LLS 7, and circumferential navigation around the perimeter of the interior of tank wall 3. Using the IET 106 and the bifurcated design of the robot 10 (and its offset sensor package LSP 16) enables successful accomplishment of this objective. Navigation around the tank wall 3 may be difficult due to the constant friction between the CB 19 of robot 10, UVS 5, and tank wall 3. The above described motion controller 47 may compensate for this using inputs from the pointcloud depth camera(s) 23 and/or 33, ultrasonic transducer 24, and the IMU(s) 41 contained in the LSP 16. A design feature on the CB 19, which may make the 2-dimensional control problem 1-dimensional, is another part of this control scheme. Specifically, the above described roller element(s) 27 (as shown in FIG. 22) also keeps the LSP 16 of inspection robot 10 at a specified distance away from the top of the LLS 7, which simplifies the gap 8 evaluation task. The inspection robot 10 having the ability to effectively move past the grounding straps 38 (placed at regular intervals around the tank) is also necessary for ensuring complete, circumferential navigation by inspection robot 10.

[0152] The main piece of data that is required for the inspection is information about the size and shape of the gap 8 between the LLS 9 and the tank wall 3 (or if one even exists). The detection methodology disclosed herein employs a visual sensor (e.g., depth camera 23) and the ultrasonic transducer 24 (or other capable range finder device) to evaluate the top portion of the gap 8, the DRP 28 passing through the CB 19 and LSP 16 to characterize the lower portion of the gap 8, and an air quality/mass flow rate sensor (e.g., gas monitor 30) to assess if an unacceptable amount of combustible vapors has accumulated in the space 9 between the UVS 5 and the LLS 9. It is believed that there does not currently exist any inspection approach that can do all three of those things. The location of a specific gap 8 within the tank may be identified using a localization algorithm that receives data from the drive wheel 13 encoders, a visual odometry fastener classifier, and the IMU(s) 41. The findings about the dimensions of the LLS 7 gap 8 may be postprocessed and inserted into a 3D CAD model of the tank. This capability can allow the inspection results to integrate seamlessly with software packages (e.g., Digital Twin®, Inspection Data Management Systems, or Enterprise Asset Management Systems) that facility managers are readily embracing these days.

[0153] For the inspection robot 10 to be allowed to enter into the vapor space 9 adjacent the interior wall 3 of a storage tank (which is necessary in order for it to do its job), it must not present a fire hazard. An Ex-rated certification may be needed for the robot 10 in order to prove its safety to facility managers. Motors and other electrical components in housings 15 and 29 of, and elsewhere in, inspection robot 10 can present a challenge for this certification unless they are rated “intrinsically safe.” This can be somewhat cost and size prohibitive, however, and as such the safety of inspection robot 10 can be ensured in a different way. Positive pressurization and liquid immersion of components are certification features of the UDA 11. Power draw management (intrinsic safety) and hermetic sealing (air tightness) are features used to certify the UDA 11 and LSP 16.

[0154] While not a factor in the C1D1 certification requirements, the inspection robot 10 and associated method 50 may also employ active monitoring of onboard temperature, pressure, air quality, and motion data. A safety con-

troller programmed onto the robot's 10 onboard computer 34 may shut down the system or limit it to certain functions in the event of a safety red flag. The controller may activate an emergency shut down (ESD) switch 14, contained within the UDA 11, to break the circuit and effectively remove the third element necessary for a fire: an ignition source. ESD switch may be utilized for the above described power cutting 95 step of method 50. This safety controller may help protect the system and storage tank in the event of exposure to dangerous levels of flammable vapors during an inspection routine. The gas monitor 30 will be instrumental in the throwing or not of a safety red flag.

[0155] There are two different types of storage tanks that need their seals inspected: 1) external floating roof (EFR, as in FIG. 18) or open-top storage tanks and 2) internal floating roof (IFR) or closed-top storage tanks. The methods described thus far have primarily been concerned with deployment and operation of an inspection robot 10 in an EFR environment. However, the inspection of IFRs is of primary importance to tank owners due to the downtime cost associated with shutting a tank down for inspection. There is no UVS 5 for these tank types—only the LLS 7 is present, and as such the inspection process is much easier due to there not being any friction to overcome. However, the deployment of this robot onto the inner tank shell 3 and management of the tether 35 is much more challenging. The operator cannot simply climb the stairwell and place the robot 10 on the wall 3. Instead, the operator must make use of the openings at various locations around the sides and tops of these tanks (e.g., a manway 501 on top of a closed roof tank 502) to guide and deliver the robot 10 to the inner tank wall 3, where the adhesion system utilizing the magnets 32 will take effect to removably attach robot 10 from the interior wall 3, as shown in FIG. 34.

[0156] Still referring to FIG. 34, an operator may removably couple the pole or pole-like object 504 to a coupling means 507 coupled to a portion 505 of the robot 10 (e.g., on top of its housing 15). For this purpose, an end 508 of the pole or pole-like object 504 may have a mating feature such as a tab 509, as shown in the inset 503 of FIG. 34. In some embodiments, coupling means 507 and the mating feature at the end 508 of the pole or pole-like object 504 may be, or at least resemble, a Luer lock mechanism. The operator may insert the end 508 into the mating coupling means 507 outside of the manway 501 with a rotation maneuver 506, insert the robot 10 so attached through the manway 501 and move the end 508 and robot 10 to magnetically attached the robot 10 to the wall 3. Next, the operator may rotate the pole or pole-like object 504 in an opposite direction of the aforementioned initial rotation maneuver 506. An unlocking, rotation maneuver 506 will then occur where the pole or pole-like object 504 will become disengaged from the robot 10, allowing the robot 10 to proceed to navigate to its starting point for the inspection. In the case of the Luer lock embodiment of coupling means 507, the operator may also apply a force to insert the end 508 into coupling means 507 while also rotating pole or pole-like object 504. With robot 10 now magnetically coupled to the wall 3 and the end 508 disengaged from coupling means 507, the operator can remove the pole or pole-like object 504 from the interior of the tank through the manway 501, and the above described process of method 50 may be commenced to advantageous ends. Similarly, when the robot 10 is finished with its mission and navigates up the wall 3 and back to the top of

the tank, a locking, rotation maneuver **506** will be used with the pole **504** to re-engage with the robot's **10** connection point **507**. The robot **10** can then be removed from the wall **3** through a swinging, pulling or similar motion(s) of the pole **504** handled by the operator. This removal of the magnetic wall-crawler robot **10** may be made easier when the robot **10** is driven up onto a rubber mat **51** that may be positioned on a portion of the wall **3** at a convenient location to facilitate access by the operator by way of the mat's **511** own coupling means **512** in like manner as described above with reference to coupling means **507**. Having robot **10** drive onto the rubber mat **511** in this way can reduce the force at which the magnets **32** couple to the metal wall **3** which retain enough such force to maintain robot **10** so attached. Ground clearance may also be increased by driving robot **10** onto the rubber mat **511** in the manner described. The aforementioned reduced magnetic force can make it easier for the operator to remove robot **10** from wall **3**, e.g., at the conclusion of robot's **10** inspection mission. Notably, the above manner of usage of the rubber mat **511** during removal of the robot **10** from the wall **3** as described above for enclosed storage tanks may find analogous advantageous use with the floating roof storage tank examples described herein that are not also closed roof tanks **511**.

