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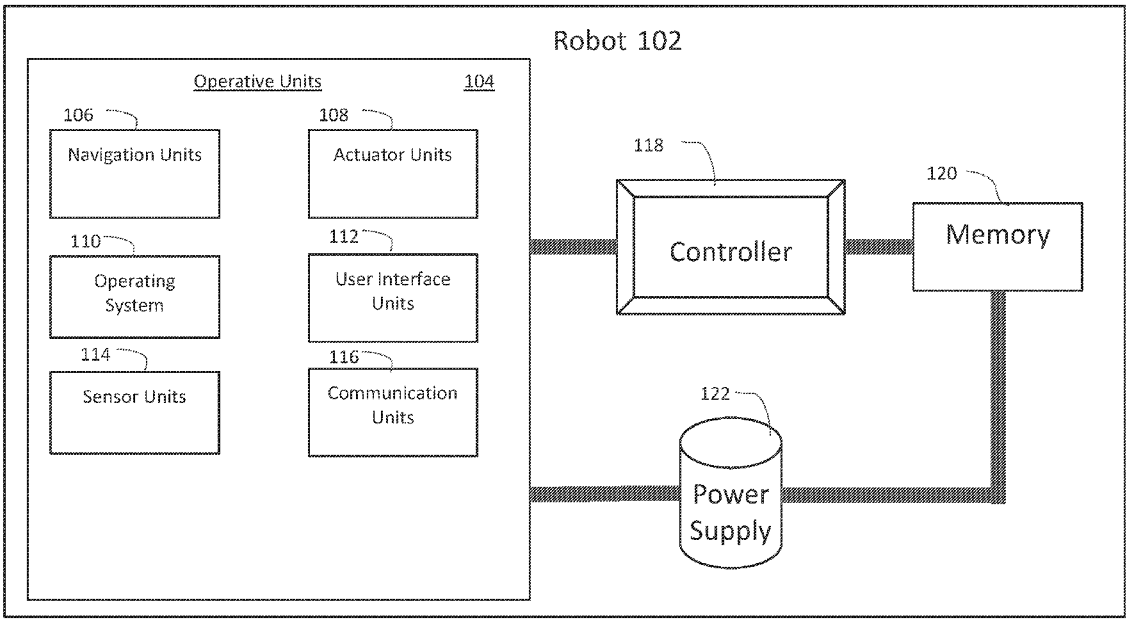

FIG. 1A

(57) **Abstract:** Systems and methods for detecting glass for robots are disclosed herein. According to at least one non-limiting exemplary embodiment, a method for detecting glass objects using a LiDAR or light based time-of-flight ("ToF") sensor is disclosed. According to at least one non-limiting exemplary embodiment, a method for detecting glass objects using an image sensor is disclosed. Both methods may be used in conjunction to enable a robot to quickly detect, verify, and map glass objects on a computer readable map.

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SYSTEMS AND METHODS FOR DETECTING GLASS AND SPECULAR SURFACES FOR ROBOTS

Priority

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 63/025,670 filed on May 15, 2020 under 35 U.S.C. § 119, the entire disclosure of which is incorporated herein by reference.

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Summary

[0003] The present application relates generally to robotics, and more specifically to systems and methods for detection of transparent, glass and specular surfaces for robots or autonomous devices.

[0004] The needs in the conventional technology are satisfied by the present disclosure, which provides for, *inter alia*, systems and methods for detection of glass for robots. The present disclosure is directed towards a practical application of detecting glass and specular surfaces for use by robots to plan routes and avoid collision with objects that typical LiDAR and time-of-flight sensors struggle to detect.

[0005] Exemplary embodiments described herein have innovative features, no single one of which is indispensable or solely responsible for their desirable attributes. Without limiting the scope of the claims, some of the advantageous features will be summarized. One skilled in the art would appreciate that, as used herein, the term robot may generally refer to an autonomous vehicle or object that travels a route, executes a task, or otherwise moves automatically upon executing or processing computer-readable instructions.

[0006] According to at least one non-limiting exemplary embodiment, a method for detecting glass and specular surfaces using a time-of-flight (“ToF”) sensor is disclosed herein.

The method comprises a controller of a robot, collecting measurements using a sensor as a robot navigates along a route in an environment, the measurements comprising a plurality of points localized on a computer-readable map; identifying one or more first points of the measurements based on a first threshold; identifying one or more of the first points of the measurement as an object based on a second threshold value, the object comprises glass or specular surfaces; and updating the computer-readable map to comprise the object in the environment.

[0007] According to at least one non-limiting exemplary embodiment, the method further comprises the controller, discretizing the computer-readable map into a plurality of angular bins, each angular bin comprising an arc length defined about an origin, the origin comprising a fixed point within an environment; populating each angular bin of the plurality of angular bins with a summation of distances between the one or more first points encompassed therein and the origin; and comparing the summation of distances for each angular bin to the second threshold value, the one or more first points encompassed within each angular bin are identified as representing the object upon the summation of distances exceeding the second threshold value for a respective angular bin.

[0008] According to at least one non-limiting exemplary embodiment, the first threshold comprises a first angular range and a second angular range, the one or more first points are identified from the plurality of points based on a lack of detection of points within the first angular range, and the one or more first points are within the second angular range, the second angular range being encompassed within the first angular range.

[0009] According to at least one non-limiting exemplary embodiment, the method may further comprise sweeping the first and second angular ranges of the first threshold about a local sensor origin of the one or more sensors; and identifying the one or more first points based on the first threshold at various angles about the local sensor origin.

[0010] According to at least one non-limiting exemplary embodiment, the first threshold comprises a spatial separation between points of a first scan and points of a second scan, points of the first scan being separated by the spatial separation to points of the second scan corresponds to the points of the first scan and points of the second scan comprising the one or more first points, the second scan being subsequent to the first scan, the spatial separation being based on a speed of the robot and a sampling or scan rate of the sensor.

[0011] According to at least one non-limiting exemplary embodiment, the one or more identified first points are separated apart from each other at a greater distance compared to separation between other points of the plurality of points, the first points corresponding to the object and the other points corresponding to another object, the another object corresponding to non-glass or non-specular surface.

[0012] According to at least one non-limiting exemplary embodiment, the one or more identified first points include a density lower than density of the other points of the plurality of points.

[0013] According to at least one non-limiting exemplary embodiment, the method may further comprise navigating the robot to the object based on the computer-readable map; and utilizing a camera sensor to detect a reflection of the robot to verify the one or more objects comprising glass or specular surfaces.

[0014] According to at least one non-limiting exemplary embodiment, the method may further comprise the robot performing a visual display upon navigating the robot to the object; and detecting a reflection of the visual display using the camera sensor to verify the one or more objects comprising glass or specular surfaces.

[0015] According to at least one non-limiting exemplary embodiment, the identification of the one or more first points is performed after the robot has navigated the route based on a computer-readable map generated at least in part during navigation of the route.

[0016] According to at least one non-limiting exemplary embodiment, the identification of the one or more first points is performed after the robot has navigated the route based on a computer-readable map generated at least in part during navigation of the route.

[0017] According to at least one non-limiting exemplary embodiment, the identification of the one or more first points is performed after the robot has navigated the route based on a computer-readable map generated at least in part during navigation of the route.

[0018] According to at least one non-limiting exemplary embodiment, a non-transitory computer-readable storage medium is disclosed herein. The non-transitory computer-readable storage medium may comprise a plurality of computer-readable instructions embodied thereon that, when executed by one or more processors, configure the one or more processors to, collect measurements using a sensor as the robot navigates a route, the measurements comprising a plurality of points localized on a computer-readable map; identify one or more first points of the measurements based on a first threshold; discretize the computer-readable map into a plurality of angular bins, each angular bin comprising an arc length defined about an origin, the origin comprising a fixed point within an environment; populate each angular bin of the plurality with a summation of distances between each of the one or more first points encompassed therein and the origin; compare the summation of distances for each angular bin to a threshold value, the one or more first points encompassed within each angular bin are identified as representing one or more objects upon the summation of distances exceeding the threshold value for a respective angular bin, the one or more objects comprising glass or specular surfaces; and update the computer-readable map to comprise the one or more objects.

[0019] According to at least one non-limiting exemplary embodiment, the first threshold comprises a first angular range and a second angular range, the one or more first points are identified based on a lack of detection of points within the first angular range and the one or more first points are within the second angular range, the second angular range being encompassed within the first angular range.

[0020] According to at least one non-limiting exemplary embodiment, the non-transitory computer-readable storage medium may further include computer-readable instructions that configure the one or more processors to sweep the first and second angular ranges of the first threshold about a local sensor origin of the sensor; and identify the one or more first points based on the first threshold at various angles about the local sensor origin.

[0021] According to at least one non-limiting exemplary embodiment, the first threshold comprises a spatial separation between points of a first scan and points of a second scan, detection of points of the first scan being separated by the spatial separation to points of the second scan corresponds to the points of the first scan and points of the second scan comprising suspicious points, the second scan being subsequent to the first scan, the spatial separation being based on a speed of the robot and a sampling or scan rate of the sensor.

[0022] According to at least one non-limiting exemplary embodiment, the non-transitory computer-readable storage medium may further include computer-readable instructions that configure the one or more processors to navigate the robot to the one or more objects based on the computer-readable map and utilize a camera sensor to detect a reflection of the robot to verify the one or more objects comprising glass or specular surfaces.

[0023] According to at least one non-limiting exemplary embodiment, the non-transitory computer-readable storage medium may further include computer-readable instructions that configure the one or more processors to configure the robot to perform a visual display upon navigating the robot to the one or more objects, and detect a reflection of the visual display using the camera sensor to verify the one or more objects comprising glass or specular surfaces.

[0024] According to at least one non-limiting exemplary embodiment, a method for detecting glass and specular surfaces is disclosed. The method may comprise a robot, collecting images using a camera sensor as the robot navigates a route; detecting a reflection of the robot within one or more images; and performing a visual display, wherein the detection of the visual display within images from the camera sensor correspond to detection of a glass object or reflective surface.

[0025] According to at least one non-limiting exemplary embodiment, the visual display comprises at least one of the robot blinking or changing colors of one or more lights, or moving a feature of the robot.

[0026] According to at least one non-limiting exemplary embodiment, detection of the reflection comprises use of an image-recognition algorithm to identify images comprising of, at least in part, the robot.

[0027] According to at least one non-limiting exemplary embodiment, the method may further comprise the robot producing a computer-readable map of an environment of the robot, the computer-readable map comprising the glass object or reflective surface localized thereon.

[0028] These and other objects, features, and characteristics of the present disclosure, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the disclosure. As used in the specification and in the claims, the singular form of “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

Brief Description of the Drawings

[0029] The disclosed aspects will hereinafter be described in conjunction with the appended drawings, provided to illustrate and not to limit the disclosed aspects, wherein like designations denote like elements.

[0030] FIG. 1A is a functional block diagram of a main robot in accordance with some embodiments of this disclosure.

[0031] FIG. 1B is a functional block diagram of a controller or processor in accordance with some embodiments of this disclosure.

[0032] FIG. 2A(i)-(ii) illustrates a LiDAR or ToF sensor and a point cloud generated from the sensor in accordance with some embodiments of this disclosure.

[0033] FIG. 2B(i-ii) illustrates a difference between diffuse reflection and specular reflection, in accordance with some embodiments of this disclosure.

[0034] FIG. 3A-B illustrates behavior of beams of a ToF sensor when incident upon a glass surface, according to an exemplary embodiment.

[0035] FIG. 4A-B illustrates a robot utilizing a ToF sensor to detect glass, according to an exemplary embodiment.

[0036] FIG. 5 illustrates thresholds used to identify suspicious points, suspicious points potentially including localized points of a glass surface, according to an exemplary embodiment.

[0037] FIG. 6 illustrates thresholds used to identify suspicious points, according to an exemplary embodiment.

[0038] FIG. 7A illustrates a computer-readable map comprising suspicious points localized therein, according to an exemplary embodiment.

[0039] FIG. 7B illustrates angular bins utilized in conjunction with a threshold to determine if suspicious points of the map illustrated in FIG. 7A comprise glass, according to an exemplary embodiment.

[0040] FIG. 7C illustrates a computer-readable map comprising glass objects localized thereon, according to an exemplary embodiment.

[0041] FIG. 8 illustrates a method for detection of glass or verification of the detection of glass using specular reflection, according to an exemplary embodiment.

[0042] FIG. 9 is a process-flow diagram illustrating a method for a robot to detect glass using a ToF sensor, according to an exemplary embodiment.

[0043] FIG. 10 is a process-flow diagram illustrating a method for a robot to detect glass using an image sensor or camera, according to an exemplary embodiment.

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Detailed Description

[0045] Currently, robots may utilize various light detection and ranging ("LiDAR") sensors such as scanning LiDAR sensors, structured light sensors, depth cameras, and/or other time-of-flight ("ToF") sensors. These LiDAR and ToF sensors utilize beams of light emitted by these sensors, which diffusely reflect off surfaces back to a detector of the sensor. Glass, as well as other reflective surfaces such as metal and smooth white walls, may not diffusely reflect these beams, thereby making detection of glass or reflective surfaces difficult for LiDAR and ToF sensors. Conventional technology provides one method of detecting glass using a return signal strength of emitted light from a sensor. However, sensors configurable to measure signal strength with sufficient accuracy to detect a glass surface may be very costly for manufacturers of robots. Additionally, the use of return signal strength from a LiDAR or ToF sensor is further influenced by an environment of a robot (e.g., ambient lighting, distance to the glass/reflective surface, thickness of glass, etc.) that may affect signal strength, thereby making the method unreliable in many environments.

[0046] Detection of glass may be critical for safe operation of robots operating within environments comprising glass walls, windows, or mirrors. Failure to detect a glass wall may cause collision with the robot and the glass wall or potentially shatter or crack the glass wall and/or damage the robot. Highly transparent objects, such as glass, may pose a risk to robots using LiDAR and/or ToF sensors as these sensors may rely on diffuse reflection of beams off objects, wherein highly transparent objects may exhibit specular reflection or may transmit the beams through the objects, which may cause difficulties for a robot to localize these objects. Accordingly, there is a need in the art for systems and methods for detection of glass and specular surfaces for robots.

[0047] Various aspects of the novel systems, apparatuses, and methods disclosed herein are described more fully hereinafter with reference to the accompanying drawings to address the issues present in conventional technology. This disclosure can, however, be embodied in many different forms and should not be construed as limited to any specific structure or function presented throughout this disclosure. Rather, these aspects are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the disclosure to those skilled in the art. Based on the teachings herein, one skilled in the art would appreciate that the scope of the disclosure is intended to cover any aspect of the novel systems, apparatuses, and methods disclosed herein, whether implemented independently of, or combined with, any other aspect of the disclosure. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, the scope of the disclosure is intended to cover such an apparatus or method that is practiced using other structure, functionality, or structure and functionality in addition to or other than the various aspects of the disclosure set forth herein. It should be understood that any aspect disclosed herein may be implemented by one or more elements of a claim.

[0048] Although particular aspects are described herein, many variations and permutations of these aspects fall within the scope of the disclosure. Although some benefits and advantages of the preferred aspects are mentioned, the scope of the disclosure is not intended to be limited to particular benefits, uses, and/or objectives. The detailed description and drawings are merely illustrative of the disclosure rather than limiting, the scope of the disclosure being defined by the appended claims and equivalents thereof.

[0049] The present disclosure provides for systems and methods of glass detection for robots. As used herein, a robot may include mechanical and/or virtual entities configured to carry out a complex series of tasks or actions autonomously. In some exemplary embodiments, robots may be machines that are guided and/or instructed by computer programs and/or electronic circuitry. In some exemplary embodiments, robots may include electro-mechanical components that are configured for navigation, where the robot may move from one location to another. Such robots may include autonomous and/or semi-autonomous cars, floor cleaners, rovers, drones, planes, boats, carts, trams, wheelchairs, industrial equipment, stocking machines, mobile platforms, personal transportation devices (e.g., hover boards, scooters, self-balancing vehicles such as manufactured by Segway®, etc.), trailer movers, vehicles, and the like. Robots may also include any autonomous and/or semi-autonomous machine for transporting items, people, animals, cargo, freight, objects, luggage, and/or anything desirable from one location to another.

[0050] As used herein, a glass object may comprise any material that is substantially transparent (e.g., 20% transmissivity, or greater) to a wavelength of light in at least one of the infrared, visible, ultraviolet wavelengths, or other wavelength of light used by sensors of a robot. Glass objects may comprise objects (e.g., glass cups, statues, etc.) or surfaces (e.g., windows). One skilled in the art may appreciate that the systems and methods disclosed herein may be similarly applied to objects which are opaque in the visible light bandwidth but substantially transparent in the wavelength of a sensor used to sense the objects (e.g., transparent to infrared for scanning LiDAR sensors). Substantially transparent, as used herein, may similarly be used to describe any surface or object which is difficult to detect using a time-of-flight sensor at any other angle than normal incidence, as illustrated in FIG. 3A-B below, due to high transmissivity of the object (e.g., glass) which causes beams emitted from the sensor to transmit a majority of its energy through the object.

[0051] As used herein, a specular object or surface may comprise an object or surface that exhibits specular reflection, such as mirrors, metallic surfaces, glass (in some instances, as described in FIG. 3A-B), and/or substantially smooth surfaces (e.g., glossy walls). In some instances, specular objects and/or surfaces may further comprise a high reflectivity. That is, specular objects or surfaces may include any object or surface of which a beam of light incident upon the objects or surfaces at an angle reflects therefrom at the same angle.

[0052] As used herein, network interfaces may include any signal, data, or software interface with a component, network, or process including, without limitation, those of the FireWire (e.g., FW400, FW800, FWS800T, FWS1600, FWS3200, etc.), universal serial bus ("USB") (e.g., USB 1.X, USB 2.0, USB 3.0, USB Type-C, etc.), Ethernet (e.g., 10/100, 10/100/1000 (Gigabit Ethernet), 10-Gig-E, etc.), multimedia over coax alliance technology ("MoCA"), Coaxsys (e.g., TVNET™), radio frequency tuner (e.g., in-band or OOB, cable modem, etc.), Wi-Fi (802.11), WiMAX (e.g., WiMAX (802.16)), PAN (e.g., PAN/802.15), cellular (e.g., 3G, LTE/LTE-A/TD-LTE/TD-LTE, GSM, etc.), IrDA families, etc. As used herein, Wi-Fi may include one or more of IEEE-Std. 802.11, variants of IEEE-Std. 802.11, standards related to IEEE-Std. 802.11 (e.g., 802.11 a/b/g/n/ac/ad/af/ah/ai/aj/aq/ax/ay), and/or other wireless standards.

