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(54) **ROBOT CONFIGURATION WITH THREE-DIMENSIONAL LIDAR**

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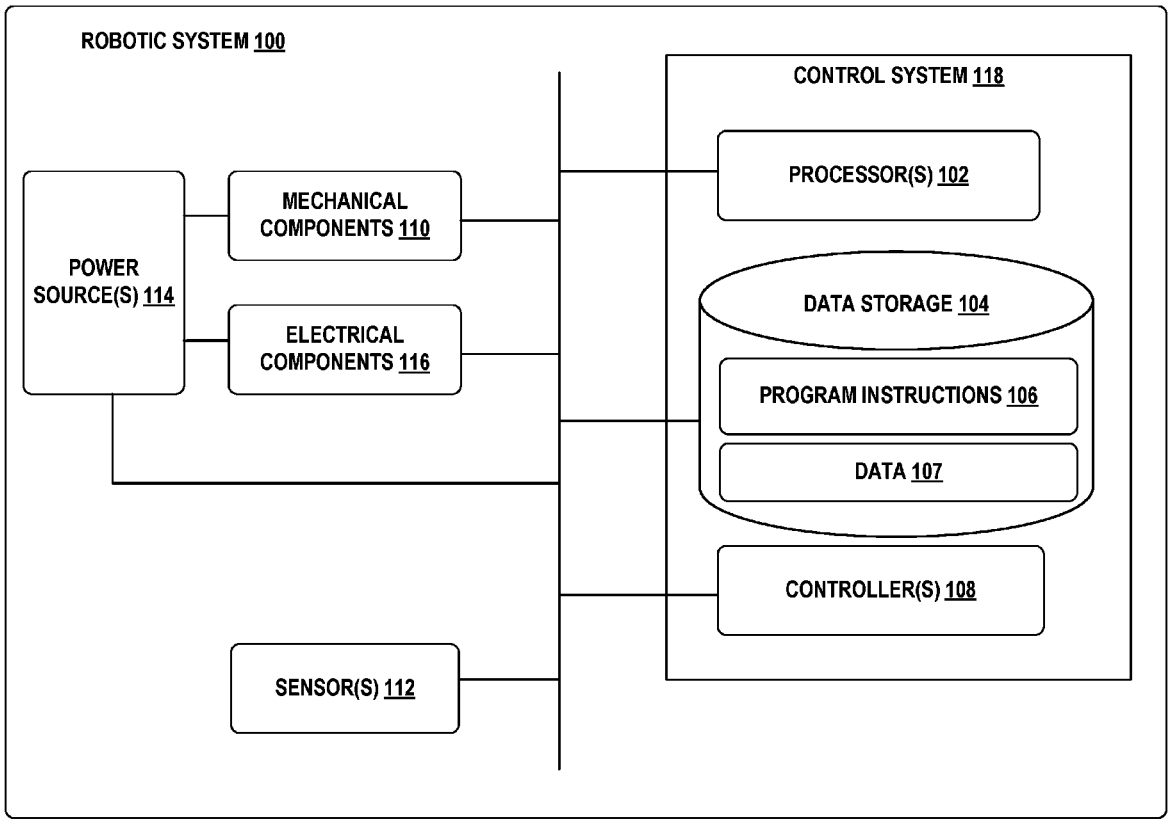
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B25J 17/02	(2006.01)
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(57) **ABSTRACT**

A mobile robotic device includes a mobile base and a mast fixed relative to the mobile base. The mast includes a carved-out portion. The mobile robotic device further includes a three-dimensional (3D) lidar sensor mounted in the carved-out portion of the mast and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device.



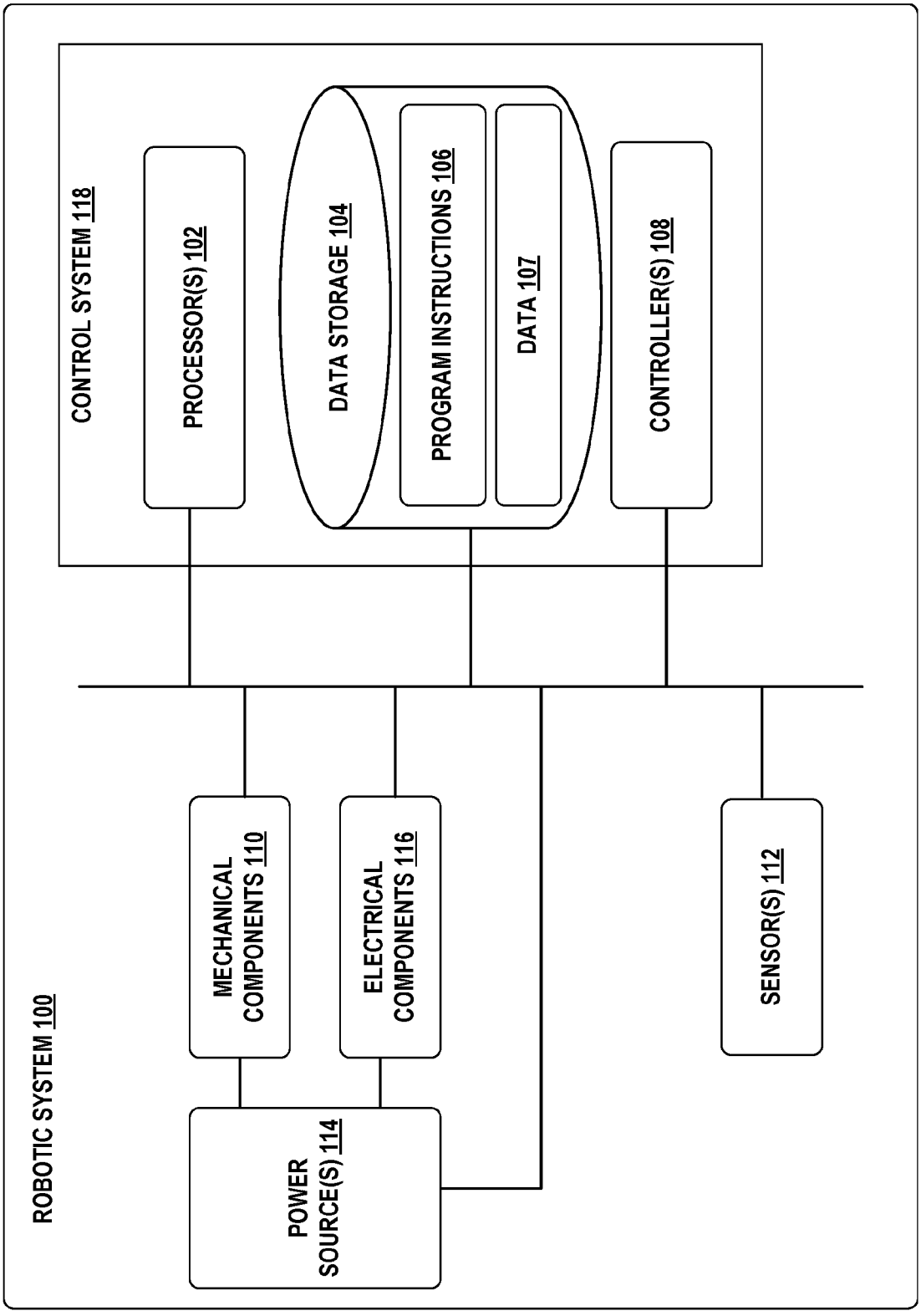

ROBOTIC SYSTEM 100
CONTROL SYSTEM 118
PROCESSOR(S) 102
DATA STORAGE 104
PROGRAM INSTRUCTIONS 106
DATA 107
CONTROLLER(S) 108
MECHANICAL COMPONENTS 110
ELECTRICAL COMPONENTS 116
SENSOR(S) 112
POWER SOURCE(S) 114