[0157] Owners of floating roof storage tanks will benefit from the present technology over their current methodology because it is a solution that eliminates confined space entries by people, helps prevent excess product emissions, drastically reduces costs associated with tank down-time, and delivers on-time, accurate inspection results. Now, more than ever companies are concerned with the well-being of their employees and contractors. Maintaining a healthy and happy relationship between company and employee is critical for the success of the business. One way in which companies can do this is by making their operations safer for their employees. With the present technology, employees will no longer have to crawl down onto the tank roofs for these seal inspections, a task which they have never particularly relished due to its safety issues.

[0158] Additionally, storage tank operators are under more and more scrutiny by state and/or federal regulators when it comes to reducing their contribution to greenhouse gases. Real-time knowledge about the state of the roof **6** seals **5** and **7** minimizes the possibility of a serious failure that could pollute the surrounding area and result in a large fine. This leads to a higher environmental, social, and governance score, which makes the company look more attractive to investors. During times when margins are under pressure, energy companies look for ways to reduce costs. A robot that could be deployed at their convenience without having to shut down the tank for inspection would be a useful tool for facility managers. It gives them a clear, real-time understanding about the state of one of their asset types.

[0159] The inspection robot **10** and associated method **50** may also enable businesses to better plan tank seal repairs, which can be very costly if put off and potentially impossible depending on the financial state of the business. With the present technology, confined-space permits may not be needed and inspection results are more immediate. This allows for the efficient planning of repairs and makes the job of facility managers that much easier. The evaluation and/or measurement accuracy of the seal gap **8** improves with the solution provided by the provided technology as a computer image processing algorithm may be utilized that sizes the

gap **8** based on inputs from the depth camera **23**, no longer relying on the ability of a human eye to estimate the size of the gap **8**. The speed of the tank seal inspection routine may also improve by a factor of **8X** with the inspection robot **10** and associated method **50**, allowing inspectors to move on more quickly to other tasks around the facility.

[0160] Tank seal designs vary and there is no guarantee that one robot design will work for all tank types. This limitation can be overcome by using different offsets for the necessary sensor packages according to the present technology. Some tanks have irregular structural additions on the UVS **5** such as ground straps **38**, which may require more complicated offset mounts or navigation strategies, both of which can be planned given visual or CAD data on the tanks and seals to be inspected. The maneuverability of the disclosed inspection robot **10** may also not be the same for every tank due to varying amounts of sludge that can build up on the inner wall **3** of the tank. This can be accounted for by using more aggressive tracks **17** that dig into the sludge, which, along with magnets **32**, can help to achieve the required frictional force between the tracks **17** and wall **3**. Depending on the level of sludge and thickness of the tank wall **3**, the size and/or strength of the magnets **32** (providing adhesion) and their offset from the wall **3** may also need to be adjusted for a particular application. Means for operators to conveniently make such adjustments on the fly may be included on or within housing **15**, or elsewhere, on robot **10**. External and internal floating roof tanks may require different deployment methods to get the sensor package, e.g., of LSP **16**, in place to visualize and inspect the seal(s) **5** and **7**. External floating roofs may require a simple mechanical wedge to open the secondary seal while internal floating roofs may require indirect access to the tank wall and seal via an opening in the top or sides of the tank.

[0161] As may be recognized and appreciated by persons of ordinary skill in the art, the engineering that goes into the Ex-rated capability of the inspection robot **10** according to the present technology may be leveraged to produce other robots for a variety of other storage inspection use cases in, for example and without limitation, the energy, chemical, paper/pulp, and agricultural industries, where there is a risk of spark ignition. As with the energy industry, similar types of tanks are used in a variety of industries which store large volumes of fluids, and the disclosed robot **10** and associated method **50** may be applicable to all of them (especially chemical plants). Likewise, for inspection service providers, the technical benefits provided by the present technology are readily apparent, including as they may relate to API 653 and STI SP001 standards. Of course, persons having ordinary skill in the art are expected to readily recognize and appreciate a variety of advantageous applications of the robot **10** according to the present technology in use cases beyond strictly storage tanks (e.g., pipelines, HVAC ducts, etc.) beyond those involving fire and explosion hazards, and are further expected to be capable of applying the present technology to such other use cases without undue experimentation being required.

EXAMPLE 2

[0162] In some embodiments, a tank inspection method (e.g., method **50**) including the step of actuating, by a drive assembly (e.g., UDA **11**) of a robot (e.g., tank inspection robot **10**), wheels of the robot to navigate the robot to one or more circumferential seals positioned proximate to an

interior wall of a storage tank. The tank inspection method may also include the step of collecting, by at least one sensor of the robot, data sufficient to evaluate a health, integrity, or effectiveness of the one or more circumferential seals between a floating roof, and the interior wall of the storage tank. In an example, the tank inspection method may also include the step of magnetically coupling the robot to the interior wall of the storage tank before, or concurrent with, the performance of the actuating step.

[0163] In some embodiments, the tank inspection method may further include the step(s) of removing and/or displacing, using a plow mechanism **803** (e.g., as shown in FIG. **36**), and/or wiper mechanism, of the robot, sludge or other contaminant(s) from the interior wall of the storage tank. In an example, the sludge or other contaminant(s) may tend to decrease friction and/or decrease magnetic adhesion between the tracks or other portions of the robot (e.g., having magnets **32**) and the interior wall of the storage tank during performance of portions of the tank inspection method according to the present technology. As such, performance of the removing and/or displacement step(s) in the method may increase friction and/or magnetic adhesion between the tracks or other portions of the robot and the interior wall of the storage tank during performance of at least the actuating step. In another example, removing and/or displacing the sludge or other contaminant(s) from the interior wall may advantageously prevent, or at least mitigate, slippage of the robot during performance of at least the actuating step in the tank inspection method.

[0164] Referring to FIG. **36**, the plow mechanism **803** may be wedge-shaped, or triangular shaped pair of pieces positioned on opposing sides of the robot **10** as forward facing means for scraping or plowing undesirable material from the wall during the actuating, or other steps, of the method **50**. Such undesirable material may include sludge or other contaminants that could inhibit adhesion and maneuverability of the robot **10** during the inspection mission according to the present technology.