[0053] As used herein, controller, controlling device, processor, processing device, microprocessing device, and/or digital processing device may include any type of digital processing device such as, without limitation, digital signal processing devices (“DSPs”), reduced instruction set computers (“RISC”), complex instruction set computers (“CISC”), microprocessing devices, gate arrays (e.g., field programmable gate arrays (“FPGAs”)), programmable logic device (“PLDs”), reconfigurable computer fabrics (“RCFs”), array processing devices, secure microprocessing devices, and application-specific integrated circuits (“ASICs”). Such digital processing devices may be contained on a single unitary integrated circuit die or distributed across multiple components.

[0054] As used herein, a computer program and/or software may include any sequence of machine-cognizable steps that perform a function. Such computer program and/or software may be rendered in any programming language or environment including, for example, C/C++, C#, Fortran, COBOL, MATLAB™, PASCAL, GO, RUST, SCALA, Python, assembly language, markup languages (e.g., HTML, SGML, XML, VoXML) and the like, as well as object-oriented environments such as the Common Object Request Broker Architecture (“CORBA”), JAVA™ (including J2ME, Java Beans, etc.), Binary Runtime Environment (e.g., “BREW”) and the like.

[0055] As used herein, connection, link, and/or wireless link may include a causal link between any two or more entities (whether physical or logical/virtual), which enables information exchange between the entities.

[0056] As used herein, a computer and/or computing device may include, but are not limited to, personal computers (“PCs”) and minicomputers, whether desktop, laptop, or otherwise, mainframe computers, workstations, servers, personal digital assistants (“PDAs”), handheld computers, embedded computers, programmable logic devices, personal communicators, tablet computers, mobile devices, portable navigation aids, J2ME equipped devices, cellular telephones, smart phones, personal integrated communication or entertainment devices, and/or any other device capable of executing a set of instructions and processing an incoming data signal.

[0057] Detailed descriptions of the various embodiments of the system and methods of the disclosure are provided. While many examples discussed herein may refer to specific exemplary embodiments, it will be appreciated by one skilled in the art that the described systems and methods contained herein are applicable to any kind of robot. Myriad other embodiments or uses for the technology described herein would be readily envisaged by those having ordinary skill in the art, given the contents of the present disclosure.

[0058] Advantageously, the systems and methods of this disclosure at least, (i) enable robots to detect glass using a time-of-flight ("ToF") sensor; (ii) enable robots to detect glass using an RGB camera sensor; (iii) improve safety of operating robots within environments comprising glass; and (iv) enhance computer-readable maps generated by robots by localizing glass objects therein. Other advantages are readily discernible by one having ordinary skill in the art given the contents of the present disclosure.

[0059] FIG. 1A is a functional block diagram of a robot **102** in accordance with some principles of this disclosure. As illustrated in FIG. 1A, robot **102** may include controller **118**, memory **120**, user interface unit **112**, sensor units **114**, navigation units **106**, actuator unit **108**, and communications unit **116**, as well as other components and subcomponents (e.g., some of which may not be illustrated). Although a specific embodiment is illustrated in FIG. 1A, it is appreciated that the architecture may be varied in certain embodiments as would be readily apparent to one of ordinary skill given the contents of the present disclosure. As used herein, robot **102** may be representative at least in part of any robot described in this disclosure.

[0060] Controller **118** may control the various operations performed by robot **102**. Controller **118** may include and/or comprise one or more processors (e.g., microprocessors) and other peripherals. As previously mentioned and used herein, a processor, microprocessor, and/or digital processor may include any type of digital processing device such as, without limitation, digital signal processors ("DSPs"), reduced instruction set computers ("RISC"), general-purpose ("CISC") processors, microprocessors, gate arrays (e.g., field programmable gate arrays ("FPGAs")), programmable logic device ("PLDs"), reconfigurable computer fabrics ("RCFs"), array processors, secure microprocessors, and application-specific integrated circuits ("ASICs"). Peripherals may include hardware accelerators configured to perform a specific function using hardware elements such as, without limitation, encryption/description hardware, algebraic processing devices (e.g., tensor processing units, quadratic problem solvers, multipliers, etc.), data compressors, encoders, arithmetic logic units ("ALU") and the like. Such digital processors may be contained on a single unitary integrated circuit die, or distributed across multiple components.

[0061] Controller **118** may be operatively and/or communicatively coupled to memory

120. Memory **120** may include any type of integrated circuit or other storage device configured to store digital data including, without limitation, read-only memory ("ROM"), random access memory ("RAM"), non-volatile random access memory ("NVRAM"), programmable read-only memory ("PROM"), electrically erasable programmable read-only memory ("EEPROM"), dynamic random-access memory ("DRAM"), Mobile DRAM, synchronous DRAM ("SDRAM"), double data rate SDRAM ("DDR/2 SDRAM"), extended data output ("EDO") RAM, fast page mode RAM ("FPM"), reduced latency DRAM ("RLDRAM"), static RAM ("SRAM"), flash memory (e.g., NAND/NOR), memristor memory, pseudostatic RAM ("PSRAM"), etc. Memory **120** may provide instructions and data to controller **118**. For example, memory **120** may be a non-transitory, computer-readable storage apparatus and/or medium having a plurality of instructions stored thereon, the instructions being executable by a processing apparatus (e.g., controller **118**) to operate robot **102**. In some cases, the instructions may be configured to, when executed by the processing apparatus, cause the processing apparatus or device to perform the various methods, features, and/or functionality described in this disclosure. Accordingly, controller **118** may perform logical and/or arithmetic operations based on program instructions stored within memory **120**. In some cases, the instructions and/or data of memory **120** may be stored in a combination of hardware, some located locally within robot **102**, and some located remote from robot **102** (e.g., in a cloud, server, network, etc.).

[0062] It should be readily apparent to one of ordinary skill in the art that a processing device may be internal to or on-board a robot and/or external to robot **102** and be communicatively coupled to controller **118** of robot **102** utilizing communication units **116** wherein the external processing device may receive data from robot **102**, process the data, and transmit computer-readable instructions back to controller **118**. In at least one non-limiting exemplary embodiment, the processing device may be on a remote server (not shown).

[0063] In some exemplary embodiments, memory **120**, shown in FIG. 1A, may store a library of sensor data. In some cases, the sensor data may be associated at least in part with the detection of objects and/or people in the environment of the robot **102**. In exemplary embodiments, this library may include sensor data related to objects and/or people in different conditions, such as sensor data related to objects and/or people with different compositions (e.g., materials, reflective properties, molecular makeup, etc.), different lighting conditions, angles, sizes, distances, clarity (e.g., blurred, obstructed/occluded, partially off frame, etc.), colors, surroundings, and/or other conditions. The sensor data in the library may be taken by a sensor (e.g., a sensor of sensor units **114** or any other sensor) and/or generated automatically, such as with a computer program that is configured to generate/simulate (e.g., in a virtual world) library sensor data (e.g., which may generate/simulate these library data entirely digitally and/or beginning from actual sensor data) from different lighting conditions, angles, sizes, distances, clarity (e.g., blurred, obstructed/occluded, partially off frame, etc.), colors, surroundings, and/or other conditions. The number of images in the library may depend at least in part on one or more of the amount of available data, the variability of the surrounding environment in which robot **102** operates, the complexity of objects and/or people, the variability in appearance of objects, physical properties of robots, the characteristics of the sensors, and/or the amount of available storage space (e.g., in the library, memory **120**, and/or local or remote storage). In exemplary embodiments, at least a portion of the library may be stored on a network (e.g., cloud, server, distributed network, etc.) and/or may not be stored completely within memory **120**. As yet another exemplary embodiment, various robots (e.g., that are commonly associated, such as robots by a common manufacturer, user, network, etc.) may be networked so that data captured by individual robots are collectively shared with other robots. In such a fashion, these robots may be configured to learn and/or share sensor data in order to facilitate the ability to readily detect and/or identify errors and/or assist events.

[0064] Still referring to FIG. 1A, operative units **104** may be coupled to controller **118**, or any other controller, to perform the various operations described in this disclosure. One, more, or none of the modules in operative units **104** may be included in some embodiments. Throughout this disclosure, reference may be made to various controllers and/or processing devices. In some embodiments, a single controller (e.g., controller **118**) may serve as the various controllers and/or processing devices described. In other embodiments different controllers and/or processing devices may be used, such as controllers and/or processing devices used particularly for one or more operative units **104**. Controller **118** may send and/or receive signals, such as power signals, status signals, data signals, electrical signals, and/or any other desirable signals, including discrete and analog signals to operative units **104**. Controller **118** may coordinate and/or manage operative units **104**, and/or set timings (e.g., synchronously or asynchronously), turn off/on control power budgets, receive/send network instructions and/or updates, update firmware, send interrogatory signals, receive and/or send statuses, and/or perform any operations for running features of robot **102**.

[0065] Returning to FIG. 1A, operative units **104** may include various units that perform functions for robot **102**. For example, operative units **104** include at least navigation units **106**, actuator units **108**, user interface units **112**, sensor units **114**, and communication units **116**. Operative units **104** may also comprise other units that provide the various functionality of robot **102**. In exemplary embodiments, operative units **104** may be instantiated in software, hardware, or both software and hardware. For example, in some cases, units of operative units **104** may comprise computer-implemented instructions executed by a controller. In exemplary embodiments, units of operative unit **104** may comprise hardcoded logic. In exemplary embodiments, units of operative units **104** may comprise both computer-implemented instructions executed by a controller and hardcoded logic. Where operative units **104** are implemented in part in software, operative units **104** may include units/modules of code configured to provide one or more functionalities.

[0066] In exemplary embodiments, navigation units **106** may include systems and methods that may computationally construct and update a map of an environment, localize robot **102** (e.g., find the position) in a map, and navigate robot **102** to/from destinations. Wherein, one skilled in the art may appreciate that updating of the map of the environment may be performed in real-time while the robot **102** is traveling along the route. Alternatively, the map may be updated at a subsequent, later time when the robot **102** is stationary or no longer traveling along the route. The mapping may be performed by imposing data obtained in part by sensor units **114** into a computer-readable map representative at least in part of the environment. In exemplary embodiments, a map of an environment may be uploaded to robot **102** through user interface units **112**, uploaded wirelessly or through wired connection, or taught to robot **102** by a user.

[0067] In exemplary embodiments, navigation units **106** may include components and/or software configured to provide directional instructions for robot **102** to navigate. Navigation units **106** may process maps, routes, and localization information generated by mapping and localization units, data from sensor units **114**, and/or other operative units **104**.

[0068] Still referring to FIG. 1A, actuator units **108** may include actuators such as electric motors, gas motors, driven magnet systems, solenoid/ratchet systems, piezoelectric systems (e.g., inchworm motors), magnetostrictive elements, gesticulation, and/or any way of driving an actuator known in the art. By way of illustration, such actuators may actuate the wheels for robot **102** to navigate a route; navigate around obstacles; rotate cameras and sensors. Actuator unit **108** may include any system used for actuating, in some cases to perform tasks. According to exemplary embodiments, actuator unit **108** may include systems that allow movement of robot **102**, such as motorized propulsion. For example, motorized propulsion may move robot **102** in a forward or backward direction, and/or be used at least in part in turning robot **102** (e.g., left, right, and/or any other direction). By way of illustration, actuator unit **108** may control if robot **102** is moving or is stopped and/or allow robot **102** to navigate from one location to another location.

[0069] According to exemplary embodiments, sensor units **114** may comprise systems and/or methods that may detect characteristics within and/or around robot **102**. Sensor units **114** may comprise a plurality and/or a combination of sensors. Sensor units **114** may include sensors that are internal to robot **102** or external, and/or have components that are partially internal and/or partially external. In some cases, sensor units **114** may include one or more exteroceptive sensors, such as sonars, light detection and ranging ("LiDAR") sensors, radars, lasers, cameras (including video cameras, e.g., red-blue-green ("RBG") cameras, infrared cameras, three-dimensional ("3D") cameras, thermal cameras, etc.), time-of-flight ("ToF") cameras, structured light cameras, antennas, motion detectors, microphones, and/or any other sensor known in the art). According to some exemplary embodiments, sensor units **114** may collect raw measurements (e.g., currents, voltages, resistances, gate logic, etc.) and/or transformed measurements (e.g., distances, angles, detected points in obstacles, etc.). In some cases, measurements may be aggregated and/or summarized. Sensor units **114** may generate data based at least in part on distance or height measurements. Such data may be stored in data structures, such as matrices, arrays, queues, lists, stacks, bags, etc.

[0070] According to exemplary embodiments, sensor units **114** may include sensors that may measure internal characteristics of robot **102**. For example, sensor units **114** may measure temperature, power levels, statuses, and/or any characteristic of robot **102**. In some cases, sensor units **114** may be configured to determine the odometry of robot **102**. For example, sensor units **114** may include proprioceptive sensors, which may comprise sensors such as accelerometers, inertial measurement units ("IMU"), odometers, gyroscopes, speedometers, cameras (e.g. using visual odometry), clock/timer, and the like. Odometry may facilitate autonomous navigation and/or autonomous actions of robot **102**. This odometry may include robot **102**'s position (e.g., where position may include robot's location, displacement and/or orientation, and may sometimes be interchangeable with the term pose as used herein) relative to the initial location. Such data may be stored in data structures, such as matrices, arrays, queues, lists, stacks, bags, etc. According to exemplary embodiments, the data structure of the sensor data may be called an image.

[0071] According to exemplary embodiments, sensor units **114** may be in part external to the robot **102** and coupled to communications units **116**. For example, a security camera within an environment of a robot **102** may provide a controller **118** of the robot **102** with a video feed via wired or wireless communication channel(s). In some instances, sensor units **114** may include sensors configured to detect a presence of an object at a location such as, for example without limitation, a pressure or motion sensor may be disposed at a shopping cart storage location of a grocery store, wherein the controller **118** of the robot **102** may utilize data from the pressure or motion sensor to determine if the robot **102** should retrieve more shopping carts for customers.

[0072] According to exemplary embodiments, user interface units **112** may be configured to enable a user to interact with robot **102**. For example, user interface units **112** may include touch panels, buttons, keypads/keyboards, ports (e.g., universal serial bus ("USB"), digital visual interface ("DVI"), Display Port, E-Sata, Firewire, PS/2, Serial, VGA, SCSI, audioport, high-definition multimedia interface ("HDMI"), personal computer memory card international association ("PCMCIA") ports, memory card ports (e.g., secure digital ("SD") and miniSD), and/or ports for computer-readable medium), mice, rollerballs, consoles, vibrators, audio transducers, and/or any interface for a user to input and/or receive data and/or commands, whether coupled wirelessly or through wires. Users may interact through voice commands or gestures. User interface units **218** may include a display, such as, without limitation, liquid crystal display ("LCDs"), light-emitting diode ("LED") displays, LED LCD displays, in-plane-switching ("IPS") displays, cathode ray tubes, plasma displays, high definition ("HD") panels, 4K displays, retina displays, organic LED displays, touchscreens, surfaces, canvases, and/or any displays, televisions, monitors, panels, and/or devices known in the art for visual presentation. According to exemplary embodiments user interface units **112** may be positioned on the body of robot **102**. According to exemplary embodiments, user interface units **112** may be positioned away from the body of robot **102** but may be communicatively coupled to robot **102** (e.g., via communication units including transmitters, receivers, and/or transceivers) directly or indirectly (e.g., through a network, server, and/or a cloud). According to exemplary embodiments, user interface units **112** may include one or more projections of images on a surface (e.g., the floor) proximally located to the robot, e.g., to provide information to the occupant or to people around the robot. The information could be the direction of future movement of the robot, such as an indication of moving forward, left, right, back, at an angle, and/or any other direction. In some cases, such information may utilize arrows, colors, symbols, etc.

[0073] According to exemplary embodiments, communications unit **116** may include one or more receivers, transmitters, and/or transceivers. Communications unit **116** may be configured to send/receive a transmission protocol, such as BLUETOOTH®, ZIGBEE®, Wi-Fi, induction wireless data transmission, radio frequencies, radio transmission, radio-frequency identification (“RFID”), near-field communication (“NFC”), infrared, network interfaces, cellular technologies such as 3G (3GPP/3GPP2), high-speed downlink packet access (“HSDPA”), high-speed uplink packet access (“HSUPA”), time division multiple access (“TDMA”), code division multiple access (“CDMA”) (e.g., IS-95A, wideband code division multiple access (“WCDMA”), etc.), frequency hopping spread spectrum (“FHSS”), direct sequence spread spectrum (“DSSS”), global system for mobile communication (“GSM”), Personal Area Network (“PAN”) (e.g., PAN/802.15), worldwide interoperability for microwave access (“WiMAX”), 802.20, long term evolution (“LTE”) (e.g., LTE/LTE-A), time division LTE (“TD-LTE”), global system for mobile communication (“GSM”), narrowband/frequency-division multiple access (“FDMA”), orthogonal frequency-division multiplexing (“OFDM”), analog cellular, cellular digital packet data (“CDPD”), satellite systems, millimeter wave or microwave systems, acoustic, infrared (e.g., infrared data association (“IrDA”)), and/or any other form of wireless data transmission.

[0074] Communications unit **116** may also be configured to send/receive signals utilizing a transmission protocol over wired connections, such as any cable that has a signal line and ground. For example, such cables may include Ethernet cables, coaxial cables, Universal Serial Bus (“USB”), FireWire, and/or any connection known in the art. Such protocols may be used by communications unit **116** to communicate to external systems, such as computers, smart phones, tablets, data capture systems, mobile telecommunications networks, clouds, servers, or the like. Communications unit **116** may be configured to send and receive signals comprised of numbers, letters, alphanumeric characters, and/or symbols. In some cases, signals may be encrypted, using algorithms such as 128-bit or 256-bit keys and/or other encryption algorithms complying with standards such as the Advanced Encryption Standard ("AES"), RSA, Data Encryption Standard ("DES"), Triple DES and the like. Communications unit **116** may be configured to send and receive statuses, commands, and other data/information. For example, communications unit **116** may communicate with a user operator to allow the user to control robot **102**. Communications unit **116** may communicate with a server/network (e.g., a network) in order to allow robot **102** to send data, statuses, commands, and other communications to the server. The server may also be communicatively coupled to computer(s) and/or device(s) that may be used to monitor and/or control robot **102** remotely. Communications unit **116** may also receive updates (e.g., firmware or data updates), data, statuses, commands, and other communications from a server for robot **102**.