Figure 1

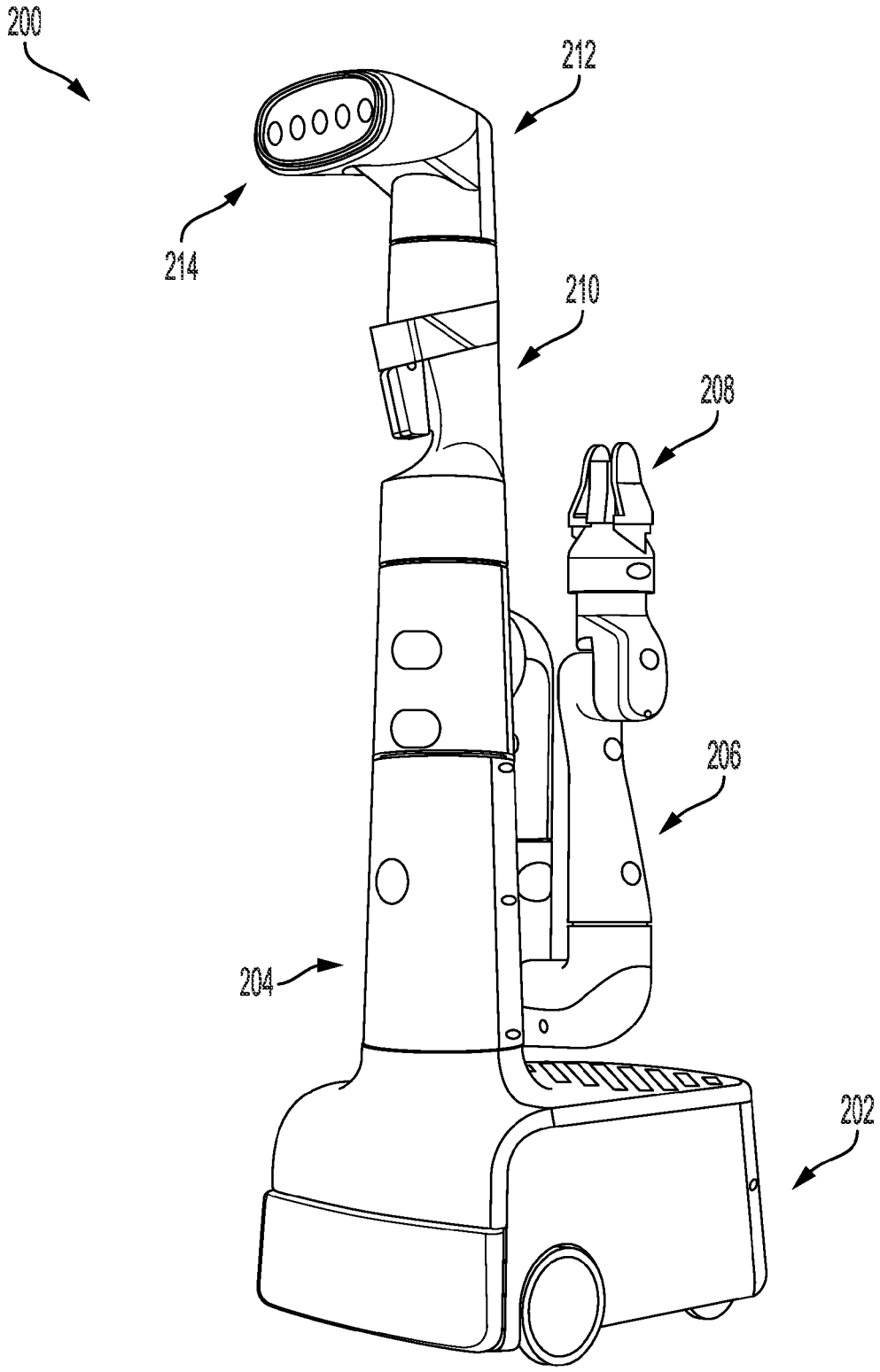


Figure 2

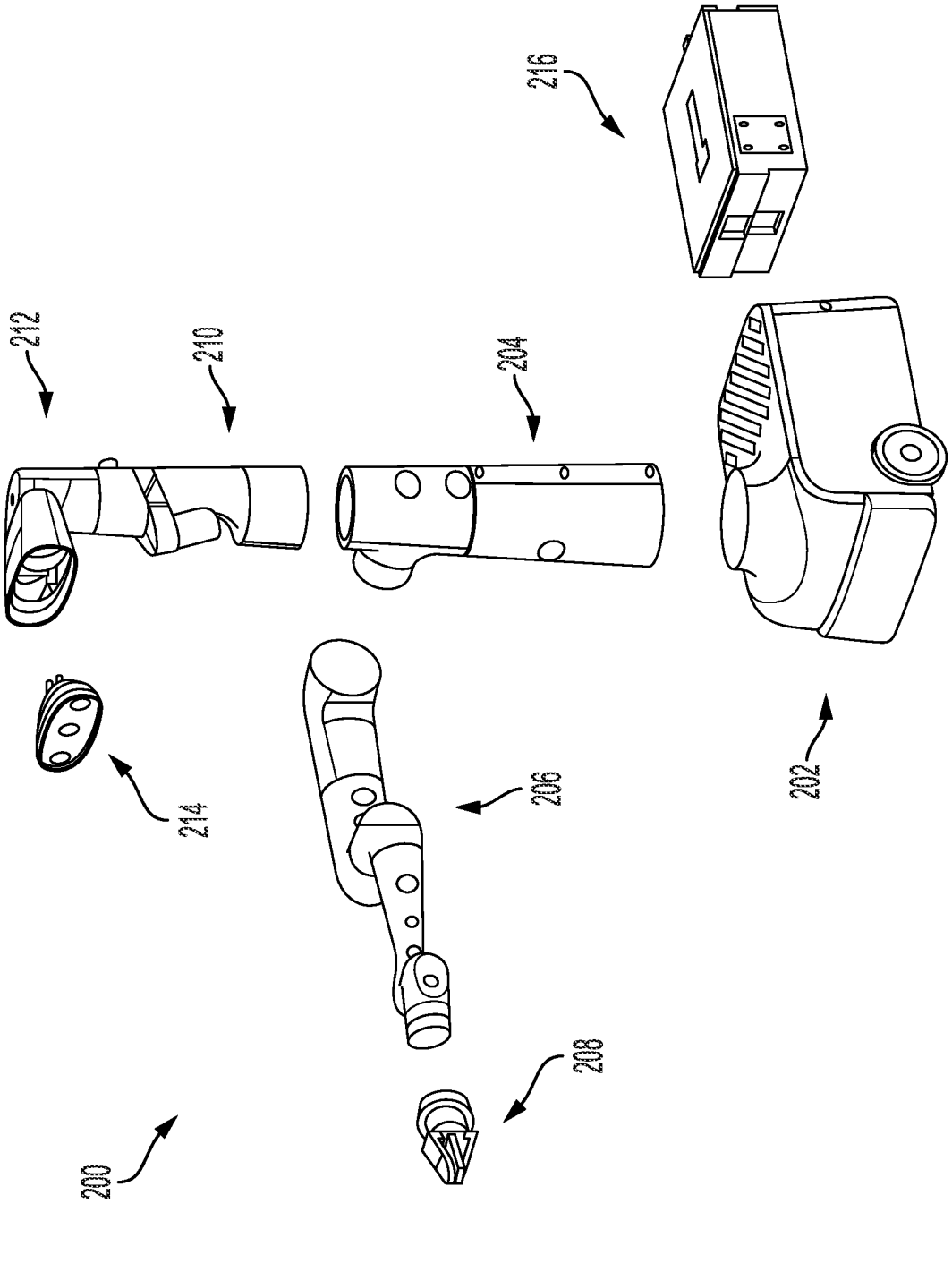


Figure 3

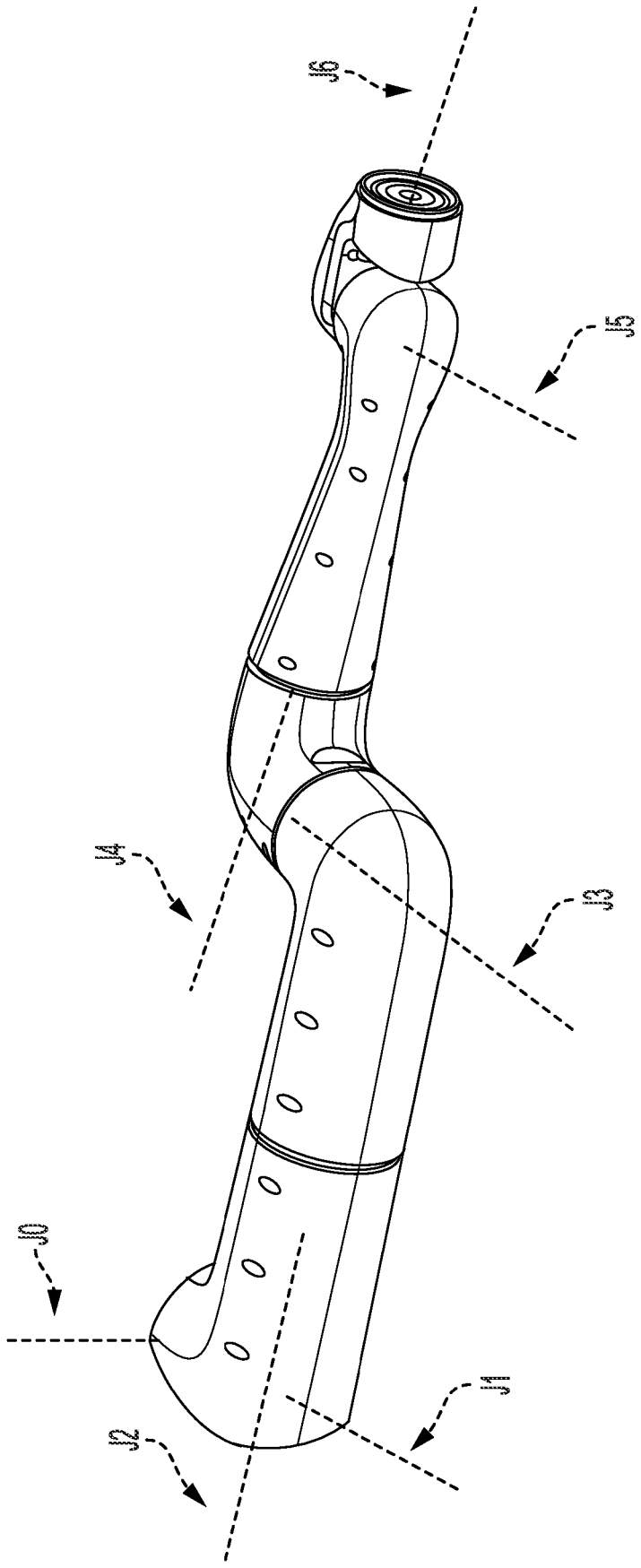


Figure 4

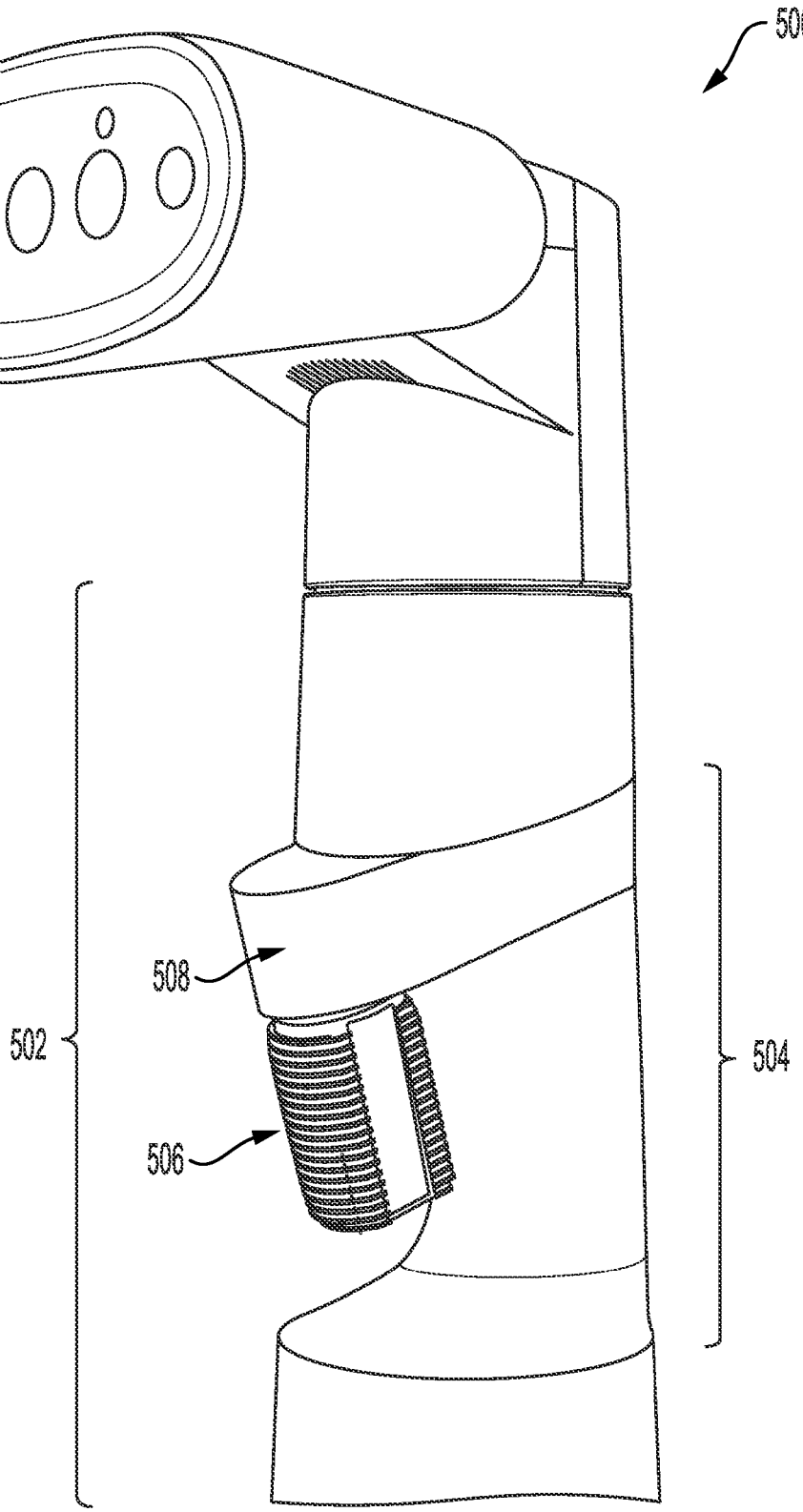


Figure 5A

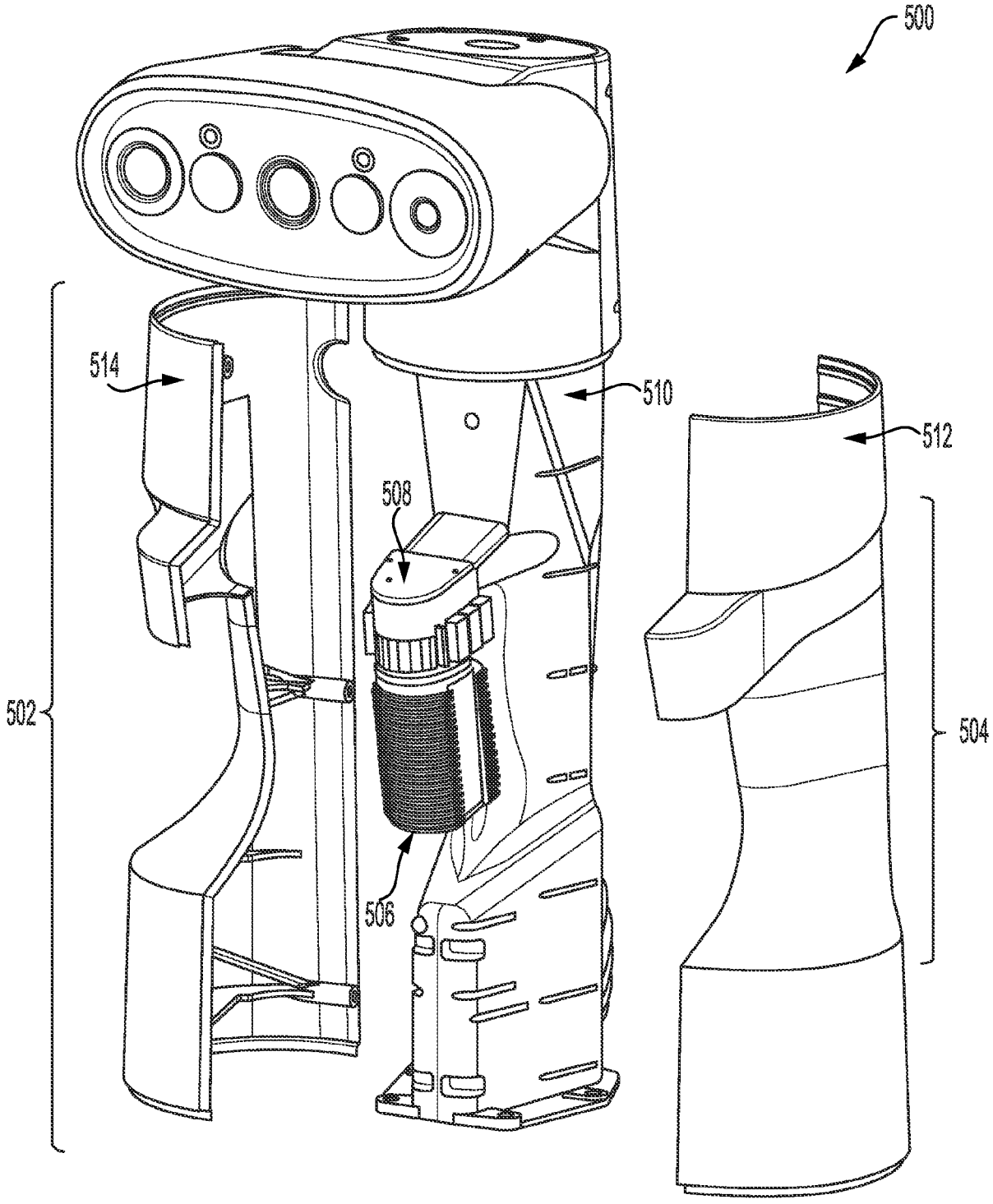


Figure 5B

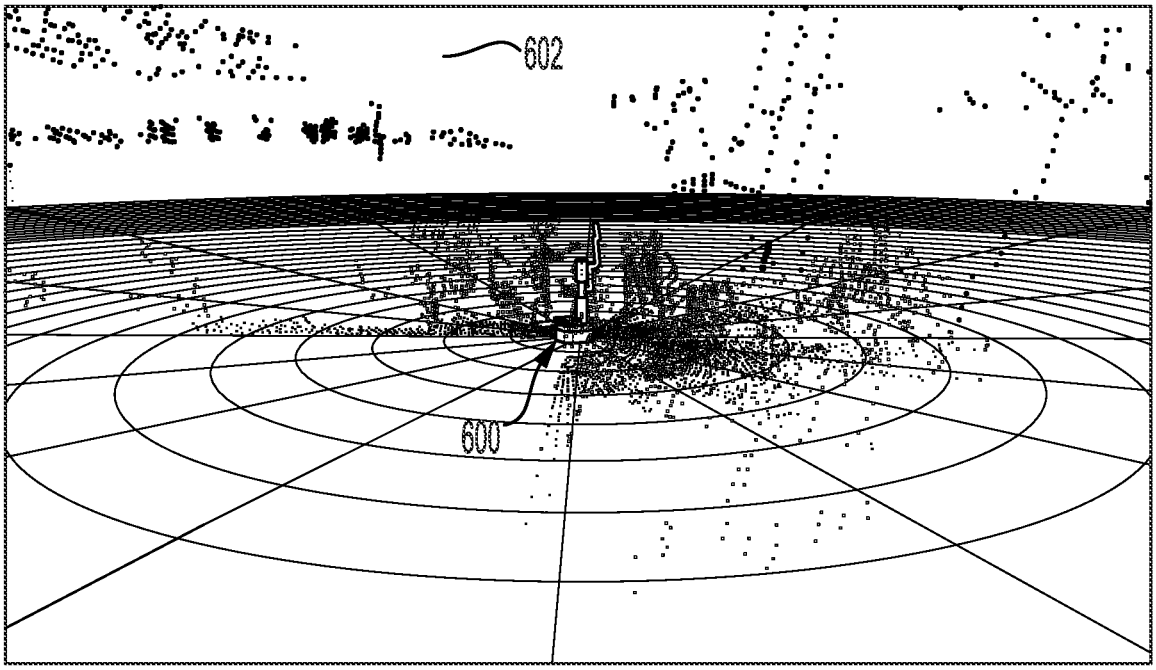


Figure 6A

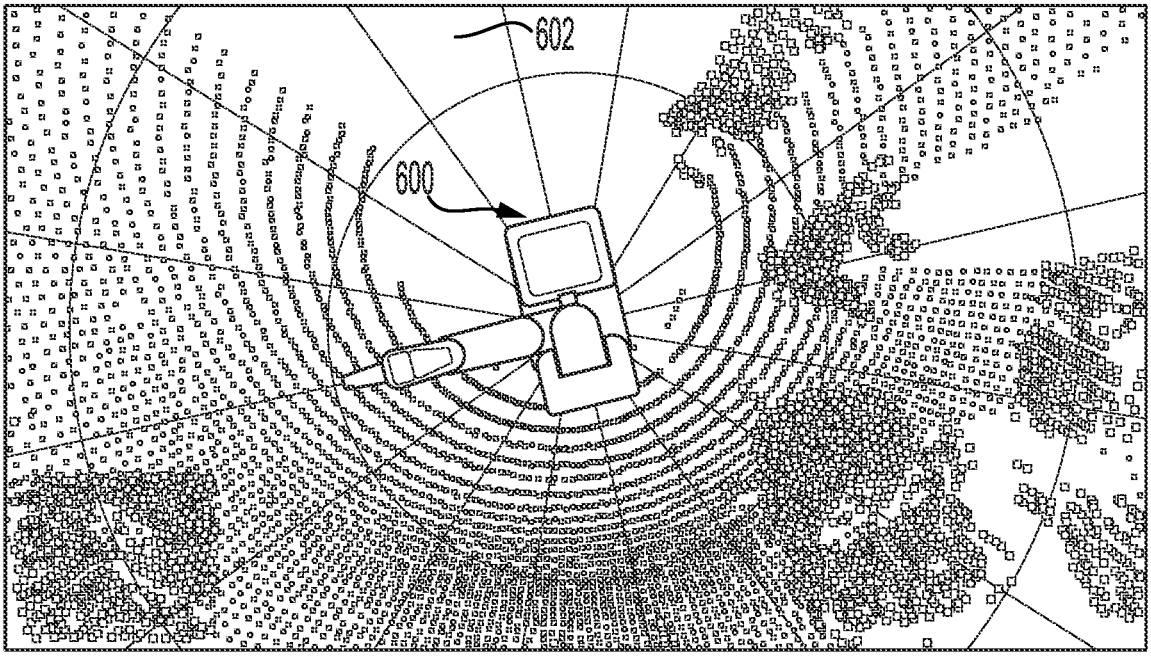


Figure 6B

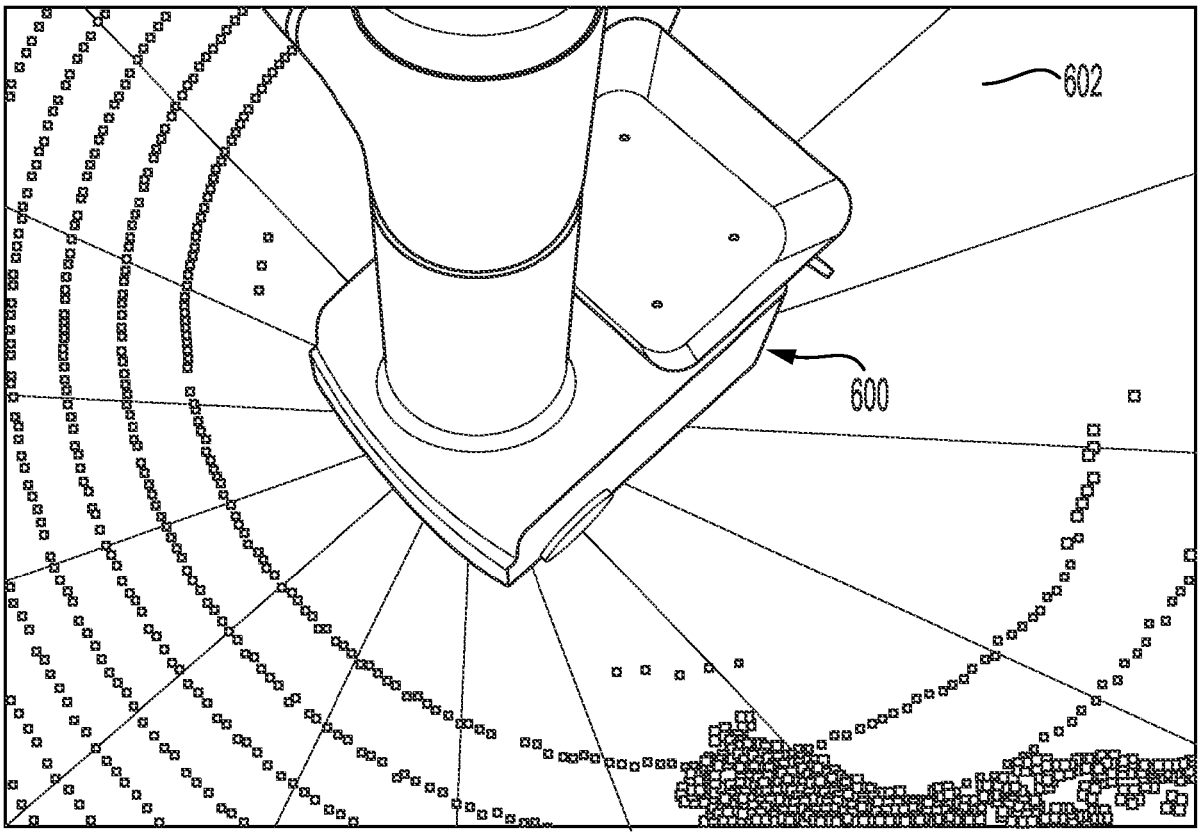


Figure 6C

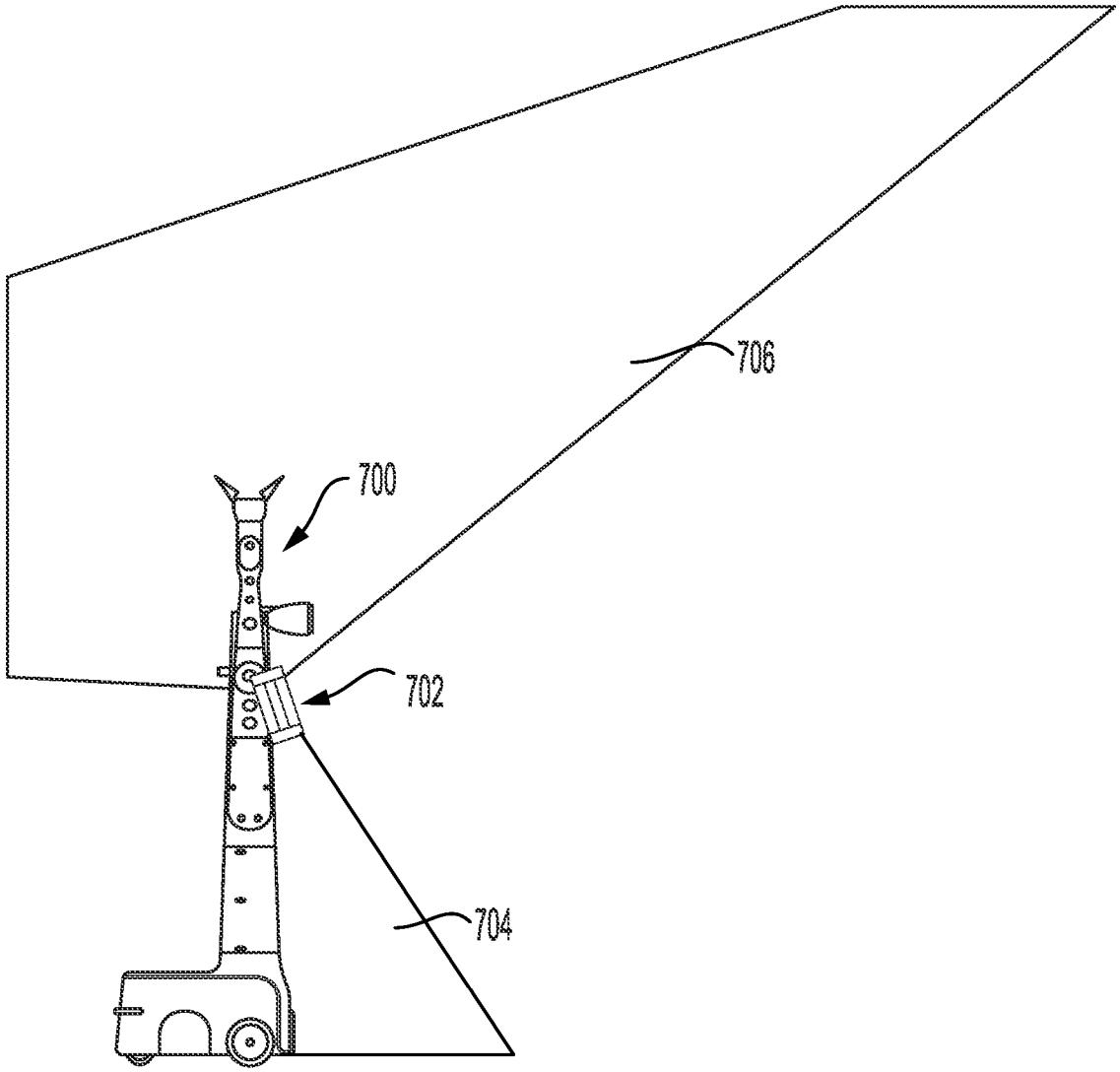


Figure 7

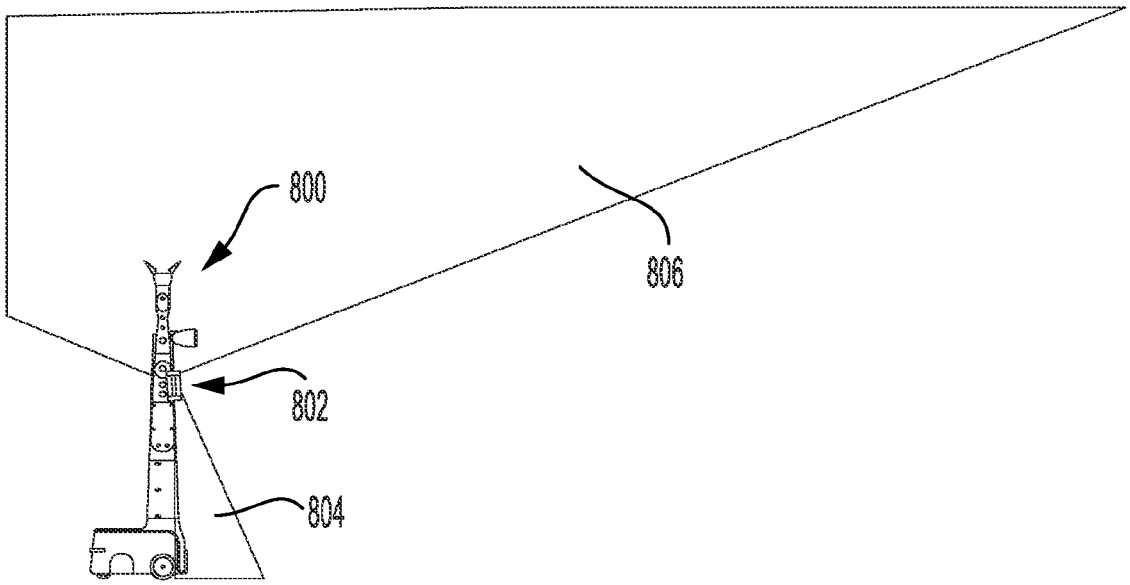


Figure 8

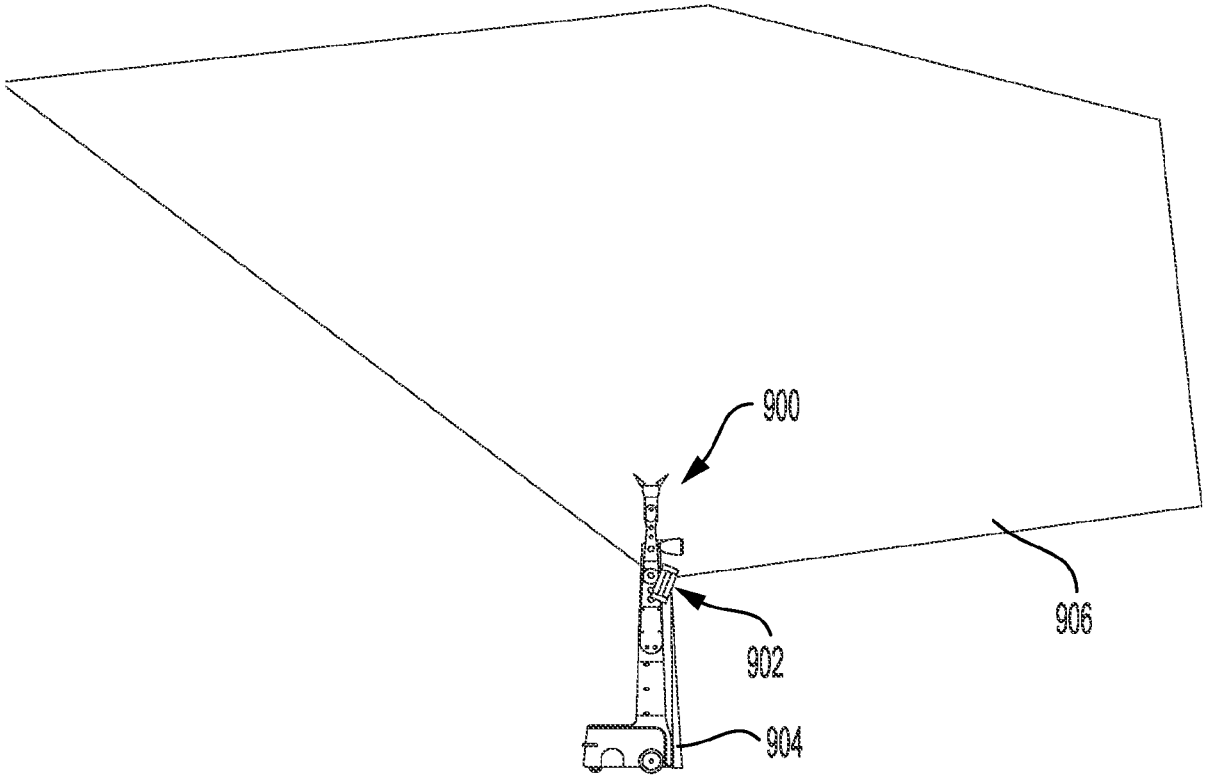


Figure 9

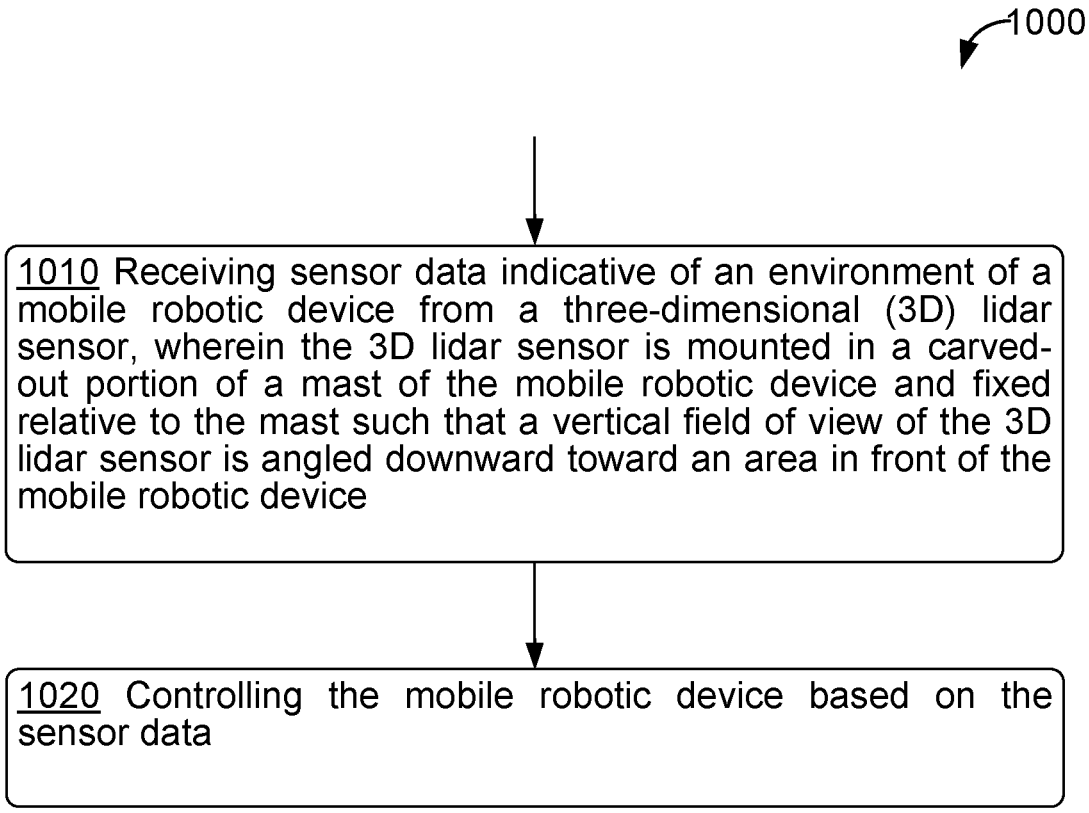

1000
1010 Receiving sensor data indicative of an environment of a mobile robotic device from a three-dimensional (3D) lidar sensor, wherein the 3D lidar sensor is mounted in a carved-out portion of a mast of the mobile robotic device and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device
1020 Controlling the mobile robotic device based on the sensor data

Figure 10

ROBOT CONFIGURATION WITH THREE-DIMENSIONAL LIDAR

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present application is a continuation of U.S. Pat. Application No. 16/528,141, filed on Jul. 31, 2019, which claims priority to U.S. Provisional Pat. Application No. 62/853,534 filed on May 28, 2019, the entire contents of which are incorporated herein by reference, as if fully set forth in this description.

BACKGROUND

[0002] As technology advances, various types of robotic devices are being created for performing a variety of functions that may assist users. Robotic devices may be used for applications involving material handling, transportation, welding, assembly, and dispensing, among others. Over time, the manner in which these robotic systems operate is becoming more intelligent, efficient, and intuitive. As robotic systems become increasingly prevalent in numerous aspects of modern life, it is desirable for robotic systems to be efficient. Therefore, a demand for efficient robotic systems has helped open up a field of innovation in actuators, movement, sensing techniques, as well as component design and assembly.