[0165] In one embodiment, the step of collecting in the tank inspection method may include collecting, using a forward-facing depth camera of the robot, at least one of: visual, and pointcloud, data sufficient to plan a path or trajectory for performance of the actuating step. In one example, the aforementioned data sufficient to plan the path or trajectory may include data representative of one or more physical characteristics of the one or more circumferential seals, the actuating step may include causing the robot to navigate along the path or trajectory to a starting position for a tank inspection routine based on the data representative of one or more physical characteristics. In another example, the aforementioned data sufficient to plan the path or trajectory may include data representative of at least one obstacle present between the robot and the one or more circumferential seals, and the actuating step may include causing the robot to navigate along a trajectory in such a manner so as to avoid interference with the at least one obstacle.

[0166] In some embodiments, the step of collecting in the tank inspection method may include collecting, using at least one depth camera of the robot, pointcloud data. In an example, the tank inspection method may also include the step of generating, based at least in part on the pointcloud data, a two- or three-dimensional model of at least one of: the one or more circumferential seals, and a portion of the

interior wall, to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals.

[0167] In one embodiment, the at least one sensor may be positioned on, or in, a sensor package (e.g., LSP **16**) of the robot. In an example, the tank inspection method may also include the step of inserting at least a portion of the sensor package between the one or more circumferential seals and the interior wall of the storage tank. The inserting step of the method may be performed before, or concurrent with, the collecting step.

[0168] Regarding the inserting step of the tank inspection method according to this Example 2, the robot may include a connector bridge (e.g., CB **19**) coupled to and between the drive assembly and the sensor package to thereby position the sensor package including the at least one sensor apart and spaced from a portion of the robot having the drive assembly. In some embodiments, the connector bridge may include active or passive roller elements. In one example, the tank inspection method may further include—after, or concurrent with, the inserting, and while the connector bridge is positioned between the one or more circumferential seals and the interior wall—the step of moving the sensor package with the active or passive roller elements in contact with the interior wall to thereby reduce friction during the moving as compared to the moving in the absence of the active or passive roller elements. In another example, the tank inspection method may further include—after, or concurrent with, the inserting, the step of moving the sensor package around the tank while the connector bridge is positioned between the one or more circumferential seals and the interior wall with the active or passive roller elements in contact with the interior wall to thereby reduce friction during the moving as compared to the moving in the absence of the active or passive roller elements.

[0169] Further in regard to the inserting step of the tank inspection method according to this Example 2, in one embodiment, the tank inspection method according to the present technology may also include the steps of: (a) determining, by a motion controller (e.g., motion controller **47**) of the robot before or concurrent with at least one of: the actuating step, the inserting step, and the moving step, at least one factor for compensating for frictional or other disturbances whilst the at least a portion of the sensor package is inserted between the one or more circumferential seals and the interior wall of the storage tank; and (b) applying the at least one factor for use by the drive assembly for the at least one of: the actuating step, the inserting step, and the moving step, to compensate for the frictional or other disturbances.

[0170] In some embodiments, the tank inspection method according to the present technology may include the step of evaluating a physical condition of the one or more circumferential seals based at least in part on the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals. In one embodiment, the at least one sensor may include at least one depth camera. In one example, the collecting step of the tank inspection method may include collecting, using the at least one depth camera, pointcloud data to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals. In some embodiments, the collecting step of the tank inspection method may include collecting color data of at least one of: the interior wall, and the one or more circumferential seals, to facilitate characterizing and/or evaluating the

health, integrity, or effectiveness of the one or more circumferential seals or a seal assembly including the one or more circumferential seals.

[0171] In one embodiment, the tank inspection method according to the present technology may further include the step of operating the robot for an inspection routine within the storage tank while using one or more proven protection methodologies to make the robot explosion-proof and safe for potentially flammable environments (e.g., one or more of those safety-related components and associated techniques as described above in Example 1).

[0172] In some embodiments, the tank inspection method may also include the step of flowing an inert gas from a source outside of the robot into one or more housings of the robot to maintain at least one of: a positive pressure, and a non-combustible operating environment, inside of the one or more housings (e.g., housing(s) **15** and/or **29**). In one example, the tank inspection method may further include the steps of: (a) determining, based on data representative of the monitored interior environment collected by at least one of: an onboard gas monitor, a pressure sensor, and a temperature sensor, of the robot, a failure or abnormality of the flowing of the inert gas from the aforementioned external source to maintain a positive pressurization within the one or more housings; and (b) in response to determining the failure or abnormality of the flowing, activating an onboard positive pressurization subsystem of the robot to restore a safe operating condition within the one or more housings. In another example, the tank inspection method additionally, or instead, include the step of: (c) in response to determining the failure or abnormality of the flowing, activating a fan cooling subsystem of the robot to restore a safe operating condition within the one or more housings. In one embodiment, either or both of the aforementioned activating steps of the tank inspection method may include flowing an inert gas from a gas canister positioned onboard the robot into the one or more housings.

[0173] In one embodiment, the tank inspection method according to the present technology may include the step of causing static electricity or other unintended electric charge, already present in or on the robot, or built-up during operation of the robot, to be discharged, by way of one or more appropriate means, from the robot to a sink external to the robot. Aspects of the tether described above with reference to Example 1 (e.g., a ground wire thereof) may be utilized in this manner. In some embodiments, the tank inspection method may include the steps of: (a) determining, by a safety state monitoring system of the robot, an unsafe operating condition for the robot during an inspection routine; and (b) in response to determining the unsafe condition, causing, by a deadman switch, the robot to be powered down.

[0174] In one embodiment, the tank inspection method may include the step of managing a delivery mechanism for a tether assembly of the robot to facilitate preventing entanglement of the tether with one or more features of the storage tank. In an example, the method may also include the step of maintaining the tether assembly on or proximate to the interior wall of the storage tank to facilitate avoidance of, prevention, or at least reduction of a frequency, of entanglement of the tether assembly including the tether with, obstacles during performance of at least the actuating step. In another example, the managing step may include the aforementioned maintaining step. In some embodiments, the

aforementioned maintaining step of the method may include magnetically coupling (e.g., using appropriate means such as, for example and without limitation, rolling trailer **301**) a portion of the tether assembly to the interior wall of the storage tank.

[0175] Regarding the above described collecting step of the tank inspection method according to this Example 2, the method may also include the steps of: (a) collecting, using the at least one sensor, data representative of a physical condition, or a mechanical integrity, of the one or more circumferential seals; and (b) determining, based at least in part on the data representative of a physical condition or mechanical integrity of the one or more circumferential seals, an indication resulting from a deterioration of: the physical condition, or the mechanical integrity. In some embodiments, the at least one sensor may include a physical measuring apparatus operably coupled to the sensor package of the robot, and the collecting step may include the steps of: deploying the physical measuring apparatus into a gap (e.g., gap **8**) between the interior wall and the one or more circumferential seals; and taking a direct measurement of the gap using the physical measuring apparatus. The step of taking may include generating data representative of the direct measurement.

