US 20220194245A1

(19) **United States**

(12) **Patent Application Publication**

Gonano et al.

(10) **Pub. No.: US 2022/0194245 A1**

(43) **Pub. Date: Jun. 23, 2022**

(54) **ROBUST DOCKING OF ROBOTS WITH IMPERFECT SENSING**

(71) Applicant: **Boston Dynamics, Inc.**, Waltham, MA (US)

(72) Inventors: **Dion Gonano**, Somerville, MA (US); **Eric Cary Whitman**, Arlington, MA (US); **Christopher Stathis**, Bedford, MA (US); **Matthew Jacob Klingensmith**, Somerville, MA (US)

(73) Assignee: **Boston Dynamics, Inc.**, Waltham, MA (US)

(21) Appl. No.: **17/644,696**

(22) Filed: **Dec. 16, 2021**

Related U.S. Application Data

(60) Provisional application No. 63/129,390, filed on Dec. 22, 2020.

Publication Classification

(51) **Int. Cl.**

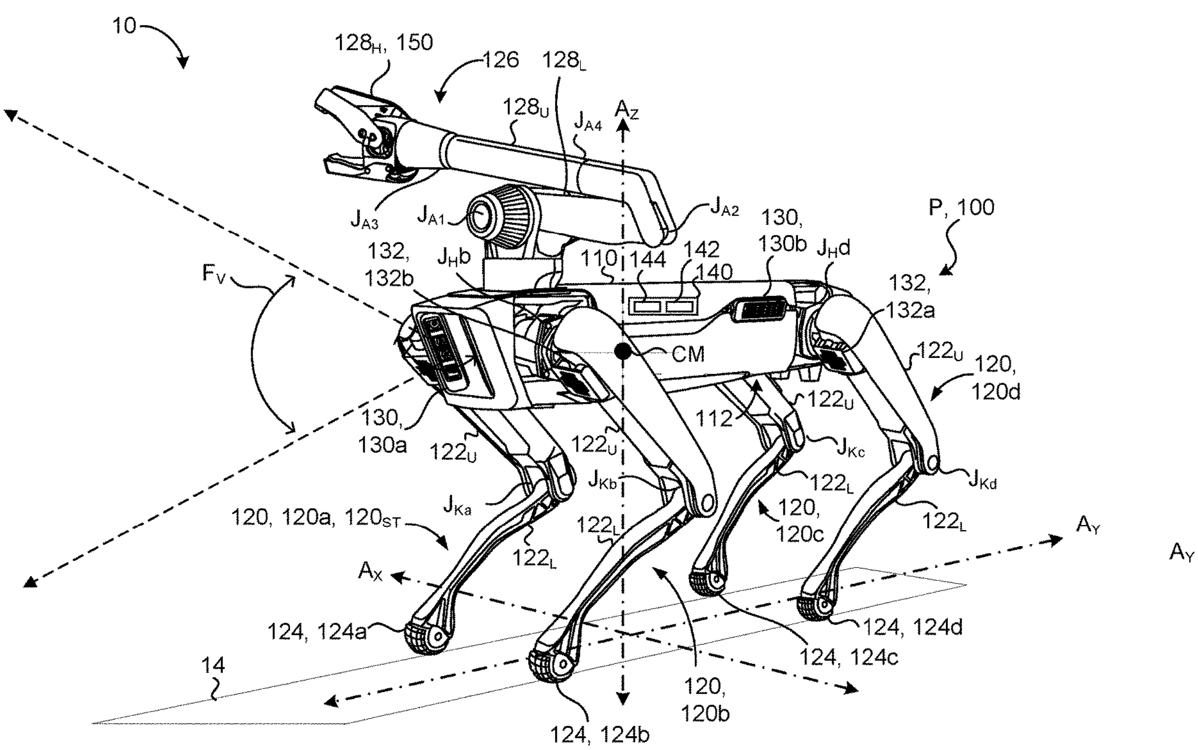
B60L 53/36	(2006.01)
G05D 1/02	(2006.01)
B62D 57/02	(2006.01)
B60L 53/16	(2006.01)

(52) **U.S. Cl.**

CPC ***B60L 53/36*** (2019.02); ***G05D 1/0225*** (2013.01); ***B60L 53/16*** (2019.02); ***G05D 1/0274*** (2013.01); ***B62D 57/02*** (2013.01); ***G05D 1/0214*** (2013.01)

(57) **ABSTRACT**

A computer-implemented method when executed by data processing hardware of a legged robot causes the data processing hardware to perform operations including receiving sensor data corresponding to an area including at least a portion of a docking station. The operations include determining an estimated pose for the docking station based on an initial pose of the legged robot relative to the docking station. The operations include identifying one or more docking station features from the received sensor data. The operations include matching the one or more identified docking station features to one or more known docking station features. The operations include adjusting the estimated pose for the docking station to a corrected pose for the docking station based on an orientation of the one or more identified docking station features that match the one or more known docking station features.



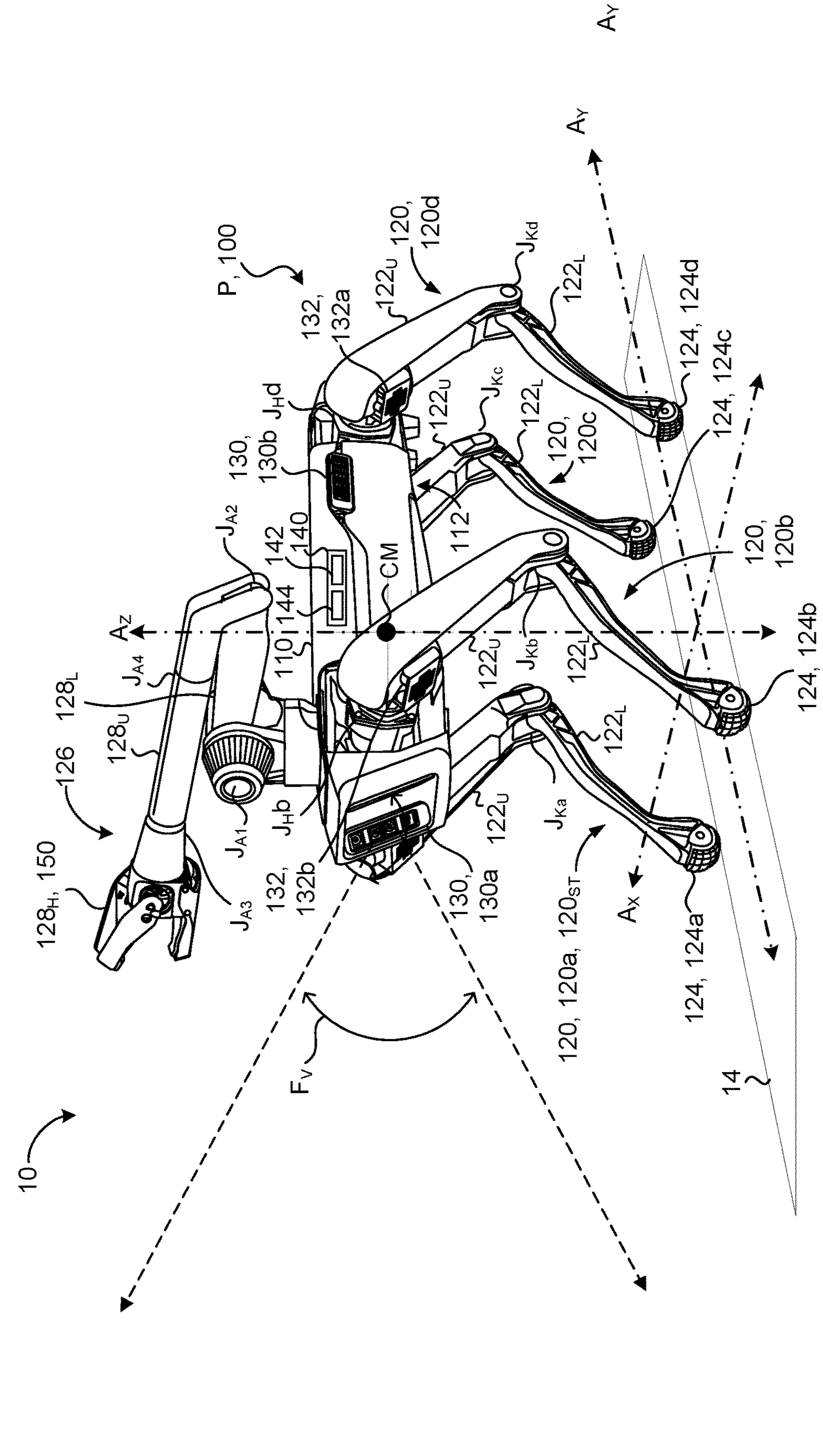

10
P, 100
126
128H, 150
128U
128L
JA1
JA2
JA3
JA4
110
112
140
142
144
CM
130, 130a
130, 130b
132, 132a
132, 132b
JHb
JHd
120, 120a, 120ST
120, 120b
120, 120c
120, 120d
122U
122L
JKa
JKb
JKc
JKd
124, 124a
124, 124b
124, 124c
124, 124d
AX
AY
AZ
FV
14

FIG. 1A

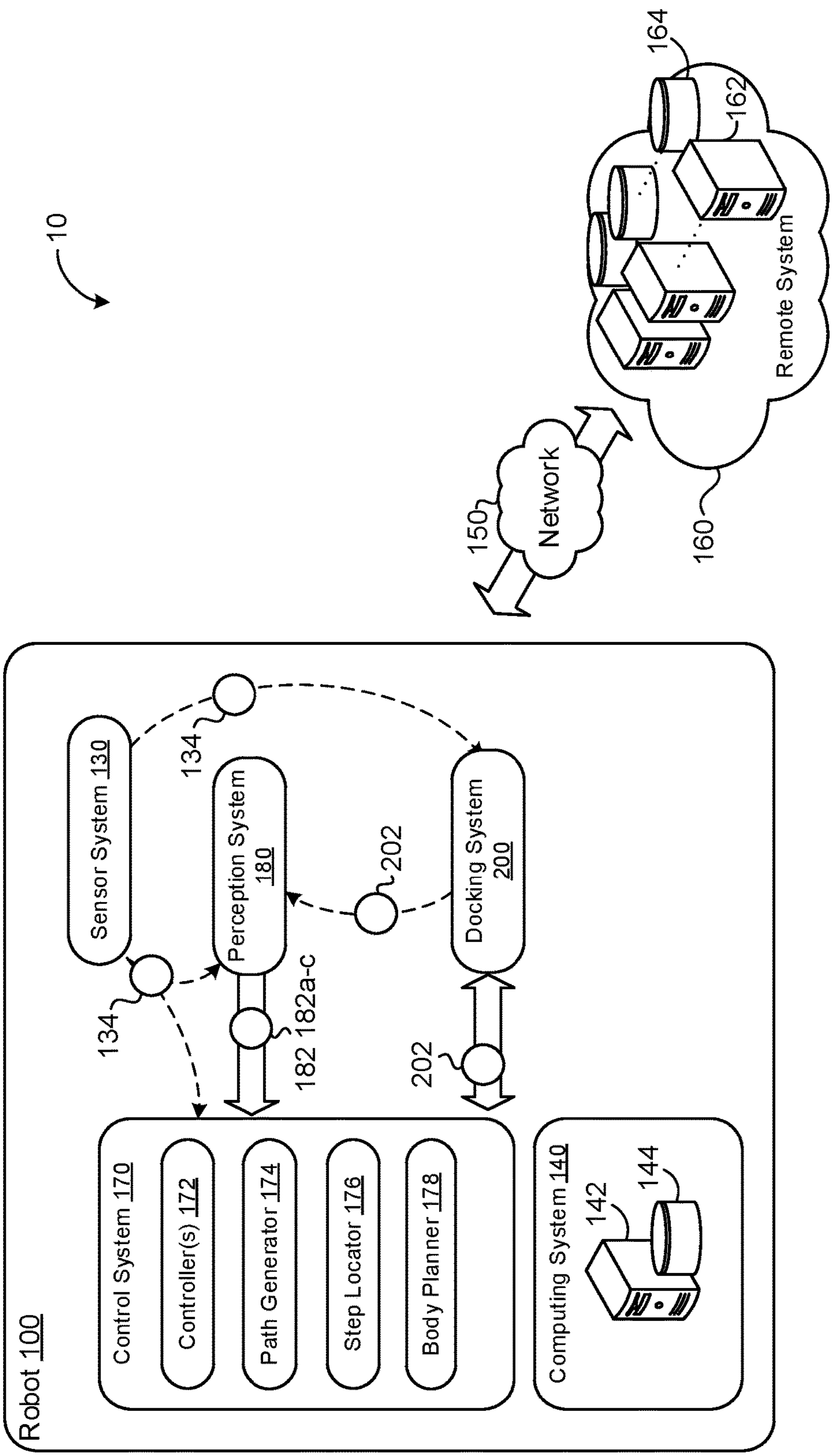

10
164
162
Remote System
Network
150
160
Robot 100
Sensor System 130
134
Perception System 180
202
Docking System 200
134
182 182a-c
202
Control System 170
Controller(s) 172
Path Generator 174
Step Locator 176
Body Planner 178
Computing System 140
142
144