SUMMARY

[0003] An example mobile robotic device includes a three-dimensional (3D) lidar sensor mounted to a fixed mast of the robot. The position and orientation of the 3D lidar sensor and resulting field of view may be optimized so that sensor data from the 3D lidar sensor may be used for front cliff detection, obstacle detection, and robot localization.

[0004] In an embodiment, a mobile robotic device is provided. The mobile robotic device includes a mobile base. The mobile robotic device further includes a mast fixed relative to the mobile base, where the mast includes a carved-out portion. The mobile robotic device additionally includes a 3D lidar sensor mounted in the carved-out portion of the mast and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device.

[0005] In another embodiment, a method is provided. The method includes receiving sensor data indicative of an environment of a mobile robotic device from a three-dimensional 3D lidar sensor, where the 3D lidar sensor is mounted in a carved-out portion of a mast of the mobile robotic device and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device. The method further includes controlling the mobile robotic device based on the sensor data.

[0006] In an additional embodiment, a mast for a mobile robotic device is provided. The mast includes a carved-out portion. The mast further includes a 3D lidar sensor mounted in the carved-out portion of the mast and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward in a direction extending outward from the carved-out portion of the mast.

[0007] In a further embodiment, a non-transitory computer readable medium is provided which includes programming instructions executable by at least one processor to cause the at least one processor to perform functions. The functions include receiving sensor data indicative of an environment of a mobile robotic device from a three-dimensional 3D lidar sensor, where the 3D lidar sensor is mounted in a carved-out portion of a mast of the mobile robotic device and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device. The functions further include controlling the mobile robotic device based on the sensor data.