[0075] In exemplary embodiments, operating system **110** may be configured to manage memory **120**, controller **118**, power supply **122**, modules in operative units **104**, and/or any software, hardware, and/or features of robot **102**. For example, and without limitation, operating system **110** may include device drivers to manage hardware recourses for robot **102**.

[0076] In exemplary embodiments, power supply **122** may include one or more batteries, including, without limitation, lithium, lithium ion, nickel-cadmium, nickel-metal hydride, nickel-hydrogen, carbon-zinc, silver-oxide, zinc-carbon, zinc-air, mercury oxide, alkaline, or any other type of battery known in the art. Certain batteries may be rechargeable, such as wirelessly (e.g., by resonant circuit and/or a resonant tank circuit) and/or plugging into an external power source. Power supply **122** may also be any supplier of energy, including wall sockets and electronic devices that convert solar, wind, water, nuclear, hydrogen, gasoline, natural gas, fossil fuels, mechanical energy, steam, and/or any power source into electricity.

[0077] One or more of the units described with respect to FIG. 1A (including memory **120**, controller **118**, sensor units **114**, user interface unit **112**, actuator unit **108**, communications unit **116**, mapping and localization unit **126**, and/or other units) may be integrated onto robot **102**, such as in an integrated system. However, according to some exemplary embodiments, one or more of these units may be part of an attachable module. This module may be attached to an existing apparatus to automate so that it behaves as a robot. Accordingly, the features described in this disclosure with reference to robot **102** may be instantiated in a module that may be attached to an existing apparatus and/or integrated onto robot **102** in an integrated system. Moreover, in some cases, a person having ordinary skill in the art would appreciate from the contents of this disclosure that at least a portion of the features described in this disclosure may also be run remotely, such as in a cloud, network, and/or server.

[0078] As used herein, a robot **102**, a controller **118**, or any other controller, processing device, or robot performing a task, operation or transformation illustrated in the figures below comprises a controller executing computer-readable instructions stored on a non-transitory computer-readable storage apparatus, such as memory **120**, as would be appreciated by one skilled in the art.

[0079] Next referring to FIG. 1B, the architecture of a processor or processing device **138** is illustrated according to an exemplary embodiment. As illustrated in FIG. 1B, the processing device **138** includes a data bus **128**, a receiver **126**, a transmitter **134**, at least one processor **130**, and a memory **132**. The receiver **126**, the processor **130** and the transmitter **134** all communicate with each other via the data bus **128**. The processor **130** is configurable to access the memory **132**, which stores computer code or computer-readable instructions in order for the processor **130** to execute the specialized algorithms. As illustrated in FIG. 1B, memory **132** may comprise some, none, different, or all of the features of memory **120** previously illustrated in FIG. 1A. The algorithms executed by the processor **130** are discussed in further detail below. The receiver **126** as shown in FIG. 1B is configurable to receive input signals **124**. The input signals **124** may comprise signals from a plurality of operative units **104** illustrated in FIG. 1A including, but not limited to, sensor data from sensor units **114**, user inputs, motor feedback, external communication signals (e.g., from a remote server), and/or any other signal from an operative unit **104** requiring further processing. The receiver **126** communicates these received signals to the processor **130** via the data bus **128**. As one skilled in the art would appreciate, the data bus **128** is the means of communication between the different components—receiver, processor, and transmitter—in the processing device. The processor **130** executes the algorithms, as discussed below, by accessing specialized computer-readable instructions from the memory **132**. Further detailed description as to the processor **130** executing the specialized algorithms in receiving, processing and transmitting of these signals is discussed above with respect to FIG. 1A. The memory **132** is a storage medium for storing computer code or instructions. The storage medium may include optical memory (e.g., CD, DVD, HD-DVD, Blu-Ray Disc, etc.), semiconductor memory (e.g., RAM, EPROM, EEPROM, etc.), and/or magnetic memory (e.g., hard-disk drive, floppy-disk drive, tape drive, MRAM, etc.), among others. Storage medium may include volatile, nonvolatile, dynamic, static, read/write, read-only, random-access, sequential-access, location-addressable, file-addressable, and/or content-addressable devices. The processor **130** may communicate output signals to transmitter **134** via data bus **128** as illustrated. The transmitter **134** may be configurable to further communicate the output signals to a plurality of operative units **104** illustrated by signal output **136**.

[0080] One of ordinary skill in the art would appreciate that the architecture illustrated in FIG. 1B may illustrate an external server architecture configurable to effectuate the control of a robotic apparatus from a remote location. That is, the server may also include a data bus, a receiver, a transmitter, a processor, and a memory that stores specialized computer-readable instructions thereon.

[0081] One of ordinary skill in the art would appreciate that a controller **118** of a robot **102** may include one or more processing devices **138** and may further include other peripheral devices used for processing information, such as ASICS, DPS, proportional-integral-derivative (“PID”) controllers, hardware accelerators (e.g., encryption/decryption hardware), and/or other peripherals (e.g., analog to digital converters) described above in FIG. 1A. The other peripheral devices when instantiated in hardware are commonly used within the art to accelerate specific tasks (e.g., multiplication, encryption, etc.) which may alternatively be performed using the system architecture of FIG. 1B. In some instances, peripheral devices are used as a means for intercommunication between the controller **118** and operative units **104** (e.g., digital to analog converters and/or amplifiers for producing actuator signals). Accordingly, as used herein, the controller **118** executing computer-readable instructions to perform a function may include one or more processing devices **138** thereof executing computer-readable instructions and, in some instances, the use of any hardware peripherals known within the art. Controller **118** may be illustrative of various processing devices **138** and peripherals integrated into a single circuit die or distributed to various locations of the robot **102** which receive, process, and output information to/from operative units **104** of the robot **102** to effectuate control of the robot **102** in accordance with instructions stored in a memory **120**, **132**. For example, controller **118** may include a plurality of processing devices **138** for performing high-level tasks (e.g., planning a route to avoid obstacles) and processing devices **138** for performing low-level tasks (e.g., producing actuator signals in accordance with the route).

[0082] FIG. 2A(i-ii) illustrates a planar light detection and ranging ("LiDAR") or a time-of-flight ("ToF") sensor **202** coupled to a robot **102**, which collects distance measurements to a wall **206** along a measurement plane in accordance with some exemplary embodiments of the present disclosure. Sensor **202**, illustrated in FIG. 2A(i), may be configured to collect distance measurements to the wall **206** by projecting a plurality of beams **208** of photons at discrete angles along a measurement plane and determining the distance to the wall **206** based on a time-of-flight of the photons leaving the sensor **202**, reflecting off the wall **206**, and returning back to the sensor **202**. The measurement plane of the sensor **202** comprises a plane along which the beams **208** are emitted which, for this exemplary embodiment illustrated, is the plane of the page.

[0083] Individual beams **208** of photons may localize respective points **204** of the wall **206** in a point cloud, the point cloud comprising a plurality of points **204** localized in 2D or 3D space as illustrated in FIG. 2A(ii). The points **204** may be defined about a local origin **210** of the sensor **202**. Distance **212** to a point **204** may comprise half the time-of-flight of a photon of a respective beam **208** used to measure the point **204** multiplied by the speed of light, wherein coordinate values (x, y) of each respective point **204** depends both on distance **212** and an angle at which the respective beam **208** was emitted from the sensor **202**. The local origin **210** may comprise a predefined point of the sensor **202** to which all distance measurements are referenced (e.g., location of a detector within the sensor **202**, focal point of a lens of sensor **202**, etc.). For example, a 5-meter distance measurement to an object corresponds to 5 meters from the local origin **210** to the object.

[0084] According to at least one non-limiting exemplary embodiment, sensor **202** may be illustrative of a depth camera or other ToF sensor configurable to measure distance, wherein the sensor **202** being a planar LiDAR sensor is not intended to be limiting. Depth cameras may operate similar to planar LiDAR sensors (i.e., measure distance based on a ToF of beams **208**); however, depth cameras may emit beams **208** using a single pulse or flash of electromagnetic energy, rather than sweeping a laser beam across a field of view. Depth cameras may additionally comprise a two-dimensional field of view.

[0085] According to at least one non-limiting exemplary embodiment, sensor **202** may be illustrative of a structured light LiDAR sensor configurable to sense distance and shape of an object by projecting a structured pattern onto the object and observing deformations of the pattern. For example, the size of the projected pattern may represent distance to the object and distortions in the pattern may provide information of the shape of the surface of the object. Structured light sensors may emit beams **208** along a plane as illustrated or in a preterminal pattern (e.g., a circle or series of separated parallel lines).

[0086] One skilled in the art would appreciate that a plurality of ToF sensors **202**, such as planar LiDAR sensors, of sensor units **114** may be coupled to a robot **102** to enhance the navigation and localization capabilities of the robot **102**. These ToF sensors **202** may be mounted in static positions (e.g., using screws, bolts, etc.) or may be mounted with servomotors configured to adjust the pose of the sensor **202**. Glass objects and specular surfaces pose a unique problem for ToF sensors **202** as glass and specular surfaces behave differently from solid and opaque surfaces when beams **208** are incident upon the glass surfaces, as illustrated in FIG. 3A-B below. Time-of-flight, as used herein, may refer to a time-of-flight of light and exclude other time-of-flight sensors, such as sonars or ultrasonic sensors as these sensors may detect glass and specular objects without issue because they are not influenced by high optical transmissivity of glass nor optical specular reflection of specular objects. Accordingly, ToF sensors as used herein may include LiDAR sensors.

[0087] FIG. 2B(i-ii) illustrates two forms of reflections, diffuse reflections and specular reflections, in accordance with some embodiments of this disclosure. First, in FIG. 2B(i), diffuse reflection of a beam **208** incident upon a surface **216** is illustrated. The surface **216** may comprise, on a micrometer to nanometer scale, jagged edges, grooves, or other imperfections that cause the beam **208** to scatter, reflect, and bounce off the surface in a plurality of directions, as shown by reflected beams **214**. One or more beams **214** may return to a sensor that emitted beam **208**, such as the ToF sensor **202** depicted in FIG. 2A(i) above, such that the surface **216** may be localized by a point **204**. However, a substantial majority of the incident power of beam **208** is not received at the detector of the sensor. One skilled in the art may appreciate that a scattered beam **214** is only detected by a ToF sensor **202** when it returns to the sensor along approximately the path traveled by incident beam **208**.

[0088] Next, FIG. 2B(ii) illustrates specular reflection of a beam **208** incident upon a specular surface **216**. Specular surfaces **216** may comprise highly reflective and/or substantially smooth surfaces. Specular reflection causes beam **208**, incident upon surface at angle θ, to be reflected at an angle equal to the incident angle θ, angle θ defined with respect to a normal of surface **216**, as illustrated by reflected beam **218** reflecting from surface **216** at an angle θ. A substantial majority of the power of the beam **208** is reflected and carried by beam **218**. This poses a challenge for ToF sensors as beams **208** incident upon specular surfaces may reflect away from the sensor and not be in part returned and detected by the sensor, unlike diffuse reflection wherein a small portion of the incident beam **208** is reflected to the sensor. One skilled in the art may appreciate that a reflected beam **218** is only detected by a ToF sensor **202** when beam **208** is normally incident upon the specular surface **216** (i.e., $\theta = 0^{\circ}$). This property of specular surfaces (e.g., mirrors), and similar properties of glass illustrated in FIG. 3, will be utilized to detect both glass and specular surfaces within an environment of a robot **102**.

[0089] FIG. 3A-B illustrates transmission behavior of beams **208** when incident upon glass **302**, according to an exemplary embodiment. Glass **302** may represent a window, pane, or any other form of glass, wherein glass may be comprised of fused quartz, fused-silica glass, soda-lime-silica glass, sodium borosilicate glass, Pyrex®, or any other substantially transparent solid material. Glass, as used herein, may comprise any of the aforementioned materials, exhibit primarily specular reflection, and be substantially transparent to a wavelength of light of a ToF sensor **202** (i.e., comprise a small reflection coefficient of 20%, 10%, 5%, etc. or transmissivity of at least 20% or higher). Beams **208** illustrated may represent paths followed by beams **208** emitted from a ToF sensor **202**, as illustrated in FIG. 2A(i) above, incident upon the glass **302** at different angles that are enumerated differently for clarity. First, in FIG. 3A, a beam **208-I** is incident on a glass **302** surface at normal incidence, or orthogonal to the surface of glass **302**. Glass **302**, in most instances, is not completely transparent (e.g., 90% transparent), thereby causing a portion of beam **208-I** to be reflected as beam **208-R** back towards a detector of the ToF sensor **202**, the reflection being primarily due to specular reflection. The reflected beam **208-R** may comprise approximately, e.g., 10% of the power of the incident beam **208-I** and may typically be detected by the ToF sensor **202** at normal incidence. However, one skilled in the art may appreciate the reflected power detected by the sensor **202** further depends on the glass **302** properties and distance to the glass **302**. Beam **208-T** comprises the remaining (e.g., 90%) portion of the energy of the incident beam **208-I** which is a transmitted beam through glass **302** and travels away from the sensor **202** and is not captured by the sensor **202**. This beam **208-T** may later reflect off a surface beyond the glass or may never return to the sensor **202**.

[0090] Next, in FIG. 3B, beam **208-I**, illustrative of a beam **208** emitted from a ToF sensor **202**, is incident upon glass **302** at a glancing or grazing angle (i.e., any angle other than normal incidence but less than a critical angle). Due to glass **302** being substantially transparent, the beam **208-I** may be substantially transmitted into and through the glass, wherein beam **208-T** is approximately of the same power as beam **208-I**. In some instances, beam **208-I** may be incident upon glass **302** at an angle greater than a critical angle, wherein beam **208-I** may exhibit specular reflection as illustrated by beam **208-R**. This specular reflection, as illustrated by beam **208-R** (dashed line indicating reflection does not always occur) may be reflected at a substantially large angle such that the sensor **202** may not receive the reflected beam **208-R** and therefore, the sensor **202** does not record a distance measurement **212** or point **204**.

[0091] It is appreciated by one skilled in the art that diffuse reflection from the surface of the glass **302** may still occur (e.g., due to small imperfections in the surface or ‘flatness’ of the glass **302**), thereby causing a portion of beam **208-I** emitted at a glancing angle to be reflected back to the ToF sensor **202**. However, this reflected portion may be of significantly lower power than a threshold detection power or signal to noise (“SNR”) ratio of the sensor **202** required for detection, thereby significantly reducing a chance of localizing a point **204** of the glass **302** using a beam incident upon the glass at any angle other than normal incidence. One skilled in the art may appreciate that a beam **208-I** incident on glass **302** at any angle other than normal incidence is either substantially transmitted through the glass **302** or reflected away from the ToF sensor **202**, thereby causing the ToF sensor **202** to fail to detect the glass **302** surface.

[0092] As illustrated in FIGS. 3A-B, only beams **208,** which are incident upon glass **302** at a substantially normal angle, are reflected back to a ToF sensor **202**, as discussed above with respect to FIG. 3A. Accordingly, the ToF sensor **202** may only generate distance measurements **212** and points **204** at locations where beams **208** are normally incident on the glass **302**. It is appreciated that some beams **208** incident upon glass **302** substantially close to normal incidence may also be detected by the detector of ToF sensor **202** (e.g., due to diffuse reflection if the surface of the glass **302** is not perfectly flat). One skilled in the art may appreciate that substantially reflective and opaque objects, such as polished surfaces, sheet metal walls, mirrors, and the like, may also exhibit a substantially similar behavior when being localized by beams **208** from a ToF sensor **202**, wherein only beams **208** normally incident upon the reflective surface may be reflected back to a detector of the sensor **202** and the remaining beams **208** being reflected from the surface of the reflective objects and away from a detector of the sensor **202** as shown in FIG. 2B(ii). Accordingly, the systems and methods disclosed herein may also be utilized for detection of substantially reflective surfaces. Both glass and reflective surfaces or objects may cause inaccurate localization of the surfaces or objects due to the behavior of beams **208** when incident upon these objects, thereby potentially causing a robot **102** to misperceive a location of the objects that may cause collisions.

[0093] FIGS. 4A-B illustrates a robot **102** navigating a route **404** (Fig. 4A), wherein a controller **118** of the robot **102** generates a computer-readable map **406** (Fig. 4B) of an environment based on measurements **208** and points **204** localized by a ToF sensor **202**, according to an exemplary embodiment. First, in FIG. 4A, the robot **102** navigates route **404** and utilizes ToF sensor **202** to collect distance measurements to nearby objects, such as glass **302** and wall **402**, made of solid opaque material (e.g., concrete, plaster, etc.), and excludes glass or specular surfaces. Wall **402** exhibits diffuse reflection. It is appreciated that memory **120** of robot **102** does not comprise prior localization data for glass **302** and wall **402** nor prior indication that the glass **302** is a glass surface or object. As illustrated in FIGS. 3A-B, only beams **208,** which are incident at substantially normal angle to the glass **302,** are reflected back to a detector of the ToF sensor **202** and produce a localized point **204** on the computer-readable map **406**.

[0094] FIG. 4A illustrates the robot **102** at two locations along the route **404** and a plurality of beams **208-I** emitted by the sensor **202** at the two locations, wherein beams **208-R** and beams **208-T** illustrate the reflected and/or transmitted portion of the emitted beams **208-I** respectively. At the first location (bottom of the page), the robot **102** utilizes the ToF sensor **202** to localize the glass **302**, wherein only one beam **208** is reflected back to the sensor **202** and the remaining beams **208** are either transmitted through the glass **302**, exhibit specular reflection off the glass **302** (if incident at an angle equal to or greater than the critical angle), or do not reflect off any objects. Only three beams **208** are illustrated while the robot **102** is at the first location for clarity. However, it is appreciated that additional beams **208** may be emitted from the ToF sensor **202** at additional angles. Later, the robot **102** may continue along the route **404** and reach the second illustrated location (top of the page) to collect another scan or measurement using the ToF sensor **202** of the opaque wall **402**. Beams **208** incident upon the wall **402** may be reflected diffusely back to the detector of the sensor **202** to localize points **204** representing the wall **402**. Accordingly, only a few points **204**, measured by beams **208** incident upon the glass **302** at normal incidence, which represent glass **302** are detected by the ToF sensor **202** and are recorded on the map **406** whereas substantially more points **204** localize the opaque wall **402**, as illustrated in FIG. 4B.