FIG. 1B

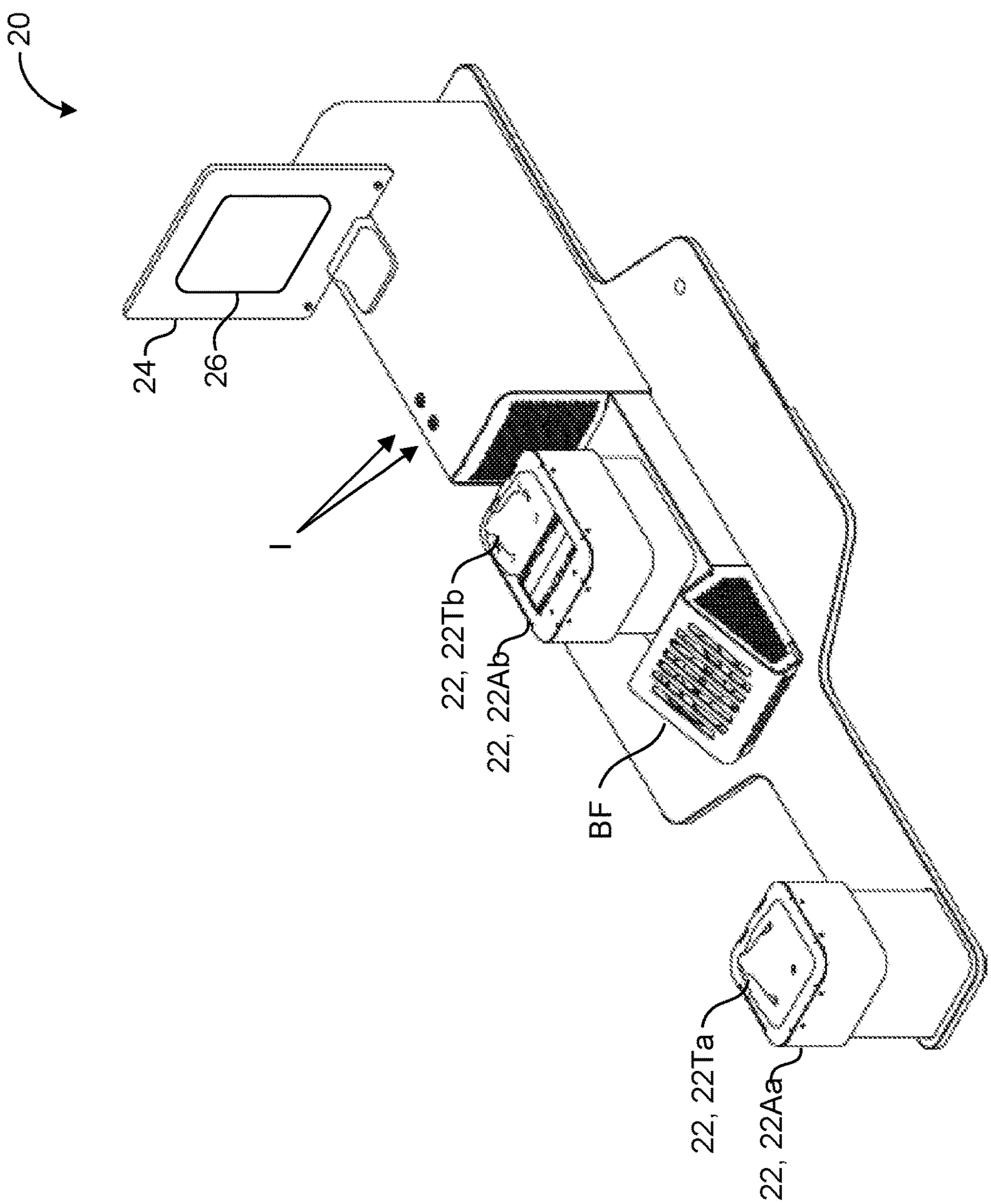


FIG. 1C

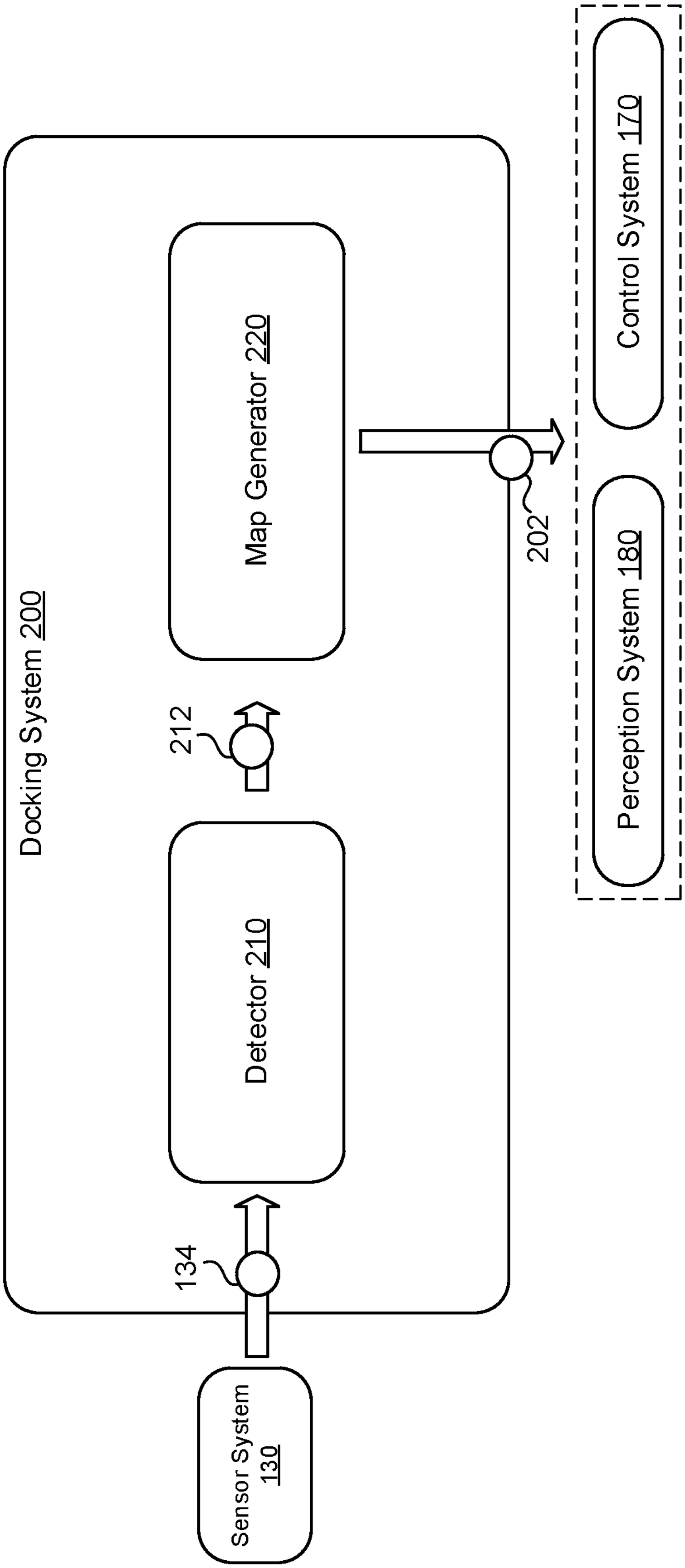

Docking System 200
Detector 210
Map Generator 220
212
134
202
Sensor System 130
Perception System 180
Control System 170

FIG. 2A

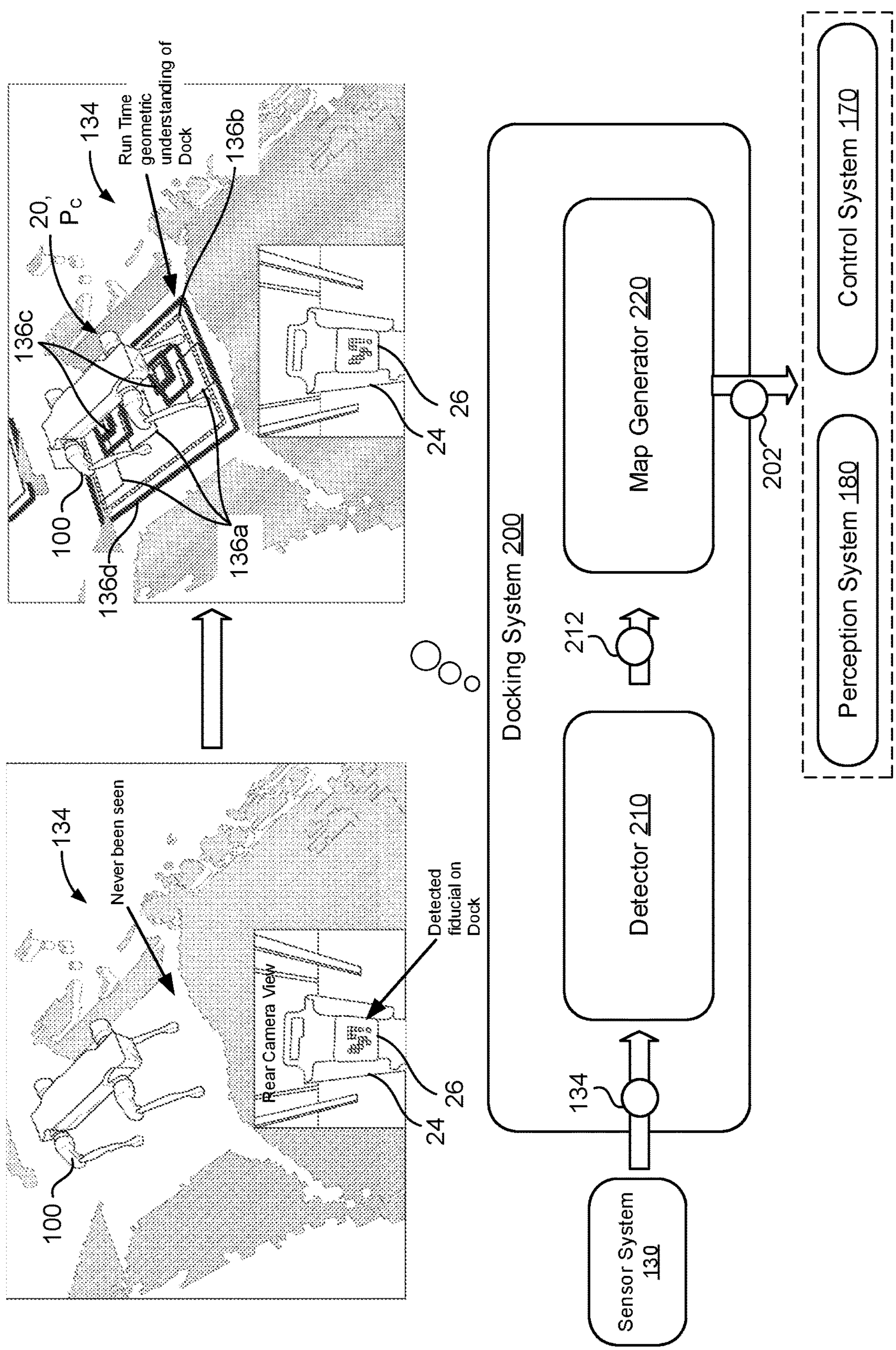

134
Never been seen
Rear Camera View
Detected fiducial on Dock
100
24
26
134
Run Time geometric understanding of Dock
20, P_C
136c
136b
136a
136d
100
24
26
Sensor System 130
134
Docking System 200
Detector 210
212
Map Generator 220
202
Perception System 180
Control System 170

FIG. 2B

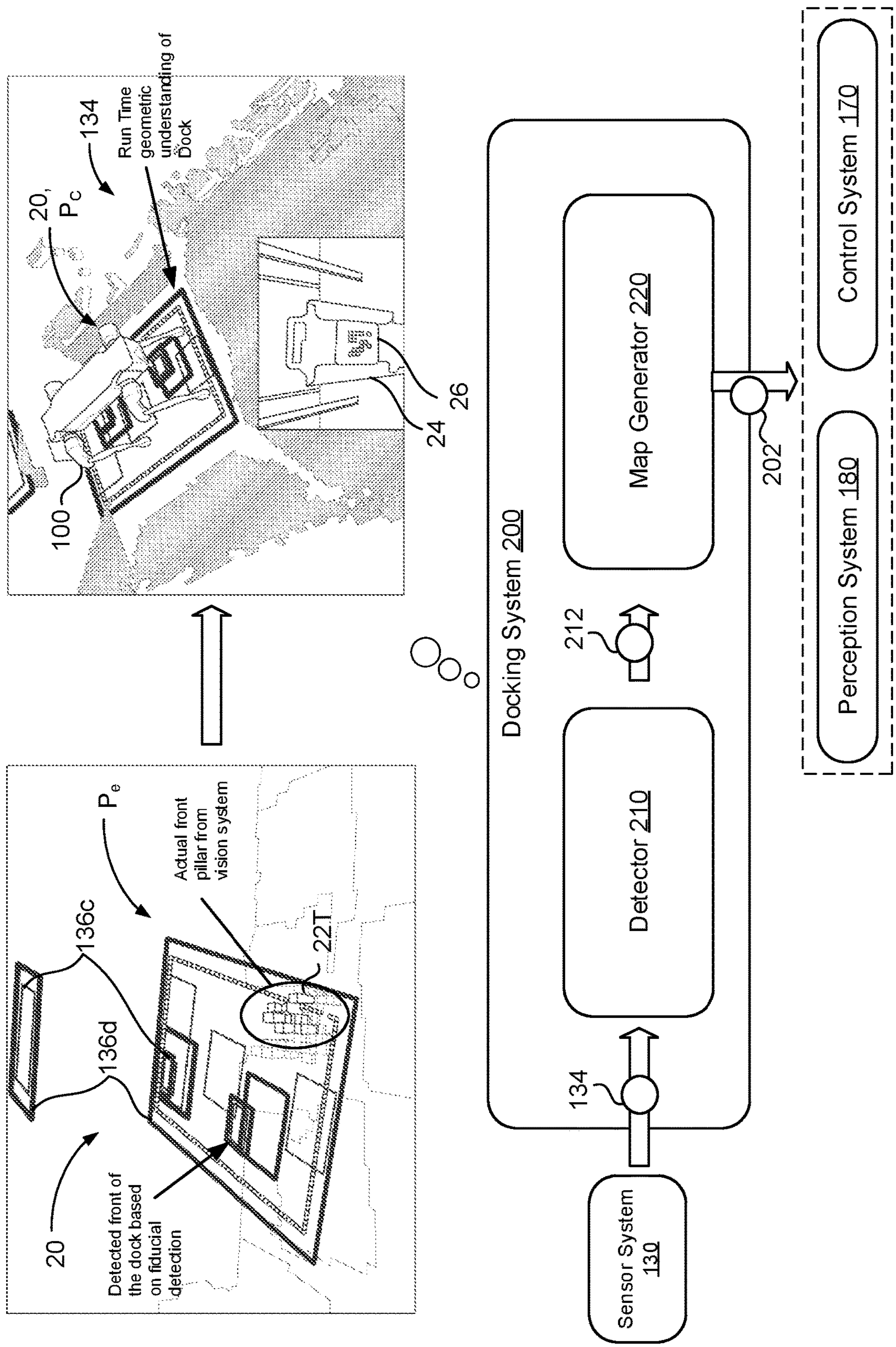

20
Detected front of the dock based on fiducial detection
136d
136c
P_e
Actual front pillar from vision system
22T
100
20, P_C
134
Run Time geometric understanding of Dock
24
26
Sensor System 130
134
Docking System 200
Detector 210
212
Map Generator 220
202
Perception System 180
Control System 170