[0008] In another embodiment, a system is provided that includes means for receiving sensor data indicative of an environment of a mobile robotic device from a three-dimensional 3D lidar sensor, where the 3D lidar sensor is mounted in a carved-out portion of a mast of the mobile robotic device and fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward an area in front of the mobile robotic device. The system further includes means for controlling the mobile robotic device based on the sensor data.

[0009] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the figures and the following detailed description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** illustrates a configuration of a robotic system, in accordance with example embodiments.

[0011] FIG. **2** illustrates a mobile robot, in accordance with example embodiments.

[0012] FIG. **3** illustrates an exploded view of a mobile robot, in accordance with example embodiments.

[0013] FIG. **4** illustrates a robotic arm, in accordance with example embodiments.

[0014] FIGS. **5**A and **5**B illustrate a robot mast with a 3D lidar sensor, in accordance with example embodiments.

[0015] FIGS. **6**A, **6**B, and **6**C illustrate detections by a 3D lidar sensor, in accordance with example embodiments.

[0016] FIGS. **7**, **8**, and **9** illustrate fields of view of a 3D lidar sensor in different mounting orientations, in accordance with example embodiments.

[0017] FIG. **10** is a block diagram of a method, in accordance with example embodiments.

DETAILED DESCRIPTION

[0018] Example methods, devices, and systems are described herein. It should be understood that the words "example" and "exemplary" are used herein to mean "serving as an example, instance, or illustration." Any embodiment or feature described herein as being an "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or features unless indicated as such. Other embodiments can be utilized, and other changes can be made, without departing from the scope of the subject matter presented herein.