[0095] FIG. 4B illustrates a computer-readable map **406** generated by the controller **118** of the robot **102** previously illustrated in FIG. 4A using a plurality of scans from the ToF sensor **202** as the robot **102** navigates route **404**. The computer-readable map **406** is based on distance measurements from the ToF sensor **202**. As illustrated, the computer-readable map **406** comprises a plurality of points **204** that localize the glass **302** and wall **402**. Due to the specular and transparent nature of glass **302**, illustrated in FIG. 3A-B above, some of the beams **208** from sensor **202** are not reflected back to the detector and/or are below threshold detection strength. Only points **204** sampled when the beams **208** from sensor **202** are normal to the glass **302** will be detected and localized by the sensor **202**. These points are spatially separated by a distance equal to a sample rate of the sensor **202** (i.e., scan or pulse period) and the speed of the robot **102** along route **404** parallel to the surface of glass **302**. In contrast, ToF sensors will detect more points from the opaque wall **402**, because more beams **208** will be diffusely reflected back to sensor **202**. As a result, the points **204** within region **408** (representative of area occupied by glass **302** outlined for clarity) are more separated or are of lower density relative to points **204** which localize opaque wall **402** (i.e., points outside region **408**). That is, the controller **118** of the robot **102** is able to differentiate between the wall **402** and the glass

302 based on the difference in spatial separation or density of localized points **204** as shown on the computer-readable map **406**.

[0096] One skilled in the art may appreciate that if route **404** is not parallel to the surface of glass **302**, the separation between points **204** representing glass **302** may further depend on a cosine of an angle of the route **404** with respect to the surface of the glass **302**. A controller **118** of the robot **102** may detect the spatial separation of points **204** within the region **408** to be larger than points **204** beyond region **408** and identify these points as "suspicious points" **504**, comprising points of the map **406** which could potentially be glass or a specular surface (e.g., a mirror) to be verified using methods illustrated below. Stated differently, the points **504** are identified by the controller **118** as "suspicious points" because of the distance between two adjacent points **204** being greater than two adjacent points **204** detected in relationship to an opaque wall or surface.

[0097] FIG. 5 is a closer view of the robot **102** depicted in FIG. 4A above to further illustrate a suspicious point **504** and a method for detecting the suspicious point **504**, according to an exemplary embodiment. Robot **102** may localize itself during every scan or pulse of light emitted from a ToF sensor **202**, illustrated in FIG. 4 above, wherein the robot **102** may localize a local origin **508** with respect to a world frame origin **706**, illustrated below in FIG. 7A and 7C. The origin **508** may comprise a fixed point on the robot **102** (with respect to the frame of reference of the robot **102**) where the position of the robot **102** is defined (i.e., the robot **102** being at position (x, y) corresponds to origin **508** being at position (x, y)). The origin **706** of a world frame may comprise a fixed point in the environment of the robot **102** (e.g., a landmark or home base) from which the robot **102** localizes its origin **508**. The relation between origin **210** and origin **508** comprises a fixed transform or spatial separation which is stored in memory **120**. Accordingly, by localizing the origin **508** within the environment, the controller **118** is always able to localize the local sensor origin **210** during autonomous navigation (e.g., during each scan or measurement from the sensor **202**).

[0098] A scan from the ToF sensor **202**, as used herein, may comprise a single sweep of a laser beam across a field of view of the sensor **202** for a planar or scanning LiDAR sensor, a single pulse, flash, or emission of electromagnetic energy (i.e., a depth image) from a depth camera sensor, or emission or sampling of a structured light pattern. The robot origin **508** may comprise any predetermined point of the robot **102** (e.g., a center point of a wheel axle) which denotes a current location of the robot **102** in its environment. A pose, or (x, y, z, yaw, pitch, roll) position, of sensor **202** with respect to robot origin **504** may be a predetermined value specified, for example, by a manufacturer of the robot **102** with respect to this origin **508**. Accordingly, sensor origin **210** may be localized by the controller **118**, using navigation units **106**, during every scan of the sensor **202** with respect to robot origin **508** using a fixed transform (assuming no calibration is required), which is further localized with respect to a world origin **706** using a transform based on a location of the robot **102**.

[0099] To determine if a point **204** generated by a scan or pulse of sensor **202** produces a suspicious point **504**, or a point that is potentially indicative of a glass surface or specular object, angular thresholds **502**, **506** are imposed. Controller **118** of the robot **102** may execute computer-readable instructions to impose these thresholds **502**, **506** on a computer-readable map (e.g., **406**) generated, at least in part, using point cloud data from sensor **202**. Threshold **502** may comprise an allowance threshold to allow for more than one point **204** generated by a scan of sensor **202** to still potentially indicate glass (e.g., due to noise). It is appreciated by one skilled in the art that the depiction of specular reflection from glass **302** depicted in FIG. 3 above is an ideal scenario, wherein more than one point **204** may be localized by sensor **202** when sensing glass **302** due to, for example, imperfections in the glass surface, noise in the sensor **202**, imperfect localization of origin **506**, and other natural phenomena familiar to one skilled in the art. If the glass was perfectly flat, the sensor **202** comprises no noise, and the controller **118** may perfectly localize the robot origin **508** and sensor origin **210**, then allowance threshold **502** is not necessary, wherein allowance threshold **502** may be tuned based on the noise level of sensor **202**, localization capabilities of controller **118**, and typical flatness of glass **302** surfaces.

[00100] Next, thresholds **506** comprise suspicion thresholds wherein, for any single scan, lack of detection or localization of any point **204** within the suspicion thresholds **506** may correspond to any one or more points **204** within allowance threshold **502** to potentially indicate detection of glass. That is, allowance threshold **502** lies within or between suspicion thresholds **506** to account for noise and other imperfections. The angular size of allowance threshold **502** may depend on noise of the sensor **202**, typical imperfections in glass surfaces, and localization capabilities of controller **118**. The angular size of the suspicion thresholds **506** may be based on a speed of robot **102**, sampling or scanning rate of the sensor **202**, and

distance between robot **102** and a surface formed by glass **302** and wall **402**. The controller **118** may, for each point **204** of a scan from a sensor **202**, center the allowance threshold **502** about each point **204** (shown by a dashed line between origin **210** and the localized point) and determine if each/every point **204** within the allowance threshold **502** are suspicious points **504** based on a lack of detection of any points **204** within suspicion threshold **506**. The combined angle formed by the two suspicion thresholds **506** and allowance threshold **502** is more than twice the angular resolution of the sensor **202** such that the combined angle comprises a field of view about the sensor origin **210** which includes at least (i) the beam **208** used to produce the point, and (ii) at least two adjacent beams **208**.

[00101] According to at least one non-limiting exemplary embodiment, controller **118** may, for any single scan or pulse by ToF sensor **202**, sweep the angles across an entire field of view of the sensor **202** about the sensor origin **210**. The sweeping may be performed to ensure that the orientation of the robot **102** is not limited to the illustrated example. If, during the sweep, points **204** are localized within allowance threshold **502** and no points are detected within suspicion thresholds **506**, then all points **204** within the allowance threshold **502** are identified by controller **118** to comprise suspicious points **504**. In some embodiments, the controller **118** positions thresholds **502**, **506** about each localized point **204** and determines if each of the points **204** are suspicious points **504** based on a lack of detecting other points **204** within thresholds **506**.

[00102] According to at least one non-limiting exemplary embodiment, a threshold number of suspicious points **504** may be required to be detected prior to the suspicious points **504** being denoted as suspicious points. For example, detection of one point **204** within threshold **502** and no points within threshold **506** may not be sufficient to indicate a glass surface or suspicious point **504** if no other nearby points **204** meet these thresholds **502**, **506** criterion. For example, this may correspond to the sensor detecting a thin object such as a wire.

[00103] FIG. 6 illustrates another method for identifying suspicious points **504** using a distance threshold **602**, according to an exemplary embodiment. The method used to determine suspicious points **504** illustrated in FIG. 6 may be advantageous in reducing computational complexity of identifying suspicious points **504** at a cost of accuracy of localizing and detecting glass **302**. To identify suspicious points **504**, a distance threshold **602** may be

utilized. Distance threshold **602** comprises a distance equal to the sampling period (i.e., pulse period or one over the scan time) of the ToF sensor **202** multiplied by the velocity of the robot **102** along path **404** and the cosine of angle θ (i.e., distance of threshold **602** $d_{threshold\,602} = T_{sample}\, v_{robot} \cos(\theta)$). Angle θ is defined as the angular difference between the path **404** of the robot **102** and the line formed by consecutive suspicious points **504**, as illustrated by axis **606**, which is substantially parallel to the surface of the glass **302**. As illustrated in FIGS. 3A-B above, only beams **208** incident upon glass **302** at substantially normal incidence are detected (i.e., reflected back to sensor **202**) and localized as points **204** on a computer-readable map or point cloud whereas the remaining beams **208** are either reflected away from the surface **302** and/or transmitted through surface **302** (if surface **302** is glass). This is illustrated by lines **604**, which denote the paths followed by three beams **208** emitted during three sequential scans as the robot **102** moves along the route **404**; the three beams **208** are normally incident upon the glass **302** surface. The remaining beams **208** emitted during the three scans travel different paths and are either reflected away from or transmitted through the glass **302** and do not reach the sensor **202** such that no points **204** are localized.

[00104] According to at least one non-limiting exemplary embodiment, the angle θ may require at least two suspicious points **504** to be identified prior to axis **606** being defined with respect to robot **102**. Accordingly, when one or no suspicious points **504** are detected, threshold **602** may instead comprise a predetermined value with no angular dependence on θ, the value being less than the speed of the robot **102** multiplied by the sampling rate of the sensor (i.e., with no angular dependence since θ is not yet defined). In some instances, the predetermined value may be based on the measured distance and angular resolution of the sensor **202**. In this embodiment, the at least two suspicious points **504** required to define the axis **606** may be identified based on two points **204**, localized by two sequential scans from the sensor, being spatially separated by the threshold value. Upon defining axis **606**, the two points **204** may or may not fall within the threshold **602** once angular dependence on θ is included and the threshold calculation utilizes the speed of the robot **102**. That is, in instances where initially no suspicious points **504** are detected, controller **118** may relax or shrink the size of thresholds **602** to generate at least two suspicious points **504** and, upon detecting two or more suspicious points **504** to define axis **606**, the controller **118** may revisit these suspicious points **504** and compare them with the threshold **602** which includes the angular

dependence on θ and the real speed of the robot **102**.

[00105] According to at least one non-limiting exemplary embodiment, angular thresholds **502**, **506** illustrated in FIG. 5 above may be utilized to identify the first at least two suspicious points **504** used to define axis **606**. In some embodiments, axis **606** may be parallel to a best fit line, which comprises a linear approximation of a line formed by suspicious points **504**.

[00106] One skilled in the art may appreciate that detection of suspicious points **504** from a plurality of points **204** may be performed after the robot **102** has completed its route. For example, a robot **102** may be shown, pushed along, or driven along a route **404** during a training process. During navigation of the route **404**, the robot **102** may collect a plurality of scans from at least the ToF sensor **202** to generate a computer-readable map of its environment. This computer-readable map may be utilized to retrospectively detect suspicious points **504** based on the location of the origin **210** of the ToF sensor **202** during navigation along the route and thresholds **502**, **504** or **602**. Advantageously, retrospectively detecting suspicious points **504** may reduce a computational load imposed on the controller **118** during navigation of the route **404** (e.g., during training).

[00107] Advantageously, the method illustrated in FIG. 6 may reduce computational complexity of identifying suspicious points **504** by: (i) removing a requirement for localizing a robot origin **508** and sensor origin **210** for every scan; and (ii) removing the calculation of angular thresholds **502**, **506** on a computer-readable map for point **204** of each scan which may take substantially more time. On the other hand, the method illustrated in FIG. 6 may be, (i) susceptible to error as one point **204** may be detected between two other points **204** on a glass **302** object due to, e.g., random noise, wherein the one point **204** may cause the two points **204** and the one point **204** to not be identified as suspicious points; and (ii) may be susceptible to false identification of one or more points **204** as suspicious points **502** as other factors may cause spatial separation between two adjacent points **504** to be equal to the threshold **602**, such as if points **204** are localized substantially far away from robot **102**. One skilled in the art may appreciate these costs and benefits may be tuned based on specifications of a robot **102** such as, for example, computing resources of a controller **118**, noise level and precision of sensor units **114**, and a plurality of other common considerations within the art.

[00108] FIG. 7A-C illustrates a controller **118** utilizing a computer-readable map **702** to

reassign suspicious points **504** to glass points **704**, the glass points **704** being shown in FIG. 7C, according to an exemplary embodiment. Glass points **704** comprise points localized on the computer-readable map **702** based on measurements from a sensor **202**, which are determined to detect a glass objects/surfaces. It is appreciated that the present disclosure is not limited to detection of glass as specular surfaces, such as mirrors, may exhibit substantially similar properties as glass as shown in FIG. 2-3 above. Accordingly, the methods discussed in the exemplary embodiment of FIG. 7A-C for detecting glass points **704** may be equally applicable for detecting points **204** which localize specular surfaces, wherein use of "glass" points **704** is intended to be illustrative and non-limiting.

[00109] First, in FIG. 7A, a robot **102** may have navigated around its environment and scanned a wall comprising, in part, glass panes or windows to produce the computer-readable map **702** based on point cloud scans from the sensor **202**. The points **204** of the map **702** illustrated are localized by the sensor **202**, wherein other sensors **202** of the robot **102** may produce other point cloud representations of the environment similar to map **702**. World origin **706** is a predetermined fixed point within the environment of the robot **102** from which localization of robot origin **508**, and thereby origin **210** of the sensor **202**, is defined. The world origin **706** may comprise, for example, a home base (e.g., a marker), a start of a route, or a landmark. The robot **102** may be located anywhere on the map **702** or may be idle external to the environment depicted by the map **702**.

[00110] Some points **204** are identified as suspicious points **504** (empty circles) using methods illustrated in FIG. 5-6 above, wherein the suspicious points **504** may possibly or potentially indicate or detect glass to be verified using a method discussed below. To confirm these suspicious points **504** are points **704** that localize glass, a controller **118** may create a plurality of angular bins. Angular bins are further illustrated in FIG. 7B graphically, wherein each angular bin comprises an arc length of a **360°** circle about the world origin **706**. That is, each angular bin comprises a discretized angular region or portion of the **360°** circle about the world origin **706**, wherein each angular bin may comprise 1°, 5°, 15°, etc. arc lengths.

[00111] Angles θ_1, θ_2, θ_3, and θ_4 represent arbitrary angular ranges wherein adjacent suspicious points **504** are detected in sequence or in an approximately straight line. In some embodiments, each suspicious point **504** and adjacent suspicious points **504** are identified as a 'potential glass' objects on a computer-readable map, wherein the angles θ_1-θ_4 represent

angular sizes of these potential glass objects formed by suspicious points **504** with respect to world origin **706**. Each angular bin may be populated with a value based on a summation of distances from the world origin **706** to all suspicious points **504** encompassed within the respective angular bin.

[00112] FIG. 7B illustrates the angular bins **708** used for glass detection in a graphical format, according to an exemplary embodiment. The horizontal axis of the graph may comprise an angle θ about a world origin **706**, illustrated in FIG. 7A above. The vertical axis may comprise a sum of distance measurements between the world origin **706** and each suspicious point **504** encompassed within a respective angular bin. As illustrated, the horizontal axis is divided into a plurality of bins **708**, each comprising a discrete angular range (e.g., 1°, 5°, 10°, etc.). For example, as illustrated in FIG. 7A, angular range θ_1 encompasses some suspicious points **504**, wherein the angular range may be discretized into two bins **708** as shown in FIG. 7B. Angular ranges θ_n may encompass one or more bins **708**, wherein some of the angular ranges θ_n starting and/or stopping at the edges of the bins **708** is not intended to be limiting. That is, angular ranges θ_n are illustrated for visual reference between FIG. 7A-B to illustrate the angular range occupied by suspicious points **504** on map **702** and are not intended to denote the angular ranges of bins **708**.

[00113] Distances to each suspicious point within the range θ_1 may be summed and plotted onto the graph illustrated in FIG. 7B, wherein the angular bins encompassed by θ_1 as illustrated in FIG. 7B comprise a sum of distances greater than a threshold **710**. Threshold **710** may comprise a static (e.g., fixed value) or dynamic threshold (e.g., based on a mean value of distances within each or all bins **708**), wherein any angular bin **708** comprising a sum of distances from the world origin **706** to suspicious points **504** encompassed therein which exceeds the threshold **710** may correspond to the suspicious points **504** encompassed therein being indicative of glass. Threshold **710** may be implemented to remove suspicious points **504** which do not localize glass objects. For example, some scans by sensor **202** may cause detection of one or very few suspicious points **504** for a plurality of reasons (e.g., noise in the sensor **202**, thin objects, spatially separate objects, etc.). Threshold **710**, however, will not be exceeded unless multiple consecutive and adjacent scans generate multiple adjacent suspicious points **504**, thereby removing suspicious points **504**, which do not localize glass from the later identified glass points **704**. By way of illustrative example, some angular bins **708** of the graph

illustrated comprise zero distance, corresponding to no or very few suspicious points **504** detected within the respective angular bin **708** whereas other angular bins **708** may include a plurality of suspicious points **504** and may therefore comprise a larger cumulative distance value.

[00114] According to at least one non-limiting exemplary embodiment, the summation of distances within each angular bin **708** may be normalized with respect to a value. The value may include, but is not limited to, a summation of all distance between the world origin **706** and all suspicious points; summation of all distances between the world origin **706** and all points **204**, **504**; an average value of distances within a respective angular bin; an average of the summations of distances for all angular bins; or a constant.

[00115] It is appreciated that the sizes or angular ranges of each angular bin **708** illustrated may be exaggerated for clarity. The exact angular range of each angular bin **708** may be smaller than as illustrated for improved localization and resolution of the objects, determined to comprise glass based on threshold **710**, at a cost of increased computational complexity or workload imposed on controller **118**.