FIG. 2C

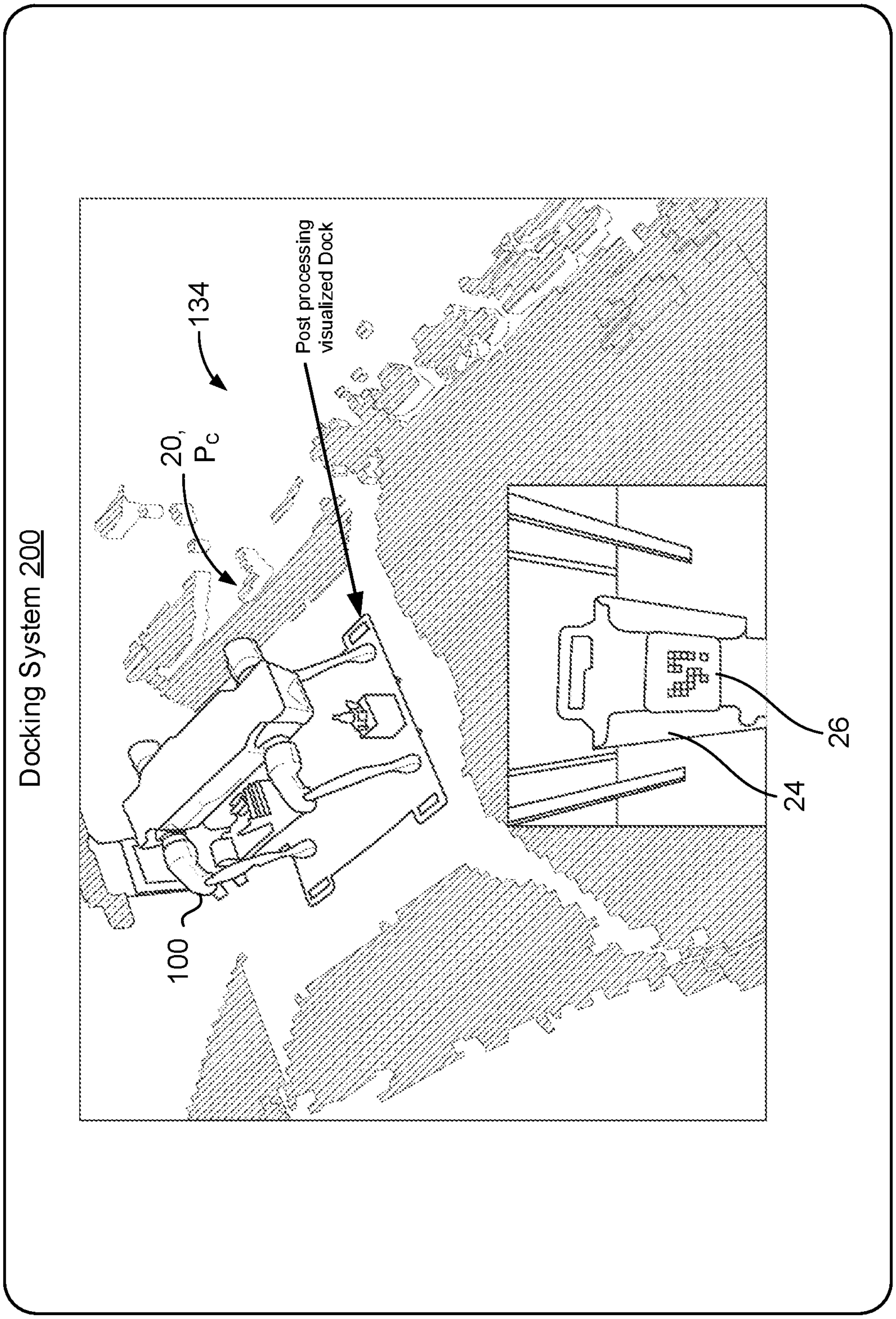

Docking System 200
134
20, P_C
Post processing visualized Dock
100
24
26

FIG. 2D

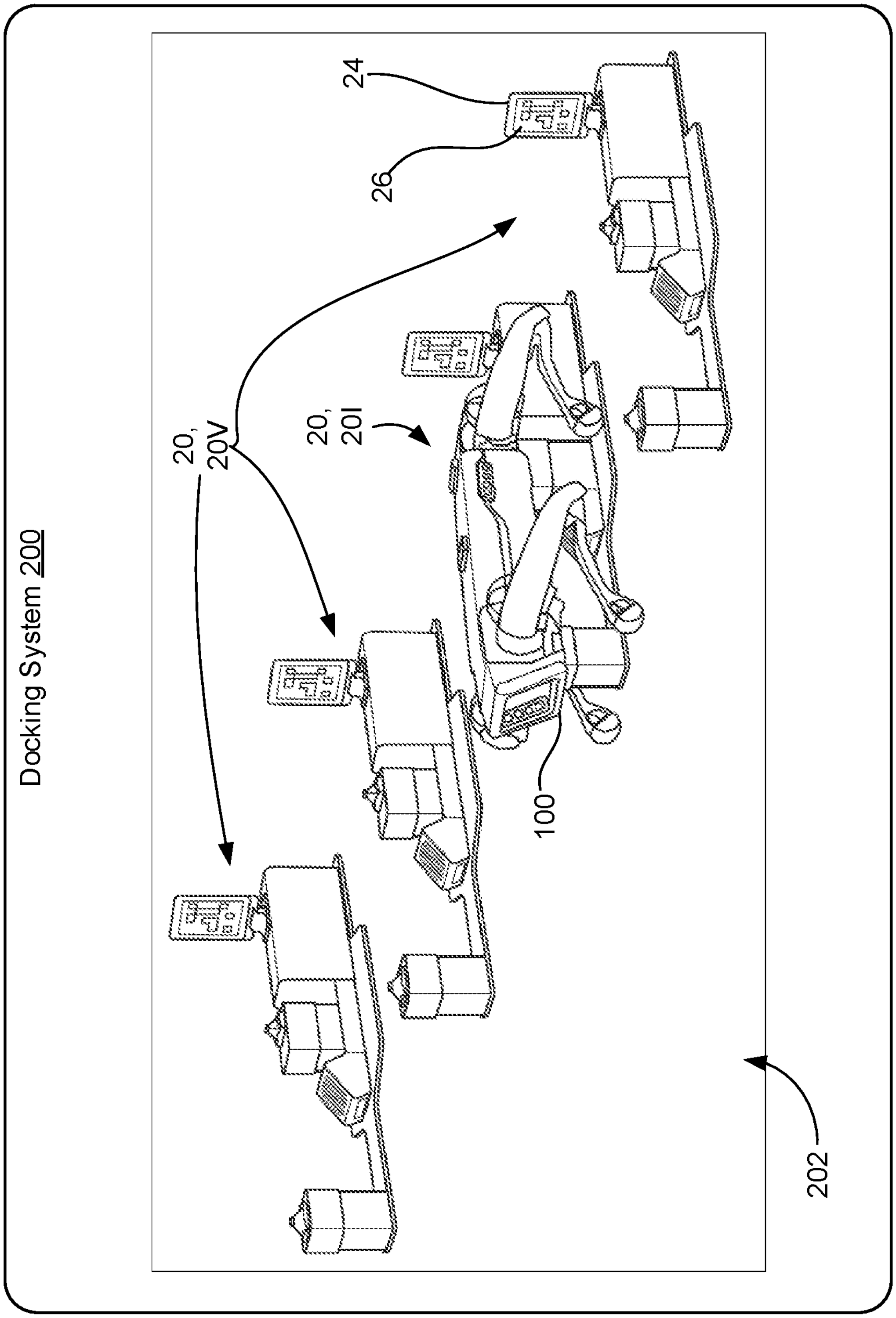


FIG. 2E

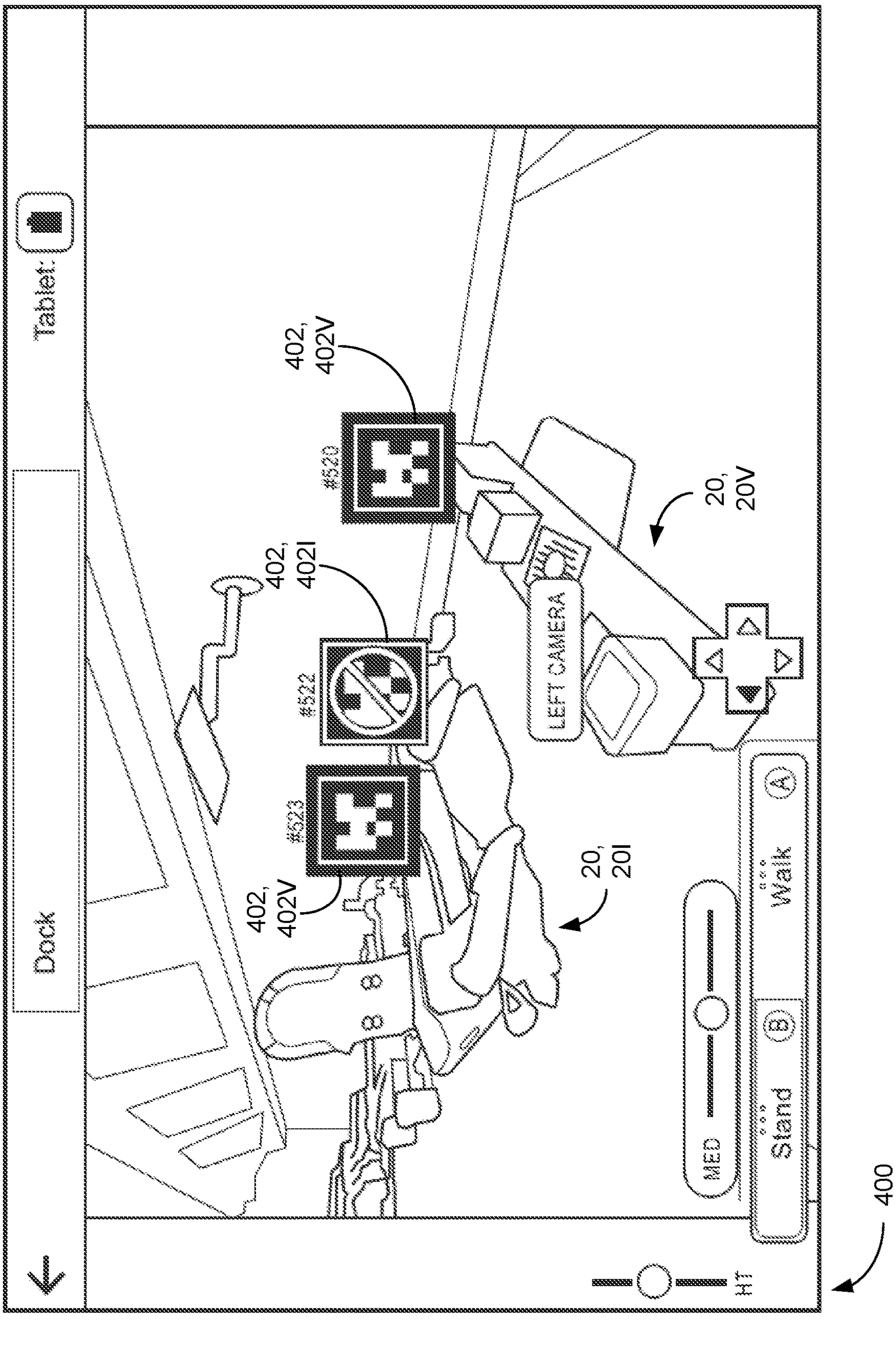

Tablet:
Dock
402,
402V
#520
402,
402I
#522
#523
402,
402V
20,
20V
20,
20I
LEFT CAMERA
Walk
A
Stand
B
MED
HT
400