[0019] Thus, the example embodiments described herein are not meant to be limiting. It will be readily understood that the aspects of the present disclosure, as generally

described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations.

[0020] Throughout this description, the articles "a" or "an" are used to introduce elements of the example embodiments. Any reference to "a" or "an" refers to "at least one," and any reference to "the" refers to "the at least one," unless otherwise specified, or unless the context clearly dictates otherwise. The intent of using the conjunction "or" within a described list of at least two terms is to indicate any of the listed terms or any combination of the listed terms.

[0021] The use of ordinal numbers such as "first," "second," "third" and so on is to distinguish respective elements rather than to denote a particular order of those elements. For purpose of this description, the terms "multiple" and "a plurality of" refer to "two or more" or "more than one."

[0022] Further, unless context suggests otherwise, the features illustrated in each of the figures may be used in combination with one another. Thus, the figures should be generally viewed as component aspects of one or more overall embodiments, with the understanding that not all illustrated features are necessary for each embodiment. In the figures, similar symbols typically identify similar components, unless context dictates otherwise. Further, unless otherwise noted, figures are not drawn to scale and are used for illustrative purposes only. Moreover, the figures are representational only and not all components are shown. For example, additional structural or restraining components might not be shown.

[0023] Additionally, any enumeration of elements, blocks, or steps in this specification or the claims is for purposes of clarity. Thus, such enumeration should not be interpreted to require or imply that these elements, blocks, or steps adhere to a particular arrangement or are carried out in a particular order.

I. Overview

[0024] A mobile robotic device may use a variety of sensors to collect information about an environment to assist the robot in operating in the environment. By optimizing the selection of sensors as well as the position and orientation of selected sensors on the robot, overall cost may be reduced while allowing the robot to achieve desired sensor coverage in regions of interest. For non-industrial robots as well as certain classes of industrial robots, it may be particularly beneficial from a cost perspective to leverage an individual sensor for multiple disparate purposes.

[0025] In some examples, a robot may be equipped with a three-dimensional (3D) lidar sensor. A 3D lidar sensor measures distance to objects in the environment by illuminating the objects with laser light and measuring reflected light with one or more sensing elements. Differences in laser return times and/or wavelengths may then be used to generate 3D representations of the environment. Some 3D lidar sensors employ a rapidly spinning mirror that reflects light from a laser into the environment to generate a 3D point cloud of reflections or returns. Consequently, 3D lidar sensors may have a horizontal field of view of 360 degrees around a vertical axis of rotation, but only in one fixed angle defining a vertical field of view. In some examples, the vertical field of view may be slightly greater than 90 degrees (e.g., approximately 95 degrees). In other examples, the vertical field of view may be significantly greater than 90 degrees, equal to 90 degrees, or less than 90 degrees. In order to maximally benefit from the available field of view of a 3D lidar sensor, the 3D lidar sensor may be mounted on a robot at a carefully chosen position and orientation.

[0026] In some examples described herein, a 3D lidar sensor may be mounted in a carved-out portion of a mast of a robotic device. The mast may be fixed relative to a mobile base of the robot. The mast may be positioned between a rotatable perception housing and a rotatable arm joint as part of a stacked tower mounted near the front of the mobile base. The 3D lidar sensor may be fixed at an orientation that causes the vertical field of view of the 3D lidar sensor to angle downwards towards an area in front of the robot. In some examples, the 3D lidar may be mounted such that its vertical axis tilts forward. The position and orientation of a 3D lidar sensor may be optimized to allow the robot to leverage depth data from the 3D lidar sensor for multiple purposes, including front cliff detection, obstacle detection, and robot localization.

[0027] In regards to front cliff detection, the 3D lidar sensor may be angled so that its vertical field of view includes the ground surface directly in front of the robot (e.g., touching or with a few centimeters of a front bumper of the robot). Sensor data from the 3D lidar sensor may therefore be used to detect unexpected changes in altitude in a ground surface in front of the robot, which may indicate a cliff that should be avoided by the robot. Inclusion of points on the ground surface directly in front of the robot covers the safety case where the robot is turned on or activated while positioned directly in front of a cliff in a new environment. The vertical field of view may additionally include points on the ground surface at further distances from the robot to allow the 3D lidar sensor to detect cliffs in the distance as well. A maximum velocity for the robot may be set based on a distance at which the 3D lidar sensor can reliably detect cliffs in front of the robot. In some examples, one or more other sensors (e.g., cameras) from the robot's perception suite may provide sensor data that may be used to aid in cliff detection in addition to the 3D lidar sensor.

[0028] In regards to obstacle detection, the vertical field of view of the 3D lidar sensor may sweep up from one extreme direction that points at the ground directly in front of the robot to a second extreme direction that extends above a height parallel to the top of a perception housing of the robot (e.g., at a distance of two meters in front of the robot). More specifically, in some examples, the vertical field of view may extend from a first angle that is between 10 and 20 degrees above a horizontal vector pointing in front of the mobile robotic device to a second angle that is between 75 and 85 degrees below the horizontal vector. The 3D lidar sensor may therefore be effective for detecting obstacles in front of the robot within the height range of the robot itself.

[0029] In regards to robot localization, by angling the vertical field of view of the 3D lidar sensor downward toward an area in front of the robot, the 3D lidar sensor will also capture sensor data indicative of surfaces behind and above the robot. Moreover, the shape of the carved-out portion of the mast may prevent the mast from obstructing too much of the upper hemisphere behind the robot from the 3D lidar sensor. Depth information about the upper hemisphere of the robot's environment may be used to help determine the robot's location in the environment. The upper hemisphere

may contain mostly static structures (e.g., portions of the ceiling and/or walls) which provide good reference points for robot localization. In some examples, the robot may maintain a voxel representation of occupied voxels in the environment. Localization based on sensor data from the 3D lidar sensor may then involve voxel matching between detections and the stored voxel representation.

[0030] By choosing a position and orientation for a 3D lidar sensor that optimizes coverage of certain areas around a robot, compromises may similarly be made in accepting blind spots. For instance, by angling the 3D lidar sensor downward toward an area in front of the robot, the vertical field of view of the 3D lidar sensor may only extend slightly above horizontal. As a result, the 3D lidar sensor may not be able to detect an area in front and substantially above the robot. In some examples, this compromise may be acceptable because the robot may be unlikely to encounter obstacles hovering above the robot. If, for instance, an operator is standing in front of the robot, the 3D lidar will be sufficient to detect a portion of the operator's body even if the operator is not fully in view of the 3D lidar sensor. Furthermore, in some examples, a separate sensor such as a camera located in a perception housing of the robot may provide coverage of the blind spot above the field of view of the 3D lidar sensor in front of the robot. In addition, while the upper hemisphere in front of the robot may not be detected by the 3D lidar sensor, the upper hemisphere behind the robot may be equally sufficient for robot localization.

[0031] An additional blind spot that may result from angling the vertical field of view of the 3D lidar sensor downward toward an area in front of the robot is an area behind the robot at ground level. In some examples, a compromise solution may involve using a group of one-dimensional (1D) time-of-flight (ToF) sensors positioned on a rear side of the mobile base of the robot to detect this area. While not as precise as the 3D lidar sensor, these 1D ToF sensors may provide sufficient depth data about the area behind the robot. The robot generally may require more detailed data about the area in front where the robot is more likely to operate by, for example, picking up and manipulating objects.

[0032] In other examples, an additional 3D lidar sensor may be mounted on the back side of the mast to detect obstacles behind the robot. The additional 3D lidar sensor may be mounted in a separate or the same carved-out portion of the mast as the front 3D lidar sensor. In various examples, the additional 3D lidar sensor may be tilted upwards, downwards, or fixed in a vertical orientation. In further examples, an additional 3D lidar may instead be mounted on the mobile base (e.g., near the rear end of the mobile) to detect obstacles behind the robot. In yet other examples, one or more different types of sensors may be used to detect obstacles behind the robot as well or instead.

II. Example Robotic Systems

[0033] FIG. **1** illustrates an example configuration of a robotic system that may be used in connection with the implementations described herein. Robotic system **100** may be configured to operate autonomously, semi-autonomously, or using directions provided by user(s). Robotic system **100** may be implemented in various forms, such as a robotic arm, industrial robot, or some other arrangement. Some example implementations involve a robotic system **100** engineered to be low cost at scale and designed to support a variety of tasks. Robotic system **100** may be designed to be capable of operating around people. Robotic system **100** may also be optimized for machine learning. Throughout this description, robotic system **100** may also be referred to as a robot, robotic device, or mobile robot, among other designations.

[0034] As shown in FIG. **1**, robotic system **100** may include processor(s) **102**, data storage **104**, and controller(s) **108**, which together may be part of control system **118**. Robotic system **100** may also include sensor(s) **112**, power source(s) **114**, mechanical components **110**, and electrical components **116**. Nonetheless, robotic system **100** is shown for illustrative purposes, and may include more or fewer components. The various components of robotic system **100** may be connected in any manner, including wired or wireless connections. Further, in some examples, components of robotic system **100** may be distributed among multiple physical entities rather than a single physical entity. Other example illustrations of robotic system **100** may exist as well.

[0035] Processor(s) **102** may operate as one or more general-purpose hardware processors or special purpose hardware processors (e.g., digital signal processors, application specific integrated circuits, etc.). Processor(s) **102** may be configured to execute computer-readable program instructions **106**, and manipulate data **107**, both of which are stored in data storage **104**. Processor(s) **102** may also directly or indirectly interact with other components of robotic system **100**, such as sensor(s) **112**, power source(s) **114**, mechanical components **110**, or electrical components **116**.

[0036] Data storage **104** may be one or more types of hardware memory. For example, data storage **104** may include or take the form of one or more computer-readable storage media that can be read or accessed by processor(s) **102**. The one or more computer-readable storage media can include volatile or non-volatile storage components, such as optical, magnetic, organic, or another type of memory or storage, which can be integrated in whole or in part with processor(s) **102**. In some implementations, data storage **104** can be a single physical device. In other implementations, data storage **104** can be implemented using two or more physical devices, which may communicate with one another via wired or wireless communication. As noted previously, data storage **104** may include the computer-readable program instructions **106** and data **107**. Data **107** may be any type of data, such as configuration data, sensor data, or diagnostic data, among other possibilities.

[0037] Controller **108** may include one or more electrical circuits, units of digital logic, computer chips, or microprocessors that are configured to (perhaps among other tasks), interface between any combination of mechanical components **110**, sensor(s) **112**, power source(s) **114**, electrical components **116**, control system **118**, or a user of robotic system **100**. In some implementations, controller **108** may be a purpose-built embedded device for performing specific operations with one or more subsystems of the robotic system **100**.

[0038] Control system **118** may monitor and physically change the operating conditions of robotic system **100**. In doing so, control system **118** may serve as a link between portions of robotic system **100**, such as between mechanical components **110** or electrical components **116**. In some instances, control system **118** may serve as an interface

between robotic system **100** and another computing device. Further, control system **118** may serve as an interface between robotic system **100** and a user. In some instances, control system **118** may include various components for communicating with robotic system **100**, including a joystick, buttons, or ports, etc. The example interfaces and communications noted above may be implemented via a wired or wireless connection, or both. Control system **118** may perform other operations for robotic system **100** as well.

[0039] During operation, control system **118** may communicate with other systems of robotic system **100** via wired or wireless connections, and may further be configured to communicate with one or more users of the robot. As one possible illustration, control system **118** may receive an input (e.g., from a user or from another robot) indicating an instruction to perform a requested task, such as to pick up and move an object from one location to another location. Based on this input, control system **118** may perform operations to cause the robotic system **100** to make a sequence of movements to perform the requested task. As another illustration, a control system may receive an input indicating an instruction to move to a requested location. In response, control system **118** (perhaps with the assistance of other components or systems) may determine a direction and speed to move robotic system **100** through an environment en route to the requested location.

[0040] Operations of control system **118** may be carried out by processor(s) **102**. Alternatively, these operations may be carried out by controller(s) **108**, or a combination of processor(s) **102** and controller(s) **108**. In some implementations, control system **118** may partially or wholly reside on a device other than robotic system **100**, and therefore may at least in part control robotic system **100** remotely.

[0041] Mechanical components **110** represent hardware of robotic system **100** that may enable robotic system **100** to perform physical operations. As a few examples, robotic system **100** may include one or more physical members, such as an arm, an end effector, a head, a neck, a torso, a base, and wheels. The physical members or other parts of robotic system **100** may further include actuators arranged to move the physical members in relation to one another. Robotic system **100** may also include one or more structured bodies for housing control system **118** or other components, and may further include other types of mechanical components. The particular mechanical components **110** used in a given robot may vary based on the design of the robot, and may also be based on the operations or tasks the robot may be configured to perform.