[0176] In one embodiment, the at least one sensor may include a distance or range measuring sensor to collect distance data, and the collecting step of the tank inspection method may include the steps of: directing the distance or range measuring sensor to collect the distance data; and determining, based at least in part on the distance data, one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals. In an example, the step of determining the one or more dimensions may include the step of determining, based at least in part on the distance data, one or more dimensions of the aforementioned gap.

[0177] In some embodiments, the at least one sensor may include a resistance probe (e.g., DRP **28**) to collect resistance or torque data, and the collecting step of the tank inspection method may include the steps of: directing the resistance probe to collect the resistance or torque data; and determining, based at least in part on the resistance or torque data, one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals. In an example, the method step of determining, based on the torque of resistance data, the one or more dimensions may include determining, based at least in part on the distance data, one or more dimensions of the aforementioned gap. In one embodiment, the at least one sensor may include at least one camera to collect at least one of color, and pointcloud, data, and the collecting step of the tank inspection method may include the steps of: directing the at least one camera to collect the at least one of color, and pointcloud, data; and determining, based at least in part on the at least one of color, and pointcloud, data, one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals.

[0178] In some embodiments, the at least one sensor includes a gas monitor (e.g., gas monitor **30**), and the collecting step of the tank inspection method may include collecting, using the gas monitor, data representative of at least one of: a concentration, and a leakage rate, of one or more gases inside the storage tank, both above or below a secondary vapor seal (e.g., UVS **5**) of the storage tank. In an

example, the tank inspection method may also include the step of determining that the at least one of: the concentration, and the leakage rate, of the one or more gases equals or exceeds an allowable safety threshold.

[0179] In one embodiment, the tank inspection method may also include the step of transmitting, by a communications interface (e.g., comm. int. **40**) of the robot, at least one of the aforementioned types of data: (i) the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals; (ii) the data representative of a physical condition, or a mechanical integrity of the one or more circumferential seals; (iii) data representative of the determined indication resulting from a deterioration of: the physical condition, or the mechanical integrity; (iv) the at least one of: visual, and pointcloud, data sufficient to plan a path or trajectory for the actuating; (v) the data representative of one or more physical characteristics of the one or more circumferential seals; (vi) the pointcloud data; (vii) the data representative of the direct measurement of the gap; (viii) the distance data; (ix) data representative of the one or more dimensions of the one or more circumferential seals; (x) the one or more dimensions of a gap; (xi) the resistance or torque data; (xii) data representative of the one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals; (xiii) the at least one of: color, and pointcloud, data; (xiv) the color data; (xv) the data representative of at least one of: a concentration, and a leakage rate, of the one or more gases; (xvi) the data representative of the two- or three-dimensional model; and (xvii) data representative that the one or more gases equals or exceeds an allowable safety threshold, to least one of: an operator, a computer, and a subsystem, of, or communicably coupled to, the robot to facilitate evaluation of the health, integrity, or effectiveness of the one or more circumferential seals or the seal assembly. In an example, the tank inspection method also includes the step of evaluating the health, integrity, or effectiveness of the one or more circumferential seals based at least in part on one or more of the above listed data types (i)-(xvii).

EXAMPLE 3

[0180] In some embodiments, a tank inspection robot may include at least one housing, and a drive assembly contained within the housing. In an example, the drive assembly may include, for example and without limitation, an electric motor-based drive train. The tank inspection robot may also include wheels disposed outside of the housing and operably coupled to the drive assembly to actuate the wheels to navigate the robot to one or more circumferential seals positioned proximate to an interior wall of a storage tank. The robot may further include at least one sensor disposed in or on a portion of the robot. The at least one sensor may be configured to collect data sufficient to evaluate a health, integrity, or effectiveness of the one or more circumferential seals between a floating roof, and an interior wall, of the storage tank. The robot may also include a connector bridge coupled to and between the drive assembly and the sensor package of the robot to thereby position the at least one sensor apart and spaced from the drive assembly.

[0181] In one embodiment, the robot may include two wheels, and the robot may also include a track operable coupled to the two wheels. In another embodiment, the robot may include four wheels, and the robot may also include two tracks including: a first track operable coupled to a first pair

of wheels of the four wheels, and a second track operably coupled to a second pair of wheels of the four wheels. In an example, the robot may further include a plurality of magnets operably coupled to: the track, or the first and second tracks.

[0182] In some embodiments, the tank inspection robot may include one or more magnets for magnetically coupling the robot to the interior wall of the storage tank. In an example, the robot may also include a plow mechanism (e.g., as shown in FIG. **36**) and/or a wiper mechanism to remove or displace sludge or other contaminant(s) from the interior wall, where the sludge or other contaminant(s) may tend to decrease friction or magnetic adhesion with the interior wall of the storage tank during operation of the robot.

[0183] In one embodiment, the tank inspection robot may include at least one light disposed on or in a portion of the robot, and configured to illuminate an area of interest outside of the housing to facilitate one or more operations of the robot including at least one of: (a) collection, by the at least one sensor, of the data sufficient to evaluate the health, integrity, or effectiveness of one or more circumferential seals; and (b) navigation of the robot along the interior wall when light is scarce inside the storage tank.

[0184] In some embodiments, the at least one sensor may include a forward-facing depth camera configured to collect at least one of: visual, and pointcloud, data sufficient for use by an operator, or a computer, of or associated with the robot to plan a path or trajectory for actuation of the wheels during operation of the robot in a tank inspection routine. In one example, the data sufficient to plan the path or trajectory may include data representative of one or more physical characteristics of the one or more circumferential seals, and the drive assembly may be configured to cause the robot to navigate along the path or trajectory to a starting position for a tank inspection routine based at least in part on the data representative of one or more physical characteristics. In another example, the data sufficient to plan the path or trajectory may include data representative of at least one obstacle present between the robot and the one or more circumferential seals, and the drive assembly may be configured to navigate the robot along the path or trajectory in such a manner so as to avoid interference with the at least one obstacle.

[0185] In one embodiment, the at least one sensor may include a depth camera configured to collect pointcloud data sufficient for use by an operator, or a computer, of or associated with the robot to generate, based at least in part on the pointcloud data, a two- or three-dimensional model of at least one of: the one or more circumferential seals, and a portion of the interior wall, to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals. In some embodiments, the tank inspection may also include a sensor package including the at least one sensor, and the drive assembly may be configured to further actuate the wheels of the robot to insert at least a portion of the sensor package between the one or more circumferential seals and the interior wall of the storage tank to facilitate collection of data by the at least one sensor during operation of the robot in a tank inspection routine. In an example, the connector bridge may include active or passive roller elements, and after, or concurrent with, the at least a portion of the sensor package being so inserted, and while the connector bridge is positioned between the one or more circum-

ferential seals and the interior wall, the drive assembly may be further configured to move the sensor package with the active or passive roller elements in contact with the interior wall to thereby reduce friction during the moving as compared to such movement in the absence of the active or passive roller elements. In another example, the connector bridge includes the one or more active or passive roller wheels, and with the at least a portion of the sensor package inserted between the one or more circumferential seals and the interior wall, the drive assembly may be further configured to actuate the wheels of the robot to move the sensor package around the tank while the connector bridge is positioned between the one or more circumferential seals and the interior wall with the active or passive roller elements in contact with the interior wall to thereby reduce friction during the movement as compared to such movement performed in the absence of the active or passive roller elements.