FIG. 2F

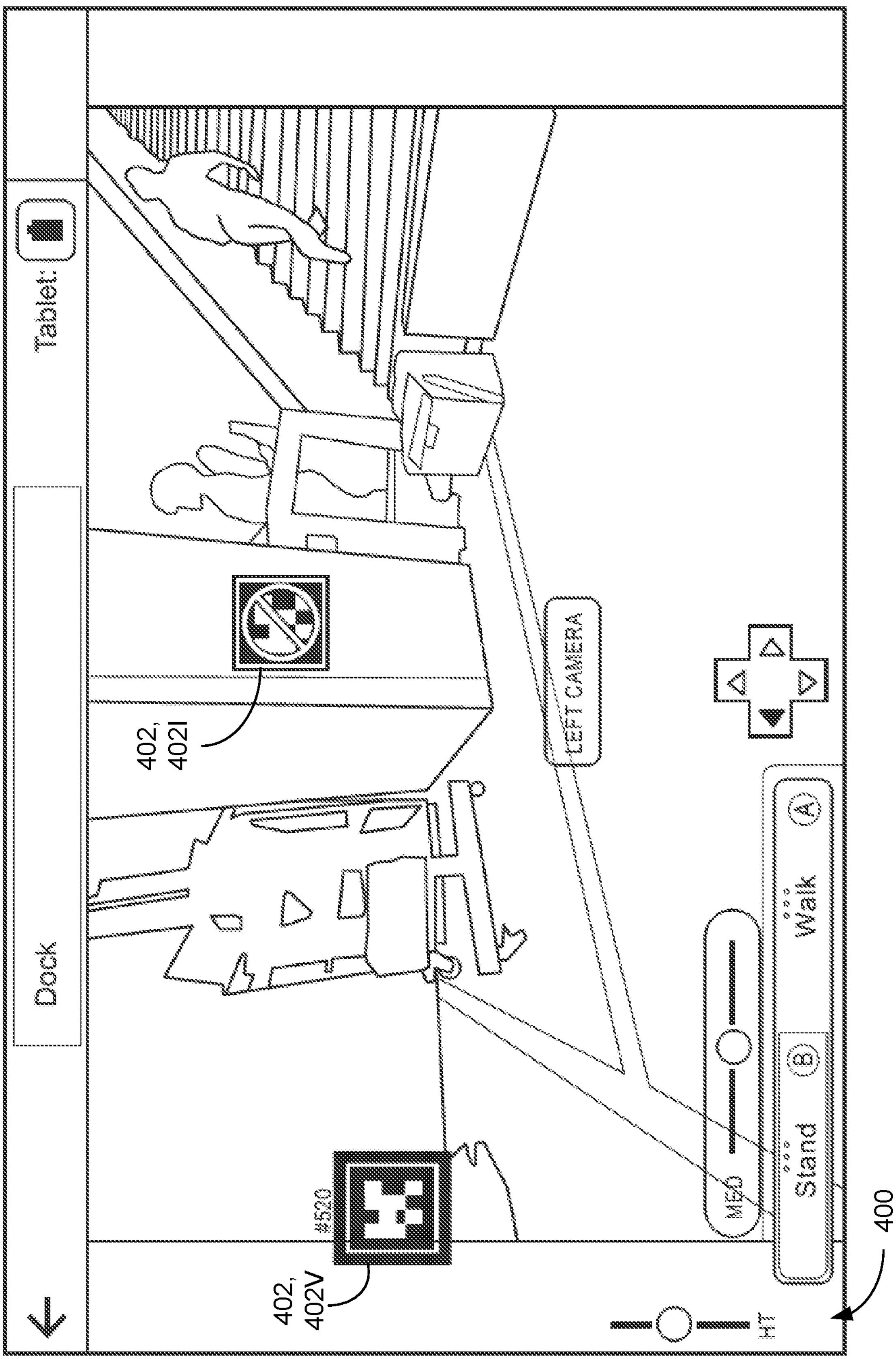

Dock
Tablet:
402,
402I
LEFT CAMERA
402,
402V
#520
MED
Stand
B
Walk
A
HT
400

FIG. 2G

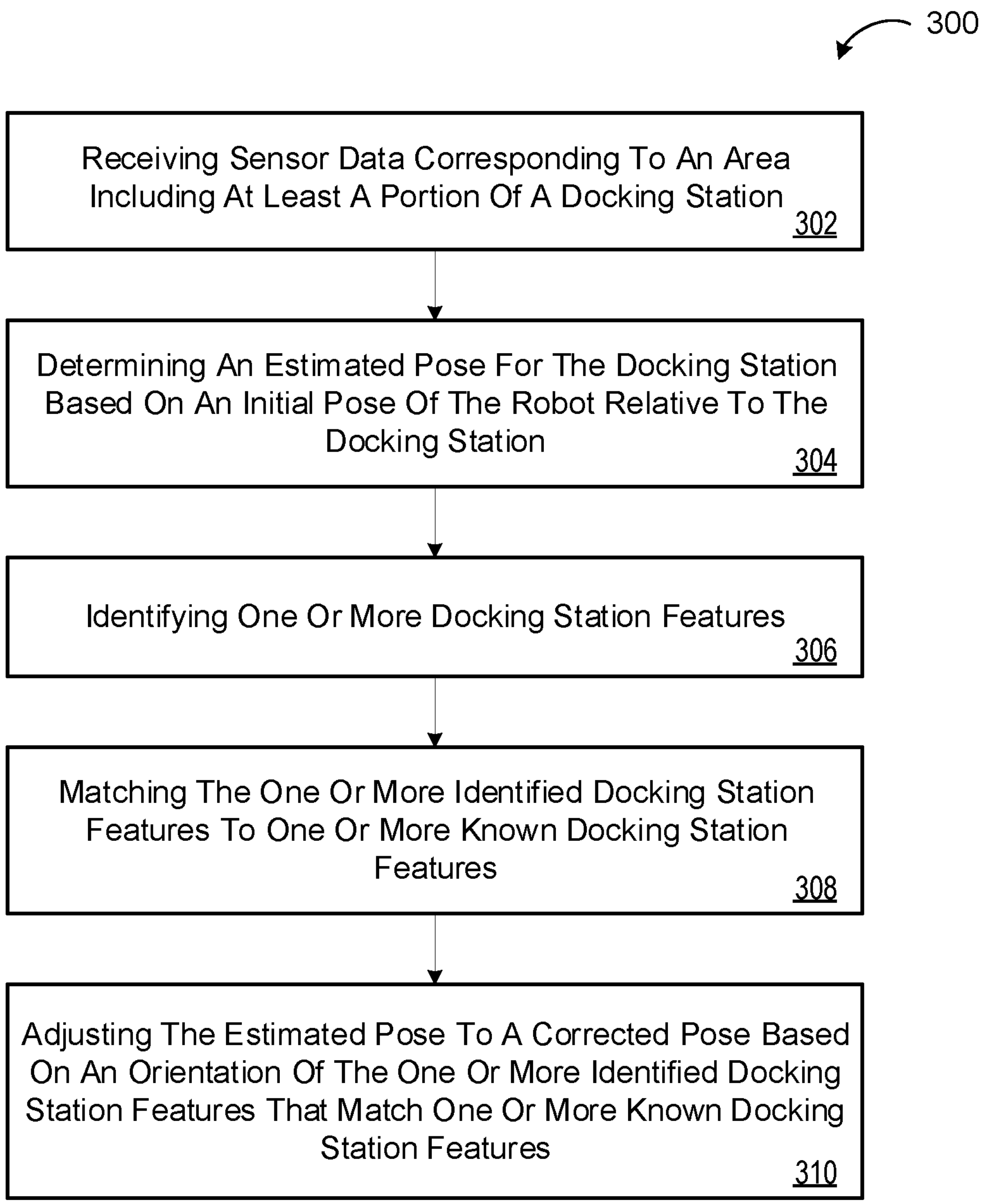

300
Receiving Sensor Data Corresponding To An Area Including At Least A Portion Of A Docking Station
302
Determining An Estimated Pose For The Docking Station Based On An Initial Pose Of The Robot Relative To The Docking Station
304
Identifying One Or More Docking Station Features
306
Matching The One Or More Identified Docking Station Features To One Or More Known Docking Station Features
308
Adjusting The Estimated Pose To A Corrected Pose Based On An Orientation Of The One Or More Identified Docking Station Features That Match One Or More Known Docking Station Features
310

FIG. 3

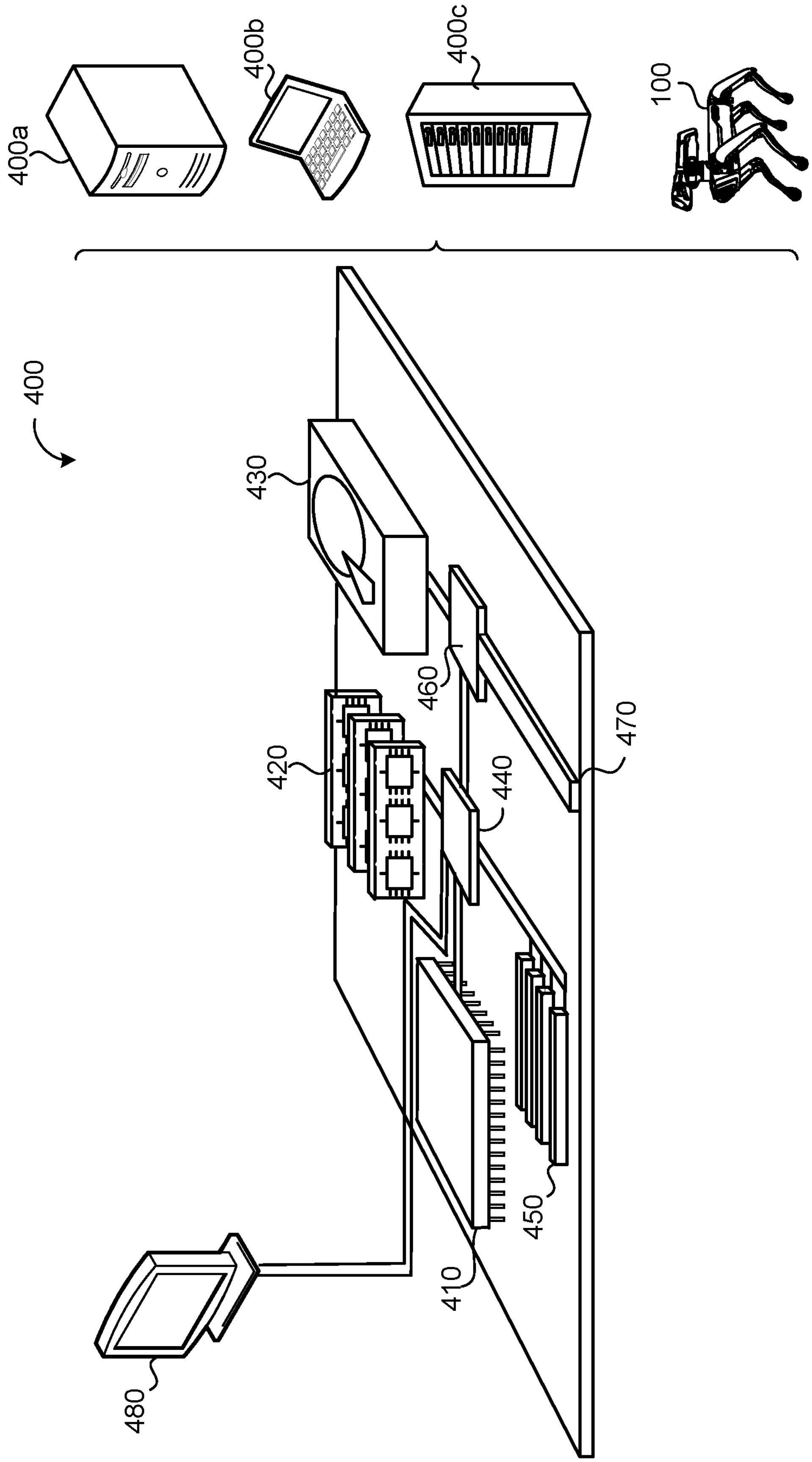


FIG. 4

ROBUST DOCKING OF ROBOTS WITH IMPERFECT SENSING

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This U.S. patent application is a continuation of, and claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 63/129,390, filed on Dec. 22, 2020. The disclosure of this prior application is considered part of the disclosure of this application and is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates to robust docking of robots with imperfect sensing.

BACKGROUND

[0003] A robot is generally defined as a reprogrammable and multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for a performance of tasks. Robots may be manipulators that are physically anchored (e.g., industrial robotic arms), mobile robots that move throughout an environment (e.g., legs, wheels, or traction based mechanisms), or some combination of a manipulator and a mobile robot. Robots are utilized in a variety of industries including, for example, manufacturing, transportation, hazardous environments, exploration, and healthcare. As such, the ability of robots to traverse environments with obstacles are features requiring various means coordinated movement provide additional benefits to such industries.

SUMMARY

[0004] An aspect of the disclosure provides a computer-implemented method. The computer-implemented method, when executed by the data processing hardware of a legged robot causes the data processing hardware to perform operations including receiving sensor data corresponding to an area including at least a portion of a docking station. The operations further include determining an estimated pose for the docking station based on an initial pose of the legged robot relative to the docking station. Additionally, the operations include identifying one or more docking station features from the received sensor data corresponding to the area including at least the portion of the docking station. Furthermore, the operations include matching the one or more identified docking station features to one or more known docking station features. The operations also include adjusting the estimated pose for the docking station to a corrected pose for the docking station based on an orientation of the one or more identified docking station features that match the one or more known docking station features.

[0005] Aspects of the disclosure may include one or more of the following optional features. In some implementations, the operations further include instructing the legged robot to dock at the docking station using the corrected pose for the docking station. In some examples, the operations further include generating a docking station map including terrain information about the docking station using the corrected pose for the docking station. In further examples, the docking station map includes one or more regions corresponding to a region where the legged robot should avoid touching down a respective foot of a leg of the legged robot. The one or more regions are located in the area including at least the portion of the docking station. In further examples, the docking station map includes one or more regions corresponding to a region where the legged robot should avoid moving a body of the legged robot. The one or more regions are located in the area including at least the portion of the docking station. In further examples, the docking station map includes one or more regions indicating a height of the identified docking station features. The one or more regions are located in the area including at least the portion of the docking station. In further examples, the docking station map includes a status indicator for the docking station. The status indicator is based on the matching of the one or more identified docking stations features to the one or more known docking station features. The status indicator identifies availability of the docking station.

[0006] In some implementations, the docking station includes a respective docking station feature associated with a contact terminal for charging a battery of the legged robot. In some embodiments, the docking station includes a respective docking station feature corresponding to an alignment tower. The alignment tower is configured to support at least a portion of the legged robot when the legged robot is in a charging pose charging a battery of the legged robot at the docking station.

[0007] In some implementations, the operations further include identifying the initial pose of the legged robot relative to the docking station by detecting a fiducial associated with the docking station configured to charge a battery associated with the legged robot, and determining the initial docking pose of the robot relative to the docking station based on the detected fiducial. In some embodiments, the robot is a quadruped.

[0008] Another aspect of the disclosure provides a battery-powered robot including a body, one or more legs coupled to the body, data processing hardware, memory hardware in communication with the data processing hardware. The memory hardware stores instructions that when executed on the data processing hardware cause the data processing hardware to perform operations including receiving sensor data corresponding to an area including at least a portion of a docking station. The operations further include determining an estimated pose for the docking station based on an initial pose of the battery-powered robot relative to the docking station. Additionally, the operations include identifying one or more docking station features from the received sensor data corresponding to the area including at least the portion of the docking station. Furthermore, the operations include matching the one or more identified docking station features to one or more known docking station features. The operations also include adjusting the estimated pose for the docking station to a corrected pose for the docking station based on an orientation of the one or more identified docking station features that match the one or more known docking station features.