[0042] In some examples, mechanical components **110** may include one or more removable components. Robotic system **100** may be configured to add or remove such removable components, which may involve assistance from a user or another robot. For example, robotic system **100** may be configured with removable end effectors or digits that can be replaced or changed as needed or desired. In some implementations, robotic system **100** may include one or more removable or replaceable battery units, control systems, power systems, bumpers, or sensors. Other types of removable components may be included within some implementations.

[0043] Robotic system **100** may include sensor(s) **112** arranged to sense aspects of robotic system **100**. Sensor(s) **112** may include one or more force sensors, torque sensors, velocity sensors, acceleration sensors, position sensors, proximity sensors, motion sensors, location sensors, load sensors, temperature sensors, touch sensors, depth sensors, ultrasonic range sensors, infrared sensors, object sensors, or cameras, among other possibilities. Within some examples, robotic system **100** may be configured to receive sensor data from sensors that are physically separated from the robot (e.g., sensors that are positioned on other robots or located within the environment in which the robot is operating).

[0044] Sensor(s) **112** may provide sensor data to processor(s) **102** (perhaps by way of data **107**) to allow for interaction of robotic system **100** with its environment, as well as monitoring of the operation of robotic system **100**. The sensor data may be used in evaluation of various factors for activation, movement, and deactivation of mechanical components **110** and electrical components **116** by control system **118**. For example, sensor(s) **112** may capture data corresponding to the terrain of the environment or location of nearby objects, which may assist with environment recognition and navigation.

[0045] In some examples, sensor(s) **112** may include RADAR (e.g., for long-range object detection, distance determination, or speed determination), LIDAR (e.g., for short-range object detection, distance determination, or speed determination), SONAR (e.g., for underwater object detection, distance determination, or speed determination), VICON® (e.g., for motion capture), one or more cameras (e.g., stereoscopic cameras for 3D vision), a global positioning system (GPS) transceiver, or other sensors for capturing information of the environment in which robotic system **100** is operating. Sensor(s) **112** may monitor the environment in real time, and detect obstacles, elements of the terrain, weather conditions, temperature, or other aspects of the environment. In another example, sensor(s) **112** may capture data corresponding to one or more characteristics of a target or identified object, such as a size, shape, profile, structure, or orientation of the object.

[0046] Further, robotic system **100** may include sensor(s) **112** configured to receive information indicative of the state of robotic system **100**, including sensor(s) **112** that may monitor the state of the various components of robotic system **100**. Sensor(s) **112** may measure activity of systems of robotic system **100** and receive information based on the operation of the various features of robotic system **100**, such as the operation of an extendable arm, an end effector, or other mechanical or electrical features of robotic system **100**. The data provided by sensor(s) **112** may enable control system **118** to determine errors in operation as well as monitor overall operation of components of robotic system **100**.

[0047] As an example, robotic system **100** may use force/torque sensors to measure load on various components of robotic system **100**. In some implementations, robotic system **100** may include one or more force/torque sensors on an arm or end effector to measure the load on the actuators that move one or more members of the arm or end effector. In some examples, the robotic system **100** may include a force/torque sensor at or near the wrist or end effector, but not at or near other joints of a robotic arm. In further examples, robotic system **100** may use one or more position sensors to sense the position of the actuators of the robotic system. For instance, such position sensors may sense states of extension, retraction, positioning, or rotation of the actuators on an arm or end effector.

[0048] As another example, sensor(s) **112** may include one or more velocity or acceleration sensors. For instance, sensor(s) **112** may include an inertial measurement unit (IMU). The IMU may sense velocity and acceleration in the world frame, with respect to the gravity vector. The velocity and acceleration sensed by the IMU may then be translated to that of robotic system **100** based on the location of the IMU in robotic system **100** and the kinematics of robotic system **100**.

[0049] Robotic system **100** may include other types of sensors not explicitly discussed herein. Additionally or alternatively, the robotic system may use particular sensors for purposes not enumerated herein.

[0050] Robotic system **100** may also include one or more power source(s) **114** configured to supply power to various components of robotic system **100**. Among other possible power systems, robotic system **100** may include a hydraulic system, electrical system, batteries, or other types of power systems. As an example illustration, robotic system **100** may include one or more batteries configured to provide charge to components of robotic system **100**. Some of mechanical components **110** or electrical components **116** may each connect to a different power source, may be powered by the same power source, or be powered by multiple power sources.

[0051] Any type of power source may be used to power robotic system **100**, such as electrical power or a gasoline engine. Additionally or alternatively, robotic system **100** may include a hydraulic system configured to provide power to mechanical components **110** using fluid power. Components of robotic system **100** may operate based on hydraulic fluid being transmitted throughout the hydraulic system to various hydraulic motors and hydraulic cylinders, for example. The hydraulic system may transfer hydraulic power by way of pressurized hydraulic fluid through tubes, flexible hoses, or other links between components of robotic system **100**. Power source(s) **114** may charge using various types of charging, such as wired connections to an outside power source, wireless charging, combustion, or other examples.

[0052] Electrical components **116** may include various mechanisms capable of processing, transferring, or providing electrical charge or electric signals. Among possible examples, electrical components **116** may include electrical wires, circuitry, or wireless communication transmitters and receivers to enable operations of robotic system **100**. Electrical components **116** may interwork with mechanical components **110** to enable robotic system **100** to perform various operations. Electrical components **116** may be configured to provide power from power source(s) **114** to the various mechanical components **110**, for example. Further, robotic system **100** may include electric motors. Other examples of electrical components **116** may exist as well.

[0053] Robotic system **100** may include a body, which may connect to or house appendages and components of the robotic system. As such, the structure of the body may vary within examples and may further depend on particular operations that a given robot may have been designed to perform. For example, a robot developed to carry heavy loads may have a wide body that enables placement of the load. Similarly, a robot designed to operate in tight spaces may have a relatively tall, narrow body. Further, the body or the other components may be developed using various types of materials, such as metals or plastics. Within other examples, a robot may have a body with a different structure or made of various types of materials.

[0054] The body or the other components may include or carry sensor(s) **112**. These sensors may be positioned in various locations on the robotic system **100**, such as on a body, a head, a neck, a base, a torso, an arm, or an end effector, among other examples.

[0055] Robotic system **100** may be configured to carry a load, such as a type of cargo that is to be transported. In some examples, the load may be placed by the robotic system **100** into a bin or other container attached to the robotic system **100**. The load may also represent external batteries or other types of power sources (e.g., solar panels) that the robotic system **100** may utilize. Carrying the load represents one example use for which the robotic system **100** may be configured, but the robotic system **100** may be configured to perform other operations as well.

[0056] As noted above, robotic system **100** may include various types of appendages, wheels, end effectors, gripping devices and so on. In some examples, robotic system **100** may include a mobile base with wheels, treads, or some other form of locomotion. Additionally, robotic system **100** may include a robotic arm or some other form of robotic manipulator. In the case of a mobile base, the base may be considered as one of mechanical components **110** and may include wheels, powered by one or more of actuators, which allow for mobility of a robotic arm in addition to the rest of the body.

[0057] FIG. **2** illustrates a mobile robot, in accordance with example embodiments. FIG. **3** illustrates an exploded view of the mobile robot, in accordance with example embodiments. More specifically, a robot **200** may include a mobile base **202**, a midsection **204**, an arm **206**, an end-of-arm system (EOAS) **208**, a mast **210**, a perception housing **212**, and a perception suite **214**. The robot **200** may also include a compute box **216** stored within mobile base **202**.

[0058] The mobile base **202** includes two drive wheels positioned at a front end of the robot **200** in order to provide locomotion to robot **200**. The mobile base **202** also includes additional casters (not shown) to facilitate motion of the mobile base **202** over a ground surface. The mobile base **202** may have a modular architecture that allows compute box **216** to be easily removed. Compute box **216** may serve as a removable control system for robot **200** (rather than a mechanically integrated control system). After removing external shells, the compute box **216** can be easily removed and/or replaced. The mobile base **202** may also be designed to allow for additional modularity. For example, the mobile base **202** may also be designed so that a power system, a battery, and/or external bumpers can all be easily removed and/or replaced.

[0059] The midsection **204** may be attached to the mobile base **202** at a front end of the mobile base **202**. The midsection **204** includes a mounting column which is fixed to the mobile base **202**. The midsection **204** additionally includes a rotational joint for arm **206**. More specifically, the midsection **204** includes the first two degrees of freedom for arm **206** (a shoulder yaw **J0** joint and a shoulder pitch **J1** joint). The mounting column and the shoulder yaw **J0** joint may form a portion of a stacked tower at the front of mobile base **202**. The mounting column and the shoulder yaw **J0** joint may be coaxial. The length of the mounting column of midsection **204** may be chosen to provide the arm **206** with sufficient height to perform manipulation tasks at com-

monly encountered height levels (e.g., coffee table top and counter top levels). The length of the mounting column of midsection **204** may also allow the shoulder pitch **J1** joint to rotate the arm **206** over the mobile base **202** without contacting the mobile base **202**.

[0060] The arm **206** may be a 7DOF robotic arm when connected to the midsection **204**. As noted, the first two DOFs of the arm **206** may be included in the midsection **204**. The remaining five DOFs may be included in a standalone section of the arm **206** as illustrated in FIGS. **2** and **3**. The arm **206** may be made up of plastic monolithic link structures. Inside the arm **206** may be housed standalone actuator modules, local motor drivers, and thru bore cabling.

[0061] The EOAS **208** may be an end effector at the end of arm **206**. EOAS **208** may allow the robot **200** to manipulate objects in the environment. As shown in FIGS. **2** and **3**, EOAS **208** may be a gripper, such as an underactuated pinch gripper. The gripper may include one or more contact sensors such as force/torque sensors and/or non-contact sensors such as one or more cameras to facilitate object detection and gripper control. EOAS **208** may also be a different type of gripper such as a suction gripper or a different type of tool such as a drill or a brush. EOAS **208** may also be swappable or include swappable components such as gripper digits.

[0062] The mast **210** may be a relatively long, narrow component between the shoulder yaw **J0** joint for arm **206** and perception housing **212**. The mast **210** may be part of the stacked tower at the front of mobile base **202**. The mast **210** may be fixed relative to the mobile base **202**. The mast **210** may be coaxial with the midsection **204**. The length of the mast **210** may facilitate perception by perception suite **214** of objects being manipulated by EOAS **208**. The mast **210** may have a length such that when the shoulder pitch **J1** joint is rotated vertical up, a topmost point of a bicep of the arm **206** is approximately aligned with a top of the mast **210**. The length of the mast **210** may then be sufficient to prevent a collision between the perception housing **212** and the arm **206** when the shoulder pitch **J1** joint is rotated vertical up.

[0063] As shown in FIGS. **2** and **3**, the mast **210** may include a 3D lidar sensor configured to collect depth information about the environment. The 3D lidar sensor may be coupled to a carved-out portion of the mast **210** and fixed at a downward angle. The lidar position may be optimized for localization, navigation, and for front cliff detection.

[0064] The perception housing **212** may include at least one sensor making up perception suite **214**. The perception housing **212** may be connected to a pan/tilt control to allow for reorienting of the perception housing **212** (e.g., to view objects being manipulated by EOAS **208**). The perception housing **212** may be a part of the stacked tower fixed to the mobile base **202**. A rear portion of the perception housing **212** may be coaxial with the mast **210**.

[0065] The perception suite **214** may include a suite of sensors configured to collect sensor data representative of the environment of the robot **200**. The perception suite **214** may include an infrared(IR)-assisted stereo depth sensor. The perception suite **214** may additionally include a wide-angled red-green-blue (RGB) camera for human-robot interaction and context information. The perception suite **214** may additionally include a high resolution RGB camera for object classification. A face light ring surrounding the perception suite **214** may also be included for improved human-robot interaction and scene illumination.

[0066] FIG. **4** illustrates a robotic arm, in accordance with example embodiments. The robotic arm includes 7 DOFs: a shoulder yaw **J0** joint, a shoulder pitch **J1** joint, a bicep roll **J2** joint, an elbow pitch **J3** joint, a forearm roll **J4** joint, a wrist pitch **J5** joint, and wrist roll **J6** joint. Each of the joints may be coupled to one or more actuators. The actuators coupled to the joints may be operable to cause movement of links down the kinematic chain (as well as any end effector attached to the robot arm).

[0067] The shoulder yaw **J0** joint allows the robot arm to rotate toward the front and toward the back of the robot. One beneficial use of this motion is to allow the robot to pick up an object in front of the robot and quickly place the object on the rear section of the robot (as well as the reverse motion). Another beneficial use of this motion is to quickly move the robot arm from a stowed configuration behind the robot to an active position in front of the robot (as well as the reverse motion).