[0186] Regarding the above described insertion of the at least a portion of the sensor package between the one or more circumferential seals and the interior wall according to this Example 3, the tank inspection robot may include a motion controller disposed in or on the housing(s). In some embodiments, the motion controller may be configured to: (a) determine, before or concurrent with said movement, at least one factor for compensating for frictional or other disturbances whilst the at least a portion of the sensor package is inserted between the one or more circumferential seals and the interior wall of the storage tank; and (b) apply the at least one factor for use by the drive assembly for actuation of the wheels during said movement to compensate for the frictional or other disturbances.

[0187] In one embodiment, the at least one sensor may include a depth camera configured to collect pointcloud data to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals. In some embodiments, the at least one sensor may be configured to collect color data of at least one of: the interior wall, and the one or more circumferential seals, to facilitate characterization of the health, integrity, or effectiveness of the one or more circumferential seals or a seal assembly including the one or more circumferential seals. In one embodiment, the tank inspection robot may include means for evaluating a physical condition of the one or more circumferential seals based at least in part on the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals.

[0188] In some embodiments, the tank inspection robot may include means for operating the robot for an inspection routine within the storage tank while using one or more proven protection methodologies to make the robot explosion-proof and safe for potentially flammable environments (e.g., one or more of those safety-related components and associated techniques as described above in Example 1). In one embodiment, the robot may include one or more electrical safety protection features, disposed in or on a portion of the robot, and including at least one of: an onboard pressure regulator; an onboard air quality regulator; one or more oil-filled enclosures for high-power draw components; at least one intrinsically safe or low-power draw sensor; at least one intrinsically safe or low-power draw motor, servo and/or actuator; and explosion-proof housing(s) with sufficient flame path features for all joints.

[0189] In some embodiments, the tank inspection robot may include means for flowing an inert gas from a source outside of the robot into at least one of the housing, or another housing, of the robot to maintain at least one of: a positive pressure, and a non-combustible operating environment, inside of the one or more housings. Such means may include, for example and without limitation, pump(s), compressor(s), fan(s), impeller(s), propeller(s), and the like. In a first example, the tank inspection robot may also include: an onboard positive pressurization subsystem disposed in or on at least one of: the housing, and another housing, of the robot; and at least one of: an onboard gas monitor, a pressure sensor, and a temperature sensor disposed in or on the at least one of: the housing, and the another housing, and configured to monitor or collect data sufficient for use by an operator, or a computer, of or associated with the robot to: (a) determine a failure or abnormality originating with, or otherwise caused by, the means for flowing to maintain a positive pressurization within the at least one of: the housing, and the another housing; and (b) in response to the failure or abnormality being determined, activate the onboard positive pressurization subsystem to restore a safe operating condition within the at least one of: the housing, and the another housing. In a second example, the robot may additionally, or instead, include a fan cooling subsystem, and the at least one of: an onboard gas monitor, a pressure sensor, and a temperature sensor, may additionally, or instead, be configured to activate the fan cooling subsystem to restore a safe operating condition within the at least one of: the housing, and the another housing, in response to the failure or abnormality being determined. In either or both of the aforementioned first and second examples, the tank inspection robot may include an onboard inert gas supply disposed in or on the at least one of: the housing, and the another housing. The onboard inert gas supply may be configured to flow an inert gas into the at least one of: the housing, and another housing, in response to the onboard positive pressurization subsystem, or the fan cooling subsystem, being activated.

[0190] In one embodiment, the tank inspection robot according to the present technology may include means for causing static electricity or other unintended electric charge, already present in or on the robot, or built-up during operation of the robot, to be discharged, from the robot to a sink external to the robot. Such means may include, for example and without limitation, the tether or tether assembly as described above in Examples 1 and 2. In some embodiments, the tank inspection robot may include: means for supplying electric power to the robot; a switch operably coupled to the means for supplying; and a safety state monitoring system. The safety state monitoring system may be configured to: determine an unsafe condition for the robot during operation of the robot in a tank inspection routine; and in response to the unsafe condition being determined, causing the switch to operate to power down the robot.

[0191] In some embodiments, the at least one sensor may be further configured to collect data representative of a physical condition, or a mechanical integrity, of the one or more circumferential seals for use by an operator, or a computer, of or associated with the robot to determine, based at least in part on the data representative of the physical condition or mechanical integrity of the one or more circumferential seals, an indication resulting from a deterioration of: the physical condition, or the mechanical integrity.

In one embodiment, the at least one sensor may include a physical measuring apparatus for deployment into a gap between the interior wall and the one or more circumferential seals. In an example, the physical measuring apparatus may be configured to take a direct measurement of the gap.

[0192] In one embodiment, the at least one sensor may include a distance or range measuring sensor configured to collect distance data sufficient for use by an operator, or a computer, of or associated with the robot to determine one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals. In an example, the distance or range measuring apparatus may be further configured to collect the distance data that is further sufficient for use by the operator, or the computer, to determine one or more dimensions of a gap between the interior wall and the one or more circumferential seals.

[0193] In some embodiments, the at least one sensor may include a resistance probe configured to collect resistance or torque data sufficient for use by an operator, or a computer, of or associated with the robot to determine one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals. In an example, the resistance probe may be further configured to collect the resistance or torque data that is further sufficient for use by the operator, or the computer, to determine one or more dimensions of a gap between the interior wall and the one or more circumferential seals. In one embodiment, the at least one sensor may include at least one camera configured to collect at least one of color, and pointcloud, data sufficient for use by an operator, or a computer, of or associated with the robot to determine one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals.

[0194] In some embodiments, the at least one sensor may include a gas monitor configured to collect data representative of at least one of: a concentration, and a leakage rate, of one or more gases inside the storage tank, both above or below a secondary vapor seal of the storage tank. In an example, the at least one sensor is further configured to collect the data representative of at least one of: a concentration, and a leakage rate, that is sufficient for use by an operator, or a computer, of or associated with the robot to determine that the at least one of: the concentration, and the leakage rate, of the one or more gases equals or exceeds an allowable safety threshold.