[0009] This aspect of the disclosure may include one or more of the following optional features. In some examples, the operations further include instructing the battery-powered robot to dock at the docking station using the corrected pose for the docking station. In some embodiments, the operations further include generating a docking station map including terrain information about the docking station using the corrected pose for the docking station. In further embodiments, the docking station map includes one or more regions corresponding to a region where the battery-powered robot should avoid touching down a respective foot of the one or more legs of the battery-powered robot. The one or more regions are located in the area including at least the portion of the docking station. In further embodiments, the docking station map includes one or more regions corresponding to a region where the battery-powered robot should avoid moving a body of the battery-powered robot. The one or more regions are located in the area including at least the portion of the docking station. In further embodiments, the docking station map includes one or more regions indicating a height of the identified docking station features. The one or more regions are located in the area including at least the portion of the docking station. In further embodiments, the docking station map includes a status indicator for the docking station. The status indicator is based on the matching of the one or more identified docking stations features to the one or more known docking station features. The status indicator identifies availability of the docking station.

[0010] In some implementations, the docking station includes a respective docking station feature associated with a contact terminal for charging a battery of the battery-powered robot. In some embodiments, the docking station includes a respective docking station feature corresponding to an alignment tower. The alignment tower is configured to support at least a portion of the battery-powered robot when the battery-powered robot is in a charging pose charging a battery of the battery-powered robot at the docking station. In some examples, the operations further include identifying the initial pose of the battery-powered robot relative to the docking station by detecting a fiducial associated with the docking station configured to charge a battery associated with the battery-powered robot, and determining the initial docking pose of the robot relative to the docking station based on the detected fiducial. In some embodiments, the battery-powered robot is a quadruped.

[0011] The details of one or more implementations of the disclosure are set forth in the accompanying drawings and the description below. Other aspects, features, and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

[0012] FIG. **1**A is a perspective view of an example robot capable of docking on a charging station.

[0013] FIG. **1**B is a schematic view of example systems of the robot of FIG. **1**A.

[0014] FIG. **1**C is a perspective view of an example charging station for the robot of FIG. **1**A.

[0015] FIGS. **2**A-**2**C are schematic views of example docking system of the robot of FIG. **1**A.

[0016] FIG. **2**D is a perspective view of an example rendering of a charging station aligned with the robot of FIG. **1**A.

[0017] FIG. **2**E is a perspective view of an example rendering of a docking station map.

[0018] FIGS. **2**F and **2**G are views of example user interfaces generated based at least in part on the docking station map of FIG. **2**E.

[0019] FIG. **3** is a flowchart of an example arrangement of operations for a method of controlling a robot to identify a docking station and adjust a pose of the robot for the docking station.

[0020] FIG. **4** is a schematic view of an example computing device that may be used to implement the systems and methods described herein.

[0021] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0022] As battery-powered robots move about environments, these battery-powered robots will expend energy and require that this expended energy eventually be replenished. In other words, the energy that a battery-powered robot is able to expend is finite and results in the robot proportionately having a finite amount of time to operate. In order to replenish the energy that the robot expends, a battery-powered robot connects to a charging station in a process known as docking. Since it is not uncommon for a robot to dock at the charging station when the robot has a low battery state, if the robot fails to properly connect or dock with the charging station, the robot may run out of battery and require some form of recovery (e.g., human recovery). Unfortunately, having to recover the robot may become an issue when the robot is operating in a remote space. That is, someone or something may not be able to readily recover the robot should the robot run out of battery power. Simply stated, this may inherently defeat the advantage of a battery-powered robot in that a battery-powered robot is able to operate remotely. To overcome such issues, it becomes necessary for the robot to have a reliable and robust docking process that ensures the robot successfully docks with the charging station.

[0023] To compound issues with charging stations for battery-powered robots, battery-powered robots that are also legged robots may further complicate the docking process. For example, legged robots demand precise leg coordination for balance while maneuvering about the environment. Generally speaking, when that environment includes obstacles, a legged robot must understand how to account for that obstacle in order to perform a given task for the robot. When the task of the robot is to dock at its charging station, the structure of the charging station itself may be similar to an obstacle for the robot. That is, it is important for the legged robot to know precisely where the dock is located in order to determine suitable footstep locations that enable the legged robot to properly connect (i.e., dock) with the charging station. Otherwise, the legged robot may trip and potentially fall on its own docking station. This is unlike other mobile robots, such as wheel-based robots, that do not have to step path plan to avoid damaging the charging station (e.g., kicking, stepping on, or falling into the charging station) or the robot itself (e.g., tripping and/or falling). Since a legged robot may approach the charging station from different angles and sometimes require repositioning to successfully dock with the charging station, the charging station may pose a unique challenge for legged robots and one that demands a docking process that enables reliable and accurate positioning for the robot.

[0024] Referring to FIGS. **1**A and **1**B, the robot **100** includes a body **110** with locomotion-based structures such as legs **120***a-d* coupled to the body **110** that enable the robot **100** to move about the environment **10**. In some examples, each leg **120** is an articulable structure such that one or more joints J permit members **122** of the leg **120** to move. For instance, each leg **120** includes a hip joint JH coupling an upper member **122**, $\mathbf{122}_U$ of the leg **120** to the body **110** and a knee joint J_K coupling the upper member **122**u of the leg **120** to a lower member **122**$_L$ of the leg **120**. Although FIG. **1**A depicts a quadruped robot with four legs **120**a-d, the robot **100** may include any number of legs or locomotive-based structures (e.g., a biped or humanoid robot with two legs, or other arrangements of one or more legs) that provide a means to traverse the terrain within the environment **10**.

[0025] The body **110** includes one or more charging terminals **112** (e.g., shown as a single charging terminal **112** near the hind legs **120**, **120**c-d of the robot **100** in a rear portion of the body **110** of the robot **100** in FIG. **1**A). The one or more charging terminals **112** may be located on an underside of the body **110** of the robot **100** such that the terminals **112** face the ground plane **14** and are configured to receive a complimentary terminal of a charging station for the robot **100**. In the example of FIG. **1**A, the robot **100** includes a single charging terminal **112** in a rear half portion of the body **110** of the robot **100** (e.g., towards the hind legs **120**, **120**c-d of the robot **100**). In some implementations, the one or more charging terminals **112** on the underside of the body **110** are centrally disposed along a longitudinal axis of the body **110** to ensure that when the charging terminals **112** of the robot **100** engage with the complimentary charging terminals of the charging station **20**, the robot **100** is balanced. In some examples, the charging terminal **112** on the body **110** of the robot **100** includes a housing that serves as a female connector to matingly receive a complimentary male connector that is part of the housing of the terminal of the robot's charging station **20**. In this sense, the charging terminal of the charging station **20** protrudes to some degree from the charging station **20** such that contact may be made between the charging terminal **112** on the body **110** of the robot **100** and the terminal on the charging station as the male connector of the charging station **20** seats or couples with the female connector of the robot **100**. In some examples, the terminal **112** of the robot **100** is simply a contact landing pad that the robot **100** may lower onto the terminal of the charging station **20**. Although FIGS. **1**A and **1**C depict that the charging station and the robot **100** each include a single charging terminal, each component may have more charging terminals (e.g., two, three, or four terminals). For instance, the robot **100** may include a pair of charging terminals **112** such that the front half portion of the body **120** has a charging terminal **112** similar to the rear half portion of the body **110**. Additionally or alternatively, instead of using a direct physical connection to charge the robot **100**, the robot **100** may charge wirelessly. For instance, the robot **100** charges using inductive charging where one or more designated portions of the robot **100** may be placed in inductive proximity with one or more specific portions of the charging station **20**. Here, similar to direct physical connections, wireless or inductive charging may demand precise placement of the robot **100** with respect to the charging station **20** to ensure that the inductive charging reliably occurs.

[0026] In order to traverse the terrain, each leg **120** has a distal end **124** that contacts a surface of the terrain (i.e., a traction surface). In other words, the distal end **124** of the leg **120** is the end of the leg **120** used by the robot **100** to pivot, plant, or generally provide traction during movement of the robot **100**. For example, the distal end **124** of a leg **120** corresponds to a foot of the robot **100**. In some examples, though not shown, the distal end **124** of the leg **120** includes an ankle joint J_A such that the distal end **124** is articulable with respect to the lower member **122**$_L$ of the leg **120**.

[0027] In the examples shown, the robot **100** includes an arm **126** that functions as a robotic manipulator. The arm **126** may be configured to move about multiple degrees of freedom in order to engage elements of the environment **10** (e.g., objects within the environment **10**). In some examples, the arm **126** includes one or more members **128**, where the members **128** are coupled by joints J such that the arm **126** may pivot or rotate about the joint(s) J. For instance, with more than one member **128**, the arm **126** may be configured to extend or to retract. To illustrate an example, FIG. **1**A depicts the arm **126** with three members **128** corresponding to a lower member **128**$_L$, an upper member **128**$_U$, and a hand member **128**$_H$ (e.g., also referred to as an end-effector **128**$_H$). Here, the lower member **128**$_L$ may rotate or pivot about a first arm joint J_{A1} located adjacent to the body **110** (e.g., where the arm **126** connects to the body **110** of the robot **100**). The lower member **128**$_L$ is coupled to the upper member **128**$_U$ at a second arm joint J_{A2} and the upper member **128**$_U$ is coupled to the hand member **128**$_H$ at a third arm joint J_{A3}. In some examples, such as FIG. **1**A, the hand member **128**$_H$ or end-effector **128**$_H$ is a mechanical gripper that includes a one or more moveable jaws configured to perform different types of grasping of elements within the environment **10**. In the example shown, the end-effector **128**$_H$ includes a fixed first jaw and a moveable second jaw that grasps objects by clamping the object between the jaws. The moveable jaw is configured to move relative to the fixed jaw in order to move between an open position for the gripper and a closed position for the gripper (e.g., closed around an object). In some implementations, the arm **126** additionally includes a fourth joint J_{A4}. The fourth joint J_{A4} may be located near the coupling of the lower member **128**$_L$ to the upper member **128**$_U$ and function to allow the upper member **128**$_U$ to twist or rotate relative to the lower member **128**$_L$. In other words, the fourth joint J_{A4} may function as a twist joint similarly to the third joint J_{A3} or wrist joint of the arm **126** adjacent the hand member **128**$_H$. For instance, as a twist joint, one member coupled at the joint J may move or rotate relative to another member coupled at the joint J (e.g., a first member coupled at the twist joint is fixed while the second member coupled at the twist joint rotates). In some implementations, the arm **126** connects to the robot **100** at a socket on the body **110** of the robot **100**. In some configurations, the socket is configured as a connector such that the arm **126** may attach or detach from the robot **100** depending on whether the arm **126** is desired for operation.

[0028] The robot **100** has a vertical gravitational axis (e.g., shown as a Z-direction axis A_Z) along a direction of gravity, and a center of mass CM, which is a position that corresponds to an average position of all parts of the robot **100** where the parts are weighted according to their masses (i.e., a point where the weighted relative position of the distributed mass of the robot **100** sums to zero). The robot **100** further has a pose P based on the CM relative to the vertical gravitational axis A_Z (i.e., the fixed reference frame with respect to gravity) to define a particular attitude or stance assumed by the robot **100**. The attitude of the robot **100** can be defined by an orientation or an angular position of the robot **100** in space. Movement by the legs **120** relative to the body **110** alters the pose P of the robot **100** (i.e., the combination of the position of the CM of the robot and the attitude or orientation of the robot **100**). Here, a height generally refers to a distance along the z-direction (e.g., along a z-direction axis A_Z). The sagittal plane of the robot **100** corresponds to the Y-Z plane extending in directions of a y-direction axis A_Y and the z-direction axis A_Z. In other words, the sagittal plane bisects the robot **100** into a left and a right side. Generally perpendicular to the sagittal plane, a ground plane (also referred to as a transverse plane) spans the X-Y plane by extending in directions of the x-direction axis A_X and the y-direction axis A_Y. The ground plane refers to a ground surface **14** where distal ends **124** of the legs **120** of the robot **100** may generate traction to help the robot **100** move about the environment **10**. Another anatomical plane of the robot **100** is the frontal plane that extends across the body **110** of the robot **100** (e.g., from a left side of the robot **100** with a first leg **120***a* to a right side of the robot **100** with a second leg **120***b*). The frontal plane spans the X-Z plane by extending in directions of the x-direction axis A_X and the z-direction axis A_Z.

[0029] In order to maneuver about the environment **10** or to perform tasks using the arm **126**, the robot **100** includes a sensor system **130** with one or more sensors **132**, **132***a-n*. For instance, FIG. **1**A illustrates a first sensor **132**, **132***a* mounted at a head of the robot **100**, a second sensor **132**, **132***b* mounted near the hip of the second leg **120***b* of the robot **100**, a third sensor **132**, **132***c* corresponding one of the sensors **132** mounted on a side of the body **110** of the robot **100**, a fourth sensor **132**, **132***d* mounted near the hip of the fourth leg **120***d* of the robot **100**, and a fifth sensor **132**, **132***e* mounted at or near the end-effector $\mathbf{128}_H$ of the arm **126** of the robot **100**. The sensors **132** may include vision/image sensors, inertial sensors (e.g., an inertial measurement unit (IMU)), force sensors, and/or kinematic sensors. Some examples of sensors **132** include a camera such as a stereo camera, a time-of-flight (TOF) sensor, a scanning light-detection and ranging (LIDAR) sensor, or a scanning laser-detection and ranging (LADAR) sensor. In some examples, the sensor **132** has a corresponding field(s) of view F_V defining a sensing range or region corresponding to the sensor **132**. For instance, FIG. **1**A depicts a field of a view F_V for the robot **100**. Each sensor **132** may be pivotable and/or rotatable such that the sensor **132** may, for example, change the field of view F_V about one or more axis (e.g., an x-axis, a y-axis, or a z-axis in relation to a ground plane).