[00116] FIG. 7C illustrates a plurality of glass objects **712** (shaded rectangles) on a computer-readable map **702**, according to an exemplary embodiment. As illustrated above in FIG. 7B, angular bins **708** encompassed by respective angles θ_1, θ_2, θ_3, and θ_4 comprise distance summations exceeding a threshold value **710**. Accordingly, all suspicious points **504** (illustrated in FIG. 7A) encompassed within the respective angular bins **708** which exceed threshold **710** may be determined to be points of a glass object/surface and may be localized as glass points **704**. Accordingly, glass objects **712**, comprising multiple glass points **704**, may be placed on the computer-readable map **702**. Glass objects **712** may comprise a special denotation on the computer-readable map **704**, which represents area occupied by glass surfaces or objects. Localizing of glass objects **712** on the map **702** may be crucial for a robot **102** to operate using the map **702** by indicating to a controller **118** of the robot **102** that regions occupied by glass objects **712** are occupied by solid and impassible objects, which may be difficult to detect using a ToF sensor **202**. Additionally, localizing points **204** beyond the glass objects **712** (i.e., on the other side of the glass) may, in some embodiments of robot **102**, cause robot **102** to stop or slow down to avoid a detected object through the glass objects **712** if the glass objects **712** are not mapped onto map **702**. Advantageously, localizing glass objects **712**

may further configure controller **118** of the robot **102** to determine that localization of objects or points **204** behind (i.e., on an opposite side of) glass objects **712** may not be considered during obstacle avoidance or route planning, wherein controller **118** may not slow or stop the robot **102** upon detecting point(s) **204** behind glass objects **712**.

[00117] For example, if a robot **102** navigating nearby an identified glass object **712** detects a moving body approaching it from an opposite side of the glass object **712** (i.e., on the other side of the glass object **712**) using a ToF sensor **202** (e.g., based on beam **208-T** shown in FIG. 3B reflecting off the moving body), the robot **102** may not anticipate slowing or stopping for the moving body as the moving body is behind a glass barrier.

[00118] As another example, points **704** may localize specular surfaces not comprising glass using the same angular bin method discussed above and further elaborated in FIG. 9 below. In this example, the objects **712** may still comprise a special denotation from other objects localized using points **204** on the computer-readable map, wherein the robot **102** produces substantially fewer points **204** than expected when navigating nearby the objects **712**. Accordingly, the robot **102** may utilize the computer-readable map to identify and localize the objects **712** (e.g., for obstacle avoidance) despite fewer points **204** being captured by a ToF sensor **202** of these objects **712**.

[00119] According to at least one non-limiting exemplary embodiment, a controller **118** of a robot **102** may identify suspicious points **504** during navigation and later identify glass points **704** from the suspicious points **502** subsequent the navigation (i.e., upon generation of the entire computer-readable map **702**). In some embodiments, the controller **118** may identify both the suspicious points **504** and glass points **704** subsequent navigation of a route. In some embodiments, the controller **118** may identify suspicious points **504** and populate the angular bins **708** as the robot **102** navigates a route and receives point cloud data from a ToF sensor **202**.

[00120] FIG. 8 illustrates a method for a robot **102** to detect glass **302** using an image camera **802** of sensor units **114**, according to an exemplary embodiment. Glass **302** may similarly be illustrative of specular surfaces such as mirrors as appreciated by one skilled in the art given the contents of the present disclosure, wherein the object **302** being “glass” is intended to be illustrative and non-limiting. As illustrated in FIG. 3 above, ToF sensors may comprise limited capabilities of detecting glass **302** due to transmission of beams **208** through

the glass **302**. Similarly, ToF sensors may comprise limited capabilities for detecting specular surfaces due to specular reflection shown in FIG. 2B(ii). Accordingly, the imaging camera **802** may be also be utilized to detect glass **302** either as a verification step to the methods disclosed above or as a separate method for glass **302** detection.

[00121] The controller **118** of the robot **102** may navigate the robot **102** along a route (e.g., navigating towards one or more suspicious points **504**) and capture images (e.g., RGB, greyscale, etc.) using imaging camera **802** which depict a surface of an object. In doing so, the controller **118** may expect, if the surface is glass or a specular surface, to observe a partial reflection of the robot **102** in the images of the surface. The controller **118** may utilize image processing methods (e.g., convolutional neural networks) to determine if the reflection of the robot **102-R** is represented within images captured by the imaging camera **802**.

[00122] In some embodiments, the robot **102** may further comprise visual indicators such as lights **804-L** and **804-R** disposed on the left and right sides of the robot **102**, respectively. The controller **118** may blink or change a color of the lights **804-L** and **804-R** in a predetermined pattern. Detection of the reflection of the lights emitted from lights **804-L** and **804-R** may indicate the surface **302** is glass or a specular surface based on employing the inventive concepts discussed above with respect to FIG. 8. In some embodiments, the robot **102** may perform a predetermined sequence of motions, such as extending, retracting, or moving a feature of the robot **102** and detecting the extension or retraction within images from camera sensor **802**. That is, the robot **102** may perform any visual display in front of an object represented by suspicious points **504** and, upon detecting the visual display within its refection **102-R** using images from camera sensor **802**, may determine the object is glass or a specular surface. It is appreciated by one skilled in the art that the method of using an imaging camera **802** may be additionally applied to highly reflective surfaces (e.g., metallic walls or mirrors), which may be further advantageous due to the difficulty of sensing a specular surface using a ToF sensor **202** as illustrated in FIG. 2B(ii).

[00123] FIG. 9 illustrates a method **900** for a controller **118** to detect glass **302** and/or specular surfaces, such as a highly reflective mirror, using a ToF sensor **202**, according to an exemplary embodiment. It is appreciated that any steps of method **900** may be effectuated by a controller **118** executing computer-readable instructions from memory **120**.

[00124] Block **902** comprises the controller **118** navigating a robot **102** along a route

using a ToF sensor. In some embodiments, the navigation of the route may be performed under user supervision as a training procedure, wherein the user may push, pull, drive, lead, or otherwise move the robot **102** along the route. In some embodiments, the navigation is performed as an exploratory measure such that the robot **102** may localize objects within its environment to generate a computer-readable map. That is, the robot **102** may navigate the route for any reason, wherein memory **120** may comprise no prior localization data of objects, such as glass objects, within the environment.

[00125] Block **904** comprises the controller **118** determining suspicious points **504** based on a first threshold, such as angular threshold **502**, **506** or distance threshold **602**. In some embodiments, for example as illustrated in FIG. 5, the first threshold **502**, **506** may comprise an angular range about a point **204**, localized by the ToF sensor **202**, where lack of detection of any other point **204** within the angular threshold **506** about the point **204** may indicate the point **204** comprises a suspicious point **504**. In some embodiments, for example as illustrated in FIG. 6, the distance threshold **602** may be used, wherein distance threshold **602** may comprise a distance between two adjacent points **204**, wherein two points **204** of two respective sequential scans separated by distance threshold **602** (with no other points **204** between the two points **204**) may indicate the detected two points **204** are suspicious points **504**.

[00126] Block **906** comprises the controller **118** verifying the suspicious points **504**, identified in block **904** above, are indicative of glass or specular surface(s) based on distance measurements of angular bins **708** exceeding a second threshold **710**, as illustrated in FIG. 7A-B above. Angular bins **708** may comprise a discretized angular range about a world origin **706**. Each angular bin **708** may be populated with a summation of distances between suspicious points **504** encompassed within a respective angular bin **708** and the world origin **706**. Upon the summation of distances for an angular bin **708** exceeding the second threshold value **710**, all suspicious points **504** within the angular bin **708** are identified as localizing glass or specular surfaces.

[00127] According to at least one non-limiting exemplary embodiment, points identified as localizing glass or specular surfaces may be localized onto a computer-readable map with a special denotation or encoding. For example, objects **712** illustrated in FIG. 7C could be labeled as “glass object” or “specular surface”, or an equivalent.

[00128] FIG. 10 illustrates a method for a controller **118** of a robot **102** to detect glass and/or specular surfaces using an image sensor **802** of sensor units **114**, according to an exemplary embodiment. It is appreciated that controller **118** performing any steps of method **1000** may be effectuated by the controller **118** executing computer-readable instructions from memory **120**.

[00129] Block **1002** comprises the controller **118** navigating the robot **102** along a route and collecting images using the image sensor **802**. Image sensor **802** may comprise an RGB image camera or greyscale image camera. In some embodiments, the navigation of the route may be performed under user supervision as a training procedure, wherein the user may push, pull, drive, or otherwise move the robot **102** along the route. In some embodiments, the navigation is performed as an exploratory measure such that the robot **102** may localize objects within its environment to generate a computer-readable map. That is, the robot **102** may navigate the route for any reason, wherein memory **120** may comprise no prior localization data of objects, such as glass objects, within the environment.

[00130] Block **1004** comprises the controller **118** detecting glass objects based on observing a reflection of the robot **102**. The controller **118** may execute specialized image recognition algorithms configured to detect the robot **102**, and thereby its reflection, in images captured by the sensor **802**. For example, the image recognition algorithms may implement a convolutional neural network or a trained model derived from a convolutional neural network. In other embodiments, the image recognition algorithm may compare captured images to images of a library, the library containing images of the robot **102**. By comparing captured images to images of the library, the controller **118** may determine if the robot reflection is present in the captured images if the captured images and images of the library are substantially similar (i.e., greater than a threshold). One skilled in the art may envision a plurality of other contemporary image/pattern recognition algorithms may also be used, without limitation. If the controller **118** receives an image of the robot **102** (i.e., its reflection in a reflective or glass surface), the controller **118** may localize an object which produces the image of the robot **102** onto a computer-readable map as a “glass object” or a “specular surface”, or equivalent definition. The localization may be performed using the sensor **802** and/or other sensor units **114**.

[00131] Block **1006** comprises the controller **118** verifying the detection of the glass or

specular surface by configuring the robot **102** to perform a visual display. The visual display may comprise, for example, a predetermined sequence of movements (e.g., shake left to right 5 times), blinking of lights (e.g., lights **804-L** and **804-R**) in a predetermined pattern, moving a feature of the robot **102** (e.g., waving a robotic arm, lever, member, support), or any other movement or visual indication. In some embodiments, the robot **102** may perform a predetermined sequence of motions, such as, extending, retracting, or moving a feature of the robot **102** and detecting the extension or retraction within images from camera sensor **802**. The visual display performed by the robot **102** occurs proximate the identified glass object or specular surface such that a reflection may be detected by imaging sensor **802**. The visual display, when detected by images from sensor **802**, confirm to the controller **118** that an image received by sensor **802** comprising the robot **102** represented therein which causes the detection of the glass object or specular surface in block **1004** is, in fact, a reflection of the robot **102**, and not another robot **102** of the same make/model.

[00132] Advantageously, method **1000** may enable a robot **102** to verify objects identified as glass or specular objects (e.g., objects **712** of FIG. 7C) are in fact glass or specular objects. In some instances, methods **900** and **1000**, or parts thereof, may be performed concurrently, such as during a single training run or exploratory run. For example, point clouds may be generated as in block **902** while images are gathered as in block **1002** while the robot navigates a route in a single training run. If suspicious points are determined (block **904**) and verified that they are indicative of glass (block **906**), the controller **118** may execute blocks **1004** and **1006** of method **1000** while the robot is still in proximity to the glass objects indicated in block **906**. One can appreciate that concurrent execution of methods **900** and **1000** in this manner may be best utilized such as within small environments (e.g., a single room) comprising few glass or specular objects.

[00133] In other instances, methods **900** and **1000** may be executed separately but sequentially. For example, one skilled in the art may appreciate that method **1000** may take a substantial amount of time to verify all glass and specular objects within large environments (e.g., an entire building). Accordingly, the method **1000** may be executed subsequent to method **900** as a verification step to ensure glass or specular objects were identified correctly in method **900**. For example, the controller **118** may configure the robot to execute a route through the environment in block **1002** that navigates the robot directly to putative glass

objects identified in block **906** and execute blocks **1004** and **1006** for verification. In instances of multistory buildings where some floors may have similar floor plans, the controller may determine that some glass objects identified in block **906** in one floor are substantially similar to those identified in other floors and not verify them by method **1000**. The controller may execute a route in block **1002** to navigate the robot only to dissimilar putative glass objects for verification in blocks **1004** and **1006**.

[00134] It will be recognized that while certain aspects of the disclosure are described in terms of a specific sequence of steps of a method, these descriptions are only illustrative of the broader methods of the disclosure, and may be modified as required by the particular application. Certain steps may be rendered unnecessary or optional under certain circumstances. Additionally, certain steps or functionality may be added to the disclosed embodiments, or the order of performance of two or more steps permuted. All such variations are considered to be encompassed within the disclosure disclosed and claimed herein.

[00135] While the above detailed description has shown, described, and pointed out novel features of the disclosure as applied to various exemplary embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the device or process illustrated may be made by those skilled in the art without departing from the disclosure. The foregoing description is of the best mode presently contemplated of carrying out the disclosure. This description is in no way meant to be limiting, but rather should be taken as illustrative of the general principles of the disclosure. The scope of the disclosure should be determined with reference to the claims.

[00136] While the disclosure has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive. The disclosure is not limited to the disclosed embodiments. Variations to the disclosed embodiments and/or implementations may be understood and effected by those skilled in the art in practicing the claimed disclosure, from a study of the drawings, the disclosure and the appended claims.

[00137] It should be noted that the use of particular terminology when describing certain features or aspects of the disclosure should not be taken to imply that the terminology is being re-defined herein to be restricted to include any specific characteristics of the features or aspects of the disclosure with which that terminology is associated. Terms and phrases used

in this application, and variations thereof, especially in the appended claims, unless otherwise expressly stated, should be construed as open ended as opposed to limiting. As examples of the foregoing, the term "including" should be read to mean "including, without limitation," "including but not limited to," or the like; the term "includes" should be interpreted as "includes but is not limited to". The term "comprising" as used herein is synonymous with "including," "containing," or "characterized by," and is inclusive or open-ended and does not exclude additional, unrecited elements or method steps; the term "having" should be interpreted as "having at least;" the term "such as" should be interpreted as "such as, without limitation. The term "example" or the abbreviation "e.g." is used to provide exemplary instances of the item in discussion, not an exhaustive or limiting list thereof, and should be interpreted as "example, but without limitation". The terms "illustration", "illustrative" and the like should be interpreted as "illustration, not limitation". Adjectives such as "known," "normal," "standard," and terms of similar meaning should not be construed as limiting the item described to a given time period or to an item available as of a given time, but instead should be read to encompass known, normal, or standard technologies that may be available or known now or at any time in the future; and use of terms like "preferably," "preferred," "desired," or "desirable," and words of similar meaning should not be understood as implying that certain features are critical, essential, or even important to the structure or function of the present disclosure, but instead as merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment. Likewise, a group of items linked with the conjunction "and" should not be read as requiring that each and every one of those items be present in the grouping, but rather should be read as "and/or" unless expressly stated otherwise. Similarly, a group of items linked with the conjunction "or" should not be read as requiring mutual exclusivity among that group, but rather should be read as "and/or" unless expressly stated otherwise. The terms "about" or "approximate" and the like are synonymous and are used to indicate that the value modified by the term has an understood range associated with it, where the range may be ±20%, ±15%, ±10%, ±5%, or ±1%. The term "substantially" is used to indicate that a result (e.g., measurement value) is close to a targeted value, where close may mean, for example, the result is within 80% of the value, within 90% of the value, within 95% of the value, or within 99% of the value. Also, as used herein "defined" or "determined" may include "predefined" or "predetermined" and/or otherwise determined values, conditions, thresholds, measurements, and the like.

WHAT IS CLAIMED IS:

1. A method for detecting an object, comprising:

collecting measurements using a sensor as a robot navigates along a route in an environment, the measurements comprising a plurality of points localized on a computer readable map;

identifying one or more first points of the collected measurements based on a first threshold;

identifying one or more of the first points of the measurement as an object based on a second threshold value, the object comprises either a glass or specular surface; and

updating the computer readable map to comprise the object in the environment.

2. The method of Claim 1, further comprising:

discretizing the computer readable map into a plurality of angular bins, each angular bin comprising an arc length defined about an origin, the origin comprising a fixed point within the environment;

populating each angular bin of the plurality of angular bins with a summation of distances between the one or more first points encompassed therein and the origin; and

comparing the summation of distances for each angular bin to the second threshold value, the one or more first points encompassed within each angular bin are identified as representing the object upon the summation of distances exceeding the second threshold value for a respective angular bin.

3. The method of Claim 2, wherein the first threshold comprises an angular range, the angular range being centered about each point of the plurality of points, each point

is one of the one or more first points if it is the only point within the angular range, the angular range being larger than the angular resolution of the sensor.

4. The method of Claim 3, wherein the first threshold corresponds to a value of spatial separation between points of a first scan and points of a second scan, a point of the first scan and a nearest point of the second scan separated by at least the spatial separation are included in the one or more first points, the second scan being captured subsequent the first scan by the sensor.

5. The method of Claim 1,

wherein the one or more identified first points are separated apart from each other at a greater distance compared to separation between other points of the plurality of points, the first points corresponding to the object and the other points corresponding to another object, the another object corresponding to non-glass or non-specular surface, and

wherein the one or more identified first points include a density lower than density of the other points of the plurality of points.

6. The method of Claim 1, further comprising:

navigating the robot to the object based on the computer readable map; and

utilizing a camera sensor to detect a reflection of the robot to verify the object comprises glass or a specular surface.

7. The method of Claim 6, further comprising:

performing a visual display upon navigating the robot to the object; and

detecting a reflection of the visual display using the camera sensor to verify the object comprises glass or a specular surface.

8. The method of Claim 1, wherein,

the identification of the one or more first points is performed after the robot has navigated the route based on the computer readable map generated at least in part during navigation of the route.

9. The method of Claim 3, wherein,

the identification of the one or more first points is performed after the robot has navigated the route based on the computer readable map generated at least in part during navigation of the route.

10. The method of Claim 4, wherein,

the identification of the one or more first points is performed after the robot has navigated the route based on the computer readable map generated at least in part during navigation of the route.

11. A non-transitory computer readable storage medium comprising a plurality of computer readable instructions embodied thereon, that when executed by at least one processor, configure the at least one processor to,

collect measurements using a sensor as the robot navigates a route, the measurements comprising a plurality of points localized on a computer readable map;

identify one or more first points of the measurements based on a first threshold;

identify one or more of the first points of the measurement as an object based on a second threshold value, the object comprises either glass or specular surfaces; and

update the computer readable map to comprise the object.

12. The non-transitory computer readable storage medium of Claim 10, further comprising computer readable instructions that configure the at least one processor to:

discretize the computer readable map into a plurality of angular bins, each angular bin comprising an arc length defined about an origin, the origin comprising a fixed point within an environment;

populate each angular bin of the plurality with a summation of distances between each of the one or more first points encompassed therein and the origin; and

compare the summation of distances for each angular bin to the second threshold value, the one or more first points encompassed within each angular bin are identified as representing object upon the summation of distances exceeding the second threshold value for a respective angular bin, the object comprising glass or a specular surface.