[0195] In one embodiment, the tank inspection robot may include a communications interface. In an example, the communications interface may be configured to transmit at least one of: (i) the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals; (ii) the data representative of a physical condition, or a mechanical integrity of the one or more circumferential seals; (iii) data representative of the determined indication resulting from a deterioration of: the physical condition, or the mechanical integrity; (iv) the at least one of: visual, and pointcloud, data sufficient to plan a path or trajectory for the actuating; (v) the data representative of one or more physical characteristics of the one or more circumferential seals; (vi) the pointcloud data; (vii) the data representative of the direct measurement of the gap; (viii) the distance data; (ix) data representative of the one or more dimensions of the one or more circumferential seals; (x) the one or more dimensions of a gap; (xi) the resistance or torque data; (xii) data

representative of the one or more dimensions of the one or more circumferential seals or a seal assembly including the one or more circumferential seals; (xiii) the at least one of: color, and pointcloud, data; (xiv) the color data; (xv) the data representative of at least one of: a concentration, and a leakage rate, of the one or more gases; (xvi) the data representative of the two- or three-dimensional model; and (xvii) data representative that the one or more gases equals or exceeds an allowable safety threshold, to at least one of: an operator, a computer, and a subsystem, of, or communicably coupled to, the communications interface to facilitate evaluation of the health, integrity, or effectiveness of the one or more circumferential seals or the seal assembly. In an example, the tank inspection robot method also includes means for evaluating the health, integrity, or effectiveness of the one or more circumferential seals based at least in part on one or more of the data (i)-(xvii).

[0196] In some embodiments, the tank inspection robot may also include the aforementioned computer disposed in or on the housing, and operably coupled to the at least one sensor. In an example, the computer is further operably coupled to the communications interface. In some embodiments, the robot may further include at least one memory storage device operably coupled to the computer. In an example, the memory storage device(s) may be configured to receive and store data at least one of: collected by the at least one sensor, and processed by the computer, during operation of the robot in a tank inspection routine.

EXAMPLE 4

[0197] In some embodiments, a robotic tank inspection system may include the tank inspection robot according to any one or more of the several embodiments according to the present technology as disclosed herein. The robotic tank inspection system may also include a tether assembly including a power and/or communication tether couplable, or coupled to, the robot. The robotic tank inspection system may further include means for managing a delivery mechanism for the tether assembly to facilitate preventing entanglement of the tether with one or more features of the storage tank.

[0198] In one embodiment, the tank inspection system may include means for maintaining the tether or the tether assembly on or proximate to the interior wall of the storage tank to facilitate avoidance of, or prevention of entanglement with, obstacles during operation of the robot in a tank inspection routine. In an example, the means for maintaining may include means for magnetically coupling (e.g., rolling trailer **301**) a portion of the tether or the tether assembly to the interior wall.

[0199] In some embodiment, the robotic tank inspection system may include at least one computing system communicably coupled to the robot and positioned remotely therefrom outside of an interior space of the storage tank. In an example, the at least one computing system may be configured to receive, and process, at least the data sufficient to evaluate a health, integrity, or effectiveness of the one or more circumferential seals to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals.

EXAMPLE 5

[0200] In some embodiments, a tether and tether management system for the tank inspection robot of any of the

above described embodiments may include a tether assembly including at least one of: power, communication, and inert gas, lines for operably coupling to the robot during operation thereof. The tether and tether management system may also include means for managing the tether assembly during operation of the robot in a tank inspection routine.

EXAMPLE 6

[0201] In some embodiments, a deployment mechanism for the tank inspection robot of any one of the above described embodiments may include means for inserting the robot via a pole or pole-like object onto the interior wall of the storage tank. In an example, the means for inserting is configured to insert the robot into an at least partially closed-roof storage tank by way of a manway or other opening in a roof or side of the at least partially closed-roof storage tank.

[0202] In one embodiment, the deployment mechanism may include a rubber or rubberized mat including one or more magnets coupled to at least one side of the rubber or rubberized mat for removably coupling the rubber or rubberized mat to the interior wall.

EXAMPLE 7

[0203] In some embodiments, the present technology provides one or more non-transitory computer readable media. The one or more non-transitory media may have program instructions stored thereon (e.g., as processor-executable software and/or firmware code). When executed by at least one processor of or associated with the machine, the program instructions may cause the machine to: (a) direct a drive assembly of a tank inspection robot (e.g., robot 10) to actuate wheels of the robot to navigate the robot to one or more circumferential seals positioned proximate to an interior wall of a storage tank; and direct at least one sensor (e.g., any one or more of the sensors disclosed herein) of the robot to collect data sufficient to evaluate a health, integrity or effectiveness of the one or more circumferential seals between a floating roof, and the interior wall of the storage tank.

[0204] In one embodiment, when executed by the at least one processor, the program instructions further cause the machine to direct to robot and/or one or more of its component parts (e.g., any of the various mechanical, electrical and/or functional features of the robot as disclosed herein, including at least the drive assembly and the at least one sensor) to perform at least one of the steps of the tank inspection method (e.g., method 50) of any applicable embodiment disclosed herein according to the present technology.

Exemplary Computer System Overview

[0205] Aspects and implementations of the inspection system of the disclosure have been described in the general context of various steps and operations. A variety of these steps and operations may be performed by hardware components or may be embodied in computer-executable instructions, which may be used to cause a general-purpose or special-purpose processor (e.g., in a computer, server, or other computing device) programmed with the instructions to perform the steps or operations. For example, the steps or operations may be performed by a combination of hardware, software, and/or firmware.

[0206] FIG. 35 is a block diagram illustrating an example machine representing the computer systemization of the inspection platform. The controller 1800 may be in communication with entities including one or more users 1825 client/terminal devices 1820, user input devices 1805, peripheral devices 1810, an optional co-processor device(s) (e.g., cryptographic processor devices) 1815, and networks 1830. Users may engage with the controller 1800 via terminal devices 1820 over networks 1830.

[0207] Computers may employ central processing unit (CPU) or processor to process information. Processors may include programmable general-purpose or special-purpose microprocessors, programmable controllers, application-specific integrated circuits (ASICs), programmable logic devices (PLDs), embedded components, combination of such devices and the like. Processors execute program components in response to user and/or system-generated requests. One or more of these components may be implemented in software, hardware or both hardware and software. Processors pass instructions (e.g., operational and data instructions) to enable various operations.

[0208] The controller 1800 may include clock 1865, CPU 1870, memory such as read only memory (ROM) 1885 and random access memory (RAM) 1880 and co-processor 1875 among others. These controller components may be connected to a system bus 1860, and through the system bus 1860 to an interface bus 1835. Further, user input devices 1805, peripheral devices 1810, co-processor devices 1815, and the like, may be connected through the interface bus 1835 to the system bus 1860. The interface bus 1835 may be connected to a number of interface adapters such as processor interface 1840, input output interfaces (I/O) 1845, network interfaces 1850, storage interfaces 1855, and the like.