[0030] When surveying a field of view F_V with a sensor **132**, the sensor system **130** generates sensor data **134** (also referred to as image data) corresponding to the field of view F_V. The sensor system **130** may generate the field of view F_V with a sensor **132** mounted on or near the body **110** of the robot **100** (e.g., sensor(s) **132***a*, **132***b*). The sensor system may additionally and/or alternatively generate the field of view F_V with a sensor **132** mounted at or near the end-effector $\mathbf{128}_H$ of the arm **126** (e.g., sensor(s) **132***c*). The one or more sensors **132** may capture sensor data **134** that defines the three-dimensional point cloud for the area within the environment **10** about the robot **100**. In some examples, the sensor data **134** is image data that corresponds to a three-dimensional volumetric point cloud generated by a three-dimensional volumetric image sensor **132**. Additionally or alternatively, when the robot **100** is maneuvering about the environment **10**, the sensor system **130** gathers pose data for the robot **100** that includes inertial measurement data (e.g., measured by an IMU). In some examples, the pose data includes kinematic data and/or orientation data about the robot **100**, for instance, kinematic data and/or orientation data about joints J or other portions of a leg **120** or arm **126** of the robot **100**. With the sensor data **134**, various systems of the robot **100** may use the sensor data **134** to define a current state of the robot **100** (e.g., of the kinematics of the robot **100**) and/or a current state of the environment **10** about the robot **100**.

[0031] In some implementations, the sensor system **130** includes sensor(s) **132** coupled to a joint J. Moreover, these sensors **132** may couple to a motor M that operates a joint J of the robot **100** (e.g., sensors **132**, **132***b-d*). Here, these sensors **132** generate joint dynamics in the form of joint-based sensor data **134**. Joint dynamics collected as joint-based sensor data **134** may include joint angles (e.g., an upper member $\mathbf{122}_U$ relative to a lower member $\mathbf{122}_L$ or hand member $\mathbf{126}_H$ relative to another member of the arm **126** or robot **100**), joint speed (e.g., joint angular velocity or joint angular acceleration), and/or forces experienced at a joint J (also referred to as joint forces). Joint-based sensor data generated by one or more sensors **132** may be raw sensor data, data that is further processed to form different types of joint dynamics, or some combination of both. For instance, a sensor **132** measures joint position (or a position of member(s) **122** coupled at a joint J) and systems of the robot **100** perform further processing to derive velocity and/or acceleration from the positional data. In other examples, a sensor **132** is configured to measure velocity and/or acceleration directly.

[0032] As the sensor system **130** gathers sensor data **134**, a computing system **140** stores, processes, and/or to communicates the sensor data **134** to various systems of the robot **100** (e.g., the control system **170**, the perception system **180**, and/or the docking system **200**). In order to perform computing tasks related to the sensor data **134**, the computing system **140** of the robot **100** includes data processing hardware **142** and memory hardware **144**. The data processing hardware **142** is configured to execute instructions stored in the memory hardware **144** to perform computing tasks related to activities (e.g., movement and/or movement based activities) for the robot **100**. Generally speaking, the computing system **140** refers to one or more locations of data processing hardware **142** and/or memory hardware **144**.

[0033] In some examples, the computing system **140** is a local system located on the robot **100**. When located on the robot **100**, the computing system **140** may be centralized (i.e., in a single location/area on the robot **100**, for example, the body **110** of the robot **100**), decentralized (i.e., located at various locations about the robot **100**), or a hybrid combination of both (e.g., where a majority of centralized hardware and a minority of decentralized hardware). To illustrate some differences, a decentralized computing system **140** may allow processing to occur at an activity location (e.g., at motor that moves a joint of a leg **120**) while a centralized computing system **140** may allow for a central processing hub that communicates to systems located at various positions on the robot **100** (e.g., communicate to the motor that moves the joint of the leg **120**).

[0034] Additionally or alternatively, the computing system **140** includes computing resources that are located remotely from the robot **100**. For instance, the computing system **140** communicates via a network **150** with a remote system **160** (e.g., a remote server or a cloud-based environment). Much like the computing system **140**, the remote system **160** includes remote computing resources, such as remote data processing hardware **162** and remote memory hardware **164**. Here, sensor data **134** or other processed data (e.g., data processing locally by the computing system **140**) may be stored in the remote system **160** and may be accessible to the computing system **140**. In additional examples, the computing system **140** is configured to utilize the remote resources **162**, **164** as extensions of the computing resources **142**, **144** such that resources of the computing system **140** may reside on resources of the remote system **160**.

[0035] In some implementations, as shown in FIGS. **1A** and **1B**, the robot **100** includes a control system **170** and a perception system **180**. The perception system **180** is configured to receive the sensor data **134** from the sensor system **130** and process the sensor data **134** to generate maps **182**. With the maps **182** generated by the perception system **180**, the perception system **180** may communicate the maps **182** to the control system **170** in order to perform controlled actions for the robot **100**, such as moving the robot **100** about the environment **10**. In some examples, by having the perception system **180** separate from, yet in communication with the control system **170**, processing for the control system **170** may focus on controlling the robot **100** while the processing for the perception system **180** focuses on interpreting the sensor data **134** gathered by the sensor system **130**. For instance, these systems **170**, **180** execute their processing in parallel to ensure accurate, fluid movement of the robot **100** in an environment **10**.

[0036] A given controller **172** may control the robot **100** by controlling movement about one or more joints J of the robot **100**. In some configurations, the given controller **172** is software with programming logic that controls at least one joint J or a motor M which operates, or is coupled to, a joint J. For instance, the controller **172** controls an amount of force that is applied to a joint J (e.g., torque at a joint J). As programmable controllers **172**, the number of joints J that a controller **172** controls is scalable and/or customizable for a particular control purpose. A controller **172** may control a single joint J (e.g., control a torque at a single joint J), multiple joints J, or actuation of one or more members **122**, **128** (e.g., actuation of the hand member $\mathbf{128}_H$) of the robot **100**. By controlling one or more joints J, actuators or motors M, the controller **172** may coordinate movement for all different parts of the robot **100** (e.g., the body **110**, one or more legs **120**, the arm **126**). For example, to perform some movements or tasks, a controller **172** may be configured to control movement of multiple parts of the robot **100** such as, for example, two legs **120***a-b*, four legs **120***a-d*, or two legs **120***a-b* combined with the arm **126**.

[0037] In some examples, the control system **170** includes at least one controller **172**, a path generator **174**, a step locator **176**, and a body planner **178**. The control system **170** may be configured to communicate with at least one sensor system **130** and any other system of the robot **100** (e.g., the perception system **180** and/or the docking system **200**). The control system **170** performs operations and other functions using the computing system **140**. The controller **172** is configured to control movement of the robot **100** to traverse about the environment **10** based on input or feedback from the systems of the robot **100** (e.g., the sensor system **130**, the perception system **180**, and/or the docking system **200**). This may include movement between poses and/or behaviors of the robot **100**. For example, the controller **172** controls different footstep patterns, leg patterns, body movement patterns, or vision system-sensing patterns.

[0038] In some implementations, the control system **170** includes specialty controllers **172** that are dedicated to a particular control purpose. These specialty controllers **172** may include the path generator **174**, the step locator **176**, and/or the body planner **178**. Referring to FIG. **1B**, the path generator **174** is configured to determine horizontal motion for the robot **100**. For instance, the horizontal motion refers to translation (i.e., movement in the X-Y plane) and/or yaw (i.e., rotation about the Z-direction axis A_Z) of the robot **100**. The path generator **174** determines obstacles within the environment **10** about the robot **100** based on the sensor data **134**. The path generator **174** communicates the obstacles to the step locator **176** such that the step locator **176** may identify foot placements for legs **120** of the robot **100** (e.g., locations to place the distal ends **124** of the legs **120** of the robot **100**). The step locator **176** generates the foot placements (i.e., locations where the robot **100** should step) using inputs from the perception system **180** (e.g., map(s) **182**). The body planner **178**, much like the step locator **176**, receives inputs from the perception system **180** (e.g., map(s) **182**). Generally speaking, the body planner **178** is configured to adjust dynamics of the body **110** of the robot **100** (e.g., rotation, such as pitch or yaw and/or height of COM) to successfully move about the environment **10**.

[0039] The perception system **180** is a system of the robot **100** that helps the robot **100** to move more precisely in a terrain with various obstacles. As the sensors **132** collect sensor data **134** for the space about the robot **100** (i.e., the robot's environment **10**), the perception system **180** uses the sensor data **134** to form one or more maps **182** for the environment **10**. Once the perception system **180** generates a map **182**, the perception system **180** is also configured to add information to the map **182** (e.g., by projecting sensor data **134** on a preexisting map) and/or to remove information from the map **182**.

[0040] In some examples, the one or more maps **182** generated by the perception system **180** are a ground height map **182**, **182***a*, a no step map **182**, **182***b*, and a body obstacle map **182**, **182***c*. The ground height map **182***a* refers to a map **182** generated by the perception system **180** based on spatial occupancy of an area (e.g., the environment **10**) divided into three-dimensional volume units (e.g., voxels from a voxel map). In some implementations, the ground height map **182***a* functions such that, at each X-Y location within a grid of the map **182** (e.g., designated as a cell of the ground height map **182***a*), the ground height map **182***a* specifies a height. In other words, the ground height map **182***a* conveys that, at a particular X-Y location in a horizontal plane, the robot **100** should step at a certain height.

[0041] The no step map **182***b* generally refers to a map **182** that defines regions where the robot **100** is not allowed to step in order to advise the robot **100** when the robot **100** may step at a particular horizontal location (i.e., location in the X-Y plane). In some examples, much like the body obstacle map **182***c* and the ground height map **182***a*, the no step map **182***b* is partitioned into a grid of cells where each cell represents a particular area in the environment **10** about the robot **100**. For instance, each cell is a three centimeter square. For ease of explanation, each cell exists within an X-Y plane within the environment **10**. When the perception system **180** generates the no-step map **182***b*, the perception system **180** may generate a Boolean value map where the

Boolean value map identifies no step regions and step regions. A no step region refers to a region of one or more cells where an obstacle exists while a step region refers to a region of one or more cells where an obstacle is not perceived to exist. The perception system **180** further processes the Boolean value map such that the no step map **182***b* includes a signed-distance field. Here, the signed-distance field for the no step map **182***b* includes a distance to a boundary of an obstacle (e.g., a distance to a boundary of the no step region) and a vector v (e.g., defining nearest direction to the boundary of the no step region) to the boundary of an obstacle.

[0042] The body obstacle map **182***c* generally determines whether the body **110** of the robot **100** may overlap a location in the X-Y plane with respect to the robot **100**. In other words, the body obstacle map **182***c* identifies obstacles for the robot **100** to indicate whether the robot **100**, by overlapping at a location in the environment **10**, risks collision or potential damage with obstacles near or at the same location. As a map of obstacles for the body **110** of the robot **100**, systems of the robot **100** (e.g., the control system **170**) may use the body obstacle map **182***c* to identify boundaries adjacent, or nearest to, the robot **100** as well as to identify directions (e.g., an optimal direction) to move the robot **100** in order to avoid an obstacle. In some examples, much like other maps **182**, the perception system **180** generates the body obstacle map **182***c* according to a grid of cells (e.g., a grid of the X-Y plane). Here, each cell within the body obstacle map **182***c* includes a distance from an obstacle and a vector pointing to the closest cell that is an obstacle (i.e., a boundary of the obstacle).

[0043] FIG. **1**C is an example of a charging station **20** (also referred to as a docking station) for the robot **100**. The charging station **20** generally includes one or more features **22** and a fiducial plate **24** for displaying a fiducial **26** associated with the charging station **20**. In this example, the charging station **20** also includes indicators I for conveying whether the robot **100** is charging or generally powered-on as well as a battery fan BF for cooling the battery of the robot **100** when the robot **100** is docked on the charging station **20**. In some examples, the features **22** of the charging station **20** may include one or more alignment towers **22**A (e.g., shown as two alignment towers **22**, **22**A*a*, **22**A*b*) and one or more terminals **22**T that are configured to charge the battery of the robot **100**. Each alignment tower **22**A (e.g., the rear alignment tower **22**A*b*) may include a charging terminal **22**T with an electrically conductive contact surface to charge the battery of the robot **100**. In some implementations, such as FIG. **1**C, the charging station **20** includes two alignment towers **22**A, **22**A*a-b* with a single charging terminal **22**T associated with the rear alignment tower **22**A*b* that will connect or electrically couple with the robot **100** at a rear portion of the robot **100** (e.g., near the hind legs **120**, **120***c-d* of the robot **100**). In this implementation, the charging terminal **22**, **22**T is located adjacent to an alignment feature of the rear tower **22**A*b* (e.g., shown as a conical indexing structure). Although FIG. **1**C illustrates a single charging terminal **22**T, the charging station **20** may include any number of charging terminals **22**T to adequately charge the robot **100** (i.e., to mate with terminal(s) **112** of the robot **100**). In some configurations, the top surface of the alignment tower **22**A that faces the robot **100** protrudes from the alignment tower **22**A in a conical-like or pyramid-like structure for alignment purposes. Although the charging terminal **22**T of the charging station **20** is shown as separate from the apex or peak of the alignment tower **22**A, the charging terminal **22**T may additionally or alternatively be configured to be located at the apex or peak protruding at the top of the alignment tower **22**A. In either configuration, the charging terminal **22**T of the charging station **20** may couple with one or more complimentary charging terminals **112** (e.g., charging terminal **112**) on the robot **100**.

[0044] The fiducial plate **24** generally refers to a structure that is capable of displaying the fiducial **26**. Here, a fiducial **26** refers to an object that the robot **100** may use as a point of reference (e.g., a local or global identifier of some spatial relationship). A fiducial **26** may be encoded with a data payload that includes information relevant to the operation of the robot **100** and/or information about the point of reference that the fiducial **26** represents. For instance, the payload of the fiducial **26** associated with the charging station **20** may identify information about the charging station **20**. As an example, a robot **100** may be associated with or designated to a particular charging station **20** and the fiducial **26** may be encoded with information that identifies this relationship. The information may include a unique identifier for the charging station **20** that is recognizable to the robot **100** corresponding to the charging station **20** (e.g., the robot **100** shares the same identifier). In some examples, the sensor system **130** and/or the perception system **180** uses the fiducial **26** as a visual marker to establish a reference point within the environment **10** about the robot **100** (e.g., for localization of the robot **100**). In some configurations, the fiducial **26** is a visual marker used for localization by the robot **100**. Some examples of the types of visual fiducials **26** that may be used by systems of the robot **100** include AprilTags or QR codes that are not significantly influenced by lighting conditions and/or other environmental conditions. The type of fiducial **26** associated with the charging station **20** may be based on a desired detection range for the fiducial and/or the size of the payload encoded by the fiducial **26**.