13. The non-transitory computer readable storage medium of Claim 12, wherein the first threshold comprises an angular range, the angular range being centered about each of the plurality of points, each point is determined to be one of the one or more first points if it is the only point within the angular range, the angular range being larger than the angular resolution of the sensor.

14. The non-transitory computer readable storage medium of Claim 12, wherein the first threshold corresponds to a value of spatial separation between points of a first scan and points of a second scan, a point of the first scan and a nearest point of the second scan separated by at least the spatial separation are included in the one or more first points, the second scan being captured subsequent the first scan by the sensor.

15. The non-transitory computer readable storage medium of Claim 11,

wherein the one or more identified first points are separated apart from each other at a greater distance compared to separation between other points of the plurality of points, the first points corresponding to the object and the other points corresponding to another object, the another object corresponding to non-glass or non-specular surface, and

wherein the one or more identified first points include a density lower than density of the other points of the plurality of points.

16. The non-transitory computer readable storage medium of Claim 11, further comprising computer readable instructions that configure the at least one processor to:

navigate the robot to the objects based on the computer readable map; and

utilize a camera sensor to detect a reflection of the robot to verify the object comprises glass or a specular surfaces.

17. The non-transitory computer readable storage medium of Claim 16, further comprising computer readable instructions that configure the at least one processor to:

perform a visual display upon navigating the robot to the object; and

detect a reflection of the visual display using the camera sensor to verify the object comprise glass or a specular surfaces.

18. A method for detecting an object by a robot, comprising:

collecting one or more images using a camera sensor as the robot navigates a route in an environment;

detecting a reflection of the robot within the one or more images;

performing a visual display; and

detecting the visual display within the one or more images collected from the camera sensor,

wherein the detection of the visual display corresponds to detection of the object, wherein the object comprises a glass object or a reflective surface.

19. The method of Claim 18, wherein the visual display comprises at least one of the, (i) blinking or changing colors of one or more lights, or (ii) moving a feature of the robot.

20. The method of Claim 18, wherein the detection of the reflection comprises use of an image recognition algorithm to identify images comprising of, at least in part, the robot.

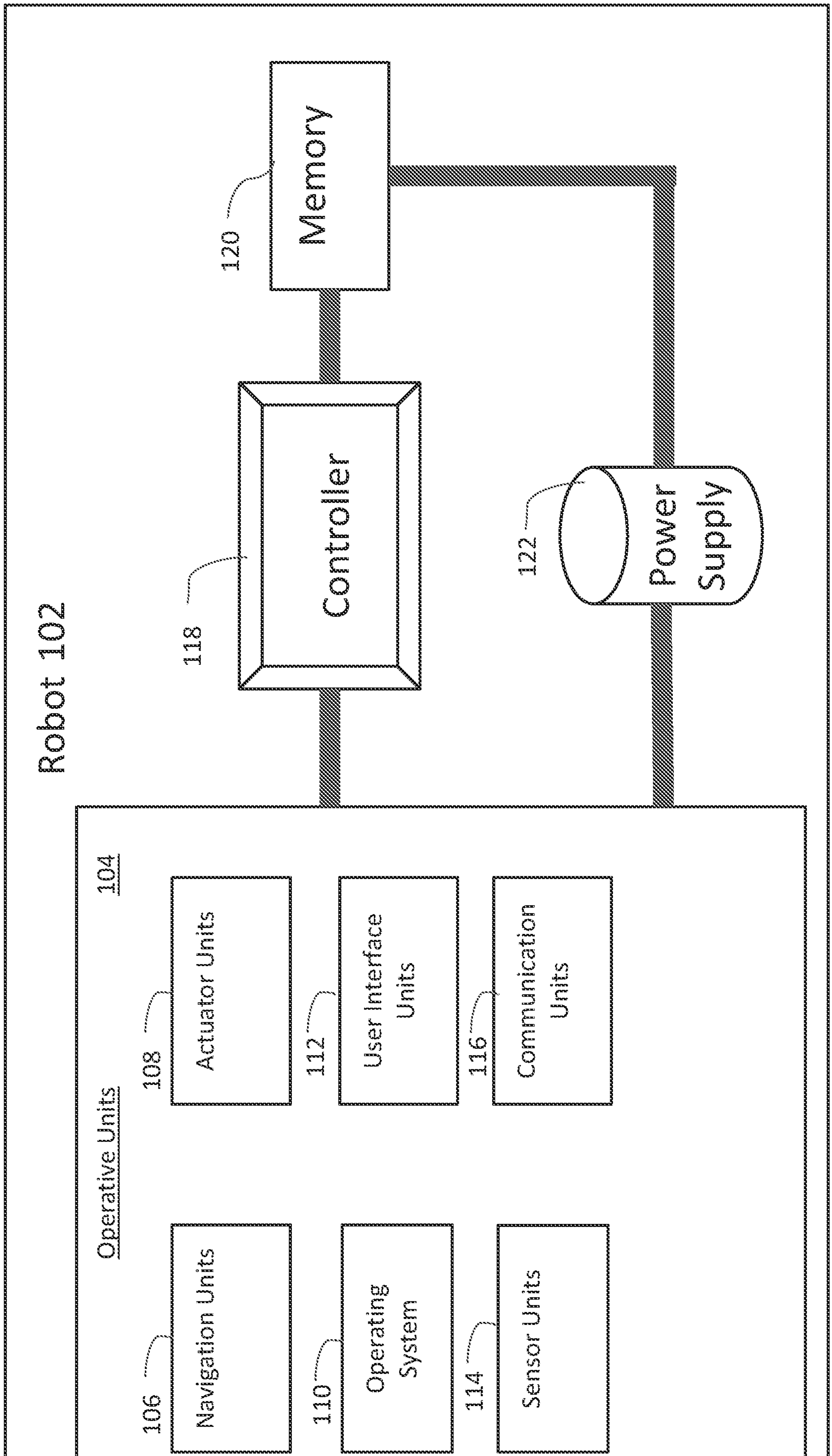
Robot 102
120
Memory
118
Controller
122
Power Supply
Operative Units
104
106
Navigation Units
108
Actuator Units
110
Operating System
112
User Interface Units
114
Sensor Units
116
Communication Units

FIG. 1A

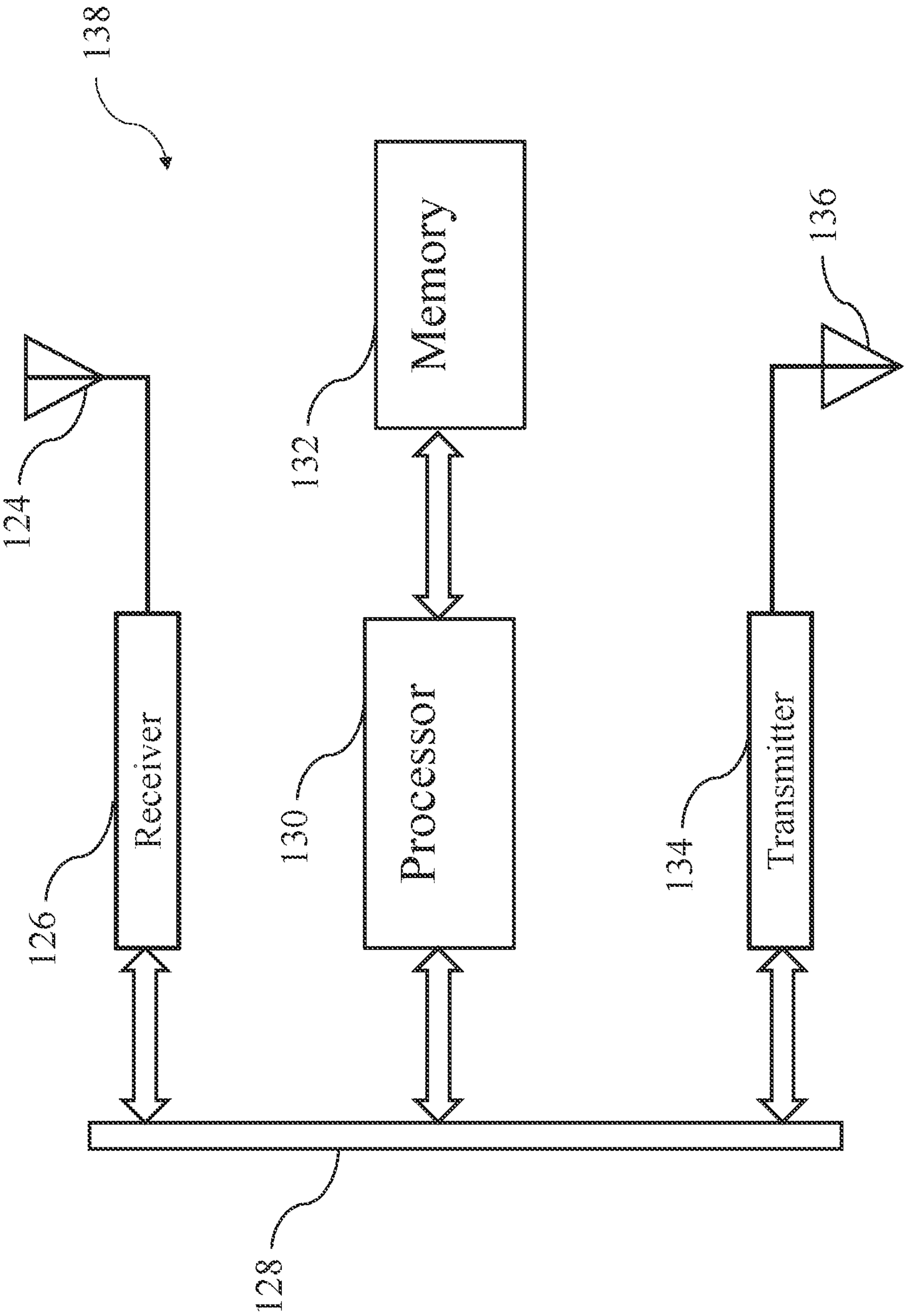
138
124
Receiver
126
132
Memory
Processor
130
136
Transmitter
134
128

FIG. 1B

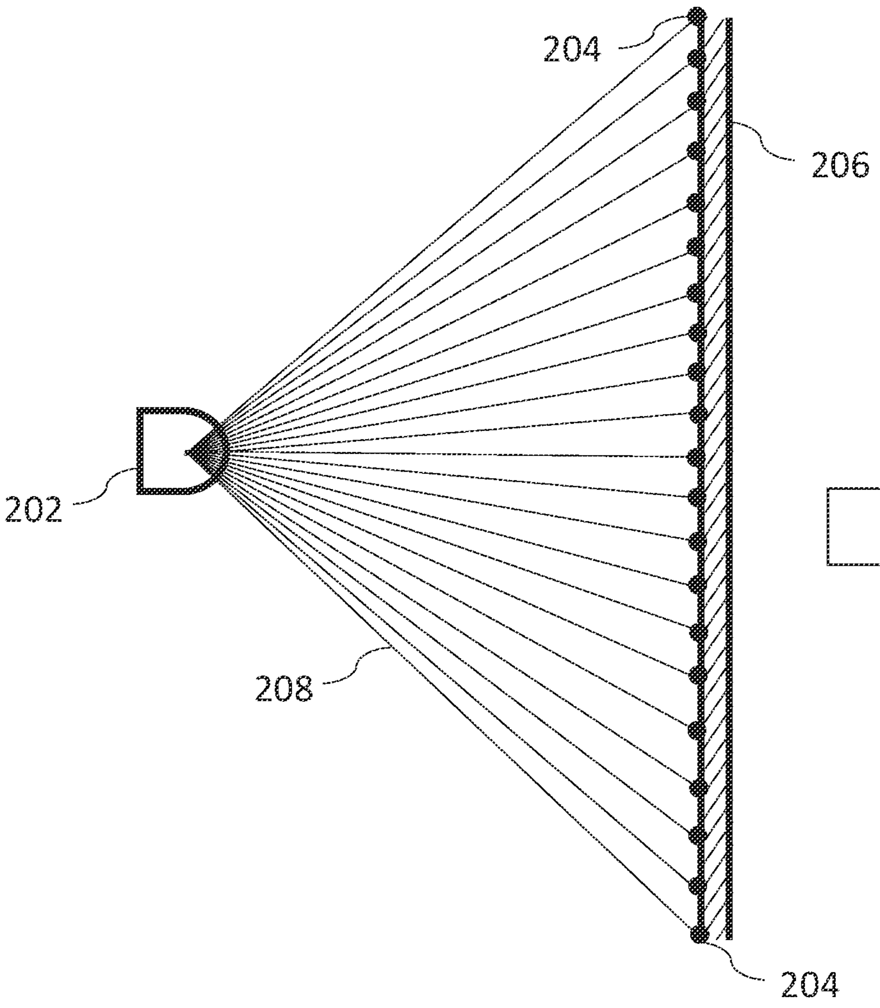

FIG. 2A(i)

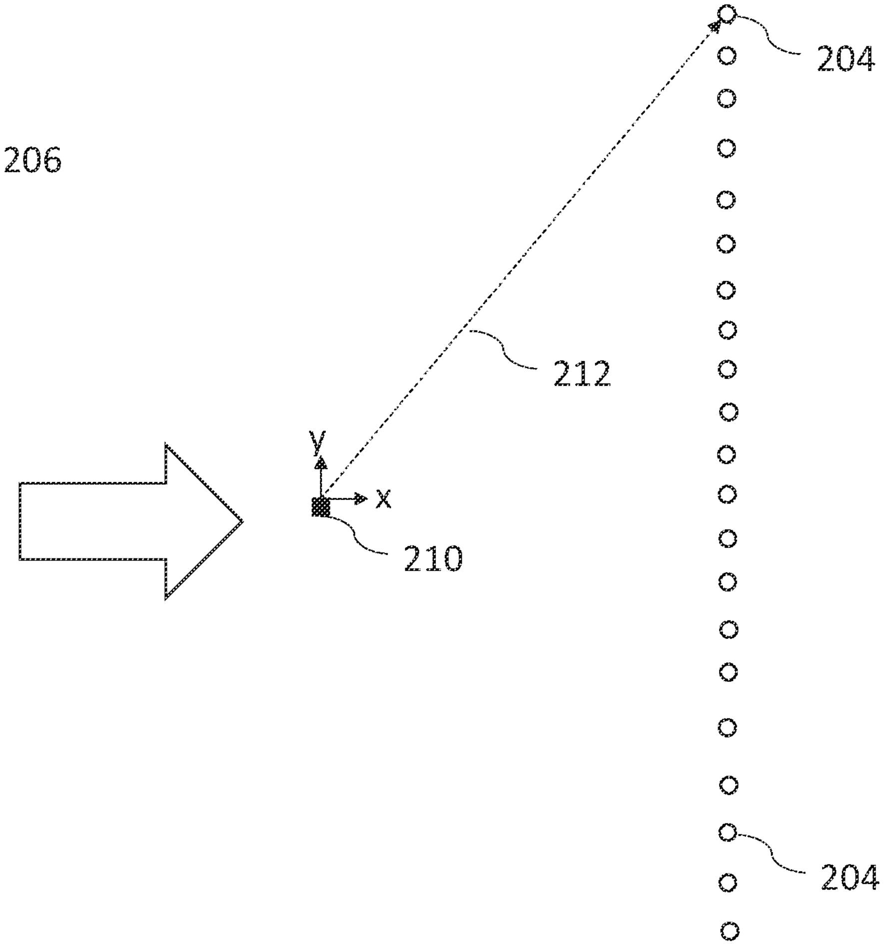

FIG. 2A(ii)

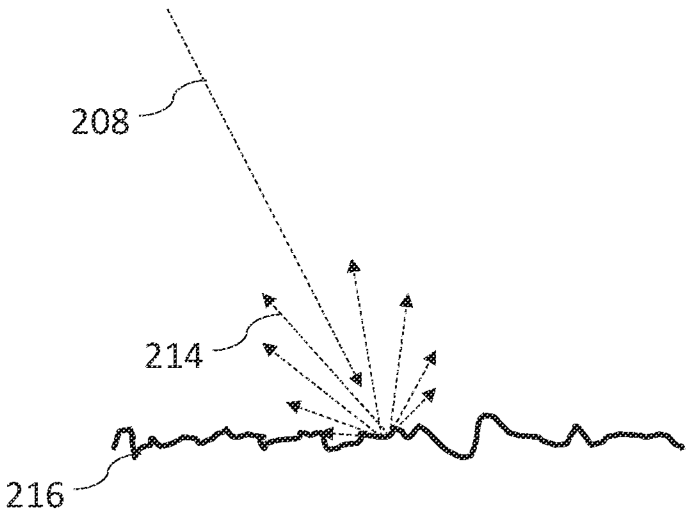

FIG. 2B(i)

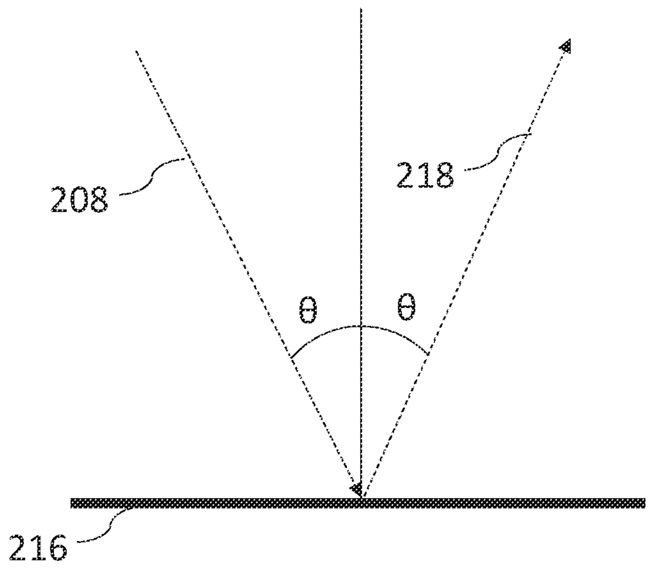

FIG. 2B(ii)