[0209] Processor interface 1840 may facilitate communication between co-processor devices 1815 and co-processor 1875. In one implementation, processor interface 1840 may expedite encryption and decryption of requests or data. Input output interfaces (I/O) 1845 facilitate communication between user input devices 1805, peripheral devices 1810, co-processor devices 1815, and/or the like and components of the controller 1800 using protocols such as those for handling audio, data, video interface, wireless transceivers, or the like (e.g., Bluetooth, IEEE 1394a-b, serial, universal serial bus (USB), Digital Visual Interface (DVI), 802.11a/b/g/n/x, cellular, etc.). Network interfaces 1850 may be in communication with the network 1830. Through the network 1830, the controller 1800 may be accessible to remote terminal devices 1820. Network interfaces 1850 may use various wired and wireless connection protocols such as, direct connect, Ethernet, wireless connection such as IEEE 802.11a-x, and the like.

[0210] Examples of network 1830 include the Internet, Local Area Network (LAN), Metropolitan Area Network (MAN), a Wide Area Network (WAN), wireless network (e.g., using Wireless Application Protocol WAP), a secured custom connection, and the like. The network interfaces 1850 can include a firewall which can, in some aspects, govern and/or manage permission to access/proxy data in a computer network, and track varying levels of trust between different machines and/or applications. The firewall can be any number of modules having any combination of hardware and/or software components able to enforce a predetermined set of access rights between a particular set of machines and applications, machines and machines, and/or

applications and applications, for example, to regulate the flow of traffic and resource sharing between these varying entities. The firewall may additionally manage and/or have access to an access control list which details permissions including, for example, the access and operation rights of an object by an individual, a machine, and/or an application, and the circumstances under which the permission rights stand. Other network security functions performed or included in the functions of the firewall, can be, for example, but are not limited to, intrusion-prevention, intrusion detection, next-generation firewall, personal firewall, etc., without deviating from the novel art of this disclosure.

[0211] Storage interfaces **1855** may be in communication with a number of storage devices such as, storage devices **1890**, removable disc devices, and the like. The storage interfaces **1855** may use various connection protocols such as Serial Advanced Technology Attachment (SATA), IEEE 1394, Ethernet, Universal Serial Bus (USB), and the like.

[0212] User input devices **1805** and peripheral devices **1810** may be connected to I/O interface **1845** and potentially other interfaces, buses and/or components. User input devices **1805** may include card readers, fingerprint readers, joysticks, keyboards, microphones, mouse, remote controls, retina readers, touch screens, sensors, and/or the like. Peripheral devices **1810** may include antenna, audio devices (e.g., microphone, speakers, etc.), cameras, external processors, communication devices, radio frequency identifiers (RFIDs), scanners, printers, storage devices, transceivers, and/or the like. Co-processor devices **1815** may be connected to the controller **1800** through interface bus **1835**, and may include microcontrollers, processors, interfaces or other devices.

[0213] Computer executable instructions and data may be stored in memory (e.g., registers, cache memory, random access memory, flash, etc.) which is accessible by processors. These stored instruction codes (e.g., programs) may engage the processor components, motherboard and/or other system components to perform desired operations. The controller **1800** may employ various forms of memory including on-chip CPU memory (e.g., registers), RAM **1880**, ROM **1885**, and storage devices **1890**. Storage devices **1890** may employ any number of tangible, non-transitory storage devices or systems such as fixed or removable magnetic disk drive, an optical drive, solid state memory devices and other processor-readable storage media. Computer-executable instructions stored in the memory may include one or more program modules such as routines, programs, objects, components, data structures, and so on that perform particular tasks or implement particular abstract data types. For example, the memory may contain operating system (OS) component **1895**, modules and other components, database tables, and the like. These modules/components may be stored and accessed from the storage devices, including from external storage devices accessible through an interface bus.

[0214] The database components can store programs executed by the processor to process the stored data. The database components may be implemented in the form of a database that is relational, scalable and secure. Examples of such database include DB2, MySQL, Oracle, Sybase, and the like. Alternatively, the database may be implemented using various standard data-structures, such as an array, hash, list, stack, structured text file (e.g., XML), table,

and/or the like. Such data-structures may be stored in memory and/or in structured files.

[0215] The controller **1800** may be implemented in distributed computing environments, where tasks or modules are performed by remote processing devices, which are linked through a communications network, such as a Local Area Network (“LAN”), Wide Area Network (“WAN”), the Internet, and the like. In a distributed computing environment, program modules or subroutines may be located in both local and remote memory storage devices. Distributed computing may be employed to load balance and/or aggregate resources for processing. Alternatively, aspects of the controller **1800** may be distributed electronically over the Internet or over other networks (including wireless networks). Those skilled in the relevant art(s) will recognize that portions of the system may reside on a server computer, while corresponding portions reside on a client computer. Data structures and transmission of data particular to aspects of the controller **1800** are also encompassed within the scope of the disclosure.

Conclusion

[0216] Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise,” “comprising,” and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to.” As used herein, the terms “connected,” “coupled,” or any variant thereof means any connection or coupling, either direct or indirect, between two or more elements; the coupling or connection between the elements can be physical, logical, or a combination thereof. Additionally, the words “herein,” “above,” “below,” and words of similar import, when used in this application, refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word “or,” in reference to a list of two or more items, covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

[0217] The above Detailed Description of examples of the technology is not intended to be exhaustive or to limit the technology to the precise form disclosed above. While specific examples for the technology are described above for illustrative purposes, various equivalent modifications are possible within the scope of the technology, as those skilled in the relevant art will recognize. The teachings of the technology provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various examples described above can be combined to provide further implementations of the technology. Some alternative implementations of the technology may include not only additional elements to those implementations noted above, but also may include fewer elements.

[0218] These and other changes can be made to the technology in light of the above Detailed Description. While the above description describes certain examples of the technology, and describes the best mode contemplated, no matter how detailed the above appears in text, the technology can be practiced in many ways. Details of the system may vary considerably in its specific implementation, while

still being encompassed by the technology disclosed herein. As noted above, particular terminology used when describing certain features or aspects of the technology should not be taken to imply that the terminology is being redefined herein to be restricted to any specific characteristics, features, or aspects of the technology with which that terminology is associated. In general, the terms used in the following claims should not be construed to limit the technology to the specific examples disclosed in the specification, unless the above Detailed Description section explicitly defines such terms. Accordingly, the actual scope of the technology encompasses not only the disclosed examples, but also all equivalent ways of practicing or implementing the technology under the claims.

[0219] To reduce the number of claims, certain aspects of the technology are presented below in certain claim forms, but the applicant contemplates the various aspects of the technology in any number of claim forms. For example, while only one aspect of the technology is recited as a computer-readable medium claim, other aspects may likewise be embodied as a computer-readable medium claim, or in other forms, such as being embodied in a means-plus-function claim. Any claims intended to be treated under 35 U.S.C. § 112(f) will begin with the words “means for”, but use of the term “for” in any other context is not intended to invoke treatment under 35 U.S.C. § 112(f). Accordingly, the applicant reserves the right to pursue additional claims after filing this application to pursue such additional claim forms, in either this application or in a continuing application.