[0068] The shoulder pitch **J1** joint allows the robot to lift the robot arm (e.g., so that the bicep is up to perception suite level on the robot) and to lower the robot arm (e.g., so that the bicep is just above the mobile base). This motion is beneficial to allow the robot to efficiently perform manipulation operations (e.g., top grasps and side grasps) at different target height levels in the environment. For instance, the shoulder pitch **J1** joint may be rotated to a vertical up position to allow the robot to easily manipulate objects on a table in the environment. The shoulder pitch **J1** joint may be rotated to a vertical down position to allow the robot to easily manipulate objects on a ground surface in the environment.

[0069] The bicep roll **J2** joint allows the robot to rotate the bicep to move the elbow and forearm relative to the bicep. This motion may be particularly beneficial for facilitating a clear view of the EOAS by the robot's perception suite. By rotating the bicep roll **J2** joint, the robot may kick out the elbow and forearm to improve line of sight to an object held in a gripper of the robot.

[0070] Moving down the kinematic chain, alternating pitch and roll joints (a shoulder pitch **J1** joint, a bicep roll **J2** joint, an elbow pitch **J3** joint, a forearm roll **J4** joint, a wrist pitch **J5** joint, and wrist roll **J6** joint) are provided to improve the manipulability of the robotic arm. The axes of the wrist pitch **J5** joint, the wrist roll **J6** j oint, and the forearm roll **J4** joint are intersecting for reduced arm motion to reorient objects. The wrist roll **J6** point is provided instead of two pitch joints in the wrist in order to improve object rotation.

[0071] In some examples, a robotic arm such as the one illustrated in FIG. **4** may be capable of operating in a teach mode. In particular, teach mode may be an operating mode of the robotic arm that allows a user to physically interact with and guide robotic arm towards carrying out and recording various movements. In a teaching mode, an external force is applied (e.g., by the user) to the robotic arm based on a teaching input that is intended to teach the robot regarding how to carry out a specific task. The robotic arm may thus obtain data regarding how to carry out the specific task based on instructions and guidance from the user. Such data may relate to a plurality of configurations of mechanical components, joint position data, velocity data, acceleration data, torque data, force data, and power data, among other possibilities.

[0072] During teach mode the user may grasp onto the EOAS or wrist in some examples or onto any part of robotic arm in other examples, and provide an external force by physically moving robotic arm. In particular, the user may guide the robotic arm towards grasping onto an object and then moving the object from a first location to a second location. As the user guides the robotic arm during teach mode, the robot may obtain and record data related to the movement such that the robotic arm may be configured to independently carry out the task at a future time during independent operation (e.g., when the robotic arm operates independently outside of teach mode). In some examples, external forces may also be applied by other entities in the physical workspace such as by other objects, machines, or robotic systems, among other possibilities.

[0073] FIGS. **5**A and **5**B illustrate a robot mast with a 3D lidar sensor, in accordance with example embodiments. More specifically, FIG. **5**A illustrates a robot **500** that may be the same or similar to the robot illustrated and described with respect to FIGS. **2** and **3**. The robot **500** includes a mast **502**. The mast **502** includes a carved-out portion **504**. A 3D lidar sensor **506** is mounted in the carved-out portion **504** by attaching the 3D lidar sensor **506** below mounting point **508**.

[0074] In some examples, the 3D lidar sensor **506** may be configured to have a 360 degree horizontal field of view at a fixed vertical angle. In some examples, the fixed vertical angle may be greater than 90 degrees. In other examples, the fixed vertical angle may be equal to or less than 90 degrees. The horizontal field of view may be defined around a vertical axis of rotation of one or more mirrors that reflect light projected by one or more lasers into the environment of the robot **500** to collect depth measurements. In reference to FIG. **5**A, the vertical axis may run through the center of the 3D lidar sensor **506** and through the mounting point **508**. As illustrated in FIG. **5**A, the 3D lidar sensor **506** may be tilted forward. Accordingly, the vertical field of view of the 3D lidar sensor **506** may be angled downward toward an area in front of the robot **500**. As an example, the vertical axis of the 3D lidar sensor **506** may be tilted forward 16 degrees from vertical toward the front of the robot.

[0075] The carved-out portion **504** may allow the 3D lidar sensor **506** to be mounted under mounting point **508** so that the 3D lidar sensor **506** is contained within the carved-out portion **504** when viewed from the top down. The carved-out portion **504** may be positioned between two substantially cylindrical portions of the mast **502**. Additionally, at least a portion of the 3D lidar sensor may be contained between the substantially cylindrical portions without sticking out. Advantageously, by mounting the 3D lidar sensor **506** within carved-out portion **504**, the 3D lidar sensor may be prevented from obscuring other sensors in the perception suite of the robot **500**. Additionally, the carved-out portion **504** may prevent the mast **502** from obscuring an excessive amount of the horizontal field of view of the 3D lidar sensor **506**. In some examples, at least 270 degrees of the horizontal field of view of the 3D lidar sensor is not obscured by the mast **502** based on the shape of the carved-out portion **504**. In other examples, the mast **502** and/or the carved-out portion **504** may have different shapes or dimensions.

[0076] In reference to FIG. **5**B, the mast **502** of robot **500** may include a backing component **510** to which the 3D lidar sensor **506** is mounted under mounting point **508**. The backing component **510** may house wiring to connect the 3D lidar sensor **506** to the perception housing and/or midsection of the robot **500**. The backing component **510** may also house other components, such as a printed circuit board. The mast **502** may additionally include two symmetric housing components **512** and **514**. The two symmetric housing components **512** and **514** may attach to either side of the backing component **510** such that the 3D lidar sensor **506** is external to a volume encompassed by the backing component **510** and the two symmetric housing components **512** and **514**. The backing component **510** and/or the two symmetric housing components **512** and **514** may be injection molded.

[0077] In some examples, the mast **502** illustrated in FIGS. **5**A and **5**B may be part of a stacked tower positioned at a front end of a mobile base of the robot **500**. Above the mast **502**, the stacked tower may include a perception housing that can pan and tilt. Below the mast **502**, the stacked tower may include a rotational joint of a robotic arm. The rotational joint of the robotic arm may be configured to rotate the robotic arm without rotating the mast. Accordingly, the mast may remain fixed relative to the mobile base. The stacked tower may be fixed to the mobile base so that the 3D lidar sensor **506** is oriented to detect an area near ground level in front of the mobile base. The mobile base of robot may additionally include a group of 1D ToF sensors directed toward an area near ground level behind the mobile base. Taken together, this sensor arrangement may provide an appropriate compromise for certain applications, particularly where more precise data indicative of the area in front of the robot is needed than for the area behind the robot.

[0078] FIGS. **6**A, **6**B, and **6**C illustrate detections by a 3D lidar sensor, in accordance with example embodiments. More specifically, FIG. **6**A illustrates a zoomed-out angular view, FIG. **6**B illustrates a top-down view, and FIG. **6**C illustrates a zoomed-in angular view of a point cloud of detections by a 3D lidar sensor on a robot **600** in an environment **602**. The robot **600** may be the same or similar as illustrated in FIGS. **2**, **3**, and/or **5**A and **5**B.

[0079] For purposes of illustration, the individual point detections are divided into three categories. The smaller unfilled squares represent point detections on a ground surface of the environment **602**. The larger unfilled squares represent point detections on objects in the environment **602**. The filled squares represent point detections on an upper hemisphere of the environment **602** (e.g., the ceiling and/or walls).

[0080] Regarding point detections on the ground surface, as illustrated for instance by FIG. **6**B, based on the position and orientation of the 3D lidar sensor on the robot **600**, the point detections are closest to the robot **600** directly in front of the robot **600**. On the sides of the robot **600**, the point detections are further away from the robot **600**. Furthermore, the 3D lidar sensor is unable to detect the ground surface directly behind the robot **600**. These tradeoffs allow for precise front cliff detection, which may be a priority assuming the mobile base of the robot **600** typically navigates in a forward direction. In some examples, the ground surface may not be detected for a minimal distance in front of the robot, as illustrated for instance by FIG. **6**C. This distance may be kept small enough to prevent any risk of the mobile base of the robot **600** travelling over a cliff given the positioning of front wheels on the robot **600**. There may be less need to detect cliffs behind the robot **600**. Accordingly, a

less costly alternative cliff detection solution such as downward-facing 1D ToF sensors may be used on the robot **600** to detect cliffs behind the robot **600**.

[0081] Regarding point detections on objects, as illustrated for instance by FIG. **6**B, the positioning of the 3D lidar sensor may allow the robot **600** to detect at least some portion of obstacles located in front and to the sides of the robot **600**. As illustrated for instance by FIG. **6**A, the vertical field of view of the 3D lidar sensor may only allow the robot **600** to detect points on obstacles up to a height approximately parallel to a perception housing of the robot **600**. This tradeoff may be acceptable because most objects are unlikely to float above the robot without also having portions closer to ground level that will be detected by the 3D lidar sensor on robot **600**. Furthermore, one or more other sensors (e.g., cameras) in the perception suite of the robot may also provide coverage of this area. In addition, there may be less need to detect floating objects that are outside a safety critical path that the robot may traverse. Similarly, detecting objects behind the robot **600** may also be less critical. Accordingly, a less costly alternative object detection solution such as horizontally arranged 1D ToF sensors along the rear side of the robot **600** may be used to detect obstacles behind the robot **600**.

[0082] Regarding point detections on the upper hemisphere, as illustrated for instance by FIG. **6**A, points on the ceilings and/or walls behind and to the sides of the robot **600** may be detected by the 3D lidar sensor. This sensor data may be used to help localize the robot **600** in environment **602**. For example, the localization process may involve aligning detected points with a voxel grid representation of surfaces in the environment **602**. These surfaces in the upper hemisphere may be particularly appropriate for robot localization because the surfaces are largely static and unlikely to change often over time. Additionally, portions of the upper hemisphere behind and to the sides of the robot **600** may be equally effective as points of the upper hemisphere in front of the robot **600** which may not be detected based on the position and orientation of the 3D lidar sensor on the robot **600**.

[0083] It should be understood that the point clouds represented in FIGS. **6**A, **6**B, and **6**C are for purposes of illustration. In practice, the robot **600** may include additional sensors that provide additional point cloud data or other types of sensor data. Additionally, in alternative examples, different arrangements of a 3D lidar sensor on a robot may produce different point cloud representations of an environment.

[0084] FIGS. **7**, **8**, and **9** illustrate fields of view of a 3D lidar sensor in different mounting orientations, in accordance with example embodiments. More specifically, FIGS. **7**, **8**, and **9** each represent two respective blind spots resulting from a different mounting angle of a 3D lidar sensor on a robotic device. For each figure, the vertical field of view of the 3D lidar sensor covers the area between the two blind spots in a direction directly in front of the robot. For purposes of illustration, the vertical field of view of the 3D lidar sensor is represented as being slightly greater than 90 degrees in each figure. In alternative examples, a 3D lidar sensor with a different vertical field of view may be used instead.

[0085] FIG. **7** represents a first mounting position of a 3D lidar sensor on a robotic device in which the 3D lidar sensor is angled upwards towards the front of the robot. More specifically, robot **700** may include 3D lidar sensor **702** with a vertical axis tilted backwards from vertical (e.g., by an angle of 18 degrees). A first blind spot **704** in front of robot **700** may result from this mounting angle of 3D lidar sensor **702**. Additionally, a second blind spot **706** above and behind the robot **700** may also result from this mounting angle of 3D lidar sensor **702**.

[0086] In some applications, the blind spot **704** may not allow the 3D lidar sensor **702** to be used for front cliff detection because too large an area of the ground surface in front of robot **700** is not detectable by the 3D lidar sensor **702**. At the mounting angle illustrated in FIG. **7**, the 3D lidar sensor **702** may be effective for detecting an area in front and substantially above the robot **700**. Additionally, this mounting angle may be effective for robot localization using a portion of the upper hemisphere in front of the robot **700** based on the position of the blind spot **706**. In some applications, the mounting angle illustrated in FIG. **7** may be a preferred mounting angle. However, it may not be critical for the 3D lidar sensor **702** to detect the area in front and substantially above the robot **700** in some applications.

[0087] FIG. **8** represents a second mounting orientation of a 3D lidar sensor on a robotic device in which the 3D lidar sensor is vertical. More specifically, robot **800** may include 3D lidar sensor **802** with a vertical axis that is perpendicular to the ground. A first blind spot **804** in front of robot **800** may result from this mounting angle of 3D lidar sensor **802**. Additionally, a second blind spot **806** above the robot **800** may also result from this mounting angle of 3D lidar sensor **802**. Although the 3D lidar sensor **802** is mounted vertically on robot **800**, the vertical field of view of the 3D lidar sensor **802** may be angled down toward an area in front of the robot based on the internal configuration of the 3D lidar sensor **802**.