[0045] The structure of the charging station **20** may pose a unique risk to the legged robot **100**. In other words, the charging station **20** includes structures or features **22** that the perception system **180** of the robot **100** may normally perceive as obstacles or regions where the robot **100** should not step (i.e., no step regions). For instance, if one or more legs **120** of the robot **100** collide or contact an alignment tower **22**A or the structure for the fiducial plate **24**, the robot **100** may trip and possibly damage some component of itself or the charging station **20**. Since a robot **100** only has a finite charge for its battery, the robot **100** may have to return to and to dock on the charging station **20** to charge at a semi-frequent basis (e.g., once a day, multiple times a day, or several times a week). With this increased frequency, the chances that an alignment error occurs between the robot **100** and the charging station **20** may also increase. Furthermore, to dock on the charging station **20** means that the robot **100** has to successfully align its charging terminals **112** with the charging terminals **22**T of the charging station **20** to receive electrical energy that charges the battery of the robot **100**. The charging terminal **22**T may also serve as a communication link for transferring other information between the robot **100** and the charging station **20**, such as various types of data (e.g., sensor data **134** or processed sensor data). For successful alignment, the robot **100** may need to reposition itself by moving its legs **120** and/or body **110** while in or above some aspect of the charging station **20**. It should also be noted, that a charging station **20** may serve as a source of power for the robot **100**. In other words, the charging station **20** may power the robot **100** such that the robot **100** does not need a battery or expend power stored in a battery while the robot **100** is connected to the charging station **20**.

[0046] Referring back to FIG. **1**B, the docking system **200** is a system of the robot **100** that is configured to reliably dock the robot **100** at the charging station **20**. In other words, the docking system **200** attempts to address issues with docking the robot **100** on the charging station **20**. In addition to some of the issues previously discussed, the docking system **200** also addresses the issue that features **22** (e.g., the alignment tower(s) **22**A and/or the charging terminal(s) **22**T) of the charging station **20** may be quite small when compared to the size of the robot **100** and therefore the sensor system **130** and/or the perception system **180** of the robot **100** may have difficulty recognizing these features **22** when docking the robot **100**. Another issue that the docking system **200** seeks to resolve is shown in FIG. **2**B. That is, when the robot **100** stands from a docking pose successfully docked on the charging station **20**, the sensor system **130** cannot visualize aspects of the charging station **20** (e.g., the geometry of the charging station **20**) because the visual sensors **132** of the robot **100** are peering outward from the robot **100** or are occluded to some degree as to at least some features **22** of the charging station **20**. FIG. **2**B illustrates the perceived environment **10** about the robot **100** and the area under and/or immediately adjacent to the robot **100** as a black or dark area with little to no perceived information. Therefore, when the robot **100** attempts to leave the charging station **20** from the docking pose, the robot **100** may be operating blind with respect to avoidance or footpath planning in relation to the charging station **20**.

[0047] The docking system **200** may also correct or modify the detection-based errors with respect to the location of the charging station **20**. In other words, from the sensor data **134** and a pose of the robot **100** when the sensor data **134** was collected, the charging station **20** may be perceived to be at an estimated pose (i.e., have an estimated position and/or orientation) with respect to the pose of the robot **100**. Yet this estimated pose Pc (also referred to as a pose of the charging station **20**) for the charging station **20** may be inaccurate to a degree that may compromise the ability of the robot **100** to successfully dock at the charging station **20**, especially when the charging station **20** includes features **22** that demand precise alignment (e.g., the charging terminals **22**T of the charging station **20**). Therefore, the docking system **200** is configured to correct the estimated pose Pc (i.e., to generate a corrected pose Pc) for the charging station **20**. For instance, an algorithm used to detect the location of the charging station **20** (e.g., a fiducial detection algorithm) inherently has some degree of error between the estimated pose Pc of the charging station **20** (e.g., a detected pose of the charging station **20** with respect to the fiducial **26**) and the actual pose of the charging station **20** (e.g., the actual pose of the charging station **20** with respect to the fiducial **26**). For example, the type of sensor **132** or camera perceiving the charging station **20** may contribute to detection-based errors. Generally speaking, when the robot **100** uses a visual fiducial **26**, there is an existing spatial relationship between the pose of the fiducial **26** and one or more features **22** of the charging station **20** (e.g., an alignment tower **22**A of the charging station **20**). Due to this relationship, the docking system **200** receives sensor data **134** identifying the fiducial **26**. From this sensor data **134**, the docking system **200** determines the robot's **100** proximity and pose (e.g., position and orientation of the robot **100**) with respect to the existing (i.e., preconfigured) spatial relationship between the fiducial **26** and the charging system **20**. In other words, from the robot's perceived relationship between the location and/or pose state of the robot **100** and the fiducial **26**, the docking system **200** determines the robot's spatial relationship to the charging station **20** (e.g., one or more features **22** of the charging station **20**).

[0048] The docking system **200** is configured to receive sensor data **134** and to generate a docking station map **202** based on the received sensor data **134** corresponding to the charging station **20**. Here, by generating a docking station map **202**, the docking system **200** takes the sensor data **134** and uses some portion of the sensor data **134** to inject known details regarding the charging station **20**. In this respect, systems of the robot **100** may query the docking station map **202** generated by the docking system **200** to gain an accurate understanding of the charging station **20** and an area about the charging station **20**. This allows the perception system **180** and/or the control system **170** of the robot **100** to avoid relying solely on the perceived sensor data **134**.

[0049] When the robot **100** is docking (i.e., moving to the charging station **20** and assuming a docking pose that successfully couples charging terminal(s) **112** of the robot **100** to the charging terminal(s) **22**T of the charging station **20**) or de-docking (i.e., leaving the charging station area starting from the docking pose), the control system **170** for the robot **100** can utilize a fine-grained map specific to the charging station **20**, the docking station map **202**. This means that as the robot **100** moves in the vicinity of the charging station **20** (i.e., the charging station area) represented in the docking station map **202**, the control system **170** may query the docking station map **202** to determine if a particular location on the map **202** is safe or not safe for the robot **100** to move into (e.g., with its body **110**) or to step on (e.g., with a foot **124**). The docking station map **202** may be considered as a fine-grain map because the docking station map **202** may be scaled to have the necessary resolution to include features **22** of the charging station **20**. For example, the maps **182** generated by the perception system **180** and/or derived from the sensor data **134** may be at a particular resolution (e.g., a three-centimeter block resolution). Yet the docking system **200** may be configured to generate a map of greater resolution (e.g., a one centimeter block resolution) than these maps **182** in order to represent features **22** of the charging station **20** such as the charging terminals **22**T of the charging station **20**. Additionally or alternatively, the docking system **200** can generate a map of terrain information that includes, for example, edges specified by points rather than a grid of a specific resolution; thereby potentially avoiding resolution-based issues. Thus, by generating the docking station map **202**, the docking system **200** enables the robot **100** to have improved navigation and dock posing behaviors to avoid potentially costly foot placement mistakes by the robot **100** in the charging station area.

[0050] In some implementations, such as FIGS. **2A-2C**, the docking system **200** includes a detector **210** and the map generator **220**. The detector **210** is configured to receive sensor data **134** corresponding to an area that includes the charging station **20**. Based on the sensor data **134**, the detector **210** identifies that the charging station **20** is present within the area being sensed by the robot **100**. For example, the detector **210** identifies that the charging station **20** is present within the area by recognizing a fiducial **26** adjacent to the charging station **20**. In some examples, the detector **210** is able to decode information encoded in the fiducial **26** in order to identify that the charging station **20** corresponds to the robot **100**. For instance, the decoded information may include some identifier (e.g., a unique identifier UID) that indicates that the charging station **20** is for the robot **100**. When the detector **210** identifies that the charging station **20** is present in the area about the robot **100**, the detector **210** may identify a current pose P of the robot **100** in order to understand the spatial relationship between the robot **100** and the charging station **20**. In other words, the detector **210** determines a pose for the robot relative to the detected charging station **20**.

[0051] The detector **210** is also configured to use the received sensor data **134** to identify one or more features **22** of the charging station **20**. For example, the detector **210** uses perception sensor data **134** that refers to sensor data **134** from the sensor system **130** that has been processed by the perception system **180**. When the detector **210** identifies one or more features **22** of the charging station **20**, the detector **210** is able to determine whether the identified feature(s) **22** of the charging station **20** match any prior knowledge that the docking system **200** has of the charging station **20** for the robot **100**. For example, the docking system **200** is programmed with prior knowledge as to the geometry of the charging station **20** for the robot **100**. With this prior knowledge, the detector **210** may compare the identified features **22** of the charging station **20** from the sensor data **134** to geometric features of the known geometry for the charging station **20**. When the comparison between the identified features **22** of the charging station **20** from the sensor data **134** and the geometric features of the known geometry for the charging station **20** result in a match or an approximate match, the detector **210** passes the matching geometric features **212** of the known geometry for the charging station **20** to the map generator **220**.

[0052] In some examples, the docking system **200** may include an inventory of known charging stations **20** and their respective geometries. With geometries for several known charging stations **20**, the detector **210** may be configured to generate a matching score between one or more identified features **22** from the sensor data **134** and one or more geometric features for a known charging station **20**. In some implementations, when generating the matching score, the detector **210** may use multiple features **22** from the sensor data **134** and generate a matching score as an overall score as to how closely these multiple features **22** match multiple features of the geometry of a known charging station **20**. The detector **210** may score some or all of the known charging station **20** in its inventory and determine that a particular known charging station **20** with the highest score is the charging station **20** from the sensor data **134** perceived at the robot **100**.

[0053] The map generator **220** receives the matching geometric features **212** with their associated known charging station **20** and generates the docking station map **202**. The docking station map **202** generated by the map generator **220** may include regions indicating terrain planning information similar to the regions or cells of the perception system maps **182**. For instance, FIGS. **2**B and **2**C include representations of the environment **10** about the robot **100** to illustrate the map generation by the map generator **220**. Referring to FIG. **2**B, the top left image portrays little to no terrain information in the vicinity of the robot **100** (e.g., shown as a white, non-shaded area). In contrast, the top right image shows regions bounded by shaded lines **136*a*-*d*** in the same vicinity about the robot **100**. These lines **136*a*-*d*** represent the terrain information that the map generator **220** is able to derive form the geometry of the known charging station **20** that matches the identified feature(s) **22** and inject or augment to generate the docking station map **202**. Here, the areas bounded by lines **136*a*** represent no step regions (i.e., regions unsafe for foot placement). The areas bounded by lines **136*b*** represent regions that are step regions (i.e., regions that are safe for foot placement). The areas bounded by lines **136*c*** represent terrain height regions identifying, for example, the charging terminals **22**T of the docking station **20**. The areas bounded by lines **136*d*** represent regions that include an obstacle that is at a collision height with a leg **120** or body **110** of the robot **100**. By generating the docking station map **202** that includes one or more of these types of regions for the charging station **20**, the control system **170** may use the map **202** to move to and to assume a docking pose that has a reliable degree of success to charge the battery of the robot **100** without issue.

[0054] FIG. **2**C illustrates the process of matching the identified features **22** from the sensor data **134** to the geometric features of a known charging station **20**. Here, the top left image depicts where the terrain information would be located based on fiducial detection alone without or prior to any matching of features. In the top left image, the actual front alignment tower **22**A of the charging station **20** perceived by the robot **100** does not align with the regions of the terrain information. In other words, the charging station **20** is actually located at a position about 30 degrees to the right of the regions of the terrain information. In this example, the docking system **200** proceeds to match the identified features **22** (e.g., the actual front alignment tower **22**A) to the geometric features of the known charging station **20**. The docking system **200** therefore learns based on the matching process that the terrain information should be skewed to the right about 30 degrees to align with the sensed features **22** of the charging station **20**.

[0055] FIG. **2**D illustrates the high-level concept that the docking system **200** is aiming to achieve. In this figure, the robot **100** is standing at the charging station **20** above a rendering of the charging station **20** including its various features **22**. The goal of the docking system **200** is to provide a docking station map **202** to the robot **100** that most closely resembles the rendering of FIG. **2**D. In other words, the best theoretical docking station map **202** includes every minute detail about the charging station **20** to provide the robot **100** with the best information as to how to move in the vicinity of the charging station **20**. By constructing a docking station map **202** that uses prior known geometry of the features of the charging station **20**, the docking system **200** may allow the robot **100** to approach such information.

[0056] In some implementations, the docking system **200** may determine whether a charging station **20** has a status that is valid or invalid, such as based on the matching of the identified features **22** to the geometric features of the known charging station **20**. For example, the docking system may score the estimated pose P_e by how well the sensor data **134** matches the estimated pose P_e. If the docking system **200** does not score the estimated pose P_e high, such as because another robot is on the charging station **20** or the detected charging station is not a real charging station **20**, the docking system **200** marks the status of the charging station **20** as invalid. The robot **100** will not attempt to dock with a charging station **20** marked as invalid. Conversely, if the docking system **200** marks the status of the charging station **20** as valid, such as because the sensor data **134** closely matches the estimated pose P_e, the robot **100** may proceed with attempting to dock at the charging station **20**. The docking station map **202** generated by the map generator **220** may include the status designation of valid or invalid for the charging stations **20** of the docking station map **202**. Thus, the docking system **200** may determine whether the status of each charging station **20** is valid or invalid and indicate the determined status of valid or invalid with the associated charging station **20** in the generated docking station map **202**. When the docking station map **202** is then later queried by the robot **100**, the robot **100** may know whether the status of a charging station **20** is valid or invalid and determine whether to attempt docking at the charging station **20** based on the status designation.