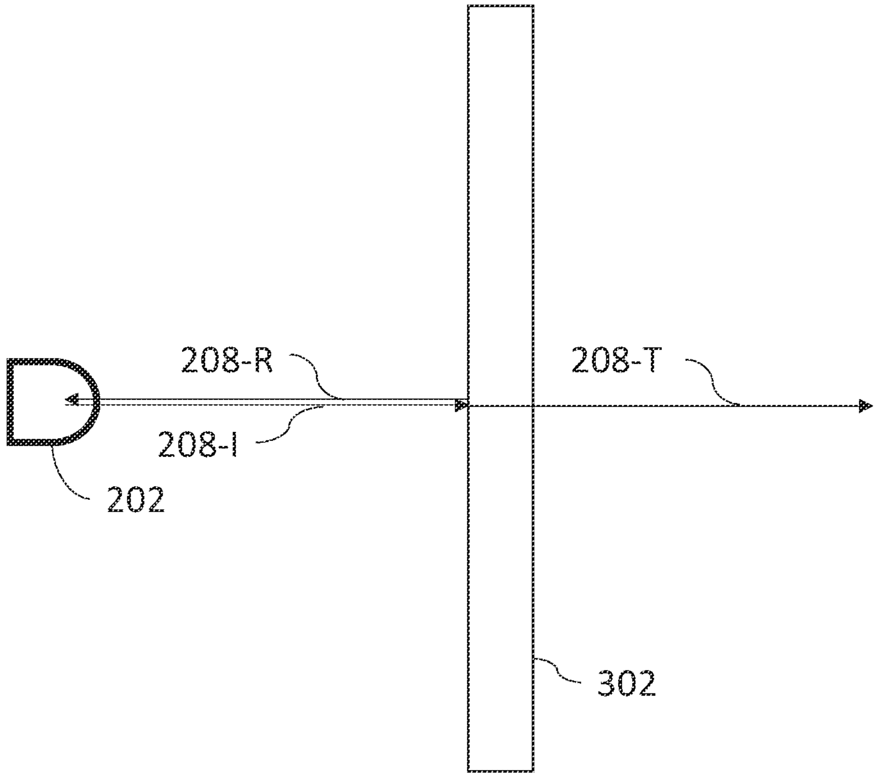

FIG. 3A

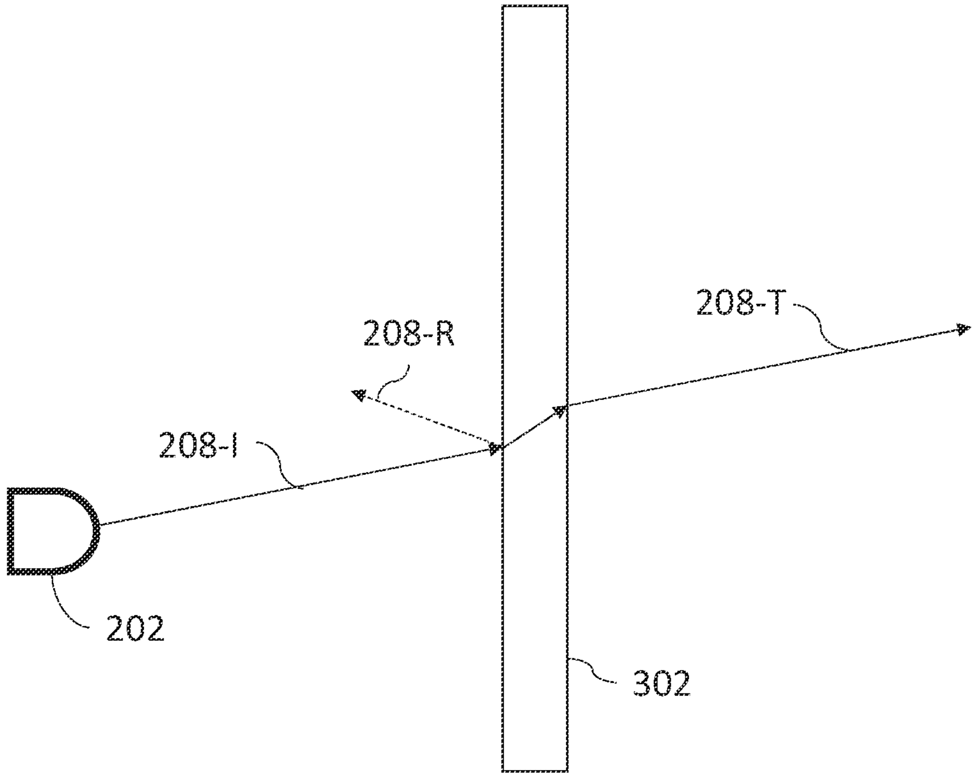

FIG. 3B

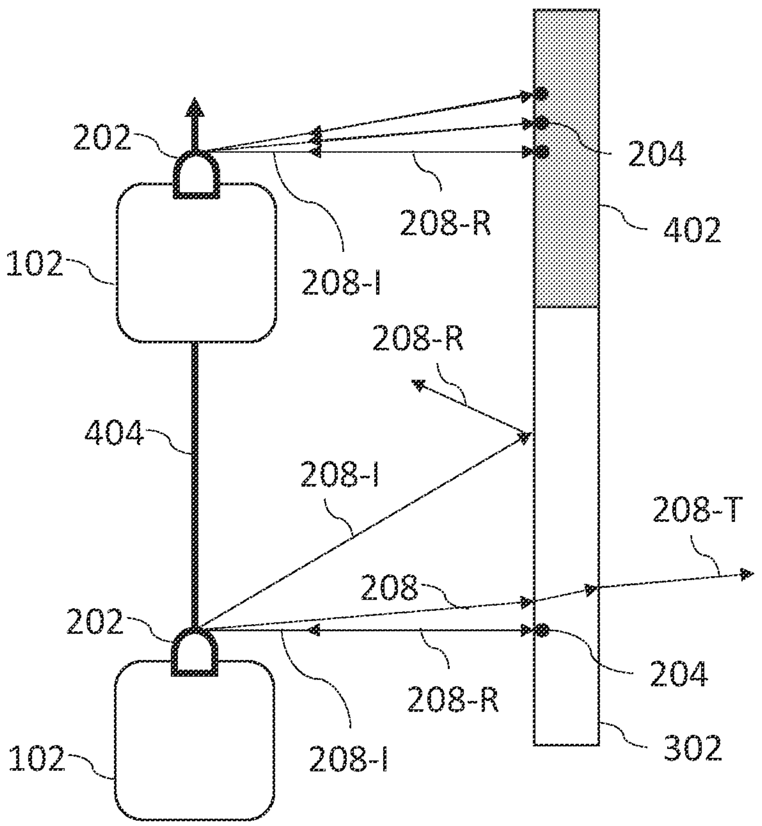
202
102
404
202
102
208-I
208-R
204
402
208-R
208-I
208-T
208
204
208-R
208-I
302