[0088] In some applications, the mounting angle of the 3D lidar sensor **802** illustrated in FIG. **8** may be the preferred mounting angle. However, although smaller than blind spot **704**, the blind spot **804** may not allow the 3D lidar sensor **802** to be used for front cliff detection because too large an area of the ground surface in front of robot **800** is still not detectable by the 3D lidar sensor **802**. In addition, the blind spot **806** may not allow the 3D lidar sensor **802** to be used effectively for robot localization because not enough of the upper hemisphere of the environment is detected by the 3D lidar sensor **802**. At the mounting angle illustrated in FIG. **8**, less of the upper hemisphere may be detected by 3D lidar sensor **802** than by 3D lidar sensor **702** in FIG. **7**.

[0089] FIG. **9** represents a third mounting orientation of a 3D lidar sensor on a robotic device in which the 3D lidar sensor is angled downwards towards the front of the robot. More specifically, robot **900** may include 3D lidar sensor **902** with a vertical axis tilted forward from vertical (e.g., by an angle of 16 degrees). A first blind spot **904** in front of robot **900** may result from this mounting angle of 3D lidar sensor **902**. Additionally, a second blind spot **906** above and in front of the robot **900** may also result from this mounting angle of 3D lidar sensor **902**.

[0090] The blind spot **904** may be sufficiently small (or in some cases, non-existent) to allow the 3D lidar sensor **902** to be used effectively for front cliff detection. In addition, the blind spot **906** may not prevent the 3D lidar sensor **902** from being used effectively for robot localization because enough of the upper hemisphere of the environment behind and above the robot **900** is detected by the 3D lidar sensor **902**.

At the mounting angle illustrated in FIG. **9**, the upper extreme vector of the vertical field of view of the 3D lidar sensor **902** may angle slightly upwards from horizontal. For instance, the vector may cross a height parallel to the top of the robot's perception housing at a distance of two meters from the robot. In some examples, this vertical field of view may also provide sufficient coverage for obstacle detection in front of the robot **900**, in addition to front cliff detection and robot localization. Accordingly, the mounting angle of the 3D lidar sensor **902** illustrated in FIG. **9** may be the preferred mounting angle in some applications.

[0091] FIG. **10** is a block diagram of a method, in accordance with example embodiments. In some examples, method **1000** of FIG. **10** may be carried out by a control system, such as control system **118** of robotic system **100**. In further examples, method **1000** may be carried by one or more processors, such as processor(s) **102**, executing program instructions, such as program instructions **106**, stored in a data storage, such as data storage **104**. Execution of method **1000** may involve any of the robots and/or robot components illustrated and described with respect to FIGS. **1-4**, **5A-5B**, **6A-6C**, **7-9**, and/or **10**. Other robotic devices may also be used in the performance of method **1000**. In further examples, some or all of the blocks of method **1000** may be performed by a control system remote from the robotic device. In yet further examples, different blocks of method **1000** may be performed by different control systems, located on and/or remote from a robotic device.

[0092] At block **1010**, method **1000** includes receiving sensor data indicative of an environment of a mobile robotic device from a 3D lidar sensor. The 3D lidar sensor may be mounted in a carved-out portion of a mast of the mobile robotic device. The 3D lidar sensor may be fixed relative to the mast such that a vertical field of view of the 3D lidar sensor is angled downward toward and area in front of the robot. In some examples, a vertical axis of the 3D lidar sensor may be tilted forward relative to vertical toward the front of the robot. The sensor data may be point cloud data.

[0093] In some examples, the 3D lidar sensor is angled such that the vertical field of view of the 3D lidar sensor includes a ground surface directly in front of the mobile robotic device. For instance, the vertical field of view of the 3D lidar sensor may include a portion of or directly align with a front bumper of a mobile base of the robotic device.

[0094] In some examples, the vertical field of view of the 3D lidar sensor is greater than ninety degrees, and the 3D lidar sensor is angled such that an upper bound of the vertical field of view of the 3D lidar sensor extends from the 3D lidar sensor at an angle above a horizontal vector pointing in front of the mobile robotic device.

[0095] In some examples, the vertical field of view of the 3D lidar sensor extends from a first angle that is between 10 and 20 degrees above a horizontal vector pointing in front of the mobile robotic device to a second angle that is between 75 and 85 degrees below the horizontal vector.

[0096] At block **1020**, the method **1000** further includes controlling the mobile robotic device based on the sensor data. Controlling the mobile robotic device may involve using the sensor data from the 3D lidar sensor for any combination of front cliff detection, obstacle detection, and robot localization.

[0097] More specifically, the sensor data may be indicative of a ground surface directly in front of a mobile base of the mobile robotic device, and the method **1000** may further involve detecting a cliff in front of the mobile robotic device. Controlling the mobile robotic device may then involve navigating the mobile base of the mobile robotic device based on the detected cliff. For instance, the mobile robotic device may be controlled to stop or change direction to avoid going over the detected cliff.

[0098] The sensor data from the 3D lidar sensor may also be indicative of one or more obstacles in front or to the side of the mobile robotic device. In that case, controlling the mobile robotic device based on the sensor data may involve avoiding contact with the one or more obstacles. For instance, the mobile robotic device may be controlled to stop or change direction to avoid hitting a detected obstacle.

[0099] The sensor data from the 3D lidar sensor may also be indicative of one or more surfaces above and behind the mobile robotic device, and the method **1000** may further involve determining a location of the mobile robotic device relative to the one or more surfaces. Determining the location of the mobile robotic device may involve aligning the sensor data with a voxel grid representation of an environment of the mobile robotic device. The mobile robotic device may then be controlled based on the determined location of the mobile robotic device relative to the one or more surfaces.

[0100] Examples described herein involve optimizing the position and orientation of a 3D lidar sensor on a mobile robotic device to leverage sensor data from the 3D lidar sensor for front cliff detection, obstacle detection, and robot localization. The sensor data may be used for other purposes as well. Furthermore, the position and orientation of the 3D lidar sensor may be adjusted to optimize the sensor data collected for different applications.

III. Conclusion

[0101] The present disclosure is not to be limited in terms of the particular embodiments described in this application, which are intended as illustrations of various aspects. Many modifications and variations can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent methods and apparatuses within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. Such modifications and variations are intended to fall within the scope of the appended claims.

[0102] The above detailed description describes various features and functions of the disclosed systems, devices, and methods with reference to the accompanying figures. In the figures, similar symbols typically identify similar components, unless context dictates otherwise. The example embodiments described herein and in the figures are not meant to be limiting. Other embodiments can be utilized, and other changes can be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

[0103] A block that represents a processing of information may correspond to circuitry that can be configured to perform the specific logical functions of a herein-described method or technique. Alternatively or additionally, a block that represents a processing of information may correspond to a module, a segment, or a portion of program code (including related data). The program code may include one or more instructions executable by a processor for implementing specific logical functions or actions in the method or technique. The program code or related data may be stored on any type of computer readable medium such as a storage device including a disk or hard drive or other storage medium.

[0104] The computer readable medium may also include non-transitory computer readable media such as computer-readable media that stores data for short periods of time like register memory, processor cache, and random access memory (RAM). The computer readable media may also include non-transitory computer readable media that stores program code or data for longer periods of time, such as secondary or persistent long term storage, like read only memory (ROM), optical or magnetic disks, compact-disc read only memory (CD-ROM), for example. The computer readable media may also be any other volatile or non-volatile storage systems. A computer readable medium may be considered a computer readable storage medium, for example, or a tangible storage device.

[0105] Moreover, a block that represents one or more information transmissions may correspond to information transmissions between software or hardware modules in the same physical device. However, other information transmissions may be between software modules or hardware modules in different physical devices.

[0106] The particular arrangements shown in the figures should not be viewed as limiting. It should be understood that other embodiments can include more or less of each element shown in a given figure. Further, some of the illustrated elements can be combined or omitted. Yet further, an example embodiment can include elements that are not illustrated in the figures.

[0107] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims.

What is claimed is:

1. A mobile robotic device, comprising:

a mobile base;

a mast fixed relative to the mobile base, wherein the mast includes a carved-out portion; and

a three-dimensional (3D) lidar sensor mounted in the carved-out portion of the mast, wherein the shape of the carved-out portion of the mast and the position and orientation of the 3D lidar sensor enables the 3D lidar sensor to capture sensor data indicative of one or more surfaces above and behind the mobile robotic device.

2. The mobile robotic device of claim **1**, wherein the 3D lidar sensor is fixed in a vertical orientation.

3. The mobile robotic device of claim **1**, wherein the 3D lidar sensor is tilted forward away from the mobile robotic device.

4. The mobile robotic device of claim **1**, wherein the 3D lidar sensor is tilted backwards towards the mobile robotic device.

5. The mobile robotic device of claim **1**, wherein a vertical field of view of the 3D lidar sensor extends from a first angle that is between 10 and 20 degrees above a horizontal vector pointing in front of the mobile robotic device to a second angle that is between 75 and 85 degrees below the horizontal vector.

6. The mobile robotic device of claim **1**, further comprising a control system configured to detect a cliff in front of the mobile base of the mobile robotic device based on sensor data from the 3D lidar sensor.

7. The mobile robotic device of claim **1**, further comprising a control system configured to detect one or more obstacles in front or to a side of the mobile robotic device based on sensor data from the 3D lidar sensor.

8. The mobile robotic device of claim **1**, further comprising a control system configured to determine a location of the mobile robotic device based on the sensor data indicative of one or more surfaces above and behind the mobile robotic device.

9. The mobile robotic device of claim **8**, wherein the control system is configured to determine the location of the mobile robotic device by aligning the sensor data with a voxel grid representation of an environment of the mobile robotic device.

10. The mobile robotic device of claim **1**, wherein the 3D lidar sensor is configured to have a 360 degree horizontal field of view, and wherein at least 270 degrees of the horizontal field of view of the 3D lidar sensor is not obscured by the mast based on a shape of the carved-out portion of the mast.

11. The mobile robotic device of claim **1**, wherein the mast comprises an overhanging mounting point for the 3D lidar sensor, wherein the 3D lidar sensor is mounted underneath the overhanging mounting point to fit within the carved-out portion of the mast.

12. The mobile robotic device of claim **1**, wherein the mast comprises:

a backing component to which the 3D lidar sensor is mounted; and

two symmetric housing components that attach to either side of the backing component such that the 3D lidar sensor is external to a volume encompassed by the backing component and the two symmetric housing components.

13. The mobile robotic device of claim **1**, wherein the mast is part of a stacked tower positioned at a front end of the mobile robotic device.

14. The mobile robotic device of claim **13**, wherein the stacked tower includes a rotational joint of a robotic arm below the mast, wherein the rotational joint is configured to rotate the robotic arm without rotating the mast.

15. The mobile robotic device of claim **1**, wherein the mobile base includes a plurality of one degree of freedom (1DOF) sensors directed toward an area behind the mobile robotic device.

16. A method comprising:

receiving sensor data indicative of an environment of a mobile robotic device from a three-dimensional (3D) lidar sensor, wherein the 3D lidar sensor is mounted in a carved-out portion of a mast of the mobile robotic device, wherein the shape of the carved-out portion of the mast and the position and orientation of the 3D lidar sensor enables the 3D lidar sensor to capture sensor data

indicative of one or more surfaces above and behind the mobile robotic device; and

controlling the mobile robotic device based on the sensor data.

17. The method of claim **16**, wherein the sensor data is indicative of a ground surface directly in front of a mobile base of the mobile robotic device, wherein the method further comprises:

detecting a cliff in front of the mobile robotic device, wherein controlling the mobile robotic device comprises navigating the mobile base of the mobile robotic device based on the detected cliff.

18. The method of claim **16**, wherein the sensor data is indicative of one or more obstacles in front or to a side of the mobile robotic device, wherein controlling the mobile robotic device comprises avoiding contact with the one or more obstacles.

19. The method of claim **16**, wherein the method further comprises:

determining a location of the mobile robotic device relative to the one or more surfaces above and behind the mobile robotic device, wherein controlling the mobile robotic device is performed based on the determined location of the mobile robotic device relative to the one or more surfaces.

20. A mast for a mobile robotic device, comprising:

a carved-out portion; and

a three-dimensional (3D) lidar sensor mounted in the carved-out portion of the mast, wherein the shape of the carved-out portion of the mast and the position and orientation of the 3D lidar sensor enables the 3D lidar sensor to capture sensor data indicative of one or more surfaces above and behind the mobile robotic device.

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