[0057] For example, FIGS. **2**E-**2**G illustrate the status indications of valid and invalid for a charging station **20**. In FIG. **2**E, a rendering of the docking station map **202**, similar to the high level rendering of FIG. **2**D, indicates knowledge of four charging stations **20** and their respective status indicators. Three charging stations are designated in the docking station map **202** as valid charging stations **20**V that the robot **100** may attempt to dock with. A fourth charging station **20** is designated in the docking station map **202** as an occupied or unavailable or invalid charging station **20**I because, based on sensor data **134**, it has been determined that the charging station **20** is invalid for the robot **100** to attempt to dock with. As shown in the illustrated implementation, the docking system **200** may determine that another robot **100** is docked at a charging station **20**, such as based on sensor data **134** or from a signal from the docked robot **100**, and mark that charging station **20** as an invalid charging station **20**I.

[0058] As shown in FIGS. **2**F and **2**G, the robot may, such as based on the docking station map **202** and the fiducial **26** for a given charging stations **20**, identify a charging station **20** in the environment **10** and the valid or invalid status indicator of the charging station **20**. FIGS. **2**F and **2**G represent example graphical user interfaces (GUIs) **400** that display images viewable by a user, the images representative of sensor data **134** captured by one or more sensors **132** at the robot **100**, so that, for example, the user may monitor maneuvers of the robot **100** or view the environment **10** about the robot **100**. The GUI **400** may display a status indicator **402** for a given charging station **20**, such as a valid status indicator **402**V or an invalid status indicator **402**I. For example, in FIG. **2**F, the robot **100** identifies, based on the docking station map **202**, the presence of two valid charging stations **20**V and one invalid charging station **20**I and the GUI **400** accordingly displays appropriate status indicators **402** at the position in the image corresponding to the respective charging stations **20**. In FIG. **2**G, the robot **100** identifies, based on the docking station map **202**, the presence of one invalid charging station **20**I and the GUI **400** displays the appropriate invalid status indicator **402**I.

[0059] In some configurations, the docking system **200** may use the geometry of the known charging station **20** and from this geometry generate a fake three-dimensional point cloud representing that geometry. With this approach, the fake point cloud is in a similar data format as to the sensor data **134**. Since both the fake point cloud and the sensor data **134** are in the same data format, the docking system **200** may perform a search of the actual sensor data **134** to locate the actual charging station **20**. For example, the docking system **200** uses an iterative closest points (ICP) algorithm to process the comparison between the fake point cloud representing the known geometry of the charging station **20** and the actual point cloud from the actual sensor data **134** sensed by the robot **100**. In some implementations, the docking system **200** narrows the search space by using fiducial detection to understand a general vicinity for the charging station **20**. In some configurations, the docking system **200** transforms the fake data and actual data to a camera-independent view by converting the actual sensor data **134** and the fake sensor data into a top-down view.

[0060] Additionally or alternatively, the robot **100** may use the docking station map **202** to perform a power-off sequence when docked on the charging station **20**. That is, the robot **100** may perform a power-off sequence after the robot **100** lowers its body **110** onto the one or more terminal contacts **22**T of the one or more alignment towers **22**A. For instance, the robot **100** may power-off and be wholly supported by the one or more alignment towers **22**A such that the legs **120** of the robot **100** are suspended from the robot **100** and no longer in contact with the ground surface **14**. In this instance, the power-off sequence may slowly reduce pressure at the feet **124** of the robot **100** (e.g., until all contact force at the feet **124** has been eliminated). When performing this power-off sequence, the robot **100** may be sensing its surroundings (i.e., generating and interpreting sensor data **134**) to determine if there are any issues during the sequence. Namely, if the robot **100** is slightly misaligned with towers **22**A or contact terminals **22**T, this power-off sequence may decouple the charging connection between the robot **100** and the charging station **20** or worse cause the robot **100** to roll (or pitch or yaw) and fall off of the tower **22**A. To prevent some of these issues, the robot **100** may use the docking station map **202** to provide the robot **100** with an understanding of its relationship with the charging station **20** during the power-off sequence. For instance, the robot **100** compares sensor data **134** received during the power-off sequence to terrain information or other details from the docking station map **202**.

[0061] FIG. **3** is a flowchart of an example arrangement of operations for a method **300** of controlling the legged robot **100** to identify the docking station **20** and adjust the pose P of the legged robot **100** for the docking station **20**. The method **300** may be a computer implemented method executed by data processing hardware **142** of the legged robot **100**, which causes the data processing hardware **142** to perform operations. At operation **302**, the method **300** includes receiving sensor data **134** corresponding to an area comprising at least a portion of a docking station **20**. The method **300**, at operation **304**, includes determining an estimated pose Pc for the docking station **20** based on an initial pose P of the legged robot **100** relative to the docking station **20**. At operation **306**, the method **300** includes identifying one or more docking station features **22** from the received sensor data **134** corresponding to the area comprising at least the portion of the docking station **20**. The method **300** further includes, at operation **308**, matching the one or more identified docking station features **22** to one or more known docking station features **22**. At operation **310**, the method **300** includes adjusting the estimated pose Pc for the docking station **20** to a corrected pose Pc for the docking station **20** based on an orientation of the one or more identified docking station features **22** that match the one or more known docking station features **22**.

[0062] FIG. **4** is schematic view of an example computing device **400** that may be used to implement the systems and methods described in this document. The computing device **400** is intended to represent various forms of digital computers, such as laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit implementations of the inventions described and/or claimed in this document.

[0063] The computing device **400** includes a processor **410** (e.g., data processing hardware **142**, **162**), memory **420** (e.g., memory hardware **144**, **164**), a storage device **430**, a high-speed interface/controller **440** connecting to the memory **420** and high-speed expansion ports **450**, and a low speed interface/controller **460** connecting to a low speed bus **470** and a storage device **430**. Each of the components **410**, **420**, **430**, **440**, **450**, and **460**, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor **410** can process instructions for execution within the computing device **400**, including instructions stored in the memory **420** or on the storage device **430** to display graphical information for a graphical user interface (GUI) on an external input/output device, such as display **480** coupled to high speed interface **440**. In other implementations, multiple processors and/or multiple buses may be used, as appropriate, along with multiple memories and types of memory. Also, multiple computing devices **400** may be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

[0064] The memory **420** stores information non-transitorily within the computing device **400**. The memory **420** may be a computer-readable medium, a volatile memory unit(s), or non-volatile memory unit(s). The non-transitory memory **420** may be physical devices used to store programs (e.g., sequences of instructions) or data (e.g., program state information) on a temporary or permanent basis for use by the computing device **400**. Examples of non-volatile memory include, but are not limited to, flash memory and read-only memory (ROM)/programmable read-only memory (PROM)/erasable programmable read-only memory (EPROM)/electronically erasable programmable read-only memory (EEPROM) (e.g., typically used for firmware, such as boot programs). Examples of volatile memory include, but are not limited to, random access memory (RAM), dynamic random access memory (DRAM), static random access memory (SRAM), phase change memory (PCM) as well as disks or tapes.

[0065] The storage device **430** is capable of providing mass storage for the computing device **400**. In some implementations, the storage device **430** is a computer-readable medium. In various different implementations, the storage device **430** may be a floppy disk device, a hard disk device, an optical disk device, or a tape device, a flash memory or other similar solid state memory device, or an array of devices, including devices in a storage area network or other configurations. In additional implementations, a computer program product is tangibly embodied in an information carrier. The computer program product contains instructions that, when executed, perform one or more methods, such as those described above. The information carrier is a computer- or machine-readable medium, such as the memory **420**, the storage device **430**, or memory on processor **410**.

[0066] The high speed controller **440** manages bandwidth-intensive operations for the computing device **400**, while the low speed controller **460** manages lower bandwidth-intensive operations. Such allocation of duties is exemplary only. In some implementations, the high-speed controller **440** is coupled to the memory **420**, the display **480** (e.g., through a graphics processor or accelerator), and to the high-speed expansion ports **450**, which may accept various expansion cards (not shown). In some implementations, the low-speed controller **460** is coupled to the storage device **430** and a low-speed expansion port **470**. The low-speed expansion port **470**, which may include various communication ports (e.g., USB, Bluetooth, Ethernet, wireless Ethernet), may be coupled to one or more input/output devices, such as a keyboard, a pointing device, a scanner, or a networking device such as a switch or router, e.g., through a network adapter.

[0067] The computing device **400** may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a standard server **400***a* or multiple times in a group of such servers **400***a*, as a laptop computer **400***b*, or as part of a rack server system **400***c*.

[0068] Various implementations of the systems and techniques described herein can be realized in digital electronic and/or optical circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

[0069] These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the terms "machine-readable medium" and "computer-readable medium" refer to any computer program product, non-transitory computer readable medium, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term "machine-readable signal" refers to any signal used to provide machine instructions and/or data to a programmable processor.

[0070] The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit). Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read only memory or a random access memory or both. The essential elements of a computer are a processor for performing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto optical disks, or optical disks. However, a computer need not have such devices. Computer readable media suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto optical disks; and CD ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0071] To provide for interaction with a user, one or more aspects of the disclosure can be implemented on a computer having a display device, e.g., a CRT (cathode ray tube), LCD (liquid crystal display) monitor, or touch screen for displaying information to the user and optionally a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

[0072] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. Accordingly, other implementations are within the scope of the following claims.

What is claimed is:

1. A computer-implemented method when executed by data processing hardware of a legged robot causes the data processing hardware to perform operations comprising:

receiving sensor data corresponding to an area comprising at least a portion of a docking station;

determining an estimated pose for the docking station based on an initial pose of the legged robot relative to the docking station;

identifying one or more docking station features from the received sensor data corresponding to the area comprising at least the portion of the docking station;

matching the one or more identified docking station features to one or more known docking station features; and

adjusting the estimated pose for the docking station to a corrected pose for the docking station based on an orientation of the one or more identified docking station features that match the one or more known docking station features.

2. The method of claim **1**, wherein the operations further comprise instructing the legged robot to dock at the docking station using the corrected pose for the docking station.

3. The method of claim **1**, wherein the operations further comprise generating a docking station map comprising terrain information about the docking station using the corrected pose for the docking station.

4. The method of claim **3**, wherein the docking station map comprises one or more regions corresponding to a region where the legged robot should avoid touching down a respective foot of a leg of the legged robot, the one or more regions located in the area comprising at least the portion of the docking station.

5. The method of claim **3**, wherein the docking station map comprises one or more regions corresponding to a region where the legged robot should avoid moving a body of the legged robot, the one or more regions located in the area comprising at least the portion of the docking station.

6. The method of claim **3**, wherein the docking station map comprises one or more regions indicating a height of the identified docking station features, the one or more regions located in the area comprising at least the portion of the docking station.

7. The method of claim **3**, wherein the docking station map comprises a status indicator for the docking station, the status indicator based on the matching of the one or more identified docking stations features to the one or more known docking station features, and the status indicator identifying availability of the docking station.

8. The method of claim **1**, wherein the docking station comprises a respective docking station feature associated with a contact terminal for charging a battery of the legged robot.

9. The method of claim **1**, wherein the docking station comprises a respective docking station feature corresponding to an alignment tower, the alignment tower configured to support at least a portion of the legged robot when the legged robot is in a charging pose charging a battery of the legged robot at the docking station.

10. The method of claim **1**, wherein the operations further comprise identifying the initial pose of the legged robot relative to the docking station by:

detecting a fiducial associated with the docking station configured to charge a battery associated with the legged robot; and

determining the initial docking pose of the legged robot relative to the docking station based on the detected fiducial.

11. The method of claim **1**, wherein the legged robot is a quadruped.

12. A battery-powered robot comprising:

a body;

one or more legs coupled to the body;

data processing hardware; and

memory hardware in communication with the data processing hardware, the memory hardware storing instructions that when executed on the data processing hardware cause the data processing hardware to perform operations comprising:

receiving sensor data corresponding to an area comprising at least a portion of a docking station;

determining an estimated pose for the docking station based on an initial pose of the battery-powered robot relative to the docking station;

identifying one or more docking station features from the received sensor data corresponding to the area comprising at least the portion of the docking station;

matching the one or more identified docking station features to one or more known docking station features; and

adjusting the estimated pose for the docking station to a corrected pose for the docking station based on an orientation of the one or more identified docking station features that match the one or more known docking station features.

13. The battery-powered robot of claim **12**, wherein the operations further comprise instructing the battery-powered robot to dock at the docking station using the corrected pose for the docking station.

14. The battery-powered robot of claim **12**, wherein the operations further comprise generating a docking station map comprising terrain information about the docking station using the corrected pose for the docking station.

15. The battery-powered robot of claim **14**, wherein the docking station map comprises one or more regions corresponding to a region where the battery-powered robot should avoid touching down a respective foot of the one or more legs of the battery-powered robot, the one or more regions located in the area comprising at least the portion of the docking station.

16. The battery-powered robot of claim **14**, wherein the docking station map comprises one or more regions corresponding to a region where the battery-powered robot should avoid moving the body of the battery-powered robot, the one or more regions located in the area comprising at least the portion of the docking station.

17. The battery-powered robot of claim **14**, wherein the docking station map comprises one or more regions indicating a height of the identified docking station features, the one or more regions located in the area comprising at least the portion of the docking station.

18. The battery-powered robot of claim **14**, wherein the docking station map comprises a status indicator for the docking station, the status indicator based on the matching of the one or more identified docking stations features to the one or more known docking station features, and the status indicator identifying availability of the docking station.

19. The battery-powered robot of claim **12**, wherein the docking station comprises a respective docking station feature associated with a contact terminal for charging a battery of the battery-powered robot.

20. The battery-powered robot of claim **12**, wherein the docking station comprises a respective docking station feature corresponding to an alignment tower, the alignment tower configured to support at least a portion of the battery-powered robot when the battery-powered robot is in a charging pose charging a battery of the battery-powered robot at the docking station.

21. The battery-powered robot of claim **12**, wherein the operations further comprise identifying the initial pose of the battery-powered robot relative to the docking station by:

detecting a fiducial associated with the docking station configured to charge a battery associated with the battery-powered robot; and

determining the initial docking pose of the battery-powered robot relative to the docking station based on the detected fiducial.

22. The battery-powered robot of claim **12**, wherein the battery-powered robot is a quadruped.

* * * * *