1-83. (canceled)

84. A tank inspection method comprising:

actuating, by a drive assembly of a robot, wheels of the robot to navigate the robot to one or more circumferential seals positioned proximate to an interior wall of a storage tank; and

collecting, by at least one sensor of the robot, data sufficient to evaluate a health, integrity, or effectiveness of the one or more circumferential seals between a floating roof, and the interior wall of the storage tank.

85. The tank inspection method of claim **84**, wherein the collecting comprises:

collecting, using the at least one sensor, data representative of a physical condition, or a mechanical integrity, of the one or more circumferential seals; and

determining, based at least in part on the data representative of a physical condition or mechanical integrity of the one or more circumferential seals, an indication resulting from a deterioration of: the physical condition, or the mechanical integrity.

86. The tank inspection method of claim **84** further comprising magnetically coupling the robot to the interior wall of the storage tank before, or concurrent with, the actuating.

87. The tank inspection method of claim **84**, wherein the collecting comprises collecting, using at least one camera of the robot, at least one of: visual, and pointcloud, data sufficient to plan a path or trajectory for the actuating.

88. The tank inspection method of claim **87**, wherein:

the data sufficient to plan the path or trajectory includes data representative of one or more physical characteristics of the one or more circumferential seals; and

the actuating comprises causing the robot to navigate along the path or trajectory to a starting position for a

tank inspection routine based on the data representative of one or more physical characteristics.

89. The tank inspection method of claim **87**, wherein:

the data sufficient to plan the path or trajectory includes data representative of at least one obstacle present between the robot and the one or more circumferential seals; and

the actuating comprises causing the robot to navigate along a trajectory in such a manner so as to avoid interference with the at least one obstacle.

90. The tank inspection method of claim **84**, wherein the at least one sensor includes at least one depth camera, and wherein the collecting comprises:

collecting, using the at least one depth camera of the robot, pointcloud data; and

generating, based on the pointcloud data, a two- or three-dimensional model of at least one of: the one or more circumferential seals, and a portion of the interior wall, to facilitate evaluation of the health, integrity or effectiveness of the one or more circumferential seals.

91. The tank inspection method of claim **84**, wherein:

the at least one sensor is positioned on, or in, a sensor package of the robot; and

the method further comprises inserting at least a portion of the sensor package between the one or more circumferential seals and the interior wall of the storage tank before, or concurrent with, the collecting.

92. The tank inspection method of claim **91**, wherein the robot includes a connector bridge coupled to and between the drive assembly and the sensor package to thereby position the sensor package including the at least one sensor apart and spaced from the drive assembly, and wherein the method further comprises:

after, or concurrent with, the inserting, moving the sensor package around the tank while the connector bridge is positioned between the one or more circumferential seals and the interior wall with the active or passive roller elements in contact with the interior wall to thereby reduce friction during the moving as compared to the moving in the absence of the active or passive roller elements.

93. The tank inspection method of claim **92** further comprising:

determining, by a motion controller of the robot before or concurrent with at least one of:

the actuating, the inserting, and the moving, at least one factor for compensating for frictional or other disturbances whilst the at least a portion of the sensor package is inserted between the one or more circumferential seals and the interior wall of the storage tank; and

applying the at least one factor for use by the drive assembly for the at least one of: the actuating, the inserting, and the moving, to compensate for the frictional or other disturbances.

94. The tank inspection method of claim **84**, wherein the collecting comprises:

deploying a sensor package including the at least one sensor into a gap between the interior wall and the one or more circumferential seals; and

measuring one or more dimensions of the gap using the at least one sensor.

95. The tank inspection method of claim **84**, wherein the at least one sensor includes a gas monitor, and wherein the

collecting comprises collecting, using the gas monitor, data representative of at least one of: a concentration, and a leakage rate, of one or more gases inside the storage tank above or below a secondary vapor seal of the storage tank.

96. The tank inspection method of claim **84** further comprising transmitting, using a communications interface of the robot, the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals to at least one of: an operator, a computer, and a subsystem, of, or communicably coupled to, the communications interface to facilitate evaluating the health, integrity, or effectiveness of the one or more circumferential seals or the seal assembly including the one or more circumferential seals.

97. A tank inspection robot comprising:
a drive assembly;

wheels disposed outside of, and operably coupled to, the drive assembly, the wheels configured to be actuated by the drive assembly to navigate the robot to one or more circumferential seals positioned proximate to an interior wall of a storage tank;

at least one sensor disposed in or on a portion of the robot, and configured to collect data sufficient to evaluate a health, integrity, or effectiveness of the one or more circumferential seals between a floating roof, and an interior wall, of the storage tank; and

a connector bridge coupled to and between the drive assembly and the at least one sensor to thereby position the at least one sensor apart and spaced from the drive assembly.

98. The tank inspection robot of claim **97** further comprising one or more magnets for magnetically coupling the robot to the interior wall of the storage tank.

99. The tank inspection robot of claim **97**, wherein the wheels include four wheels disposed outside opposing sides of the drive assembly, the robot further comprising two tracks including: a first track operable coupled to a first pair

of wheels of the four wheels, and a second track operably coupled to a second pair of wheels of the four wheels.

100. The tank inspection robot of claim **99** further comprising a plurality of magnets operably coupled to each of the first and second tracks.

101. The tank inspection robot of claim **97** further comprising at least one light disposed on or in a portion of the robot, and configured to illuminate an area of interest outside of the robot.

102. The tank inspection robot of claim **97** further comprising a communications interface configured to transmit the data sufficient to evaluate the health, integrity, or effectiveness of the one or more circumferential seals to at least one of: an operator, a computer, and a subsystem, of, or communicably coupled to, the communications interface to facilitate an evaluation of the health, integrity, or effectiveness of the one or more circumferential seals or the seal assembly including the one or more circumferential seals.

103. A robotic tank inspection system comprising:
the tank inspection robot of claim **97**;

a tether assembly including a power and/or communication tether couplable, or coupled, to the robot; and means for managing a delivery mechanism for the tether assembly to facilitate preventing entanglement of the tether with one or more features of the storage tank.

104. One or more non-transitory computer readable media having program instructions stored thereon which, when executed by at least one processor, cause a machine to:

direct a drive assembly of a tank inspection robot to actuate wheels of the robot to navigate the robot to one or more circumferential seals positioned proximate to an interior wall of a storage tank; and

direct at least one sensor of the robot to collect data sufficient to evaluate a health, integrity or effectiveness of the one or more circumferential seals between a floating roof, and the interior wall of the storage tank.

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