FIG. 4A

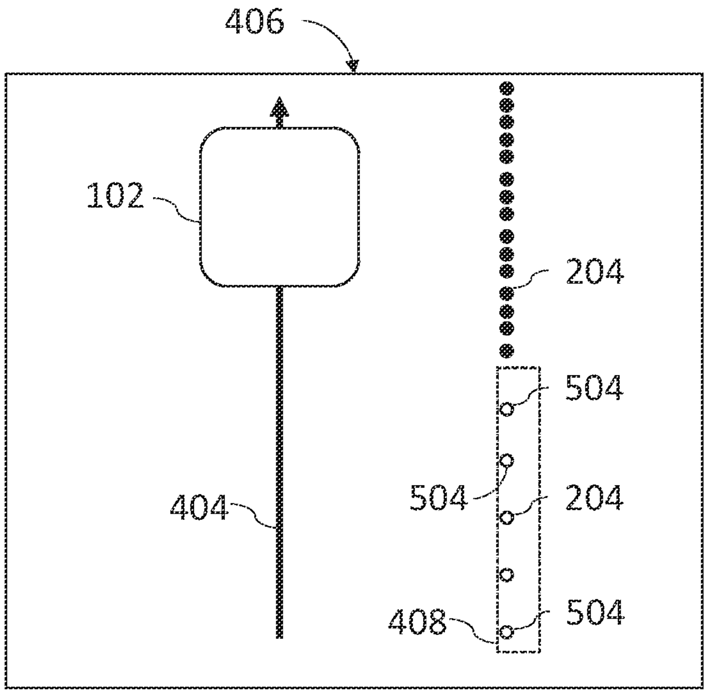
406
102
204
504
404
504
204
408
504

FIG. 4B

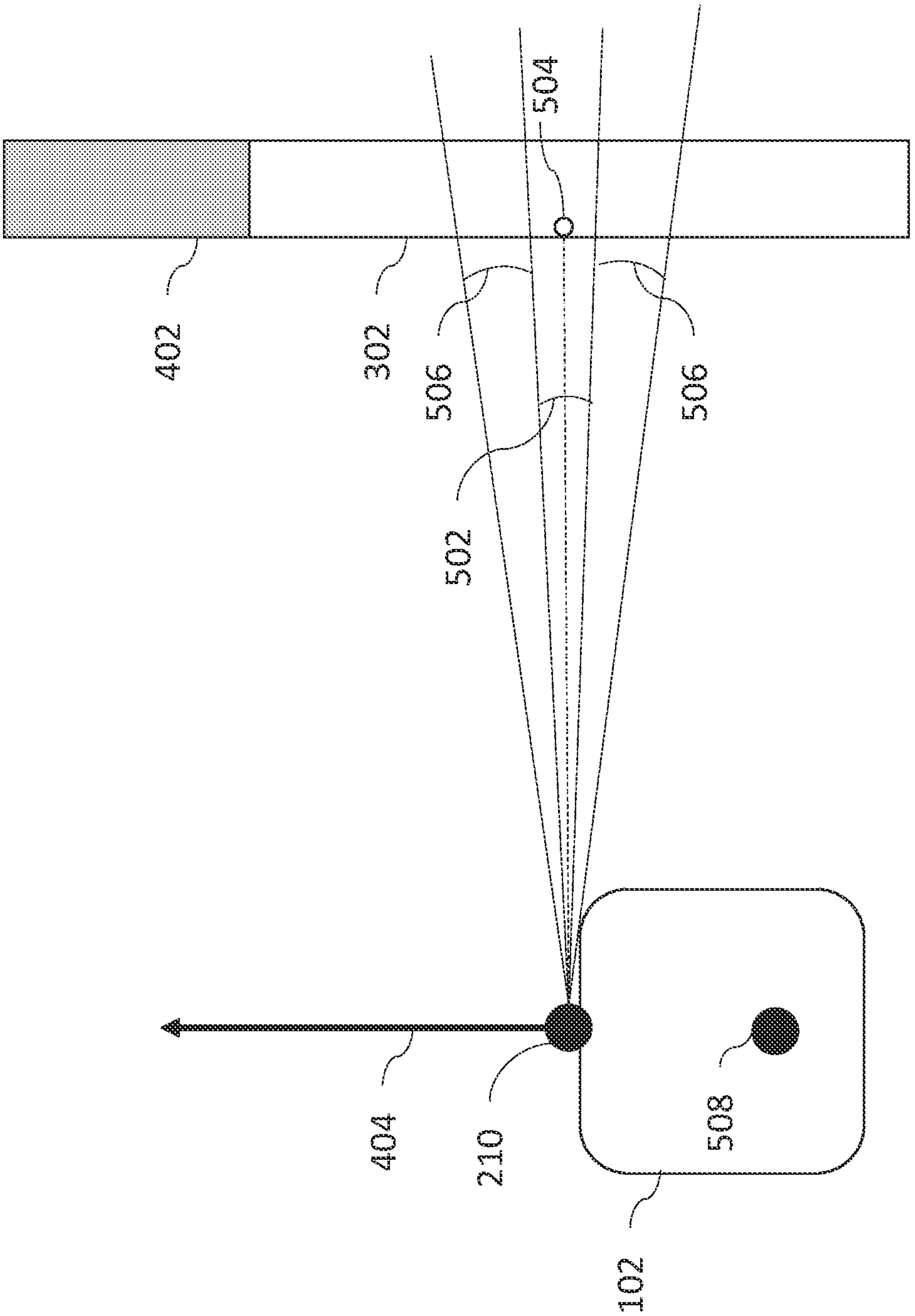

FIG. 5

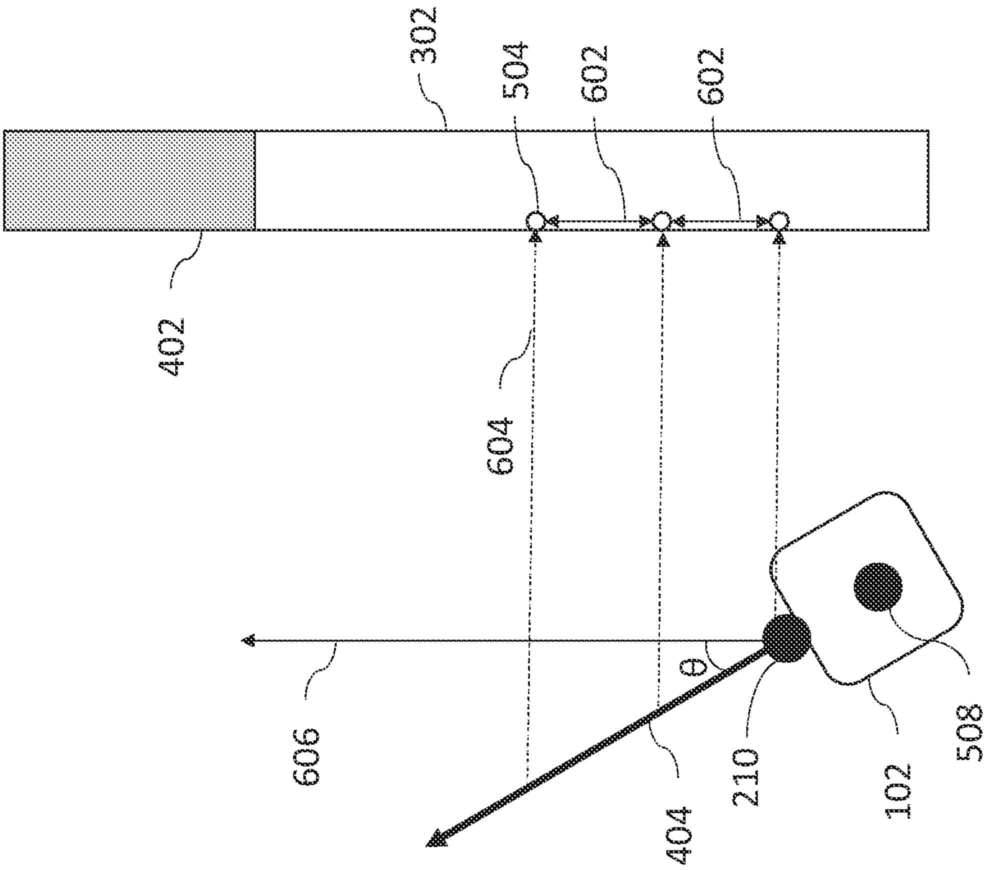

FIG. 6

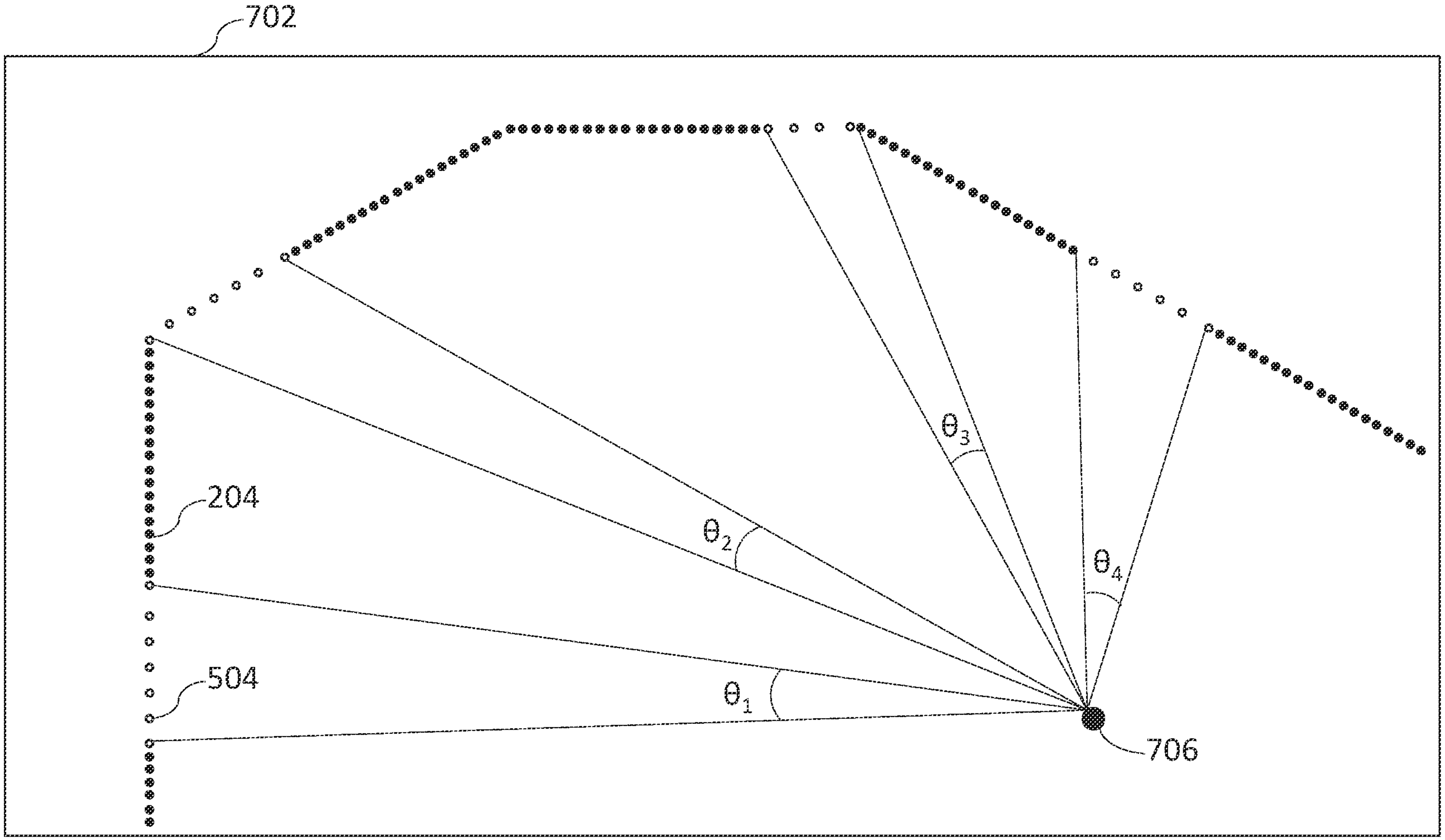

FIG. 7A

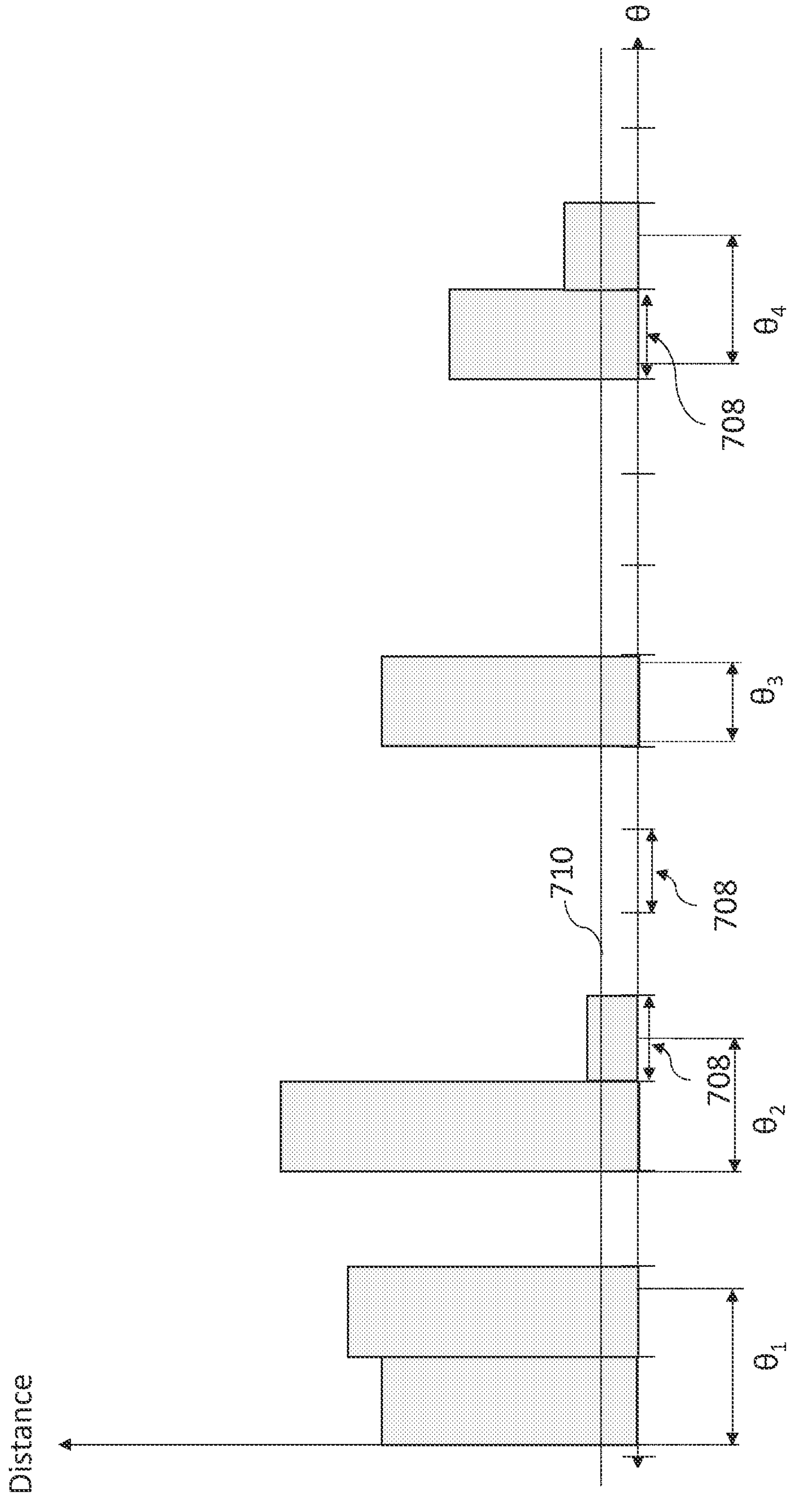

FIG. 7B

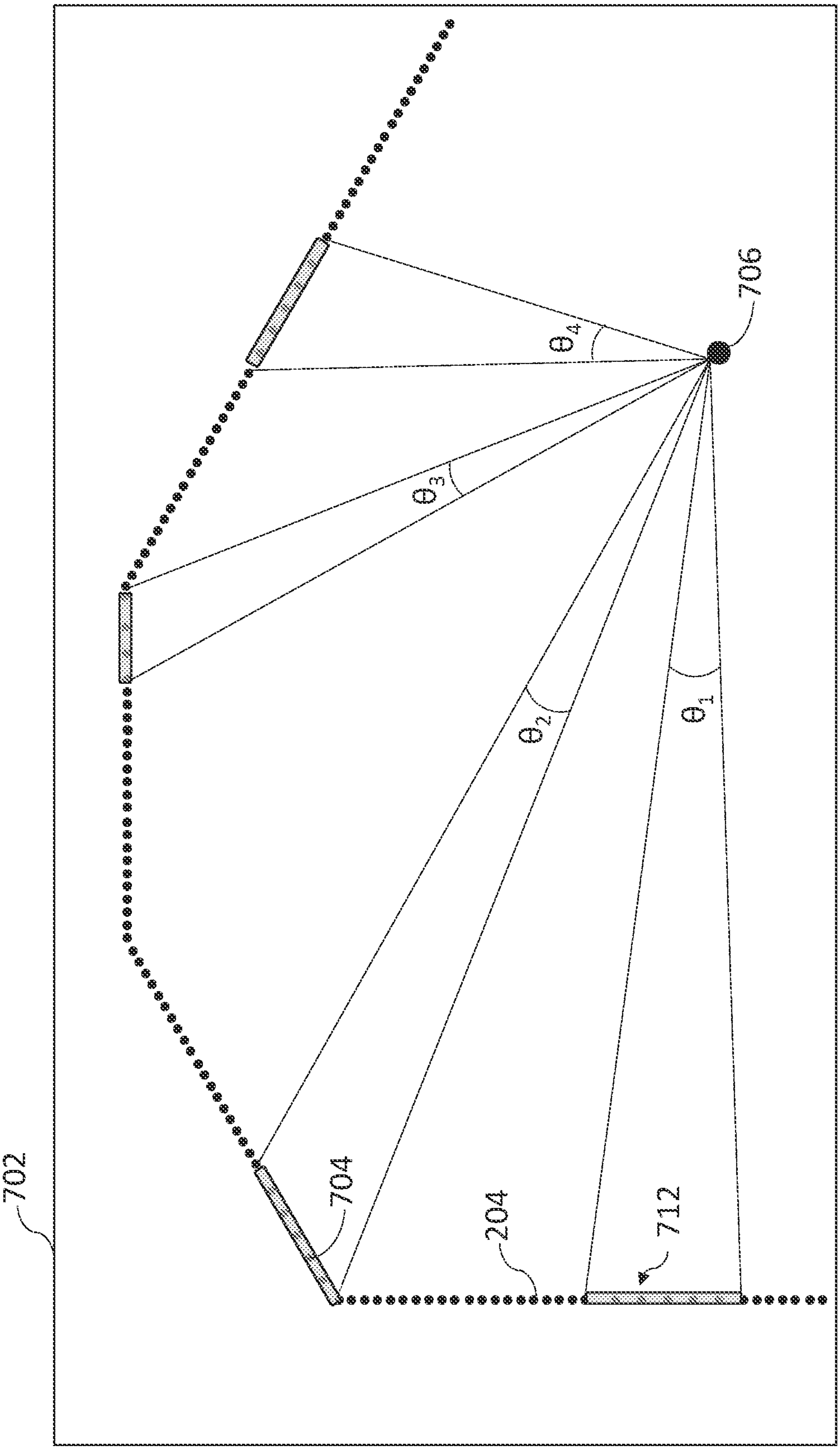

FIG. 7C

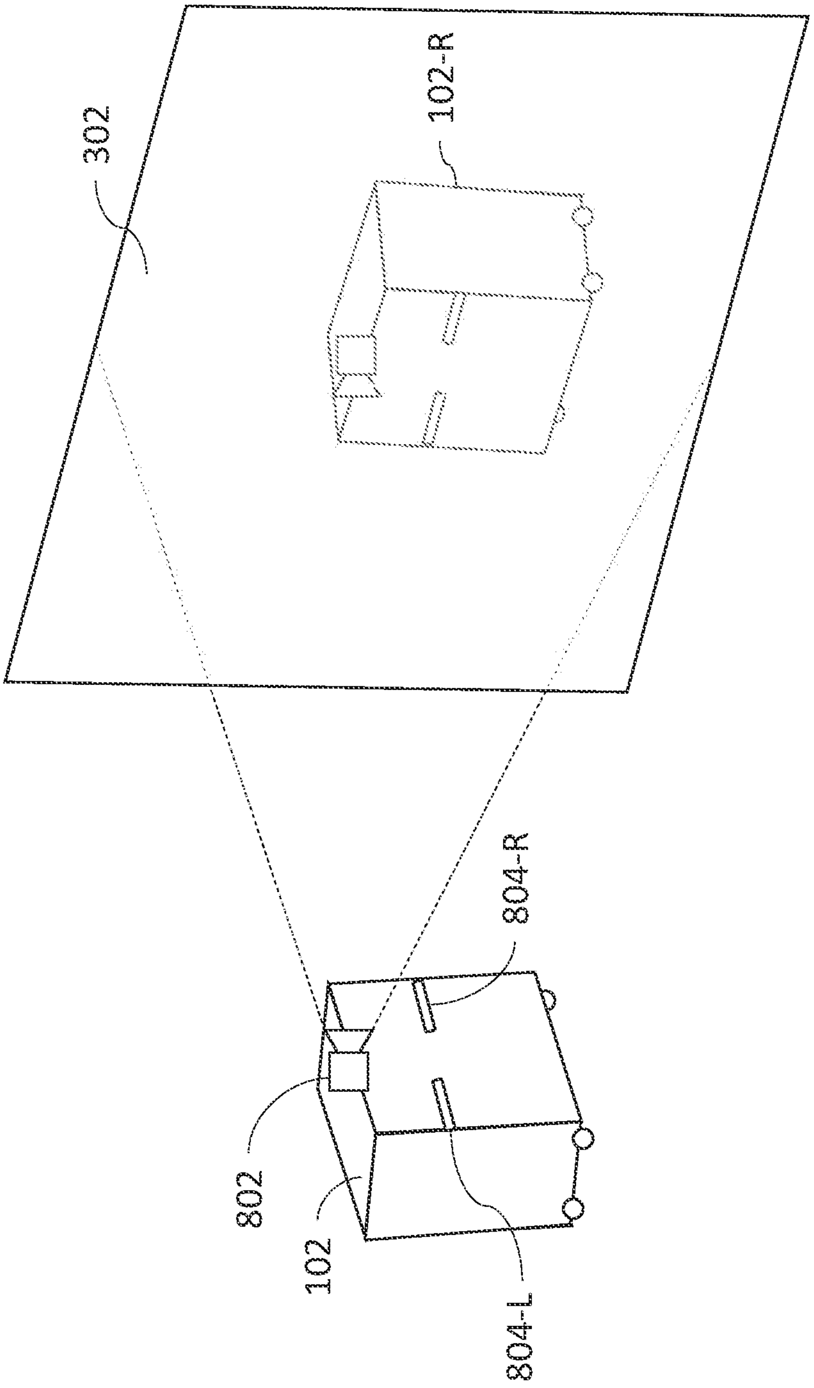

FIG. 8

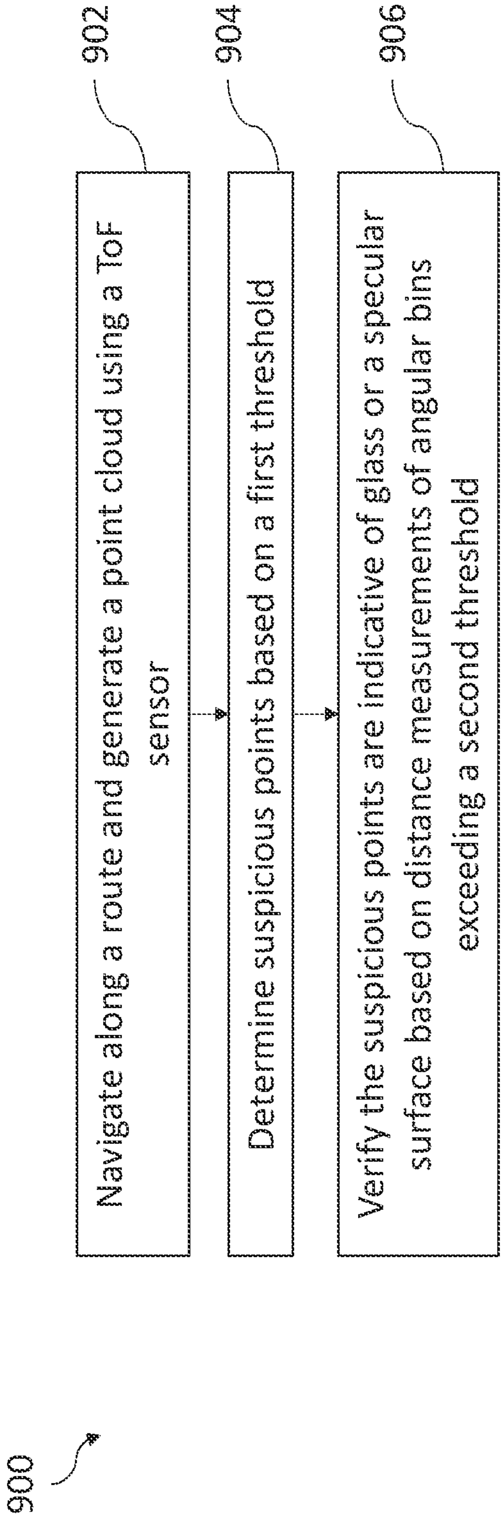
900
902
904
906
Navigate along a route and generate a point cloud using a ToF sensor
Determine suspicious points based on a first threshold
Verify the suspicious points are indicative of glass or a specular surface based on distance measurements of angular bins exceeding a second threshold

FIG. 9

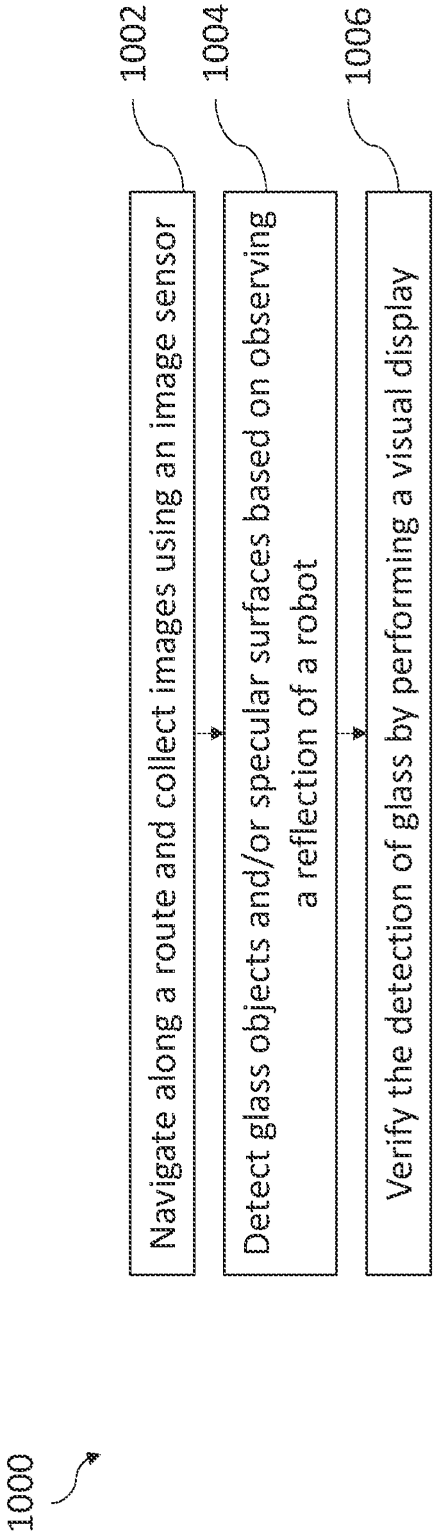
1000
1002
Navigate along a route and collect images using an image sensor
1004
Detect glass objects and/or specular surfaces based on observing a reflection of a robot
1006
Verify the detection of glass by performing a visual display

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/032696

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B25J 9/00; B25J 9/10; G05D 1/00; G05D 1/02; G05D 1/12; G05D 3/12 (2021.01)
CPC - B25J 9/1666; B25J 9/00; B25J 9/0003; B25J 9/16; B25J 9/1664; B25J 9/1694; B25J 9/1697 (2021.05)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2017/0066132 A1 (IROBOT CORPORATION) 09 March 2017 (09.03.2017) entire document	1-20
A	US 2016/0364612 A1 (GOOGLE INC.) 15 December 2016 (15.12.2016) entire document	1-20
A	SHIINA et al. "An indoor navigation algorithm incorporating representation of Quasi-Static Environmental Object and glass surface detection using LRF sensor", Proceedings of the 2017 IEEE International Conference on Robotics and Biomimetics, 08.12.2017. Retrieved on 16.07.2021. Retrieved from <URL:https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8324797> entire document	1-20
A	US 2019/0061160 A1 (BRAIN CORPORATION) 28 February 2019 (28.02.2019) entire document	1-20
A	US 2016/0188977 A1 (IROBOT CORPORATION) 30 June 2016 (30.06.2016) entire document	1-20
P, A	TIBEBU et al. "LiDAR-Based Glass Detection for Improved Occupancy Grid Mapping", Sensors, 24.03.2021. Retrieved on 15.07.2021. Retrieved from <URL: https://www.mdpi.com/1424-8220/21/7/2263#cite> entire document	1-20
A	US 2011/0208357 A1 (YAMAUCHI) 25 August 2011 (25.08.2011) entire document	1-20
P, A	ZHAO et al. "Mapping with Reflection - Detection and Utilization of Reflection in 3D Lidar Scans", IEEE International Conference on Safety, Security, and Rescue Robotics (SSRR), 27.10.2020. Retrieved on 15.07.2021. Retrieved from <URL: https://arxiv.org/pdf/1909.12483.pdf> entire document	1-20

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

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

Date of the actual completion of the international search 16 July 2021	Date of mailing of the international search report AUG 13 2021
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Harry Kim Telephone No. PCT Helpdesk: 571-272-4300